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# Joint control of terrestrial gross primary productivity by plant phenology and physiology

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# Joint control of terrestrial gross primary productivity by plant phenology and physiology

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**Terrestrial gross primary productivity (GPP) varies greatly over time and space. A better understanding of this variability is necessary for more accurate predictions of the future climate–carbon cycle feedback. Recent studies have suggested that variability in GPP is driven by a broad range of biotic and abiotic factors operating mainly through changes in vegetation phenology and physiological processes. However, it is still unclear how plant phenology and physiology can be integrated to explain the spatiotemporal variability of terrestrial GPP. Based on analyses of eddy–covariance and satellite-derived data, we decomposed annual terrestrial GPP into the length of the CO<sub>2</sub> uptake period (CUP) and the seasonal maximal capacity of CO<sub>2</sub> uptake (GPP<sub>max</sub>). The product of CUP and GPP<sub>max</sub> explained >90% of the temporal GPP variability in most areas of North America during 2000–2010 and the spatial GPP variation among globally distributed eddy flux tower sites. It also explained GPP response to the European heatwave in 2003 ( $r^2 = 0.90$ ) and GPP recovery after a fire disturbance in South Dakota ( $r^2 = 0.88$ ). Additional analysis of the eddy–covariance flux data shows that the interbiome variation in annual GPP is better explained by that in GPP<sub>max</sub> than CUP. These findings indicate that terrestrial GPP is jointly controlled by ecosystem-level plant phenology and photosynthetic capacity, and greater understanding of GPP<sub>max</sub> and CUP responses to environmental and biological variations will, thus, improve predictions of GPP over time and space.**

ecosystem carbon uptake | growing season length | photosynthetic capacity | spatiotemporal variability | climate extreme

Large variability exists among estimates of terrestrial carbon sequestration, resulting in substantial uncertainty in modeled dynamics of atmospheric CO<sub>2</sub> concentration and predicted future

climate change (1). The variability in carbon sequestration is partially caused by variation in terrestrial gross primary productivity (GPP) (2), which is the cumulative rate over time of gross plant

## Significance

**Terrestrial gross primary productivity (GPP), the total photosynthetic CO<sub>2</sub> fixation at ecosystem level, fuels all life on land. However, its spatiotemporal variability is poorly understood, because GPP is determined by many processes related to plant phenology and physiological activities. In this study, we find that plant phenological and physiological properties can be integrated in a robust index—the product of the length of CO<sub>2</sub> uptake period and the seasonal maximal photosynthesis—to explain the GPP variability over space and time in response to climate extremes and during recovery after disturbance.**

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The authors declare no conflict of interest.

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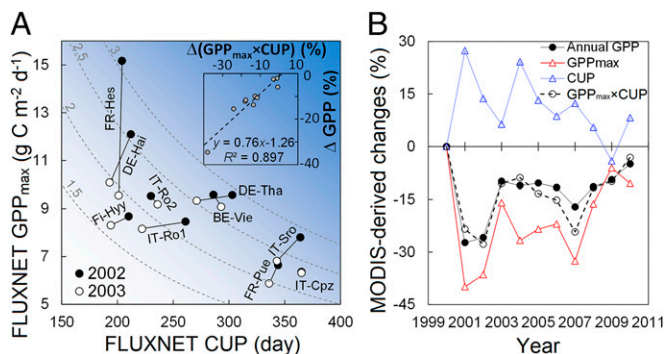
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Caribbean region and California (Fig. 1B). Spatially, across all FLUXNET sites, although there was no relationship between CUP and  $GPP_{max}$  (SI Appendix, Fig. S1),  $CUP \times GPP_{max}$  explained >95% of the spatial variation of annual observed GPP in all biomes (all  $P < 0.001$ ) (Fig. 1C and D).

The product of CUP and  $GPP_{max}$  also explains the impact of a climate extreme on ecosystem  $CO_2$  uptake. Linear regression analysis showed that the GPP reduction caused by the European heatwave in 2003 (12) across FLUXNET sites was well-explained by  $CUP \times GPP_{max}$  ( $R^2 = 0.90$ ,  $P < 0.001$ ) (Fig. 2A, Inset). However, CUP and  $GPP_{max}$  played different roles in heatwave-induced GPP reduction among sites. For example, the reduction in annual GPP mainly resulted from a decrease of  $GPP_{max}$  (−37%) for a beech forest in Sarrebourg, France but a shortening of CUP (−11%) for a spruce site in Tharandt, Germany (Fig. 2A).

We also analyzed the dynamics of satellite-derived annual GPP, CUP, and  $GPP_{max}$  during recovery from a wildfire that occurred on August 24, 2000 in the Black Hills National Forest in South Dakota (24) (SI Appendix, Fig. S2). Although  $GPP_{max}$  and CUP followed contrasting postfire trajectories, the recovery trajectory of annual GPP was well-captured by the product of CUP and  $GPP_{max}$  ( $R^2 = 0.88$ ,  $P < 0.001$ ) (Fig. 2B). Immediately after the fire, GPP was sharply reduced by 27% in 2001 (624 g C m<sup>−2</sup> y<sup>−1</sup>) and 26% in 2002 (636 g C m<sup>−2</sup> y<sup>−1</sup>) relative to GPP before the disturbance in 2000 (858 g C m<sup>−2</sup> y<sup>−1</sup>). Thereafter, annual GPP gradually recovered to 816 g C m<sup>−2</sup> y<sup>−1</sup> in 2010 (Fig. 2B). The dynamics of  $GPP_{max}$  after the fire paralleled those of annual GPP, with 40% and 36% reduction in 2001 and 2002, respectively, and then gradual recovery to 89% of prefire levels in 2010. In contrast, the CUP was extended by 30 to 60 days from 2000 (219 d) and then gradually shortened and returned to predisturbance values (Fig. 2B). The rapid extension of the CUP may have resulted from the return of grass in spring after fire disturbance (25).



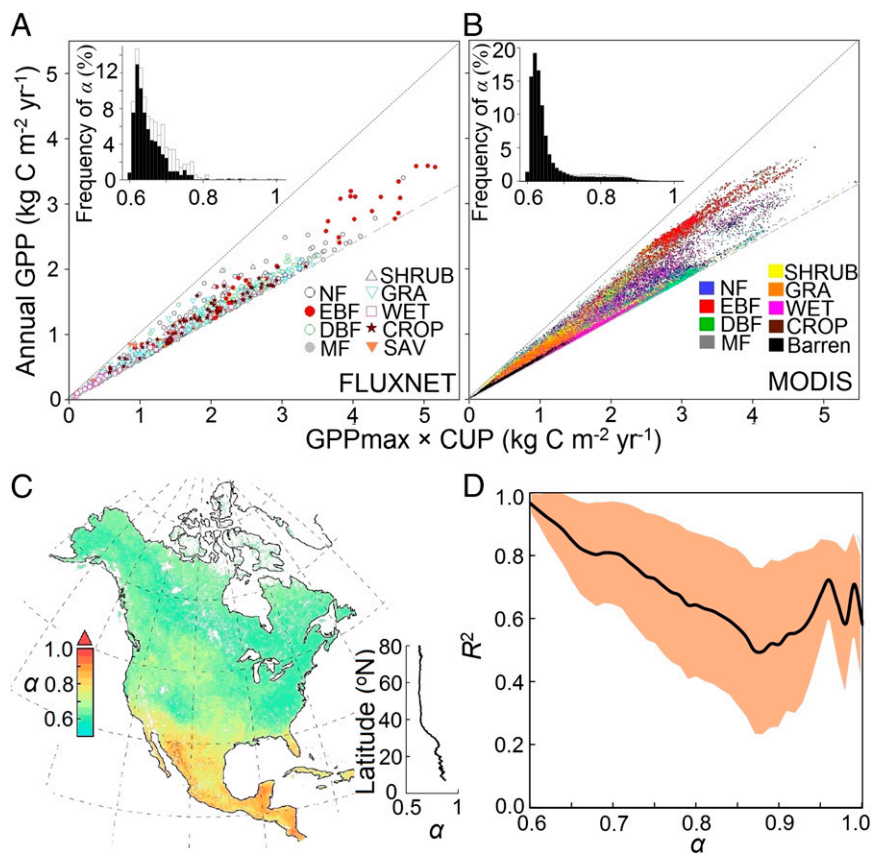
**Fig. 2.** Applications of the convergence of  $\alpha$  (the ratio between annual GPP and  $GPP_{max} \times CUP$ ) to explain GPP response to and recovery from disturbances. (A) Determination of the annual GPP reduction during the European heatwave in 2003 (12) by  $GPP_{max}$  and CUP. The dashed hyperbolic curves represent constant values (shown near the curves) of  $GPP_{max} \times CUP$  (kilograms C meter<sup>−2</sup> year<sup>−1</sup>), and the darker background blue color means a larger  $GPP_{max} \times CUP$ . Inset shows the dependences of the relative changes in annual GPP ( $\Delta GPP$ ; percentage) in 2003 from those in 2002 on the relative changes in  $GPP_{max} \times CUP$  ( $\Delta(GPP_{max} \times CUP)$ ; percentage; black circles). The ten sites are: BE-Vie (Vielsalm, Belgium), DE-Hai (Hainich, Germany), DE-Tha (Tharandt, Germany), FI-Hyy (Hyytiälä, Finland), FR-Hes (Hesse Forest- Sarrebourg, France), FR-Pue (Puechabon, France), IT-Cpz (Castelporziano, Italy), IT-Ro1 and IT-Ro2 (Roccarespanpani, Italy), IT-Sro (San Rossore, Italy). Detailed information about each FLUXNET site can be found in SI Appendix, Fig. S9 and Table S1. (B) Contrasting dynamics of  $GPP_{max}$  and CUP after an extensive wildfire in the Black Hills National Forest in South Dakota. The data were extracted from a burned  $0.1^\circ \times 0.1^\circ$  grid cell ( $43.85^\circ$  N,  $103.95^\circ$  W) (original data are plotted in SI Appendix, Fig. S2). The ratio  $\alpha$  was close to 0.62 during the 11-y span (SI Appendix, Fig. S10).

Not only did the product of CUP and  $GPP_{max}$  capture the variability in annual GPP over space and time and after disturbances, but the ratio  $\alpha$  between annual GPP and  $CUP \times GPP_{max}$  also converged across a broad range of vegetation types and environmental conditions (Fig. 3). The most frequent value of  $\alpha$  was 0.62, with 90% of  $\alpha$ -values falling within a range from 0.61 to 0.76 (Fig. 3A) based on an analysis of 213 FLUXNET sites. Those sites with  $\alpha > 0.76$  were mainly located in tropical and subtropical climate zones (Fig. 3A and SI Appendix, Fig. S3). The analysis of the MODIS product showed a similar convergence of  $\alpha$  over North America (Fig. 3B), with the most frequent value of 0.62 and a 90% range from 0.61 to 0.83. To explore the spatial distribution of  $\alpha$ , we mapped the mean annual GPP, CUP,  $GPP_{max}$ , and  $\alpha$  over 2000–2010. Although annual GPP, CUP, and  $GPP_{max}$  showed great spatial variability (SI Appendix, Fig. S4),  $\alpha$  was relatively constant around 0.62 in most areas at a latitude of  $37^\circ$  N northward and gradually approached 1.0 toward the tropical regions of North America (Fig. 3C). Across North America, the temporal linear correlation between  $CUP \times GPP_{max}$  and annual GPP was the highest in regions with  $\alpha$  around 0.62 and gradually reduced with the ratio  $\alpha$  approaching 1.0 (Fig. 3D).

High  $\alpha$ -values were mainly distributed in tropical evergreen forest and regions with multiple growing seasons, where  $GPP_{max}$  and CUP exert weak controls over GPP variability (Fig. 3A, Inset). Values of  $\alpha$  were high in tropical evergreen ecosystems, because GPP seasonality and amplitude were minimal, with plants assimilating  $CO_2$  all year round. For example, daily GPP varied minimally across seasons in a tropical rain forest in Brazil (SI Appendix, Fig. S1.3.1), with  $\alpha$  ranging between 0.77 and 0.80 from 2001 to 2003. The nontropical regions with high  $\alpha$ -values usually have two or more peaks of daily GPP within a single year. For example, the Le Bray site in France, which is comprised of a maritime pine forest, had two separate GPP peaks in late May and September of 2005 (SI Appendix, Fig. S5). This phenomenon may also occur in Mediterranean regions with hot and dry summers (26) or double/triple cropping systems, where two or more crops are grown within a single year, such as winter wheat during winter and maize during summer in the North China Plain (27). Seasonally water-limited regions where two growing season peaks are present are widely distributed in the southern part of North America, leading to an abrupt increase in  $\alpha$  at latitudes lower than about  $30^\circ$  N (Fig. 3C).

The decomposition of annual GPP into  $GPP_{max}$  and CUP allowed us to investigate the relative importance of  $GPP_{max}$  and CUP individually in regulating annual GPP variability among/within biomes (Fig. 4A). The linear correlation analysis across eight noncrop biomes showed that the biome-level GPP variability was significantly correlated to the variations in both  $GPP_{max}$  ( $r^2 = 0.79$ ,  $P = 0.003$ ) (Fig. 4B) and CUP ( $r^2 = 0.64$ ,  $P = 0.017$ ) (Fig. 4C). The partial correlation analysis across noncrop biomes revealed a larger contribution of  $GPP_{max}$  (partial  $r^2 = 0.78$ ,  $P = 0.004$ ) than CUP (partial  $r^2 = 0.21$ ,  $P < 0.001$ ) to GPP variability. A more important role of  $GPP_{max}$  than CUP in explaining the spatial variability of FLUXNET GPP was found within most biome types, including grassland (partial  $r^2 = 0.70$ ,  $P = 0.005$ ), shrubland (partial  $r^2 = 0.52$ ,  $P = 0.005$ ), savanna (partial  $r^2 = 0.89$ ,  $P = 0.001$ ), wetland (partial  $r^2 = 0.91$ ,  $P < 0.001$ ), and all forest types (partial  $r^2 = 0.79$ –0.87, all  $P < 0.01$ ) (SI Appendix, Fig. S6 and Table S2). A recent analysis has found that temperature and precipitation changes impact the net primary productivity of woody plant ecosystems mainly through their effects on growing season length, standing biomass, and stand age (28). Thus, standing biomass and stand age might be very important determinants of  $GPP_{max}$  in forest ecosystems.

The joint control of  $GPP_{max}$  and CUP on GPP variability indicates that environmental changes influence annual GPP by simultaneously affecting vegetation phenology and photosynthetic capacity. For example, climate warming leads to greater ecosystem  $CO_2$  uptake by extending CUP in most cold regions (7, 17, 29) but could reduce ecosystem  $CO_2$  uptake when



**Fig. 3.** The relationship between annual GPP and the product of CUP and  $GPP_{\max}$  (i.e.,  $\alpha$ ) from FLUXNET and satellite-derived data. The relationship between annual GPP and  $CUP \times GPP_{\max}$  is shown across (A) all FLUXNET site-years and (B) all  $0.1^\circ \times 0.1^\circ$  land grids in North America. C shows spatial distributions of satellite-derived  $\alpha$ , and D shows the relationship between  $\alpha$  and the explanation of  $GPP_{\max} \times CUP$  on temporal variability of annual GPP ( $R^2$ ) (Fig. 1B) in North America. A, Inset and B, Inset show the relative frequency distribution of estimated  $\alpha$  from all FLUXNET site-years and MODIS GPP data, respectively. The white bars are data from tropical and subtropical climate (including Mediterranean) zones and site-years with multiple GPP peaks, whereas the black bars are data from the rest of the site-years. C, Inset shows the latitudinal pattern of  $\alpha$  with a  $0.1^\circ$  interval. CROP, cropland; DBF, deciduous broadleaf forest; EBF, evergreen broadleaf forest; GRA, grassland; NF, needleleaf forest; MF, mixed forest; SAV, savanna; SHRUB, shrubland; WET, wetland.

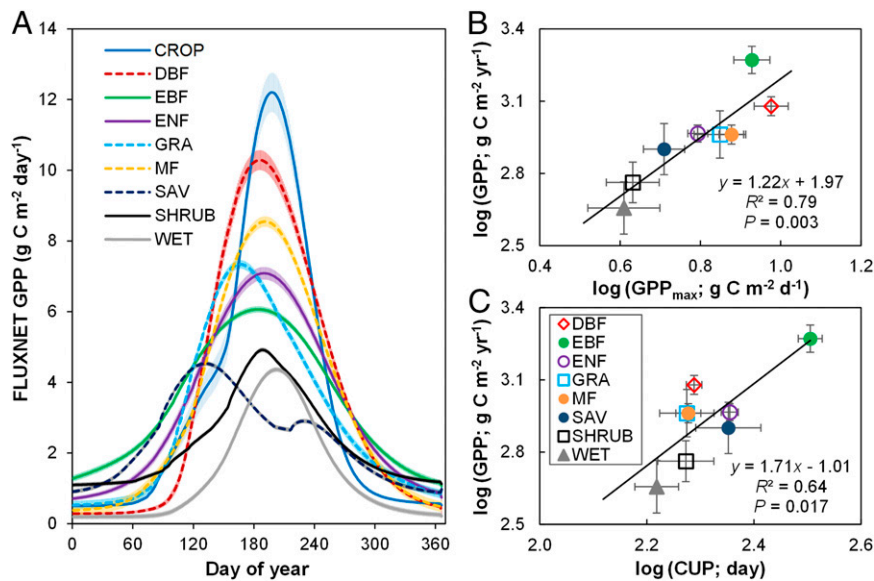
the  $GPP_{\max}$  is suppressed by the reduced snow melt water in spring (30, 31). Similarly, a recent analysis showed that warming-induced earlier springs reduced summer peak productivity during 1982–2008 in the North American boreal forests (32), which may have contributed to the declining trend of vegetation productivity associated with the climatic warming at northern high latitudes in the past few decades (33).

Given that simulated global GPP and its sensitivity to environmental factors vary substantially among current terrestrial biosphere models (13, 34), the findings in this study suggest that such uncertainty could largely stem from the different representations of vegetation phenology and photosynthetic capacity in the models. For example, although numerous vegetation phenology models have been developed for different biomes over the past few decades (35, 36), some existing terrestrial biosphere models poorly represent vegetation phenology in North America (8). Moreover, in those models, vegetation photosynthetic capacity may be unrealistically limited by the fixed parameterization of maximum rate of carboxylation (37), with observations indicating substantial temporal and spatial variations in maximum carboxylation (38, 39). Broadly collected vegetation phenology data derived from observations (40, 41), remote sensing (42, 43), and digital repeat photography (44, 45) as well as additional mechanistic understanding of canopy photosynthetic capacity (39, 46–48) could be useful to diagnose or benchmark model performances of simulating GPP (49).

Because the  $GPP_{\max}$  and CUP estimates were derived from existing data, our approach cannot be used for GPP prediction

unless  $GPP_{\max}$  and CUP can be inferred from other indicators. We first examined whether  $GPP_{\max}$  derived from MODIS GPP data was comparable with that measured by the flux towers in North America. We found that, although the two datasets had different spatial and temporal scales, the  $GPP_{\max}$  estimates from MODIS data were close to those from FLUXNET data at most sites with low  $GPP_{\max}$  (SI Appendix, Fig. S7). The FLUXNET data had much higher  $GPP_{\max}$  than MODIS data, mainly in the cropland sites with high  $GPP_{\max}$  (SI Appendix, Fig. S7). In addition to FLUXNET data, the maximum monthly sun-induced chlorophyll fluorescence data could be useful to estimate  $GPP_{\max}$  globally (50). We also examined whether the MODIS-derived CUP can be inferred from other types of satellite-derived datasets, such as the daily record of freeze/thaw status across North America (SI Appendix, section 1.8). We found that the MODIS-derived CUP is strongly correlated with the photosynthetically active period estimated from the freeze/thaw status data at most latitudes (SI Appendix, Fig. S8). The freeze/thaw status data can only provide information where the soil actually freezes in winter, partially leading to the disagreement between the two datasets in tropical regions (SI Appendix, Fig. S8). Thus, Eq. 1 could be useful for estimating and predicting annual GPP if both CUP and  $GPP_{\max}$  can be inferred from biotic and abiotic drivers measured at a global scale, the topic of a substantial body of ongoing research (15, 51).

In summary, we found a simple proximate cause to explain variation in annual GPP (i.e., Eq. 1) over space and time, in response to a climate extreme, and during recovery after disturbance.



**Fig. 4.** (A) Dynamic of daily GPP in different biomes based on the FLUXNET dataset. The curves are obtained by averaging daily GPP over all site-years of each biome type, with the shaded areas representing SEs on GPP. *B* and *C* show dependence of annual FLUXNET GPP variability on  $GPP_{max}$  and CUP, respectively, among biomes. Note that cropland was excluded in the correlation analyses. Note that there were, in total, 12 EBF sites in this analysis, and 7 of them were distributed in the temperate zone according to the MODIS IGBP (International Geosphere-Biosphere Programme) land cover classification ([glcf.umd.edu/data/lc/](http://glcf.umd.edu/data/lc/)) (*SI Appendix, Table S1*). CROP, cropland; DBF, deciduous broadleaf forest; EBF, evergreen broadleaf forest; ENF, evergreen needleleaf forest; GRA, grassland; MF, mixed forest; SAV, savanna; SHRUB, shrubland; WET, wetland.

The representation of interannual and spatial variations in GPP by the product of CUP and  $GPP_{max}$  was strong in those ecosystems with  $\alpha$ -values close to 0.62 but weaker toward the tropics or in seasonally water-limited regions, where  $\alpha$ -values approached 1.0. The strong correlation of annual GPP with the product of CUP and  $GPP_{max}$  in several different ecosystem types may be useful in detecting shifts in vegetation state and for monitoring short- and long-term response of GPP to extreme climate conditions and disturbances. Given that  $GPP_{max}$  better explains GPP variability than CUP, future studies need to emphasize the regulatory mechanisms for the dynamics of ecosystem photosynthetic capacity in terrestrial ecosystems.

## Materials and Methods

GPP estimates (positive GPP means  $CO_2$  uptake) from 213 FLUXNET sites from the La Thuile Database ([www.fluxdata.org/default.aspx](http://www.fluxdata.org/default.aspx)) (*SI Appendix, Table S1*) and the MODIS aboard National Aeronautics and Space Administration Terra satellites (MOD17A2 GPP) (23) were used in the analyses (*SI Appendix, section S1.1*). For FLUXNET sites, only those site-years with  $>300$  daily estimates were chosen from the database. Because the MODIS GPP product was well-evaluated in North America (52), we only performed our analysis on MODIS GPP in this region from 2000 to 2010.

The determinations of CUP and  $GPP_{max}$  were from the method introduced by Gu et al. (53, 54) (*SI Appendix, section S1.2*). The CUP,  $GPP_{max}$ , and the ratio between annual GPP and  $CUP \times GPP_{max}$  (i.e.,  $\alpha$ ) were estimated for each selected FLUXNET site and each  $0.1^\circ \times 0.1^\circ$  land grid cell of the MODIS product by the following steps (*SI Appendix, section S1.3*). (i) We judged if the site-year or grid cell is evergreen or not by counting the number of days with larger daily GPP than a given value ( $\alpha$  site or land grid cell was defined as evergreen if there were more than 360 d with daily GPP  $> 1 \text{ g C m}^{-2} \text{ d}^{-1}$  within 1 y). (ii) The number of seasons in the non-evergreen site-years or land grid cells was determined by a model function (*SI Appendix, section S1.3 and Eq. S6*) suggested by the TIMESAT software (55). For those site-years and grid cells with one season, we fitted a five-parameter Weibull function to the data from that year. For those site-years or land grid cells with more than one season, we fitted the Weibull function to each season.

The nonlinear data fitting was performed with the function nls in R ([www.r-project.org/](http://www.r-project.org/)) (*SI Appendix, section S1.4*). The robustness of the method was carefully validated by various approaches, including an evaluation with the data from all long-term FLUXNET sites (*SI Appendix, section S1.5*), a parameter sensitivity analysis of the Weibull function (*SI Appendix, section S1.6*), and a

random resampling test of the Weibull function (*SI Appendix, section S1.7*). Linear regression analysis was used to examine the contribution of  $CUP \times GPP_{max}$  to the temporal and spatial variations of annual GPP. The global daily record of landscape freeze/thaw data from January 1, 2000 to December 31, 2010 was analyzed for an additional indicator of CUP (*SI Appendix, section S1.8*).

To further identify the relative contribution of  $GPP_{max}$  and CUP to GPP variability, we first linearized Eq. 1 by replacing all variables with their logarithms (base 10) as

$$\log(\text{GPP}) = \log(\alpha) + \log(\text{CUP}) + \log(\text{GPP}_{max}). \quad [2]$$

Then, we applied the partial correlation analysis to examine the relative contributions of CUP and  $GPP_{max}$  to FLUXNET GPP variability among and within biomes.

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- Graven HD, et al. (2013) Enhanced seasonal exchange of CO<sub>2</sub> by northern ecosystems since 1960. *Science* 341(6150):1085–1089.
- Jung M, et al. (2012) Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *J Geophys Res Biogeosci* 116:G00J07.
- Farquhar GD, von Caemmerer S, Berry JA (1980) A biochemical model of photosynthetic CO<sub>2</sub> assimilation in leaves of C<sub>3</sub> species. *Planta* 149(1):78–90.
- Collatz GJ, Ribas-Carbo M, Berry J (1992) Coupled photosynthesis-stomatal conductance model for leaves of C<sub>4</sub> plants. *Funct Plant Biol* 19(5):519–538.
- Reich PB, Walters MB, Ellsworth DS (1992) Leaf life-span in relation to leaf, plant, and stand characteristics among diverse ecosystems. *Ecol Monogr* 62(3):365–392.
- Cramer W, et al. (1999) Comparing global models of terrestrial net primary productivity (NPP): Overview and key results. *Glob Chang Biol* 5(51):1–15.
- Xia JY, et al. (2014) Terrestrial carbon cycle affected by non-uniform climate warming. *Nat Geosci* 7(3):173–180.
- Richardson AD, et al. (2012) Terrestrial biosphere models need better representation of vegetation phenology: Results from the North American Carbon Program Site Synthesis. *Glob Chang Biol* 18(2):566–584.
- Bellenger H, Guilyardi E, Leloup J, Lengaigne M, Vialard J (2014) ENSO representation in climate models: From CMIP3 to CMIP5. *Clim Dyn* 42(7–8):1999–2018.
- Amiro BD, et al. (2010) Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *J Geophys Res Biogeosci* 115(G4):G00K02.
- Running SW (2008) Climate change. Ecosystem disturbance, carbon, and climate. *Science* 321(5889):652–653.
- Ciais P, et al. (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* 437(7058):529–533.
- Anav A, et al. (2013) Evaluating the land and ocean components of the global carbon cycling in the CMIP5 Earth System Models. *J Clim* 26:6801–6843.
- Beer C, et al. (2010) Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. *Science* 329(5993):834–838.
- Stoy PC, Trowbridge AM, Bauerle WL (2014) Controls on seasonal patterns of maximum ecosystem carbon uptake and canopy-scale photosynthetic light response: Contributions from both temperature and photoperiod. *Photosynth Res* 119(1–2):49–64.
- Xia J, Wan S (2012) The effects of warming-shifted plant phenology on ecosystem carbon exchange are regulated by precipitation in a semi-arid grassland. *PLoS ONE* 7(2):e32088.
- Piao S, Friedlingstein P, Ciais P, Viovy N, Demarty J (2007) Growing season extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades. *Global Biogeochem Cycles* 21(3):GB3018.
- Richardson AD, et al. (2010) Influence of spring and autumn phenological transitions on forest ecosystem productivity. *Philos Trans R Soc Lond B Biol Sci* 365(1555):3227–3246.
- Keenan TF, et al. (2014) Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nat Clim Chang* 4:598–604.
- Churkina G, Schimel D, Braswell BH, Xiao X (2005) Spatial analysis of growing season length control over net ecosystem exchange. *Glob Chang Biol* 11(10):1777–1787.
- Dragoni D, et al. (2011) Evidence of increased net ecosystem productivity associated with a longer vegetated season in a deciduous forest in south-central Indiana, USA. *Glob Chang Biol* 17(2):886–897.
- FLUXNET Synthesis Dataset (La Thuile 2007). Available at [www.fluxdata.org/default.aspx](http://www.fluxdata.org/default.aspx). Accessed January 2014.
- Heinsch FA, et al. (2003) *GPP and NPP (MOD17A2/A3) Products NASA MODIS Land Algorithm. MOD17 User's Guide*. Available at [datamirror.csdb.cn/modis/resource/doc/MOD17\\_UsersGuide.pdf](http://datamirror.csdb.cn/modis/resource/doc/MOD17_UsersGuide.pdf). Accessed November 2013.
- Xiao X, Biradar C, Wang A, Sheldon S, Chen Y (2011) Recovery of vegetation canopy after severe fire in 2000 at the Black Hills National Forest, South Dakota, USA. *J Resour Ecol* 2(2):106–116.
- Lentile LB, Smith FW, Shepperd WD (2005) Patch structure, fire-scar formation, and tree regeneration in a large mixed-severity fire in the South Dakota Black Hills, USA. *Can J For Res* 35(12):2875–2885.
- Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. *Glob Planet Change* 63(2–3):90–104.
- Liu XJ, Ju XT, Zhang FS, Pan JR, Christie P (2003) Nitrogen dynamics and budgets in a winter wheat-maize cropping system in the North China Plain. *Field Crops Res* 83(2):111–124.
- Michaletz ST, Cheng D, Kerkhoff AJ, Enquist BJ (2014) Convergence of terrestrial plant production across global climate gradients. *Nature* 512(7512):39–43.
- Schwartz MD, Ahas R, Aasa A (2006) Onset of spring starting earlier across the Northern Hemisphere. *Glob Chang Biol* 12(2):343–351.
- Sacks WJ, Schimel DS, Monson RK (2007) Coupling between carbon cycling and climate in a high-elevation, subalpine forest: A model-data fusion analysis. *Oecologia* 151(1):54–68.
- Hu J, Moore DJP, Burns SP, Monson RK (2010) Longer growing seasons lead to less carbon sequestration by a subalpine forest. *Glob Chang Biol* 16(2):771–783.
- Buermann W, Bikash PR, Jung M, Burn DH, Reichstein M (2013) Earlier springs decrease peak summer productivity in North American boreal forests. *Environ Res Lett* 8(2):024027.
- Jeong SJ, Ho CH, Kim BM, Feng S, Medvigy D (2013) Non-linear response of vegetation to coherent warming over northern high latitudes. *Remote Sens Lett* 4(2):123–130.
- Piao S, et al. (2013) Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO<sub>2</sub> trends. *Glob Chang Biol* 19(7):2117–2132.
- White MA, Thornton PE, Running SW (1997) A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochem Cycles* 11(2):217–234.
- Hodges T (1990) *Predicting Crop Phenology* (CRC, Boston).
- Bonan GB, et al. (2011) Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data. *J Geophys Res Biogeosci* 116(G2):G02014.
- Xu L, Baldocchi DD (2003) Seasonal trends in photosynthetic parameters and stomatal conductance of blue oak (*Quercus douglasii*) under prolonged summer drought and high temperature. *Tree Physiol* 23(13):865–877.
- Kattge J, Knorr W, Raddatz T, Wirth C (2008) Quantifying photosynthetic capacity and its relationship to leaf nitrogen content for global-scale terrestrial biosphere models. *Glob Chang Biol* 15(4):976–991.
- Dierenbach J, Badeck FW, Schaber J (2013) The plant phenological online database (PPODB): An online database for long-term phenological data. *Int J Biometeorol* 57(5):805–812.
- Wolkovich EM, et al. (2012) Warming experiments underpredict plant phenological responses to climate change. *Nature* 485(7399):494–497.
- Zhang X, et al. (2003) Monitoring vegetation phenology using MODIS. *Remote Sens Environ* 84(3):471–475.
- Jones MO, Jones LA, Kimball JS, McDonald KC (2011) Satellite passive microwave remote sensing for monitoring global land surface phenology. *Remote Sens Environ* 115(4):1102–1114.
- Richardson AD, et al. (2007) Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. *Oecologia* 152(2):323–334.
- Keenan TF, et al. (2014) Tracking forest phenology and seasonal physiology using digital repeat photography: A critical assessment. *Ecol Appl* 24(6):1478–1489.
- Zhang Y, et al. (2014) Estimation of vegetation photosynthetic capacity from space-based measurements of chlorophyll fluorescence for terrestrial biosphere models. *Glob Chang Biol* 20(12):3727–3742.
- Joiner J, et al. (2013) Global monitoring of terrestrial chlorophyll fluorescence from moderate spectral resolution near-infrared satellite measurements: Methodology, simulations, and application to GOME-2. *Atmos Meas Tech Discuss* 6(2):3883–3930.
- Zhu Z, et al. (2013) Global data sets of vegetation leaf area index (LAI) 3g and Fraction of Photosynthetically Active Radiation (FPAR) 3g derived from Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the period 1981 to 2011. *Remote Sens (Basel)* 5(2):927–948.
- Luo YQ, et al. (2012) A framework for benchmarking land models. *Biogeosciences* 9(10):3857–3874.
- Guanter L, et al. (2014) Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence. *Proc Natl Acad Sci USA* 111(14):E1327–E1333.
- Koster R, Walker G, Collatz G, Thornton P (2014) Hydroclimatic controls on the means and variability of vegetation phenology and carbon uptake. *J Clim* 27:5632–5652.
- Heinsch FA, et al. (2006) Evaluation of remote sensing based terrestrial productivity from MODIS using regional tower eddy flux network observations. *IEEE Trans Geosci Remote Sens* 44(7):1908–1925.
- Gu L, et al. (2003) *Phenology of Vegetation Photosynthesis. Phenology: An Integrative Environmental Science* (Springer, New York), pp 467–485.
- Gu L, et al. (2009) *Characterizing the Seasonal Dynamics of Plant Community Photosynthesis Across a Range of Vegetation Types. Phenology of Ecosystem Processes* (Springer, New York), pp 35–58.
- Eklundh L, Jönsson P (2012) *Timesat 3.1 Software Manual*.



## Supplementary Information (SI) Appendix for

### **Joint Control of Terrestrial Gross Primary Productivity by Plant Phenology and Physiology**

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**56 pages (including cover page)**

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## 85 **S1 Materials and Methods**

### 86 **S1.1 Data**

#### 87 S1.1.1 The FLUXNET La Thuile Database

88 The ecosystem-level GPP were estimated by the eddy covariance technique, a key method to

89 measure the net ecosystem-atmosphere exchange of CO<sub>2</sub>(1). The eddy covariance technique

90 provides a useful tool to study the seasonal dynamics of plant-community level

91 photosynthesis(2). We used data of gross primary productivity (GPP; positive GPP means

92 CO<sub>2</sub> uptake) from 213 FLUXNET sites from the La Thuile Database ([www.fluxdata.org](http://www.fluxdata.org),

93 Table S1) in our analyses. The database was a combination of measurements from the

94 networks Ameriflux, CarboEurope and Fluxnet-Canada, and covers the time period of 1993–

95 2006. Data of each site-year in the database was filtered according to the methods and criteria

96 in Reichstein *et al.*(3) and Papale *et al.*(4). Since the GPP data are not directly measured, they

97 include some inevitable uncertainties. The sources of those uncertainties have been widely

98 discussed by Beer *et al.*(5), Moncrieff *et al.*(6), Papale *et al.*(4), Moffat *et al.*(7) and Desai *et*  
99 *al.*(8). Since there is no phenological information in diurnal variations of CO<sub>2</sub> fixation, we  
100 used daily GPP in this study. There are some negative values for daily GPP in some site  
101 years. Only site years with more than 300 daily estimates were chosen from the database.

102

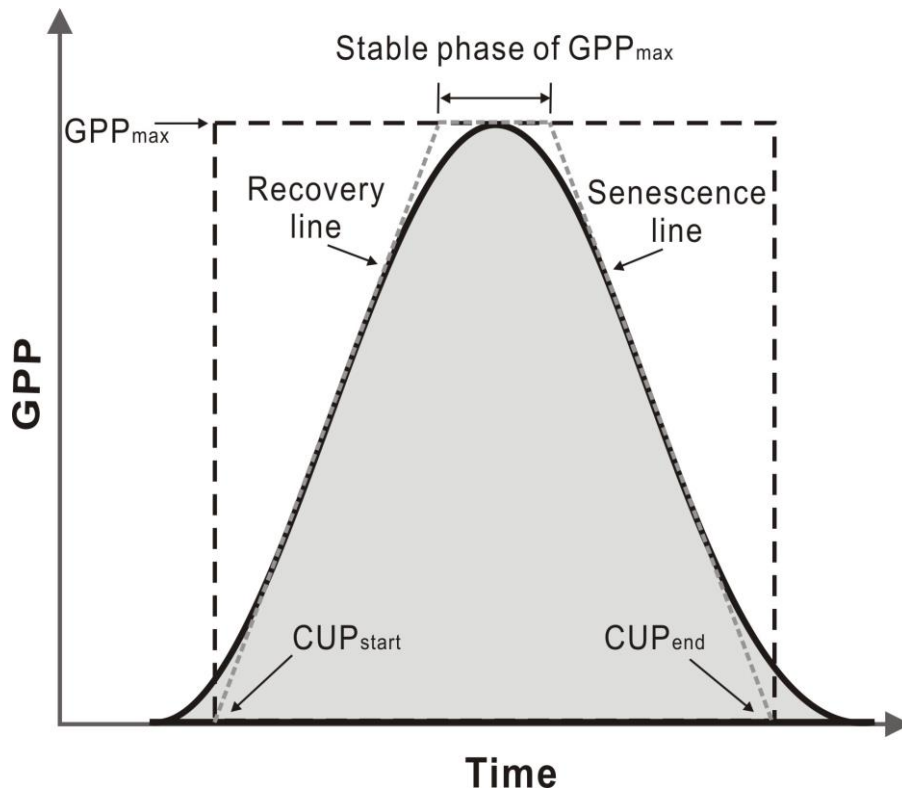
### 103 S1.1.2 MODIS GPP

104 We used the data of gross primary productivity (GPP) from the Moderate Resolution Imaging  
105 Spectroradiometer (MODIS) aboard NASA's Terra satellites (MOD17A2 GPP(9)) for North  
106 America (7.05–79.95°N, 58.55–98.85°W) during 2000-2010 in our analyses. The data set  
107 was generated by the Numerical Terradynamic Simulation Group (NTSG)/University of  
108 Montana's (UMT) as Version-55 and available from the LP DAAC(10, 11). The algorithm of  
109 MODIS GPP is described in Running *et al.*(12) and Zhao *et al.*(10). This product has  
110 considered the cloud-contamination issue while the NASA's MOD17 products (i.e., Version-  
111 5 GPP) did not. Thus, this product can avoid the underestimation in the MOD17A2-V5  
112 products (13). The accuracy of this product has been assessed by using independent  
113 measurements made in a systematic and statistically robust way and feasible for the  
114 application of scientific community. We downloaded the data and mosaicked and re-  
115 projected the data by using the MODIS Reprojection Tool. The mosaicked images were  
116 resampled into 0.1 ° × 0.1 ° by using the nearest neighbor algorithm.

117

## 118 **S1.2 Characteristics of annual GPP curve: definitions**

119 In most terrestrial ecosystems, the daily GPP throughout the whole year follows a bell-  
120 shaped curve, which can be represented by the idealized solid black line in the following  
121 figure:



122

123 **Supplementary Fig. S1.2.1. Ideal curve of seasonal GPP in terrestrial ecosystem.**

124 The shape of the above unimodal curve (Fig. S1.2.1) is determined by five consecutive  
125 phases, which are described by Gu *et al.*(14):

126 *Phase 1.* Transition stage from non-growing to growing season, with a slowly increasing  
127 GPP.

128 *Phase 2.* Recover stage with rapidly increasing GPP.

129 *Phase 3.* Stable stage in the middle of the growing season, during which the plant community  
130 keeps its maximal GPP relatively stable.

131 *Phase 4.* Senescence stage with rapidly declining GPP.

132 *Phase 5*. Transition stage from growing to non-growing season, with a slowly declining  
133 GPP.

134 The above phases of seasonal cycle of GPP include a combination of characteristics in  
135 sequence as follows:

- 136 1. ***CUP<sub>start</sub>***. The start day of CO<sub>2</sub> uptake period during a year.
- 137 2. ***Peak recovery rate of GPP***. In non-evergreen ecosystems, when plant community starts  
138 CO<sub>2</sub> fixation from the atmosphere in spring (or in newly started crops), the daily GPP rate  
139 recovers from 0 and gradually approaches its peak. The peak recovery rate of GPP can be  
140 obtained from the slope of the recovery line in Fig. S1.2.1.
- 141 3. ***GPP<sub>max</sub>***. The maximal daily GPP during the growing season.
- 142 4. ***Stable phase of GPP<sub>max</sub>***. The stable phase in which plant community keeps maximal GPP.
- 143 5. ***Peak senescence rate of GPP***. It represents the peak rate of GPP reduction during late  
144 growing season in non-evergreen ecosystems, and can be obtained from the slope of the  
145 senescence line in Fig. S1.2.1.
- 146 6. ***CUP<sub>end</sub>***. The end day of CO<sub>2</sub> uptake period during a year.

147 We define the CUP (carbon uptake period) as the number of days per year with GPP > 0.  
148 As a consequence, the CUP of an ecosystem can be calculated from CUP<sub>start</sub> and CUP<sub>end</sub>.  
149 CUP represents the duration of vegetation photosynthetic phenology, which is one of the  
150 functional aspects of plant phenology(14).

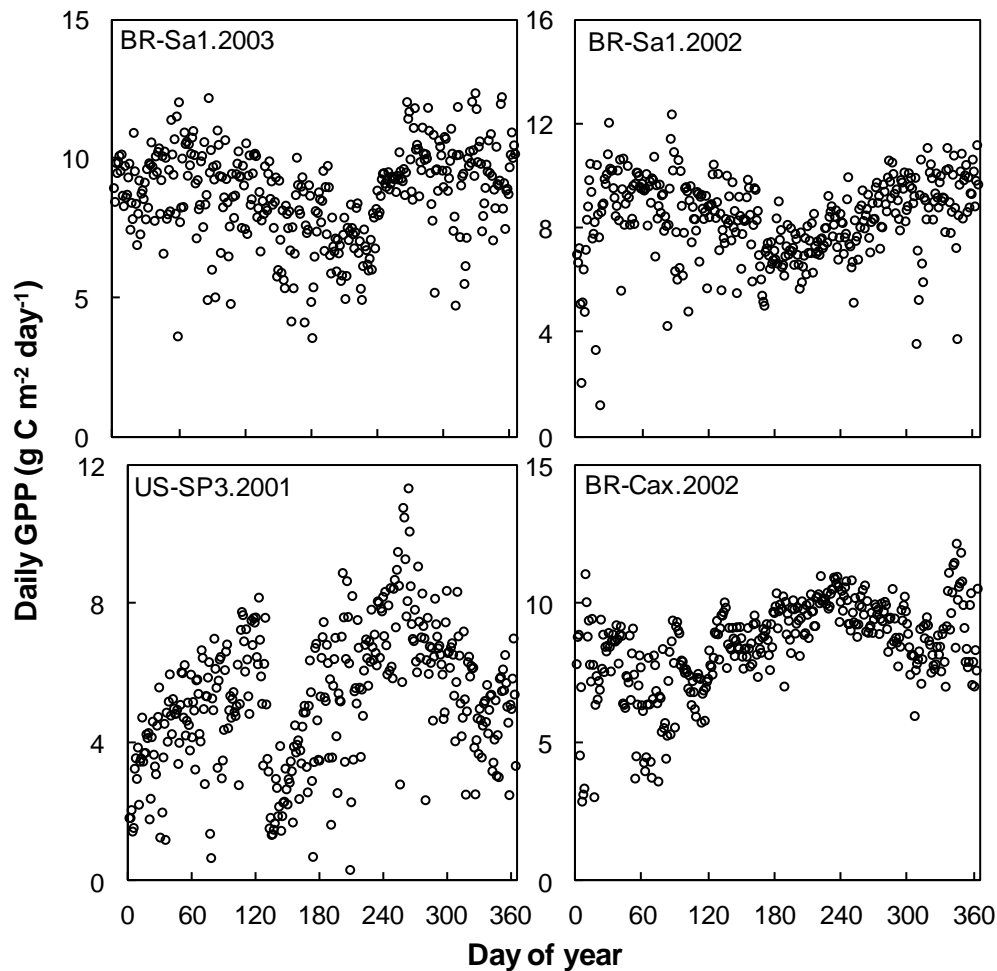
151

### 152 **S1.3 Representation of the seasonal cycle of GPP**

153 The seasonal cycle of daily GPP varies over time and across ecosystems and regions. In  
154 general, GPP seasonality in terrestrial ecosystems can be categorized into four types,  
155 including (1) one-peak during the summer-autumn growing seasons, (2) one-peak during the  
156 winter-spring seasons, (3) multiple peaks during the whole year, and (4) low seasonality such  
157 as the tropical ecosystems. Since no single function can describe the diverse GPP dynamics  
158 across the globe, we use different strategies to obtain the characteristics of annual GPP  
159 dynamics (S1.2) for each of four types of GPP seasonality above. First, we judged whether  
160 the site-year or grid cell is evergreen or not, by counting the number of days with larger daily  
161 GPP than a given value. In a second step, the number of seasons in the rest site-years or land  
162 grid cells was determined by a model function (equation 6). For those site-years and grid  
163 cells with one season, we fitted a 5-parameter Weibull function to the data from that year. For  
164 those site-years or land grid cells with more than one season, we fitted the Weibull function  
165 to each season. More details for the analyses and determinations of CUP and  $GPP_{max}$  are  
166 provided as follows:

### 167 S1.3.1. Low seasonality such as the tropical ecosystems

168 In some ecosystems, especially in tropical regions, the seasonality is low, and their CUP  
169 usually approaches 365 days (or 366 days in leap years). For example, as shown in Fig.  
170 S1.3.1, the dynamic of daily GPP in the sites of BR-Sa1, US-SP3 and BR-Cax does not  
171 include obvious recovery or senescence stages in a single year.



172

173 **Supplementary Fig. S1.3.1. Examples of evergreen site-year with low seasonality of**  
 174 **daily GPP** . The details of the sites BR-Sa1, US-SP3 and BR-Cax can be found in Table S1.

175

176 In this study, we first judge if the site-year or grid cell is evergreen or not, by counting the  
 177 number of days with larger daily GPP than a given value. Here, if there are more than 360  
 178 days with daily GPP > 1 g C m<sup>-2</sup> day<sup>-1</sup> in a site-year, the site-year is defined as evergreen with  
 179 CUP = 365 (366 for leap years). For the MODIS GPP with the 8-day interval, we obtained  
 180 daily GPP for the whole year through the linear trend between each two adjacent  
 181 observations:

182

$$GPP(i) = GPP(i) + (i - 1) \frac{GPP(i + 1) - GPP(i)}{8} \quad (1)$$



183 where  $i$  is the  $i$ th day of a given year.

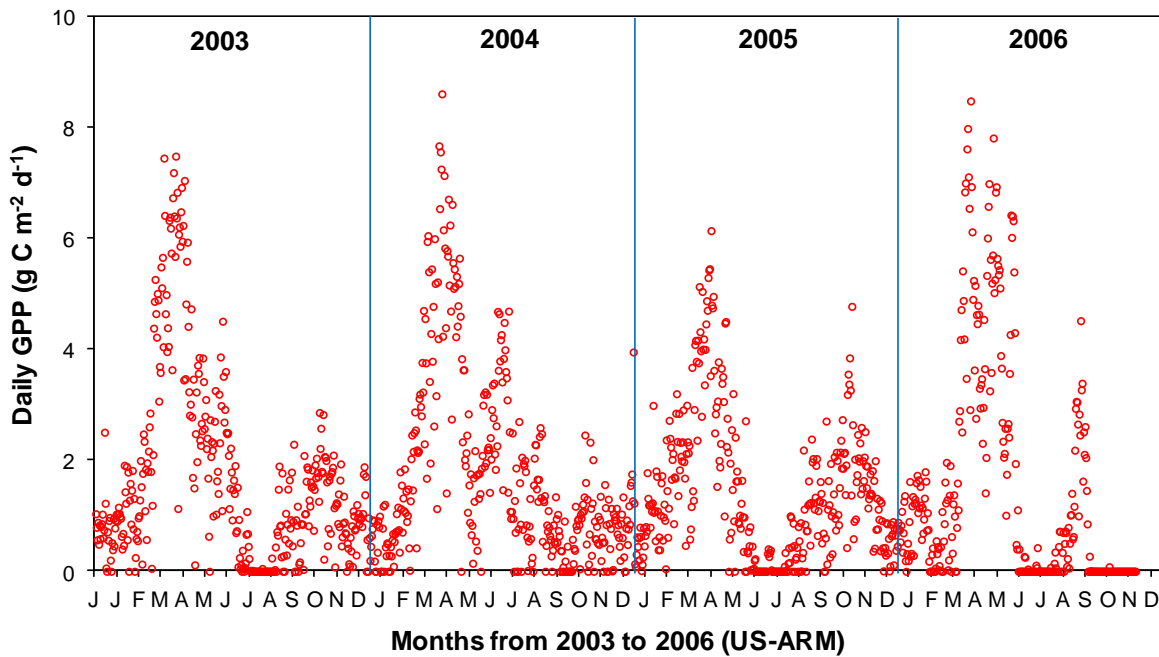
184 To get the  $GPP_{\max}$  in the whole year, we first smoothed the GPP time series using a  
185 simple moving average method, which replaces the GPP in  $i$ th day of a given year ( $GPP_i$ ,  $i =$   
186  $1, 2, \dots, N$ ) by a linear combination of nearby values in a window(15):

187 
$$\sum_{j=-n}^n c_j GPP_{i+j} \quad (2)$$

188 where  $c_j$  represents the weighted factor and equals  $1/(2n+1)$ . The data of  $GPP_i$  is replaced  
189 by the values in the window calculated by the equation (2). In this study, we choose  $n = 3$  to  
190 smooth the observed daily GPP. Then the maximal daily GPP was chosen as the  $GPP_{\max}$  in  
191 that year.

192

193 S1.3.2. Multiple peaks during the whole year

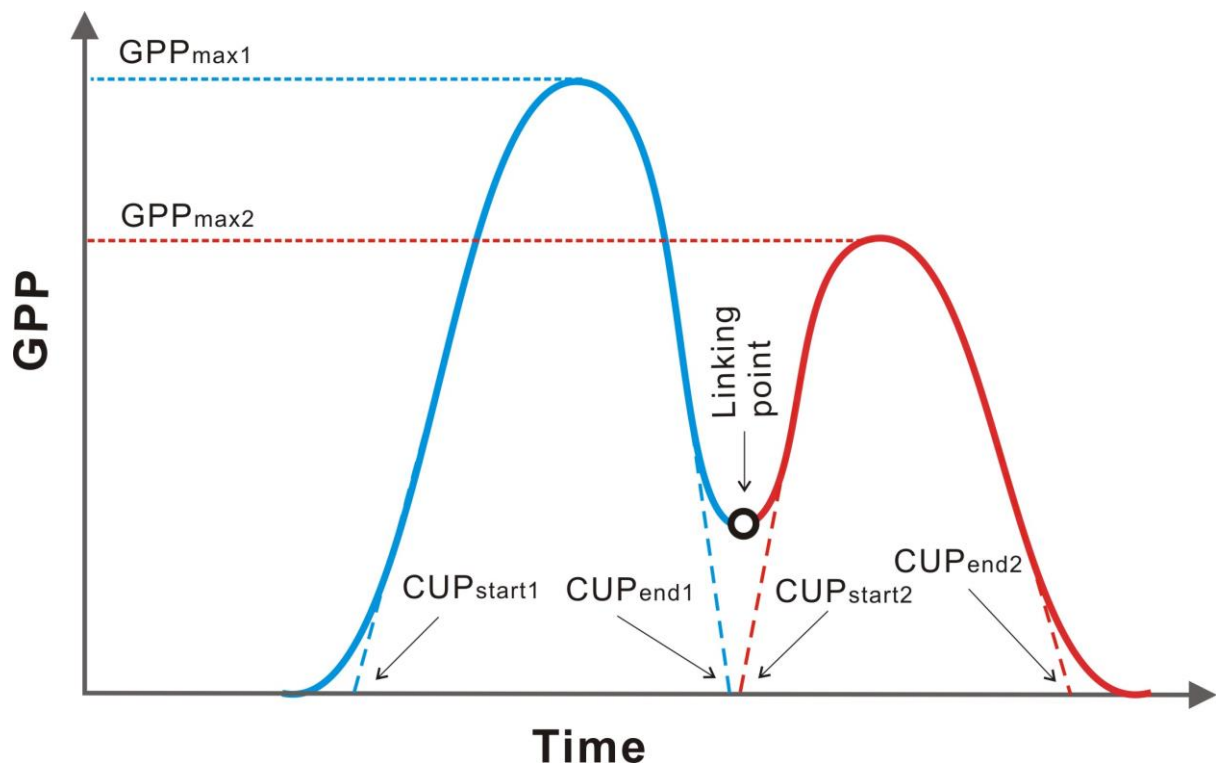


194

195 **Supplementary Fig. S1.3.2. Observed daily GPP from 2003 to 2006 in the flux site of**  
196 **US-Arm (please see its details in Table S1).** This figure shows there are mainly two peaks  
197 in this ecosystem, with one around April and the other in October. Note that the negative  
198 values from the database have been replaced by 0, and the observations after 324<sup>th</sup> day in  
199 2004 were missing in the original database.

200

201 In some ecosystems, e.g., the Mediterranean-climate regions(16), some regions in the Great  
202 Plains in the US(17) and multiple yield cropping systems(18), there are more than one  
203 vegetation peak during one year. As shown in Fig. S1.3.2, there are two peaks of daily GPP  
204 in each year in the flux site of US-Arm, with one peak occurring around April and the other  
205 in October. The multiple GPP cycles were analyzed separately with the Weibull function  
206 (see S1.3.3 and the equation 7) and their results were weighted to describe the CUP and  
207  $GPP_{max}$  in the whole year.



208

209 **Supplementary Fig. S1.3.3. Idealized curve of GPP dynamic and its characteristics in**  
 210 **sites with two peaks in a single year.** The blue and red curve respectively represent the first  
 211 and second cycle of GPP in this year.

212

213 Since sometime the two GPP cycles overlap (as shown by Fig. S1.3.3), the weighted  
 214 integration of CUP from the two GPP cycles within one year was conducted as:

$$215 \quad CUP = \begin{cases} CUP_1 + CUP_2 & \text{if no overlap between the two GPP cycles} \\ CUP_{end2} - CUP_{start1} & \text{if there is overlap between the two GPP cycles} \end{cases} \quad (3)$$

216 where  $CUP_1$  and  $CUP_2$  are the  $CO_2$  uptake period in the first and second GPP cycle,  
 217 respectively.  $CUP_{start1}$  is the initiation day of CUP for the first GPP cycle, and  $CUP_{end2}$  is the  
 218 termination day of CUP for the second GPP cycle. The weighted integration of  $GPP_{max}$  is  
 219 more complex because it depends on not only whether but also when the two GPP cycles  
 220 overlap. In this study, if there is no overlap between the two GPP cycles, the yearly  $GPP_{max}$  is  
 221 weighted as:

$$222 \quad GPP_{max} = (GPP_{max1}CUP_1 + GPP_{max2}CUP_2)/(CUP_1 + CUP_2) \quad (4)$$

223 If there is overlap between the two GPP cycles, then the yearly  $GPP_{max}$  cannot be directly  
 224 weighted as in equation 7. For these sites, we first find out the linking day ( $D_{link}$ ) between the  
 225 two GPP cycles (see the black circle in Fig. S1.3.3). Then, the weighted  $GPP_{max}$  was  
 226 calculated as:

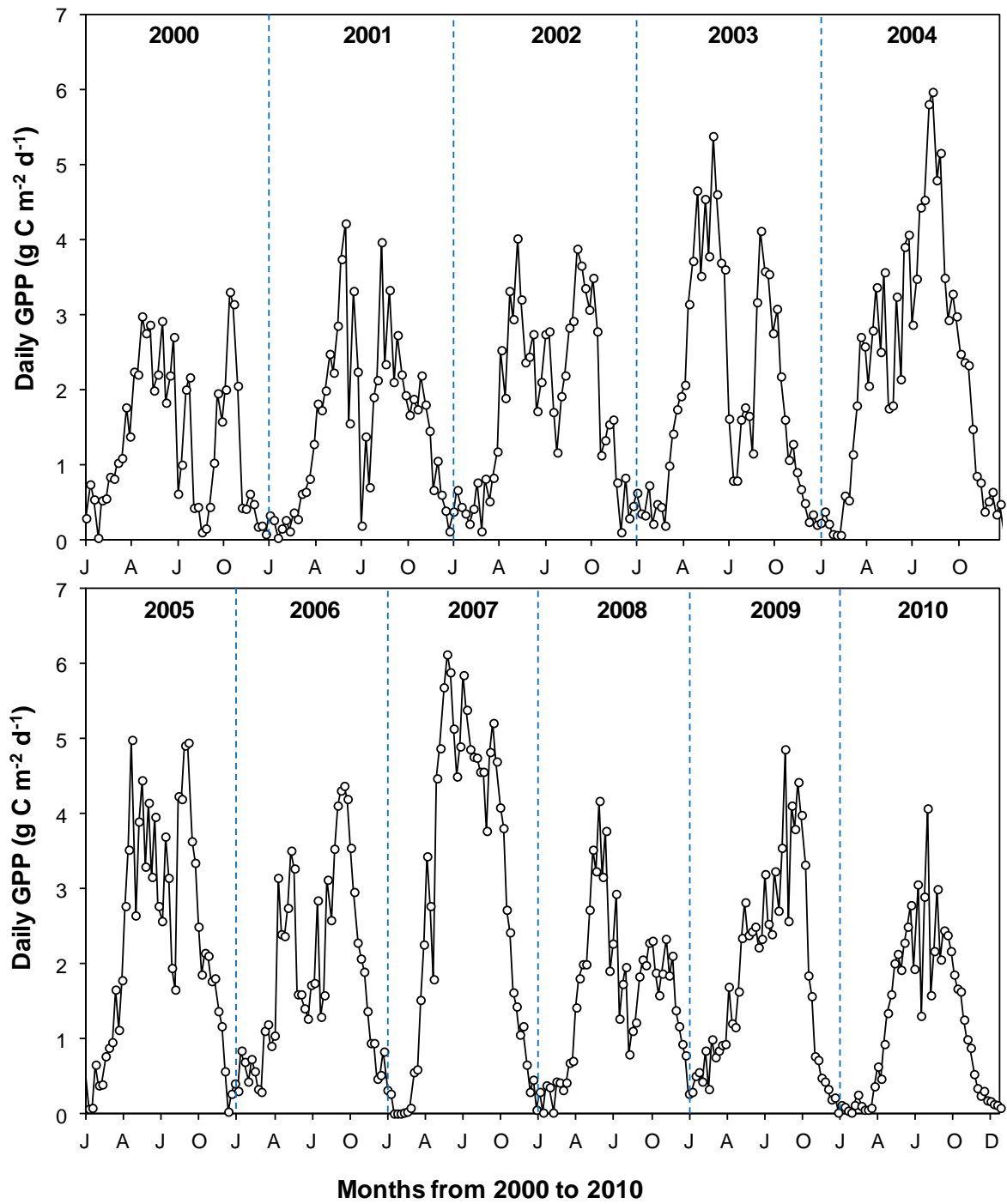
$$227 \quad GPP_{max} = \frac{GPP_{max1}(D_{link} - CUP_{start1}) + GPP_{max2}(CUP_{end2} - D_{link})}{CUP_1 + CUP_2} \quad (5)$$

228 The same strategy as the above equations has been used if there are more than two growing  
 229 seasons. Thus, one of the key steps in analyzing the GPP data in sites with multiple peaks in a  
 230 single year is to determine the number of seasons. However, the GPP observations often have

231 high-level noise (as shown by Fig. S1.3.2, S1.3.4 and S1.3.5), making it difficult to determine  
232 the number of seasons with only one year of data(19). In this study, we reduced the risk for  
233 erroneous determination of season number by triplicating the yearly GPP dynamic (see the  
234 gray circles in Fig. S1.3.5). Then, we followed the method that is used in the TIMESAT  
235 software(19), by fitting the daily GPP data  $(t_i, GPP_i)$ ,  $i = 1, 2, \dots, n$  for all 3 years (as shown  
236 in Fig. S1.3.5) to the following function:

$$237 \quad f(t) = c_1 + c_2 \sin(\omega t) + c_3 \cos(\omega t) + c_4 \sin(2\omega t) + c_4 \cos(2\omega t) \quad (6)$$

238 where  $\omega = 6\pi/n$ .  $C_1$  determines the base level, while  $c_2 \sin(\omega t) + c_3 \cos(\omega t)$  and  
239  $c_4 \sin(2\omega t) + c_4 \cos(2\omega t)$  determine the number of seasons as one and two, respectively.  
240 During the fitting, a primary maximum is always found and a secondary maximum may be  
241 found. As suggested by TIMESAT(19), the amplitude ratio between the secondary maximum  
242 and the primary maximum can be used as an index to determine the number of vegetation  
243 seasons. That is, if the ratio is below a given threshold, the ecosystem has one season during  
244 the year. In this study, we set the ratio between the secondary maximum and the primary  
245 maximum as 0.25. For example, as shown in Fig. S1.3.5, the fitted secondary and primary  
246 maximum in 2000 in the grid of N37.75°, W101.05° are 1.69 and 2.68 g C m<sup>-2</sup> d<sup>-1</sup>,  
247 respectively, and the ratio between them is 0.63. It means there are two vegetation seasons in  
248 this grid cell in 2000 (Fig. S1.3.5).



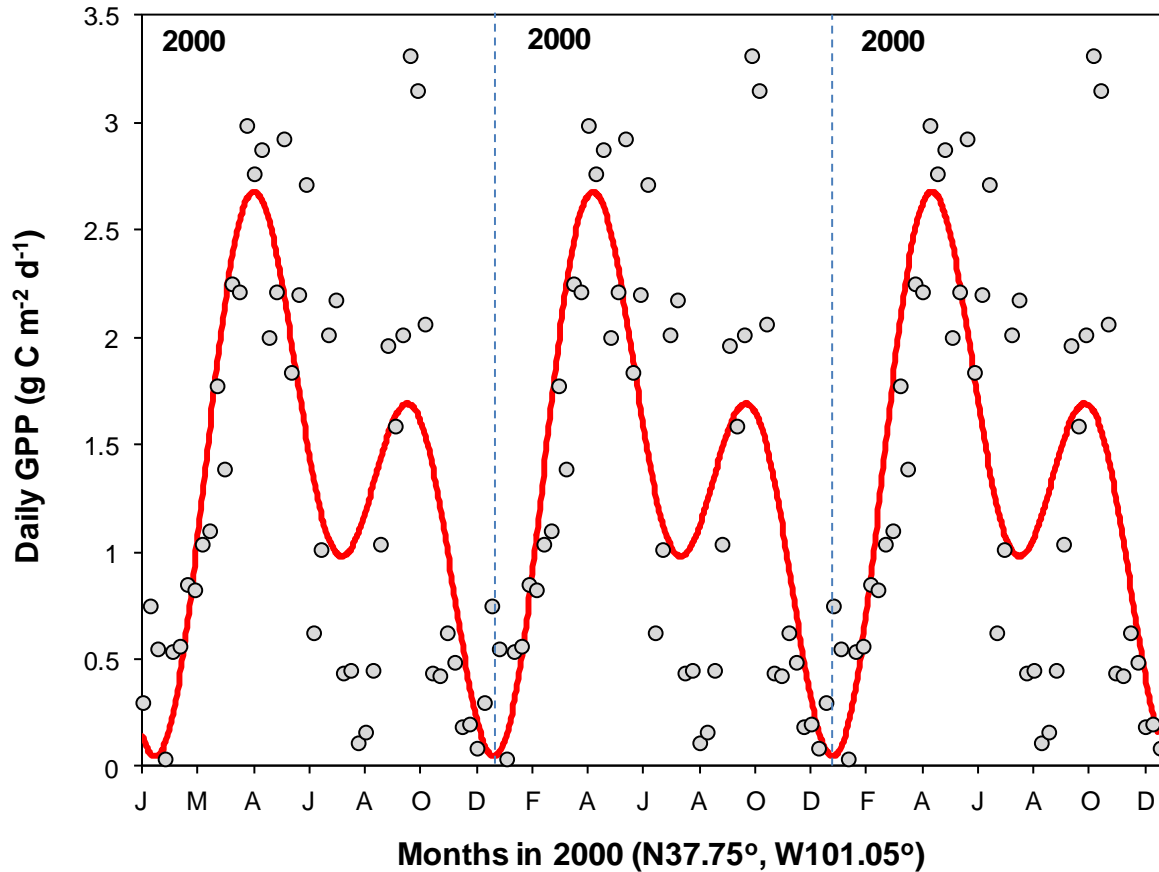
250

251

Supplementary Fig. S1.3.4. MODIS daily GPP from 2000 to 2010 in the grid cell of

252

N37.75°, W101.05°. The data in the original database were in 8-day interval.



253

254 **Supplementary Fig. S1.3.5. Triplicate of MODIS GPP in 2000 in the grid cell of N37.75°,**

255 **W101.05° .** The gray circles are the 8-day interval GPP values from the original database.

256 The red line is the fitted GPP dynamic with the equation (6).

257

258 S1.3.3. One-peak during the summer-autumn growing seasons

259 In many terrestrial ecosystems, vegetation season peaks around the middle of growing

260 season, and the seasonal cycles of daily GPP can be represented by the idealized curve in Fig.

261 S1.2.1. In order to obtain all the characteristics (see S1.2) from both FLUXNET and MODIS-

262 based GPP, we fitted a 5-parameter Weibull function to the data from each year. The Weibull

263 function is given as:

$$P(t) = \begin{cases} y_0 + a \left(\frac{c-1}{c}\right)^{\frac{1-c}{c}} \left(\left|\frac{t-x_0}{b} + \left(\frac{c-1}{c}\right)^{\frac{1}{c}}\right|^{c-1} e^{-\left|\frac{t-x_0}{b} + \left(\frac{c-1}{c}\right)^{\frac{1}{c}}\right|^{\frac{c-1}{c}}}\right) & \text{if } t \leq x_0 - b \frac{c-1}{c} \\ y_0 & \text{if } t > x_0 - b \frac{c-1}{c} \end{cases} \quad (7)$$

265 where  $t$  represents the number of days in each year, and  $P(t)$  is the corresponding daily mean  
 266 GPP ( $\text{g C m}^{-2} \text{ day}^{-1}$ );  $x_0$ ,  $y_0$ ,  $a$ ,  $b$ , and  $c$  are empirical parameters to be estimated. As shown  
 267 below, this function is flexible and fits one-peak seasonal GPP well in contrasting biomes and  
 268 years. Similar Weibull functions have been successfully applied to fit seasonal dynamics of  
 269 plant community photosynthesis. For example, Gu *et al.*(2) used a Weibull function to fit the  
 270 seasonal cycle of plant community photosynthesis separately by dividing the growing season  
 271 in its middle peak. Recently, Gu *et al.*(14) developed a new 9-parameter Weibull function  
 272 capable of capturing both recovery and senescence parts of the growing season. The Weibull  
 273 function used in this study captures both recovery and senescence parts of GPP dynamics,  
 274 and consists of fewer empirical parameters (equation 7; 5 parameters). It has been used as a  
 275 default function to fit one-peak time-series data in the Sigmaplot (Systat Software, Inc, San  
 276 Jose, CA, USA).

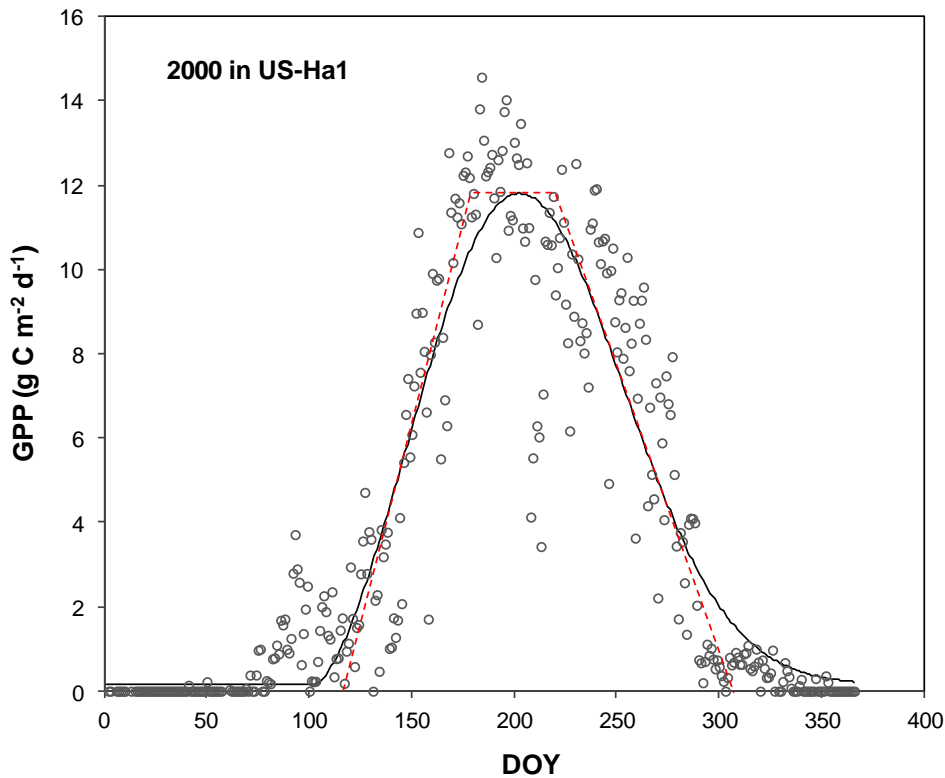
277 The fitting of data to the equation 7 was conducted in the R software (version 2.13.0;  
 278 <http://www.R-project.org>). The details of the model fitting with nonlinear regression can be  
 279 found in the section S1.4. After the curve fitting, we can obtain the fitted daily GPP in a  
 280 given year. The maximal daily GPP ( $GPP_{max}$ ) is obtained as:

$$281 \quad GPP_{max} = \max \{P(t)\} \quad (8)$$

282 where  $P(t)$  ( $t = 1, 2, \dots, n$ ) is the daily GPP in the  $t$ th day, and  $n$  is 365 for regular years and  
 283 366 for leap years. The  $\text{CO}_2$  uptake period (CUP) is determined by the initiation ( $CUP_{start}$ )  
 284 and termination ( $CUP_{end}$ ) days of CUP as:

$$285 \quad CUP = CUP_{end} - CUP_{start} \quad (9)$$

286 Since plant community photosynthesis usually fluctuates at the start and end of CUP (as  
287 shown in the Fig. S1.3.6), it is difficult to determine the days in which the ecosystem starts or  
288 stops the CO<sub>2</sub> uptake. In this study, we calculated the CUP<sub>start</sub> as the intersection between the  
289 recovery line (see the left red dashed line in Fig. S1.3.6) and the time (day of year) axis.  
290 Similarly, the CUP<sub>end</sub> was obtained by the intersection between the senescence line (see the  
291 right red dashed line in Fig. S1.3.6) and the time axis. Previous studies (2, 14) have found  
292 this approximation can capture the initiation and termination days of plant community  
293 photosynthesis in most terrestrial ecosystems. Thus, in order to calculate the CUP<sub>start</sub> and  
294 CUP<sub>end</sub>, we need to first get the recovery and senescence lines.



295  
296 **Supplementary Fig. S1.3.6. An example of fitting the equation 7 to GPP observations**  
297 **from US-Ha1 in 2000.** The black solid line is the fitted curve. The red dashed lines represent  
298 recovery, stable phase of GPP<sub>max</sub>, and senescence line in sequence.

299



300 The recovery and senescence lines represent the maximum and minimum in the growth  
 301 rate of daily GPP, respectively. Here, we use a moving linear regression approach to seek the  
 302 day in which the growth rate of daily GPP reaches maximum and minimum. The linear  
 303 model used in estimating the growth rate of daily GPP is:

$$304 \quad P(t) = \beta t + \beta_0 \quad (10)$$

305 where  $\beta$  is the theoretical slope representing the growth rate of daily GPP, and  $\beta_0$  is the  
 306 theoretical y-intercept. We conducted the linear regression analysis for day  $t$  by using the data  
 307 from day  $t - 3$  to  $t + 3$  ( $3 < t < m - 3$ ;  $m$  is 365 in regular years and 366 in leap years). The slope  
 308  $\beta$  in each day can be estimated by:

$$309 \quad \hat{\beta}(t) = \frac{7 \sum_{i=t-3}^{t+3} iP(i) - \sum_{i=t-3}^{t+3} i \sum_{i=t-3}^{t+3} P(i)}{7 \sum_{i=t-3}^{t+3} i^2 - (\sum_{i=t-3}^{t+3} i)^2} \quad (11)$$

310 The maximal ( $R_{max}$ ) and minimal ( $R_{min}$ ) change rate of daily GPP are obtained by:

$$311 \quad R_{max} = \max \{\hat{\beta}(t)\} \quad (12)$$

$$312 \quad R_{min} = \min \{\hat{\beta}(t)\} \quad (13)$$

313 The associated  $t$  with  $R_{max}$  and  $R_{min}$  are the days ( $t_{max}$  and  $t_{min}$ ) in which maximal and  
 314 minimal change rate of daily GPP occurred, respectively. Note that the value of  $R_{max}$  is  
 315 positive and  $R_{min}$  is negative. Thus, the  $CUP_{start}$  and  $CUP_{end}$  can be calculated as:

$$316 \quad CUP_{start} = t_{max} - \frac{P(t_{max})}{R_{max}} \quad (14)$$

$$317 \quad CUP_{end} = t_{min} - \frac{P(t_{min})}{R_{min}} \quad (15)$$

318 Similarly, the stable phase of  $GPP_{max}$  ( $SP_{gppmax}$ ) can be calculated as:

$$319 \quad SP_{gppmax} = SP_{gppmax_{end}} - SP_{gppmax_{start}} \quad (16)$$

320 where  $SP_{gppmax\_start}$  and  $SP_{gppmax\_end}$  are the start and end days of  $SP_{gppmax}$ , and can be solved  
321 by:

$$322 \quad SP_{gppmax\_start} = t_{max} + \frac{GPP_{max} - P(t_{max})}{R_{max}} \quad (17)$$

$$323 \quad SP_{gppmax\_end} = t_{min} + \frac{GPP_{max} - P(t_{min})}{R_{min}} \quad (18)$$

324

325 The main aim of this study is to examine the dependence of annual GPP on CUP and  $GPP_{max}$ .  
326 Such dependence can be represented by the ratio ( $\alpha$ ) between annual GPP and the product of  
327 CUP and  $GPP_{max}$  as:

$$328 \quad \alpha = \frac{\text{Annual GPP}}{CUP \times GPP_{max}} \quad (19)$$

329 where the annual GPP is the sum of daily GPP from the original observed data.

330

#### 331 S1.3.4. One-peak during the winter-spring seasons

332 In some ecosystems, the peak of daily GPP does not occur during summer-autumn  
333 seasons, but in winter or spring. For example, in some (semi-) arid regions with the  
334 Mediterranean climate, plant photosynthesis is high in mild/wet winter and spring and is low  
335 in hot/dry summer(20). As shown by Fig. S1.3.7, the daily GPP recovers in autumn, peaks in  
336 spring, and senesces in summer in the Yatir forest (IL-Yat; 31 °20'N, 35 °03'E), which is  
337 located between three distinct landscapes, including Hebron mountains, Beersheba  
338 plateau/Negev desert, and the Judean Desert and the Dead Sea Valley(21). For these sites and  
339 grids, a direct application of the equation 7 cannot capture the CUP. In the IL-Yat case, the

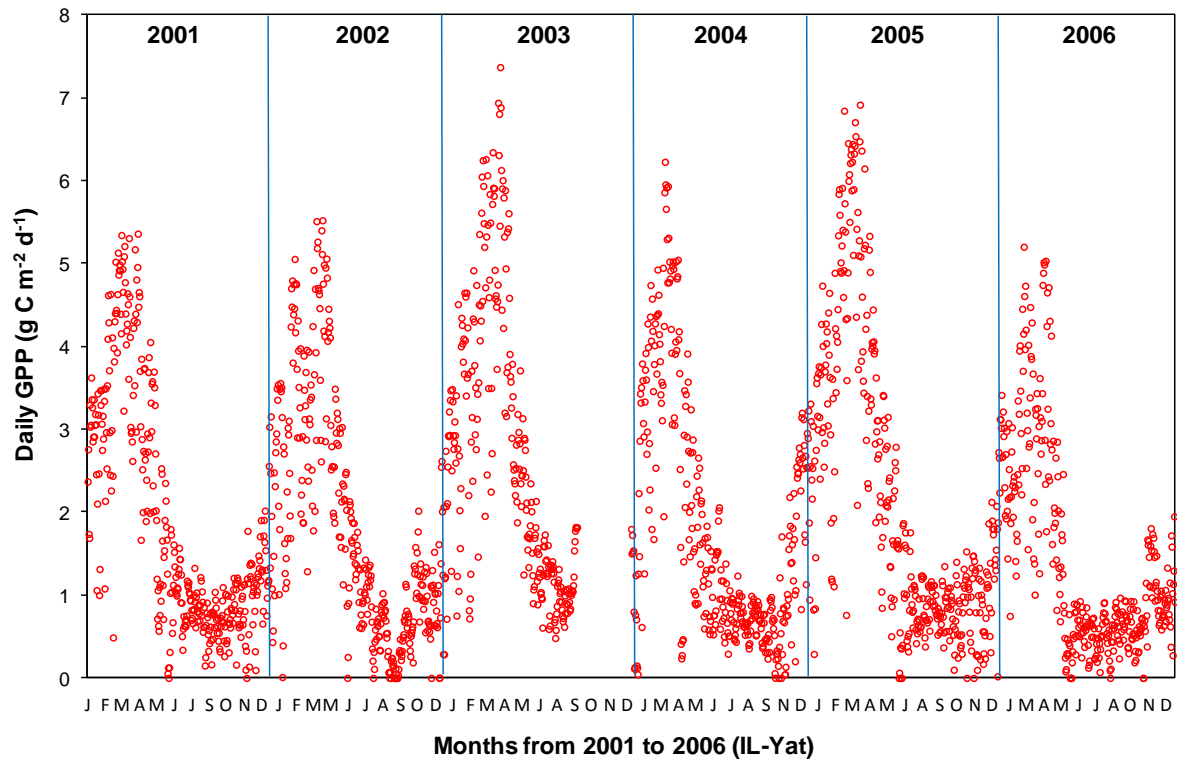
340 CUP will be underestimated because the CO<sub>2</sub> uptake period during September-December is  
341 ignored (Fig. S1.3.7).

342 For those sites and grids whose daily GPP peaks during spring or winter seasons, we  
343 obtained the entire growing season by duplicating the GPP dynamics (as shown by Fig.  
344 S1.3.8). As shown in Fig. S1.3.8, with the duplicate of daily GPP in 2001, an adjusted GPP  
345 dynamic can be obtained from August to July (as shown in red circles in Fig. S1.3.8). A key  
346 issue in this method is to determine the start and end day of the adjusted GPP dynamic. Since  
347 the FLUXNET GPP data are usually fluctuating with time, we determined the start and end  
348 day of the adjusted GPP dynamic by two steps:

349 (1) We first smooth the observed data by using a moving average method as equation 2 with  
350  $n=3$ .

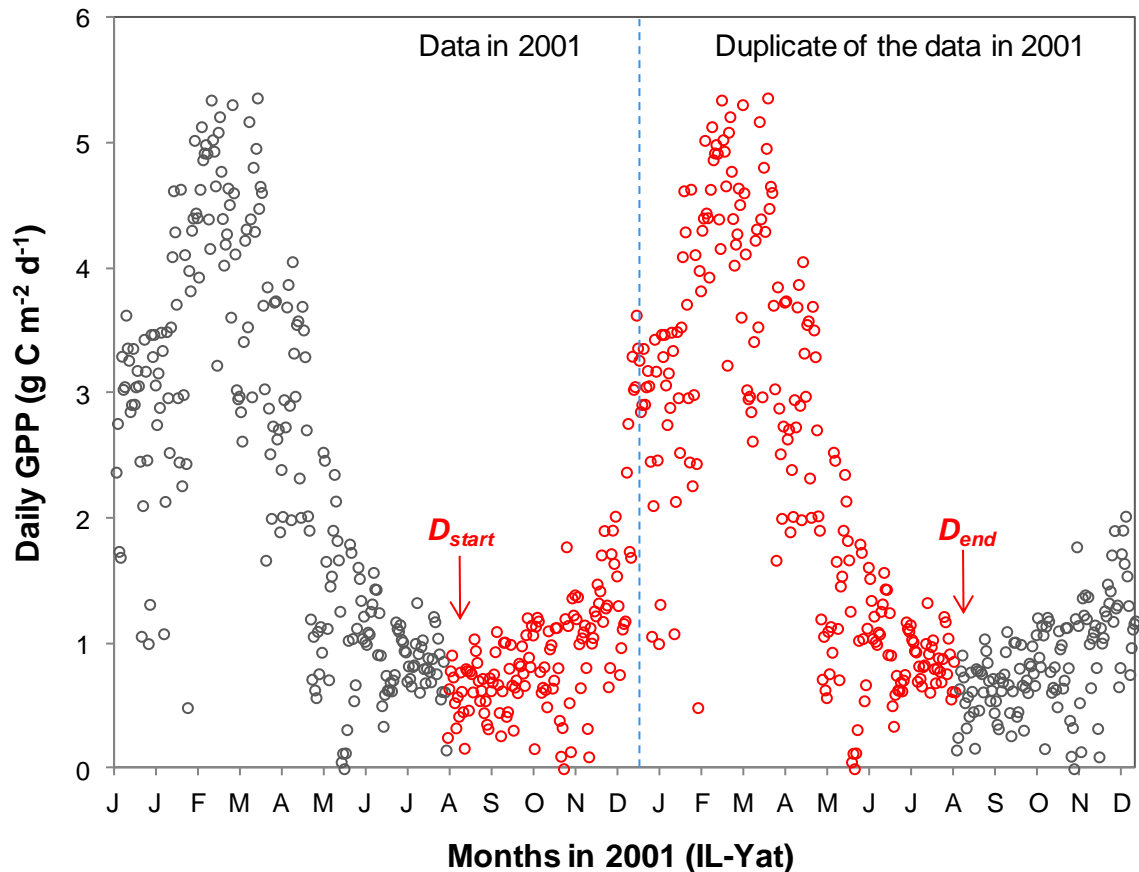
351 (2) Based on the smoothed curve in the step (1), we determined the start point of the adjusted  
352 GPP dynamic as the day ( $D_{start}$ ) with the minimum GPP throughout the year, and the end day  
353 ( $D_{end}$ ) according to the number of days in that year.

354 In the MODIS GPP product, the GPP dynamic with 8-day intervals is comparably  
355 smoother, so we only applied step (2) to get the adjusted GPP dynamic. The above adjusted  
356 GPP dynamic was then used for the analysis of CUP and  $GPP_{max}$  as the regular one-peak  
357 GPP curve in the Fig. S1.3.6. Although this method with adjusted GPP dynamic may  
358 generate some errors, it can provide a good estimation of CUP and  $GPP_{max}$  for those regions  
359 in where the single peak of daily GPP occurs in winter or spring seasons.



360

361 **Supplementary Fig. S1.3.7. Observed daily GPP from 2001 to 2006 at the flux site of IL-**  
 362 **Yat (please see its details in Table S1).** Note that the negative values from the database has  
 363 been replaced by 0, and the observations in Oct-Dec, 2004 were missing in the original  
 364 database.



365

366 **Supplementary Fig. S1.3.8.** The figure shows how GPP data from those sites with  
 367 **winter-spring peaks were adjusted and analyzed in this study.** The open circles on the left  
 368 side of the blue dashed line are observed daily GPP in 2001 in IL-Yat site, and those on the  
 369 right side of the blue dashed line are duplicated from the observed data in 2001. Then the red  
 370 open circles represent the adjusted GPP dynamic and are used in the analysis of CUP and  
 371  $GPP_{max}$  in 2001 for IL-Yat. Note that the negative values from the database have been  
 372 replaced by 0.

373

### 374 **S1.4 Non-linear regression with R**

375 As shown in both the equations 6 and 7, there are 5 unknown parameters determining the  
 376 GPP dynamic against time in a given year. In this study, we used the general normal

377 nonlinear regression model to fit the equations 6 and 7 to the observations. In general, the  
378 nonlinear regression model can be written as:

$$379 \quad y_i = f(X_i, \beta) + \varepsilon_i \quad (21)$$

380 where  $y_i$  is the observed GPP in each year,  $f$  is the expectation function, and  $X_i$  is a vector of  
381 time (days in a single year).  $\beta$  is a vector including the 5 parameters in the equations 6 and 7,  
382 and  $\varepsilon_i$  is the error term for observation  $i$ . The error  $\varepsilon_i$  varies from year to year, and the errors  
383 are assumed to be normally distributed with mean 0 and constant variance:  $\varepsilon_i \sim N(0, \sigma^2)$ .

384 The best estimates of the parameters ( $\beta$ ) represent the best fit of the  $f$  function to the  
385 observations  $y_i$ . They can be obtained by minimization of the sum of squared residuals ( $S$ )  
386 with respect to  $\beta$ :

$$387 \quad S(\beta) = \sum_{i=1}^n (y_i - f(X_i, \beta))^2 \quad (22)$$

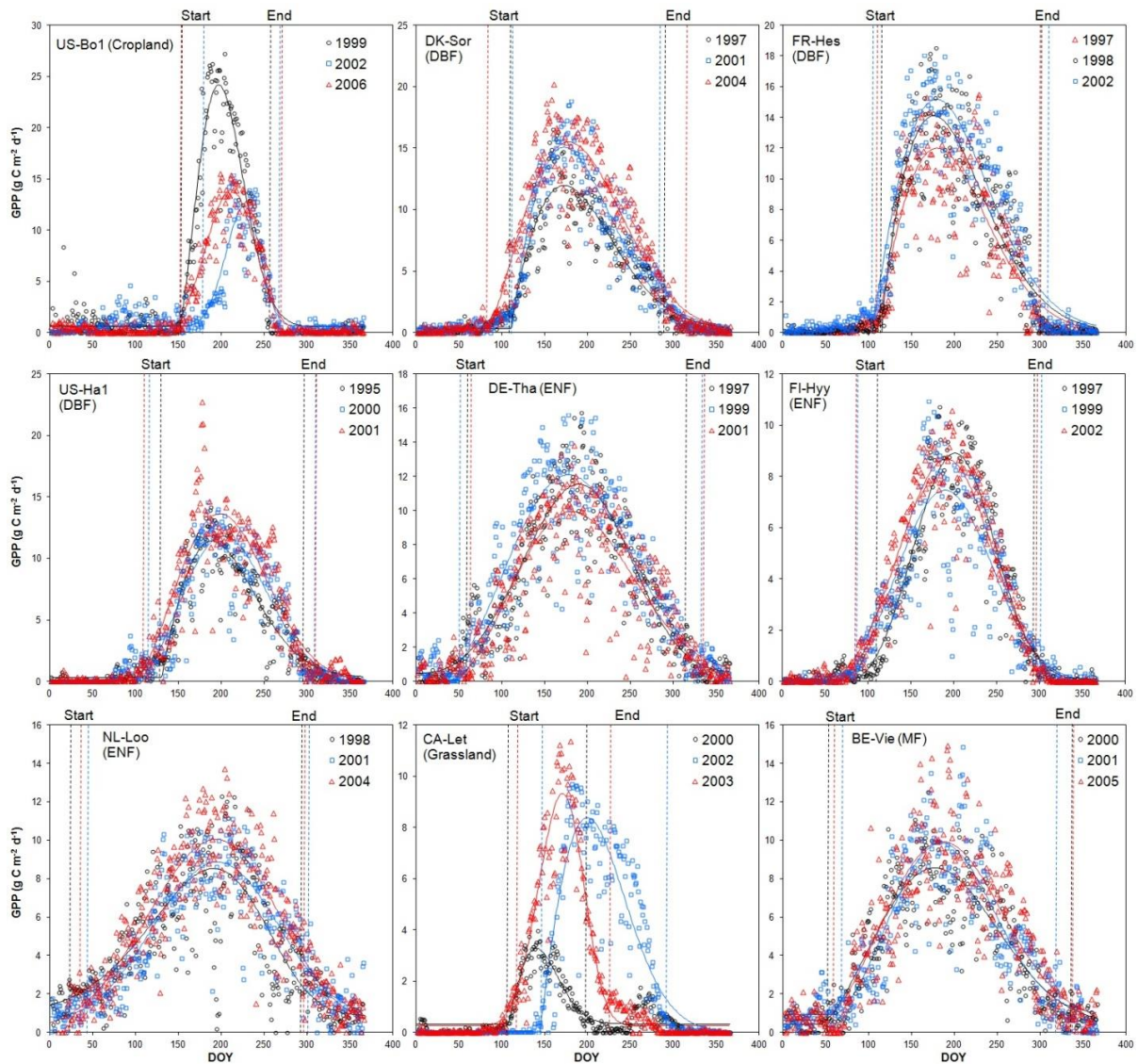
388 In each step, the Gauss-Newton method is used to determine the new parameters values based  
389 on the data, with the purpose to make the  $S(\beta)$  as small as possible. More information about  
390 the nonlinear regression can be found in Bates and Watts (22) and Fox(23).

391 In this study, the non-linear regressions were performed with the model fitting function  
392 *nls*, which is located in the standard *nls* library in **R**. The parameter estimates are obtained  
393 from the non-linear model fitting, and then used for the analyses of GPP properties in S1.3.

394

## 395 **S1.5 The performance of the Weibull function in capturing GPP dynamics** 396 **in terrestrial ecosystem**

397 Since GPP dynamics in many terrestrial ecosystems follow the single-peak curve like Fig.  
 398 S1.3.6, it is important to make sure that equation 7 can capture GPP properties in contrasting  
 399 biomes. Before we applied the equation 7 to all flux sites and grid cells, we first examined its  
 400 performance in the years with contrasting climate conditions at long-term flux sites. The  
 401 results show that the equation can well capture all years of GPP dynamics from those long-  
 402 term sites. As shown by Fig. S1.5.1, the simulated GPP curve fits observations from years  
 403 with highest, normal, and lowest values in each site well. It indicates the Weibull function  
 404 used in this study has the ability to capture GPP dynamics and the associated properties in  
 405 contrasting biomes and climate conditions.



406

407 **Supplementary Fig. S1.5.1. Performance of the Weibull function in fitting the GPP**  
 408 **dynamics with lowest (black circles and lines), median (blue circles and lines) and**  
 409 **highest (red circles and lines) annual GPP in those long-term flux sites.** The dashed  
 410 vertical lines represent the start and end days of CUP.

411

## 412 **S1.6 Parameter sensitivity analysis of the Weibull function**

413 In order to test if the convergence of  $\alpha$  is a mathematical certainty of the Weibull function,  
 414 we performed a sensitivity analysis to evaluate impact of each parameter ( $x_0$ ,  $y_0$ ,  $a$ ,  $b$ , and  $c$ )  
 415 on the estimates of CUP,  $GPP_{\max}$ ,  $CUP \times GPP_{\max}$ , and  $\alpha$ . The mathematical derivation of the  
 416 sensitivity analysis can be found as follows:

417 We first assume  $v = \left| \frac{t-x_0}{b} + \left(\frac{c-1}{c}\right)^{\frac{1}{c}} \right|$ , so then the above equation can be rewritten as:

$$418 \quad P(t) = \begin{cases} y_0 + a\left(\frac{c-1}{c}\right)^{\frac{1-c}{c}} v^{c-1} e^{(-v^c + \frac{c-1}{c})} & \text{if } t \leq x_0 - b\frac{c-1}{c} \\ y_0 & \text{if } t > x_0 - b\frac{c-1}{c} \end{cases} \quad (23)$$

419

420  $P(t)$  is a differentiable function whose derivative is:

$$421 \quad P(t)' = \begin{cases} a\left(\frac{c-1}{c}\right)^{\frac{1-c}{c}} e^{\frac{c-1}{c}} (v^{c-1} e^{-v^c})' v' & \text{if } x \leq x_0 - b\frac{c-1}{c} \\ 0 & \text{if } x > x_0 - b\frac{c-1}{c} \end{cases}$$

$$422 \quad \Rightarrow P(t)' = \begin{cases} a\left(\frac{c-1}{c}\right)^{\frac{1-c}{c}} e^{\frac{c-1}{c}} (v^{c-1} e^{-v^c})' v' & \text{if } x \leq x_0 - b\frac{c-1}{c} \\ 0 & \text{if } x > x_0 - b\frac{c-1}{c} \end{cases}$$

$$423 \quad \Rightarrow P(t)' = \begin{cases} a\left(\frac{c-1}{c}\right)^{\frac{1-c}{c}} e^{\frac{c-1}{c}} [(c-1)v^{c-2} e^{-v^c} - cv^{2(c-1)} e^{-v^c}] v' & \text{if } x \leq x_0 - b\frac{c-1}{c} \\ 0 & \text{if } x > x_0 - b\frac{c-1}{c} \end{cases} \quad (24)$$

$$424 \quad \text{where } v' = \begin{cases} \frac{1}{b} & \text{if } \frac{x-x_0}{b} + \left(\frac{c-1}{c}\right)^{\frac{1}{c}} \geq 0 \\ -\frac{1}{b} & \text{if } \frac{x-x_0}{b} + \left(\frac{c-1}{c}\right)^{\frac{1}{c}} < 0 \end{cases} \quad (25)$$



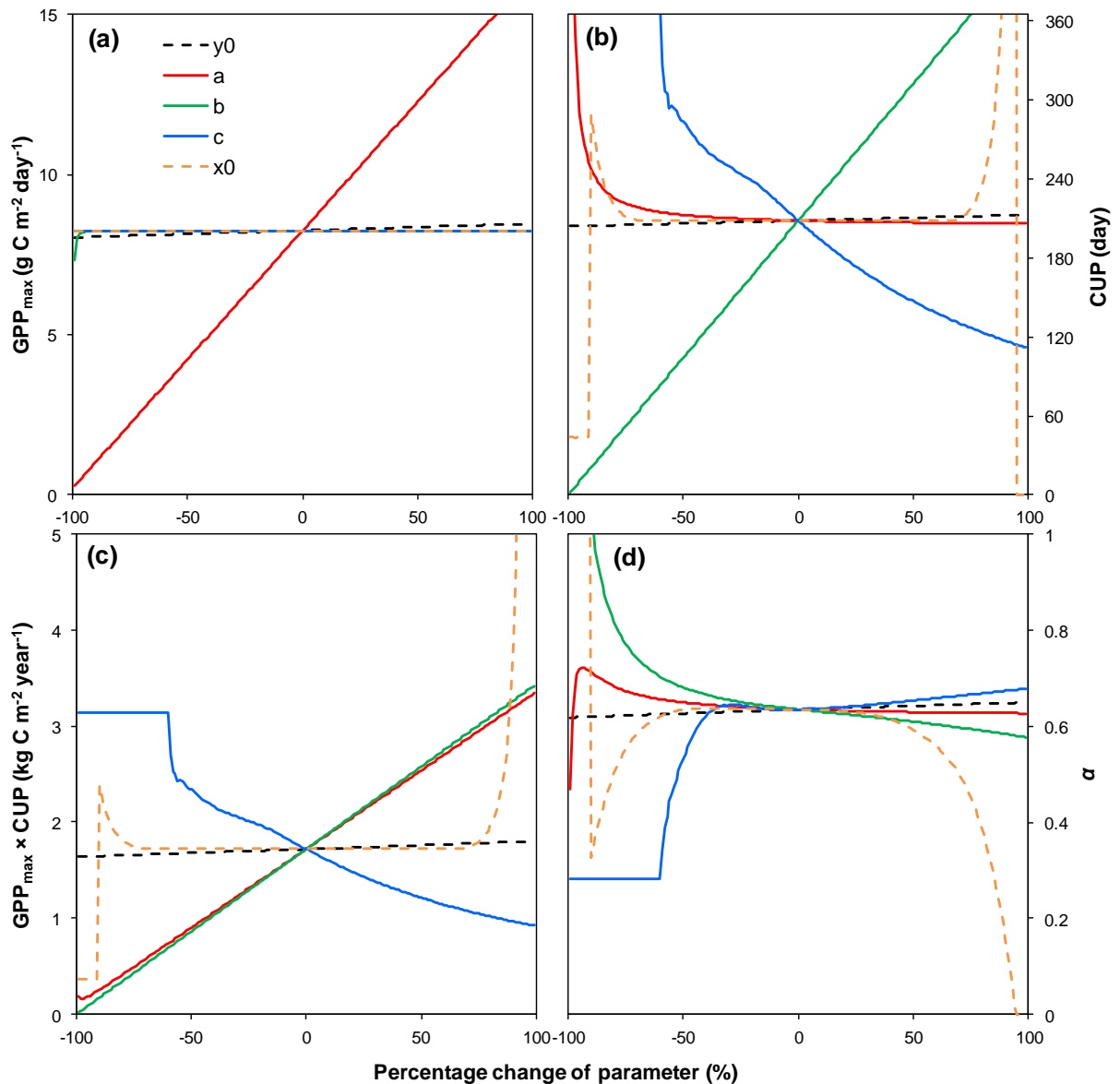
425 Similar to the equations (12) – (13), the maximal ( $R_{max}$ ) and minimal ( $R_{min}$ ) change rate of  
426 daily GPP are obtained by:

$$427 \quad R_{max} = \max \{P(t)\} \quad (26)$$

$$428 \quad R_{min} = \min \{P(t)\} \quad (27)$$

429 The  $CUP_{start}$  and  $CUP_{end}$  can be calculated by the equations (14) and (15), respectively. The  
430 CUP can be calculated as  $CUP_{end}$  minus  $CUP_{start}$ , and  $GPP_{max}$  as  $\max\{P(t)\}$ .

431 In the analysis, we first calculated the bootstrapping medians of all parameters from their  
432 estimations from the eddy-flux sites. Then, we increased each parameter from -100% to  
433 100%, with an interval of 1%, of its calculated medians with other parameters kept at the  
434 estimated values from observations. Finally, we calculated CUP,  $GPP_{max}$ ,  $CUP \times GPP_{max}$  and  
435  $\alpha$  with each combination of parameters and plotted their dependences on each parameter in  
436 Fig. S1.6.1. The sensitivity analysis showed that  $GPP_{max}$  is very sensitive to the parameter  $a$   
437 (Fig. S1.6.1a) of the Weibull function, while CUP is mainly affected by the parameters  $b$  and  
438  $c$  (Fig. S1.6.1b). The parameters  $a$ ,  $b$  and  $c$  together control the variations of the product of  
439  $GPP_{max}$  and CUP (Fig. S1.6.1c). The ratio between annual GPP and the product of  $GPP_{max}$   
440 and CUP ( $\alpha$ ) can be affected by each of the parameters ( $a$ ,  $b$ ,  $c$ ,  $x_0$ , and  $y_0$ ; Fig. S1.6.1d). It  
441 suggests the convergence of  $\alpha$  is not the mathematical certainty the of the Weibull function  
442 used in this study.



443

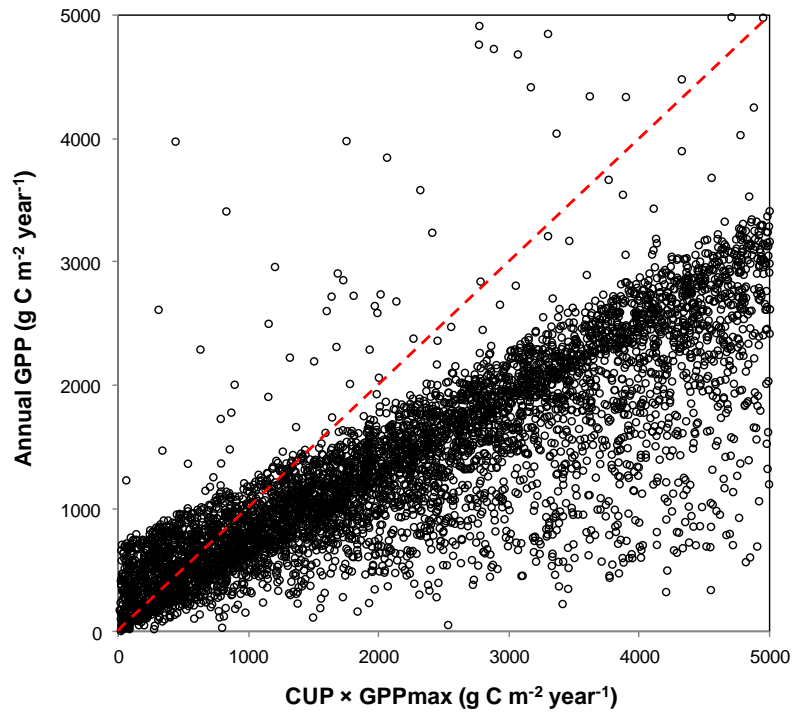
444 **Supplementary Fig. S1.6.1. Sensitivity analyses of parameters.** The results are obtained  
 445 through the following steps: (1) calculate the bootstrapping median of the parameters from  
 446 the global analyses on flux data; (2) change those parameters from -100% to +100% and  
 447 calculate the values of  $GPP_{max}$ , CUP,  $GPP_{max} \times CUP$ , and  $\alpha$  (annual GPP/(  $GPP_{max} \times CUP$ ))  
 448 with equations (23) – (25).

449

450 **S1.7 Random re-sampling test of the Weibull function**

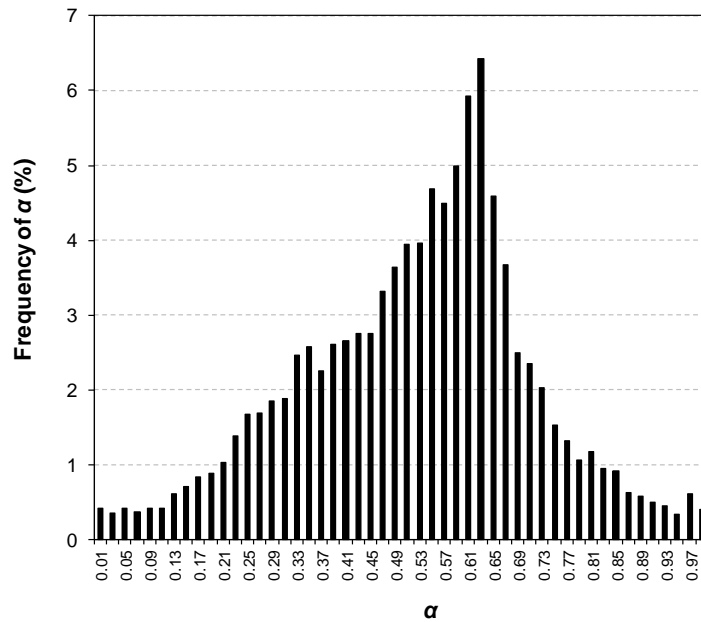
451 We further did a random re-sampling test for the performance of the Weibull function itself in  
452 affecting the ratio between annual GPP and the product of CUP and  $GPP_{\max}(\alpha)$ . The test  
453 consisted of three steps: First, we set up the ranges of each parameter ( $a$ ,  $b$ ,  $c$ ,  $x_0$ , and  $y_0$ ) in  
454 equation 7, with  $0 < a \leq 30$ ,  $0 < b \leq 500$ ,  $1 < c \leq 5$ ,  $0 < x_0 \leq 300$ ,  $0 < y_0 \leq 2$ . For each  
455 parameter, the given range covered  $> 90\%$  of the estimated values from all FLUXNET sites.  
456 Second, we equally separated the range of each parameter into 10000 samples from the  
457 lowest to largest value. For example, there were 1000 samples of parameter  $a$  including  
458 0.003, 0.006, ... , 30. In the third step, we randomly chose each parameter from its 10000  
459 samples to obtain the CUP,  $GPP_{\max}$ , and annual GPP and thus the  $\alpha$ . The random resampling  
460 of parameters was repeated by 2000 times, and the output was used for the further analyses.

461 As shown by Fig. S1.7.1, annual GPP is positively related to the product of CUP and  
462  $GPP_{\max}$ . However, the ratio ( $\alpha$ ) between them diverges. By plotting the frequency distribution  
463 of  $\alpha$  that ranges from 0 to 1, we found it follows the normal distribution ( $R^2 = 0.85$ ,  $P <$   
464  $0.001$ ; Fig. S1.7.2). Since the ranges of parameters are chosen based on the estimates in the  
465 natural ecosystems, the highest frequency of  $\alpha$  in random resampling test is close to that  
466 found in the original analysis (as shown in Fig. 1 of the main text). However the divergence  
467 of  $\alpha$  suggests that the global convergence of  $\alpha$  should be caused by ecological processes in  
468 the natural ecosystems, but not the Weibull function itself.



469

470 **Supplementary Fig. S1.7.1. Results of a random re-sampling test.** The parameter ranges  
 471 were defined according to their distributions in the FLUXNET sites. The red dashed line is  
 472 the 1:1 line.



473

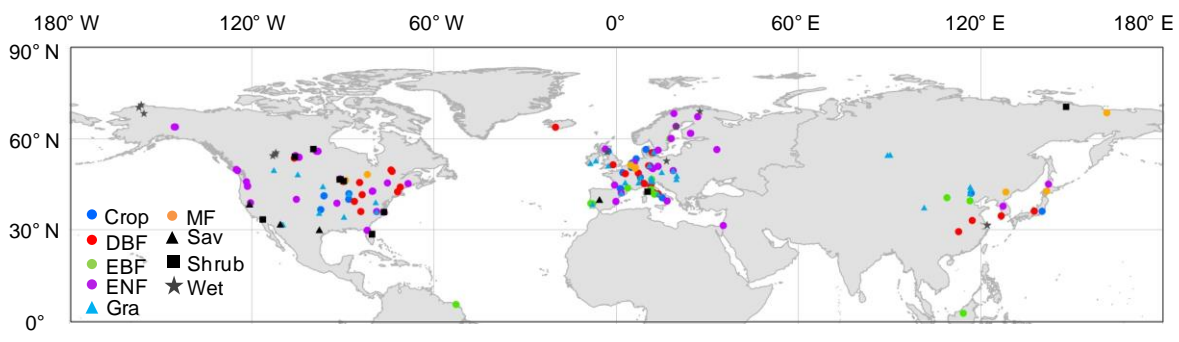
474 **Supplementary Fig. S1.7.2. Frequency of  $\alpha$  in the output of the random re-sampling**  
 475 **test.**

476 **S1.8 Freeze/Thaw Data**

477 Global daily records of landscape freeze/thaw data from 1<sup>st</sup> January 2000 to 31<sup>st</sup> December  
478 2010 were analyzed for an additional indicator of CUP. The data were obtained from the  
479 NSIDC (<http://nsidc.org/data/nsidc-0477>). More detailed information about the data were  
480 provided at: <http://nsidc.org/data/docs/measures/nsidc-0477/index.html>. We used the  
481 combined freeze/thaw data (specifically, AM and PM thawed ground-state) to estimate dates  
482 of spring thaw and autumn freeze with the approach introduced by some earlier studies (24-  
483 26). The spring thaw data was defined as the date corresponding to the 8<sup>th</sup> day of the first 15  
484 day period in a year when 80% days (i.e., 12 days) is classified as non-frozen days. The  
485 similar 80% rule was applied for determine the date of autumn freeze (i.e., end of CUP) for  
486 each grid. The global distribution of obtained CUP from the Freeze/Thaw (F/T) data was  
487 shown in Fig. S10.

488

489 **S1.9 Distribution of FLUXNET Sites**



491 **Supplementary Fig. S1.9.1. Distribution of FLUXNET sites that used in this study.** Crop,  
492 cropland; DBF, deciduous broadleaf forest; EBF, evergreen broadleaf forest; ENF, evergreen  
493 needleleaf forest; MF, mixed forest; Gra, grassland, Sav, savanna; Shrub, shrubland; Wet,  
494 wetland.

495

496 As shown in Fig. S1.9.1, the eddy covariance sites are not homogeneously distributed over  
 497 the global. More sites are distributed in North America, West Europe, and East Asia.  
 498 Although the FLUXNET sites cannot fully represent the global heterogeneity in  
 499 environmental conditions, they occupy almost all vegetation types and climate zones in  
 500 terrestrial ecosystem (Please see more details in the Supporting Online Material of Beer et  
 501 al.(5)). Our goal in this study is to test the control of phenological and physiological aspects  
 502 on terrestrial annual GPP, so the broadly distributed FLUXNET sites are plenty to represent  
 503 most vegetation and climate types in terrestrial ecosystems.

504

## 505 **S2. Supplementary Tables and Figures**

506

507 **Table S1.** Information of FLUXNET sites used in this study.

508

Site Name	PFT	Lat	Lon	Year	Ref.
AT-Neu	Grassland	47.1	11.3	2002-2006	(27)
				1997-1998,2000- 2002,2004-2006	(28)
BE-Bra	MF	51.3	4.5		
BE-Lon	Cropland	50.6	4.7	2004-2006	(29)
BE-Vie	MF	50.3	6.0	1997-2006	(30)
BR-Sa1	EBF	-2.85	-54.97	2001-2003	(31)
BR-Sa3	EBF	-3.02	-54.97	2001-2003	(32)
BR-Sp1	Savanna	-21.6	-47.7	2001	(33)
CA-Ca1	ENF	49.9	-125.3	1998-2005	(34)
CA-Ca2	ENF	49.9	-125.3	2001-2005	(34)
CA-Ca3	ENF	49.5	-124.9	2002-2005	(34)
CA-Gro	MF	48.2	-82.2	2004	(35)
CA-Let	Grassland	49.7	-112.9	1999-2005	(36)
CA-Man	ENF	55.9	-98.5	1995,1998-2000	(37)
CA-Mer	ENF	45.4	-75.5	1999-2005	(38)
CA-NS1	ENF	55.9	-98.5	2003-2005	(39)
CA-NS2	ENF	55.9	-98.5	2002-2005	(39)
CA-NS3	ENF	55.9	-98.4	2002-2005	(39)
CA-NS4	ENF	55.9	-98.4	2003-2004	(39)
CA-NS5	ENF	55.9	-98.5	2002-2005	(39)
CA-NS6	ENF	55.9	-99.0	2002-2005	(39)
CA-NS7	Shrubland	56.6	-99.9	2003-2005	(39)

CA-Oas	DBF	53.6	-106.2	1997-2005	(40)
CA-Ojp	DBF	53.9	-104.7	2000-2003,2005	(41)
CA-Qcu	DBF	49.3	-74.0	2002-2006	(42)
CA-Qfo	DBF	49.7	-74.3	2004-2006	(43)
CA-SF1	ENF	54.5	-105.8	2004	(44)
CA-SF2	ENF	54.3	-105.9	2003-2004	(44)
CA-SF3	Shrubland	54.1	-106.0	2003-2005	(44)
CA-SJ1	ENF	53.9	-104.7	2001-2005	(45)
CA-SJ2	ENF	53.9	-104.6	2003-2005	(45)
CA-SJ3	ENF	53.9	-104.6	2004-2005	(45)
CA-TP1	ENF	42.7	-80.6	2004-2005	(46)
CA-TP2	ENF	42.8	-80.5	2004-2005	(46)
CA-TP3	ENF	42.7	-80.3	2005	(46)
CA-TP4	ENF	42.7	-80.4	2004-2005	(47)
CA-WP1	Wetland	55.0	-112.5	2004-2005	(48)
CA-WP2	Wetland	55.5	-112.3	2004	(49)
CA-WP3	Wetland	54.5	-113.3	2004	(49)
CH-Oe1	Grassland	47.3	7.7	2002-2006	(50)
CH-Oe2	Cropland	47.3	7.7	2005	(51)
CN-Anh	DBF	33.0	117.0	2005-2006	(52)
CN-Bed	EBF	39.5	116.3	2005	(52)
CN-Cha	MF	42.4	128.1	2003	(53)
CN-Do1	Wetland	31.5	122.0	2005	(54)
CN-Do2	Wetland	31.6	121.9	2005	(54)
CN-Do3	Wetland	31.5	122.0	2005	(54)
CN-Du1.	Cropland	42.0	116.7	2005-2006	(55)
CN-Du2	Grassland	42.0	116.3	2006	(55)
CN-HaM	Grassland	37.4	101.2	2002-2003	(56)
CN-Hny	DBF	29.3	112.5	2005-2006	-
CN-Ku1	EBF	40.5	108.7	2006	(57)
CN-Xfs	Grassland	44.1	116.3	2004-205	-
CZ-BK1	ENF	49.5	18.5	2001,2004-2006	-
CZ-BK2	Grassland	49.5	18.5	2005-2006	-
CZ-wet	Grassland	49.0	14.8	2006	(58)
DE-Bay	ENF	50.1	11.9	1997-1999	(59)
DE-Geb	Cropland	51.1	10.9	2004-2006	(60)
DE-Gri	Cropland	50.9	13.5	2005-2006	(16)
DE-Hai	DBF	51.1	10.5	2000-2006	(61)
DE-Har	DBF	51.1	10.5	2005-2006	(62)
DE-Kli	Cropland	50.9	13.5	2005-2006	-
DE-Meh	Grassland	51.3	10.7	2004-2006	(63)
DE-Tha	ENF	51.0	13.6	1997-2006	(64)
DE-Wet	ENF	50.5	11.5	2002-2006	(65)
DK-Fou	Cropland	56.5	9.6	2005	-
DK-Lva	Grassland	55.7	12.1	2005-2006	(16)

DK-Ris	Cropland	55.5	12.1	2004-2005	(66)
DK-Sor	DBF	55.5	11.6	1996-2006	(66)
ES-ES1	ENF	39.3	-0.3	1999-2002,2004-2006	(3)
ES-ES2	Cropland	39.3	-0.3	2004-2006	-
ES-LMa	Savanna	39.9	-5.8	2004-2006	(67)
ES-VDA	Grassland	42.2	1.4	2004-2005	(61)
FI-Hyy	ENF	61.8	24.3	1997-2006	(68)
FI-Kaa	Wetland	69.1	27.3	2000-2006	(69)
FI-Sii	ENF	61.8	24.2	2004-2005	(70)
FI-Sod	ENF	67.4	26.6	2000-2006	(71)
FR-Aur	Cropland	43.5	1.1	2005	-
FR-Fon	DBF	48.5	2.8	2005-2006	-
FR-Gri	Cropland	48.8	2.0	2005-2006	(72)
FR-Hes	DBF	48.7	7.1	1997-2006	(73)
FR-Lam	Cropland	43.5	1.2	2005	-
				1997-1998,2000,2004-	(74)
FR-LBr	ENF	44.7	-0.8	2006	
FR-Lq1	Grassland	45.6	2.7	2004-2006	(16)
FR-Lq2	Grassland	45.6	2.7	2004-2006	(16)
FR-Pue	EBF	43.7	3.6	2001-2006	(75)
GF-Guy	EBF	5.3	-52.9	2005-2006	(76)
HU-Bug	Grassland	46.7	19.6	2003-2006	(77)
HU-Mat	Grassland	47.8	19.7	2004-2006	(78)
ID-Pag	EBF	2.3	114.0	2002-2003	(79)
IE-Ca1	Grassland	52.9	-6.9	2004-2006	-
IE-Dri	Grassland	52.0	-8.8	2003-2004	(80)
IL-Yat	ENF	31.3	35.1	2001-2006	(21)
IS-Gun	DBF	63.8	-20.2	1997-1998	(81)
IT-Amp	Grassland	41.9	13.6	2003-2006	(16)
IT-BCi	Cropland	40.5	15.0	2004-2006	(82)
IT-Bon	ENF	39.5	16.5	2006	-
IT-Col	DBF	41.8	13.6	1997-2005	(83)
IT-Cpz	EBF	41.7	12.4	1997,2001,2003-2006	(84)
IT-Lav	ENF	39.5	16.5	2001-2002,2004,2006	(85)
IT-Lec	EBF	43.3	11.3	2006	-
IT-LMa	Grassland	45.6	7.2	2003-2005	-
IT-Mal	Grassland	46.1	11.7	2003	-
IT-MBo	Grassland	46.0	11.0	2003-2006	(86)
IT-Non	DBF	44.7	11.1	2001-2003,2006	-
IT-Pia	Shrubland	42.6	10.1	2002-2005	(87)
IT-PT1	DBF	45.2	9.1	2002-2004	(88)
IT-Ren	EBF	46.6	11.4	1999,2001-2006	(89)
IT-Ro1	DBF	42.4	11.9	2001-2006	(90)
IT-Ro2	DBF	42.4	11.9	2002-2006	(91)
IT-SRo	ENF	39.5	16.5	1999-2006	(92)



IT-Vig	DBF	45.3	8.9	2005	-
JP-Mas	Cropland	36.1	140.0	2002-2003	(93)
JP-Tak	DBF	36.1	137.4	1999-2004	(94)
JP-Tef	ENF	45.1	142.1	2002,2004-2005	(95)
JP-Tom	MF	42.7	141.5	2001-2003	(96)
KR-Hnm	DBF	34.6	126.6	2004-2006	(97)
KR-Kw1	ENF	37.7	127.2	2005-2006	(98)
NL-Ca1	Grassland	52.0	4.9	2003-2006	(99)
NL-Hor	Grassland	52.0	5.1	2005-2006	(99)
NL-Lan	Cropland	52.0	4.9	2005	(99)
NL-Loo	ENF	52.2	5.7	1997-2006	(100)
NL-Lut	Cropland	53.4	6.4	2006	(101)
NL-Mol	Cropland	51.7	4.6	2005	(101)
PL-wet	Wetland	52.8	16.3	2004-2005	(102)
PT-Esp	EBF	38.6	-8.6	2002-2004,2006	(103)
PT-Mi1	EBF	38.5	-8.0	2003-2005	(104)
PT-Mi2	Grassland	38.5	-8.0	2006	(104)
RU-Che	MF	68.6	161.3	2003-2004	(105)
RU-Cok	Shrubland	70.6	147.9	2003	(106)
RU-Fyo	ENF	56.5	32.9	1998-2006	(107)
RU-Ha1	Grassland	54.7	90.0	2003-2004	(108)
RU-Ha3	Grassland	54.7	89.1	2004	(108)
RU-Zot	ENF	56.5	32.9	2002-2004	-
SE-Abi	ENF	68.4	18.8	2005	-
SE-Deg	Wetland	64.2	19.6	2001-2005	(109)
SE-Faj	ENF	56.3	13.6	2006	(110)
SE-Fla	ENF	64.1	19.5	1997-1998	(111)
SE-Fla	ENF	64.1	19.5	2001-2002	(111)
SE-Nor	EBF	60.1	17.5	1996-1999,2003	(112)
SE-Sk1	ENF	60.1	17.9	2005	-
SE-Sk2	ENF	60.1	17.8	2004-2005	-
UK-AMo	Wetland	55.8	-3.2	2005	(113)
UK-EBu	Grassland	55.9	-3.2	2004-2006	(114)
UK-ESa	Cropland	55.9	-2.9	2004-2005	-
				1997-1998,2000-	(115)
UK-Gri	ENF	56.6	-3.8	2001,2005-2006	
UK-Ham	DBF	34.6	126.6	2004-2005	(116)
UK-PL3	DBF	51.5	-1.3	2005	-
UK-Tad	Grassland	51.2	-2.8	2001	(117)
US-ARb	Grassland	35.5	-98.0	2005-2006	-
US-ARc	Grassland	35.5	-98.0	2005-2006	-
US-ARM	Cropland	36.6	-97.5	2003-2006	(17)
US-Atq	Wetland	70.5	-157.4	2001,2003,2005-2006	(118)
US-Aud	Grassland	31.6	-110.5	2002,2005-2006	-
US-Bar	DBF	44.1	-71.3	2004-2005	(119)

US-Bkg	Grassland	44.3	-96.8	2005-2006	(120)
US-Blo	ENF	38.9	-120.6	2000-2006	(121)
US-Bn1	ENF	63.9	-145.4	2003	(122)
US-Bn2	ENF	63.9	-145.4	2003	(122)
US-Bn3	ENF	63.9	-145.7	2003	(122)
US-Bo1	Cropland	40.0	-88.3	1997-2006	(123)
US-Bo2	Cropland	40.0	-88.3	2004-2006	(123)
US-Brw	Wetland	71.3	-156.6	19,982,001	(124)
US-CaV	Grassland	39.1	-79.4	2004	-
US-Dk1	Grassland	36.0	-79.1	2002-2005	(125)
US-Dk2	DBF	36.0	-79.1	2003-2005	(125)
US-Dk3	ENF	36.0	-79.1	2001-2005	(125)
US-FPe	Grassland	48.3	-105.1	2000-2006	-
US-FR2	Savanna	29.9	-98.0	2004-2006	(126)
US-Goo	Grassland	34.3	-89.9	2002-2006	-
US-Ha1	DBF	42.5	-72.2	1992-2006	(127)
US-Ho1	ENF	45.2	-68.7	1996-2004	(128)
US-Ho2	ENF	45.2	-68.7	1999-2004	(128)
US-IB1	Cropland	41.9	-88.2	2006-2007	(129)
US-IB2	Grassland	41.8	-88.2	2006-2007	(129)
US-lvo	Wetland	68.5	-155.8	2004-2006	-
US-KS2	Shrubland	28.6	-80.7	2001-2002,2004-2006	(130)
US-Los	Shrubland	46.1	-90.0	2001-2003,2005	-
US-LPH	DBF	42.5	-72.2	2003-2004	(131)
US-Me2	ENF	44.5	-121.6	2003-2005	(132)
US-Me3	ENF	44.3	-121.6	2004-2005	(132)
US-Me4	ENF	44.5	-121.6	1996-1997,2000	(132)
US-MMS	DBF	39.3	-86.4	1999-2005	(133)
US-NC1	Shrubland	35.8	-76.7	2005-2006	(134)
US-NC2	ENF	35.8	-76.7	2005-2006	(135)
US-Ne1	Cropland	41.2	-96.5	2001-2004	(136)
US-Ne2	Cropland	41.2	-96.5	2003-2004	(136)
US-Ne3	Cropland	41.2	-96.4	2001-2004	(136)
US-NR1	ENF	40.0	-105.5	1999-2000,2002-2003	(137)
US-Oho	DBF	41.6	-83.8	2004-2005	(138)
US-PFa	MF	45.9	-90.3	1997-2000,2003	(139)
US-SO2	Shrubland	33.4	-116.6	2004-2006	(140)
US-SO3	Shrubland	33.4	-116.6	20,012,005	(140)
US-SO4	Shrubland	33.4	-116.6	2005-2006	-
US-SP1	ENF	29.7	-82.2	2005	(141)
US-SP2	ENF	29.8	-82.2	1999-2004	(142)
US-SP3	ENF	29.8	-82.2	1999,2001-2004	(142)
US-SRM	Savanna	31.8	-110.9	2004-2006	(143)
US-Syv	MF	46.2	-89.3	2002-2006	(144)
US-Ton	Savanna	38.4	-121.0	2002-2006	(145)

US-UMB	DBF	45.6	-84.7	1999-2003	(146)
US-WBW	DBF	36.0	-84.3	1995-1999	(147)
US-WCr	DBF	45.8	-90.1	1999-2006	(148)
US-Wi0	ENF	46.6	-91.1	2002	(149)
US-Wi1	DBF	46.7	-91.2	2003	(150)
US-Wi2	ENF	46.7	-91.2	2003	(150)
US-Wi4	ENF	46.7	-91.2	2002-2005	(150)
US-Wi5	ENF	46.7	-91.1	2004	(150)
US-Wi6	Shrubland	46.6	-91.3	2002	(150)
US-Wi7	Shrubland	46.6	-91.1	2005	(150)
US-Wi8	DBF	46.7	-91.3	2002	(150)
US-Wkg	Grassland	31.7	-109.9	2005-2006	(151)
US-Wrc	ENF	45.8	-122.0	1999-2002,2004,2006	(152)
VU-Coc	EBF	-15.4	167.2	2002	(153)

509

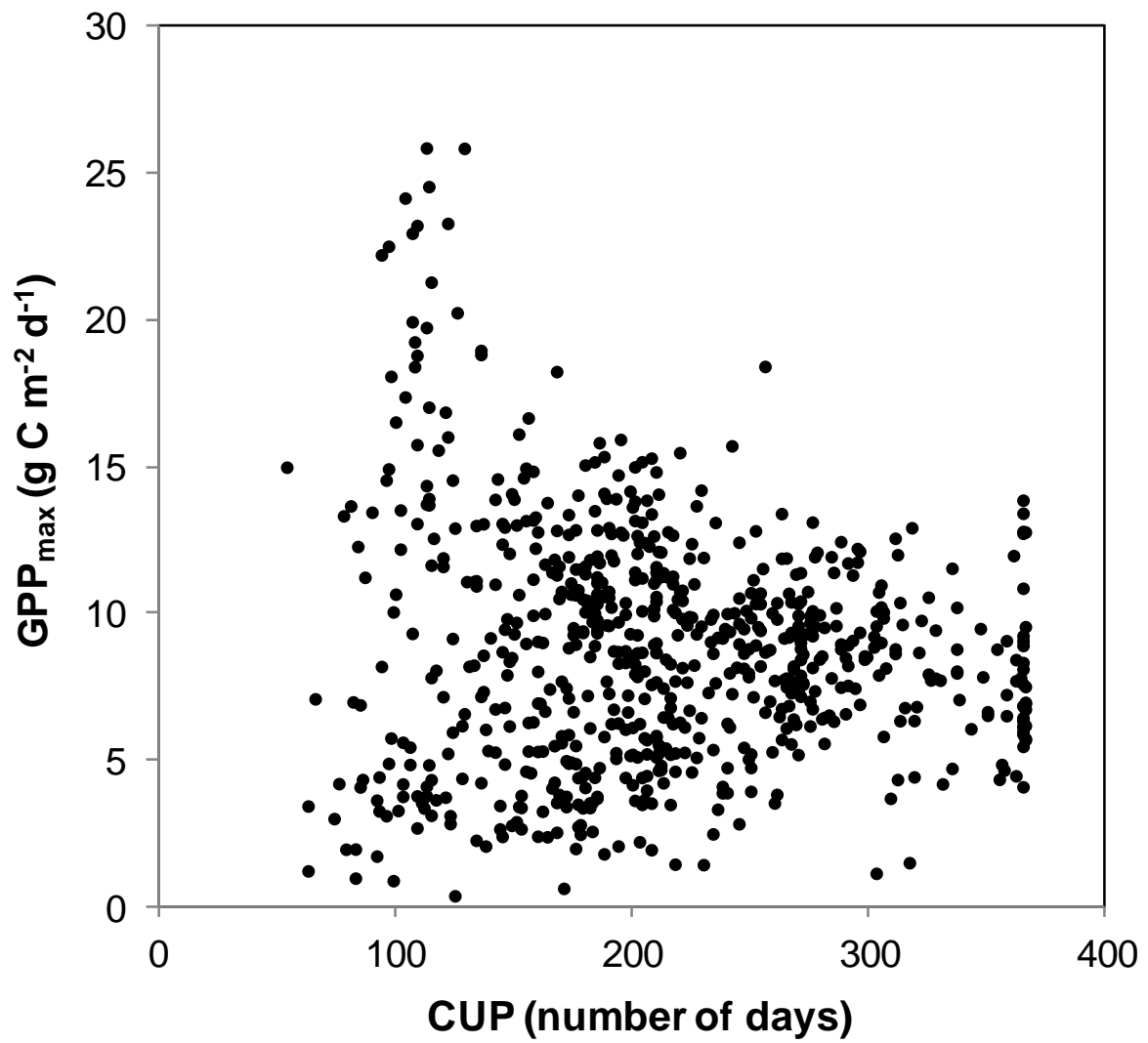
510 **Table S2.** Results of partial correlation analyses for FLUXNET GPP. The dependent variable  
 511 is annual GPP and independent variables are GPPmax and CUP.  
 512

	Variable entered	Parameter estimate	Patial $r^2$	Probability
All	GPP <sub>max</sub>	0.98	0.72	<0.001
	CUP	0.96	0.26	<0.001
ENF	GPP <sub>max</sub>	1.00	0.83	<0.001
	CUP	0.99	0.16	<0.001
DBF	GPP <sub>max</sub>	1.00	0.87	<0.001
	CUP	0.99	0.11	<0.001
EBF	GPP <sub>max</sub>	0.95	0.80	<0.001
	CUP	1.13	0.18	<0.001
MF	GPP <sub>max</sub>	0.96	0.79	0.0014
	CUP	1.01	0.21	<0.001
GRA	GPP <sub>max</sub>	1.00	0.70	0.005
	CUP	0.90	0.28	<0.001
SHRUB	GPP <sub>max</sub>	0.90	0.52	0.0053
	CUP	1.06	0.43	<0.001
SAV	GPP <sub>max</sub>	1.23	0.89	0.0014
	CUP	0.80	0.08	0.020
WET	GPP <sub>max</sub>	1.02	0.91	<0.001
	CUP	0.82	0.08	0.002
CROP	CUP	0.88	0.58	0.0012
	GPPmax	0.86	0.37	<0.001

513

514 **Figure S1.** Relationship between  $GPP_{max}$  and CUP across all FLUXNET site-years in this  
515 study.

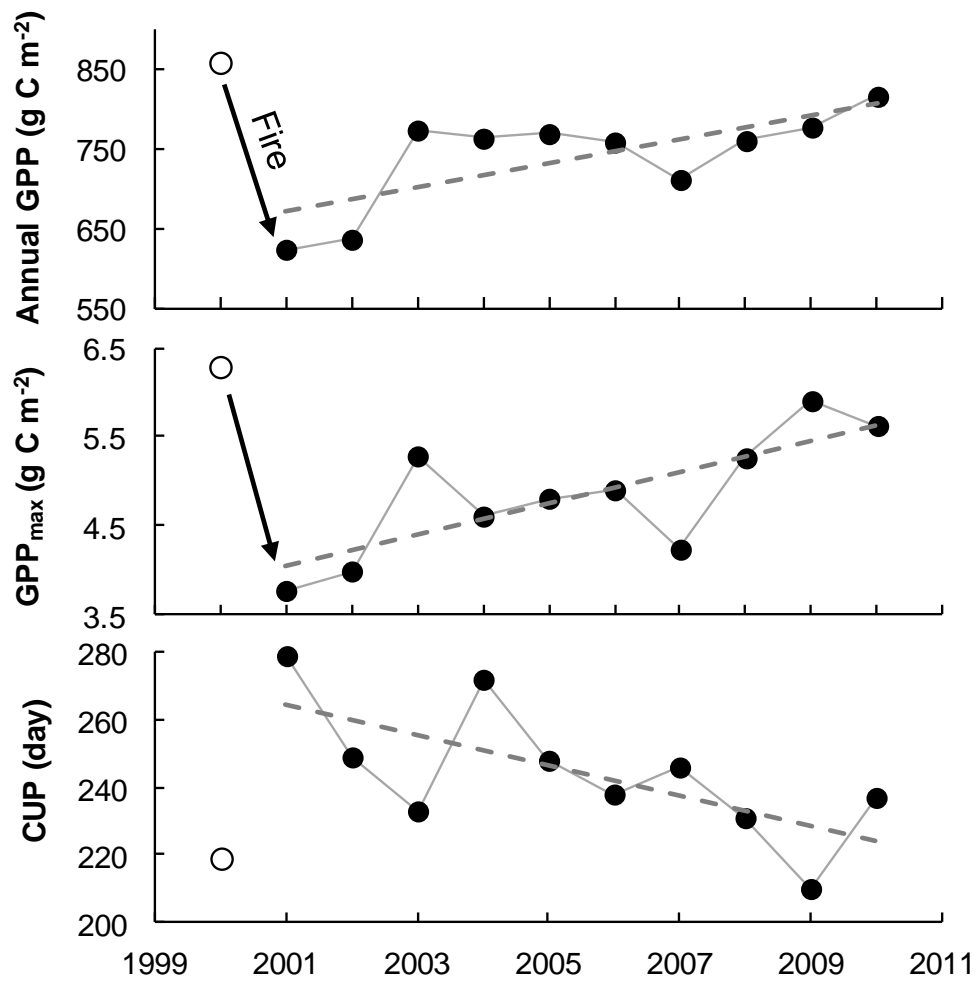
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518

519 **Figure S2.** Dynamics of annual GPP,  $GPP_{max}$  and CUP from 2000 to 2010 in the Black Hills  
 520 National Forest, South Dakota, USA. The results were obtained from the MODIS GPP  
 521 observations in a  $0.1 \times 0.1^\circ$  grid pixel ( $43.85^\circ N$ ,  $103.95^\circ W$ ) which is located in the burned  
 522 area in the Black Hills National Forest. More information about the fire disturbance and the  
 523 following recovery of vegetation greenness can be found in Xiao *et al.*(154) . The linear  
 524 regressions of annual GPP,  $GPP_{max}$  and CUP against year are all significant (all  $P < 0.05$ ).

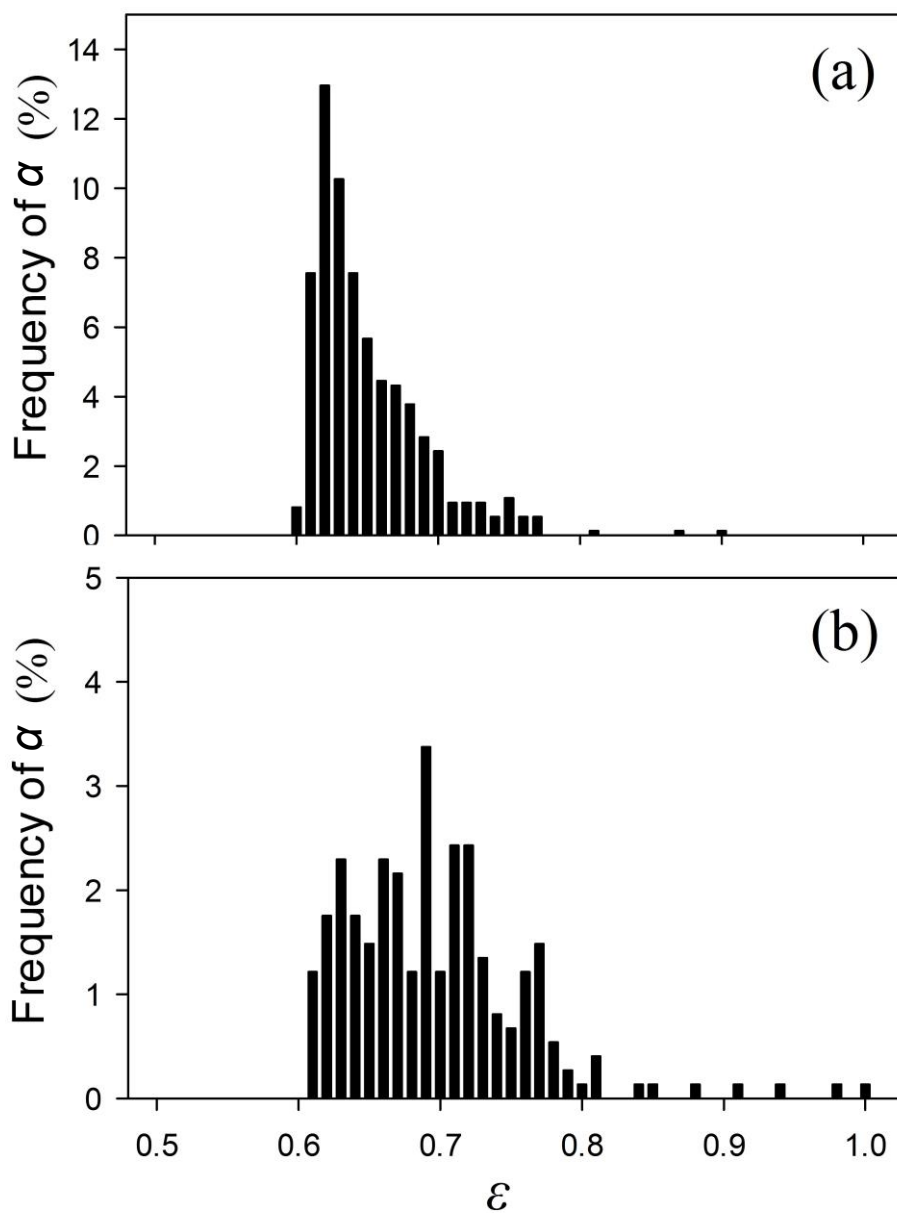


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527 **Figure S3.** The relative frequency distribution of estimated  $\alpha$  from all (a) non-tropical and (b)  
528 tropical and subtropical (including Mediterranean climate) FLUXNET site-years.

529  
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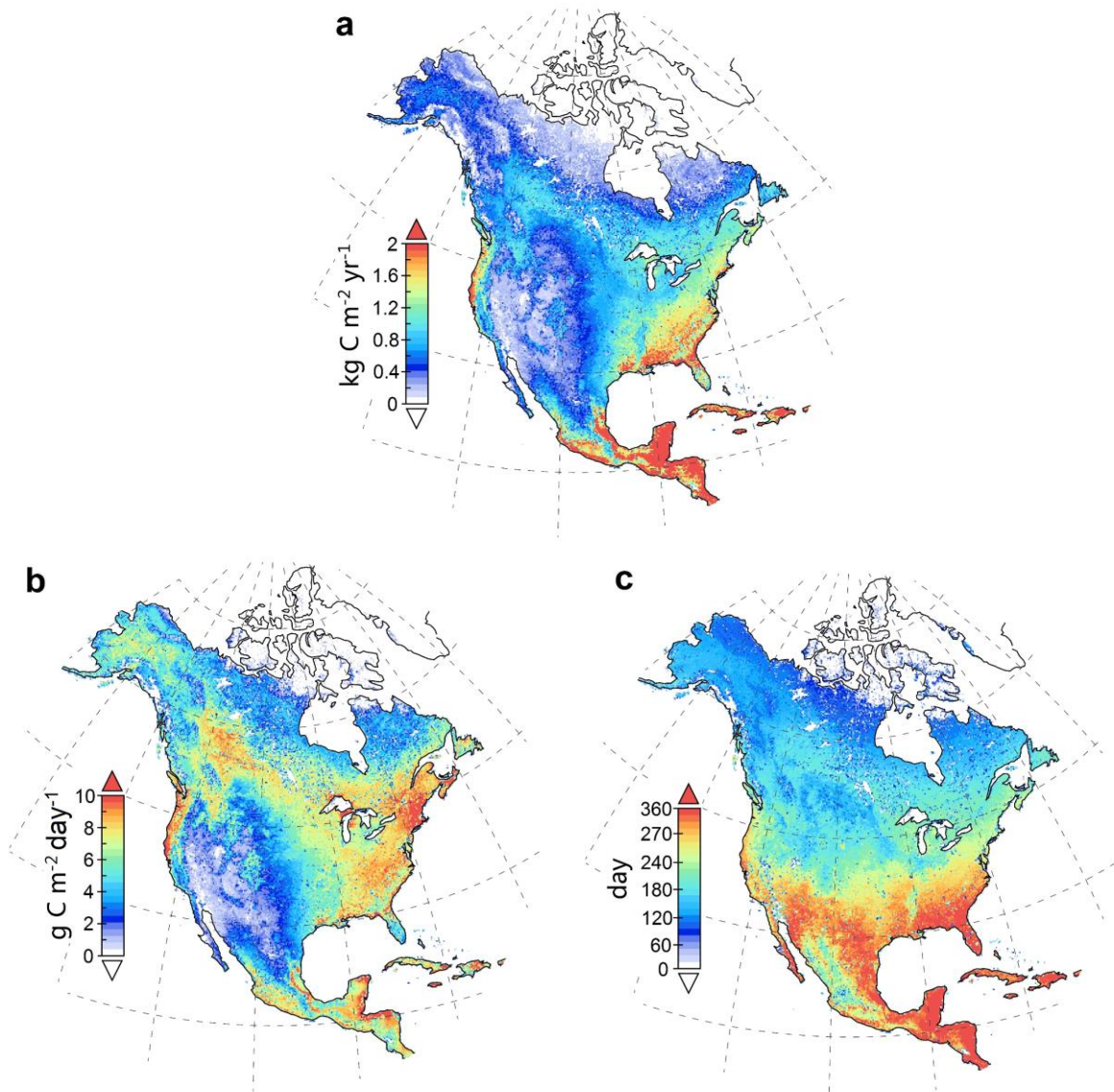


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534 **Figure S4. Spatial distributions of mean (a) annual GPP, (b)  $GPP_{max}$ , and (c) CUP in**  
535 **North America. Data in each  $0.1^\circ \times 0.1^\circ$  grid was averaged over 11 years from 2000 to 2010.**

536



537  
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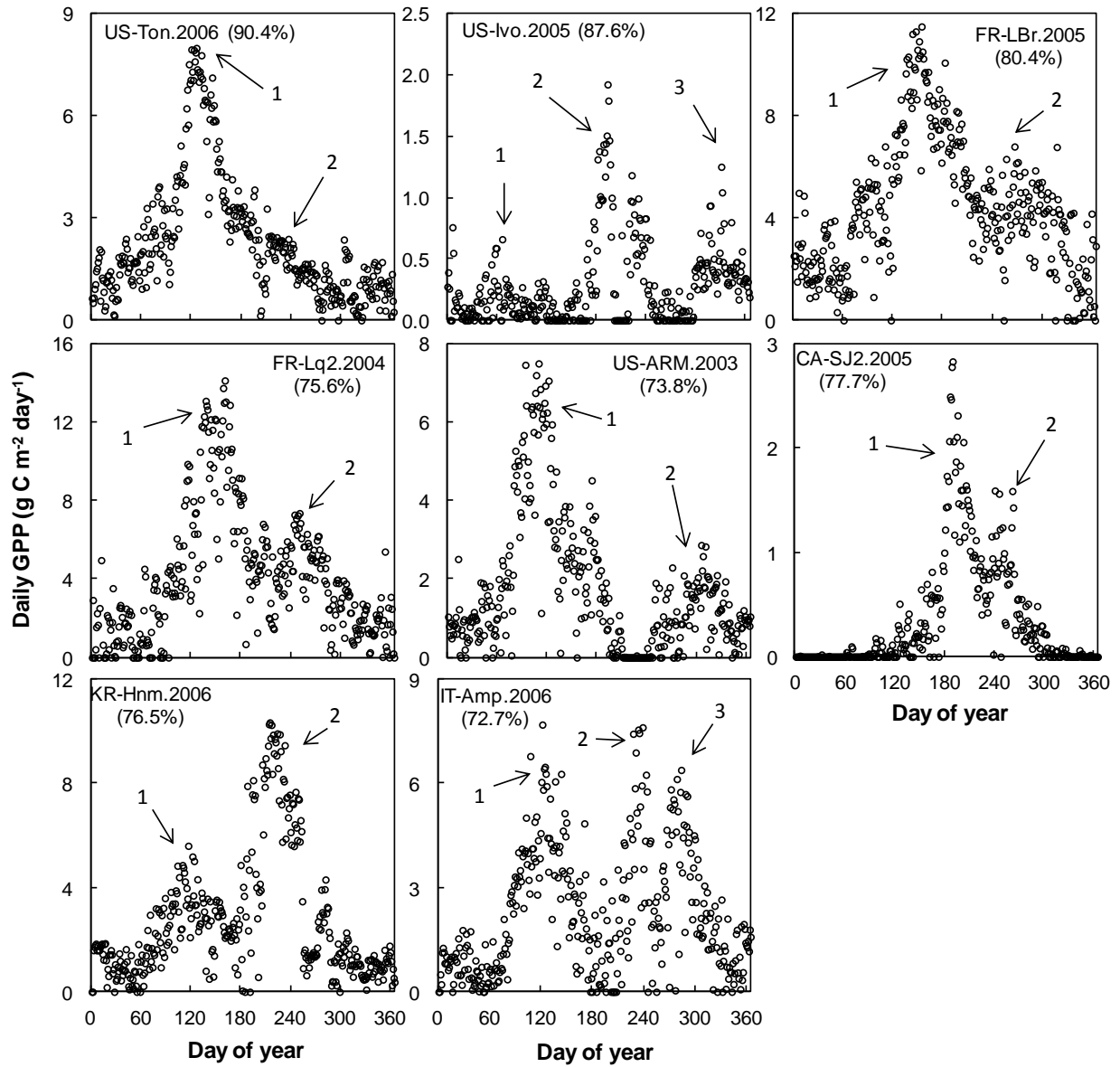


539 **Figure S5.** Examples of flux site-year with multiple peaks of daily GPP. Numbers and the

540 associated arrows show the different GPP peaks. The detailed information for each flux site

541 can be found in Table S1.

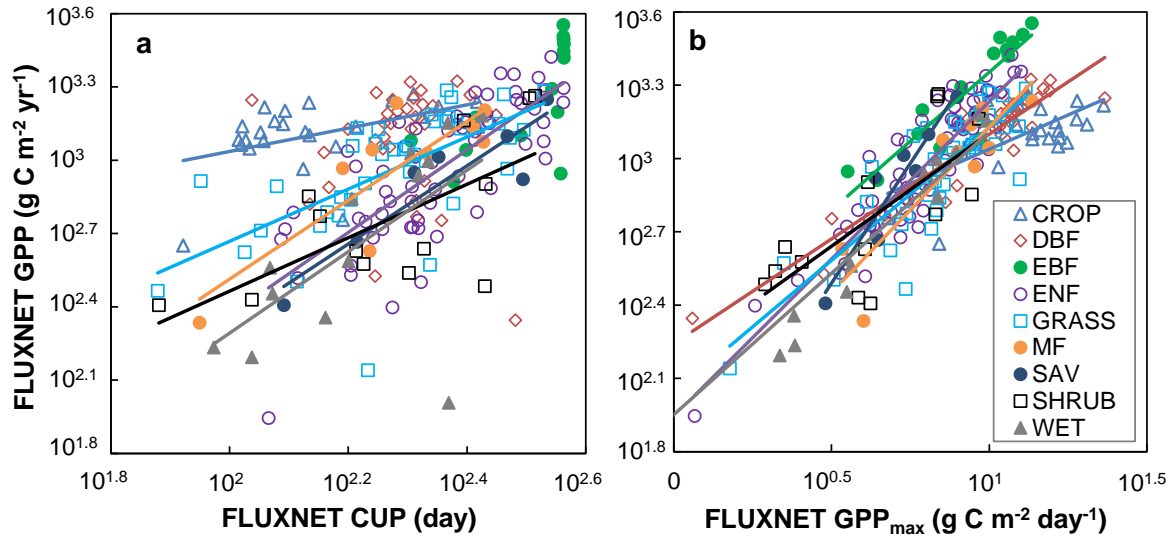
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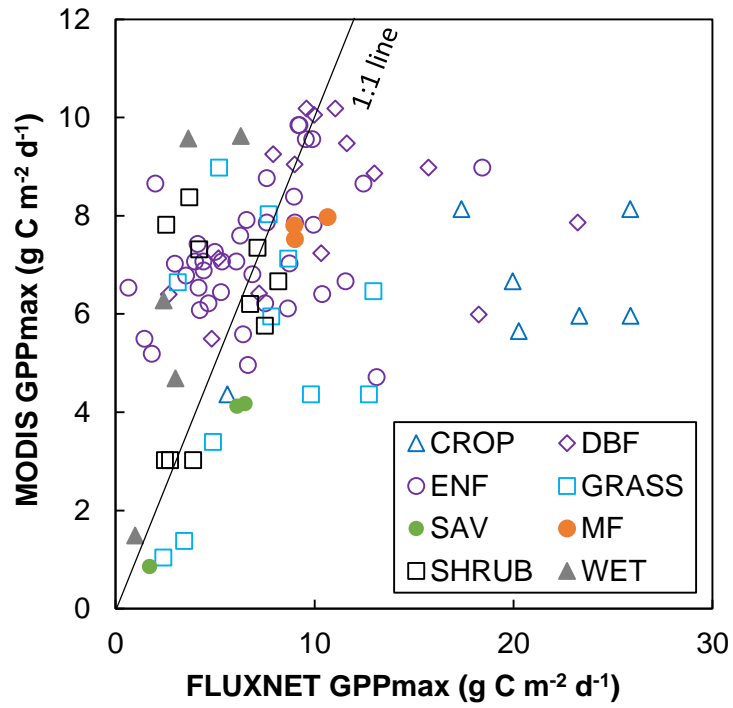
544 **Figure S6.** Dependence of annual FLUXNET GPP variability on (a) CUP and (b)  $GPP_{max}$   
545 (the linear correlation was tested at the significance level of  $P = 0.05$ ).

546



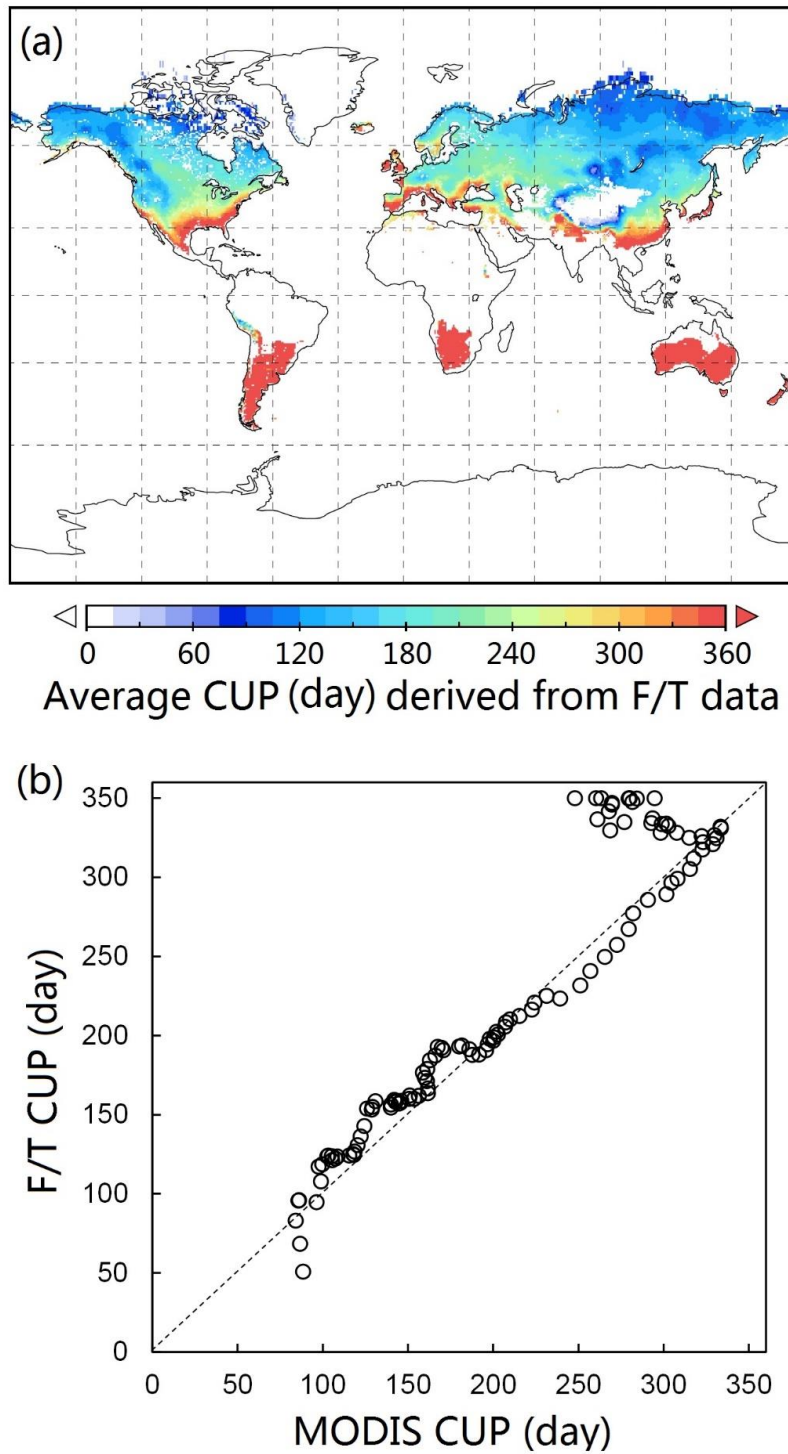
549 **Figure S7.** Relationship between MODIS- and FLUXNET-derived  $GPP_{max}$  in North  
550 America. The MODIS  $GPP_{max}$  ( $0.1^\circ$  by  $0.1^\circ$  degree) from the latitude-longitude grid cell  
551 where the flux-tower site located was used for the analysis.

552



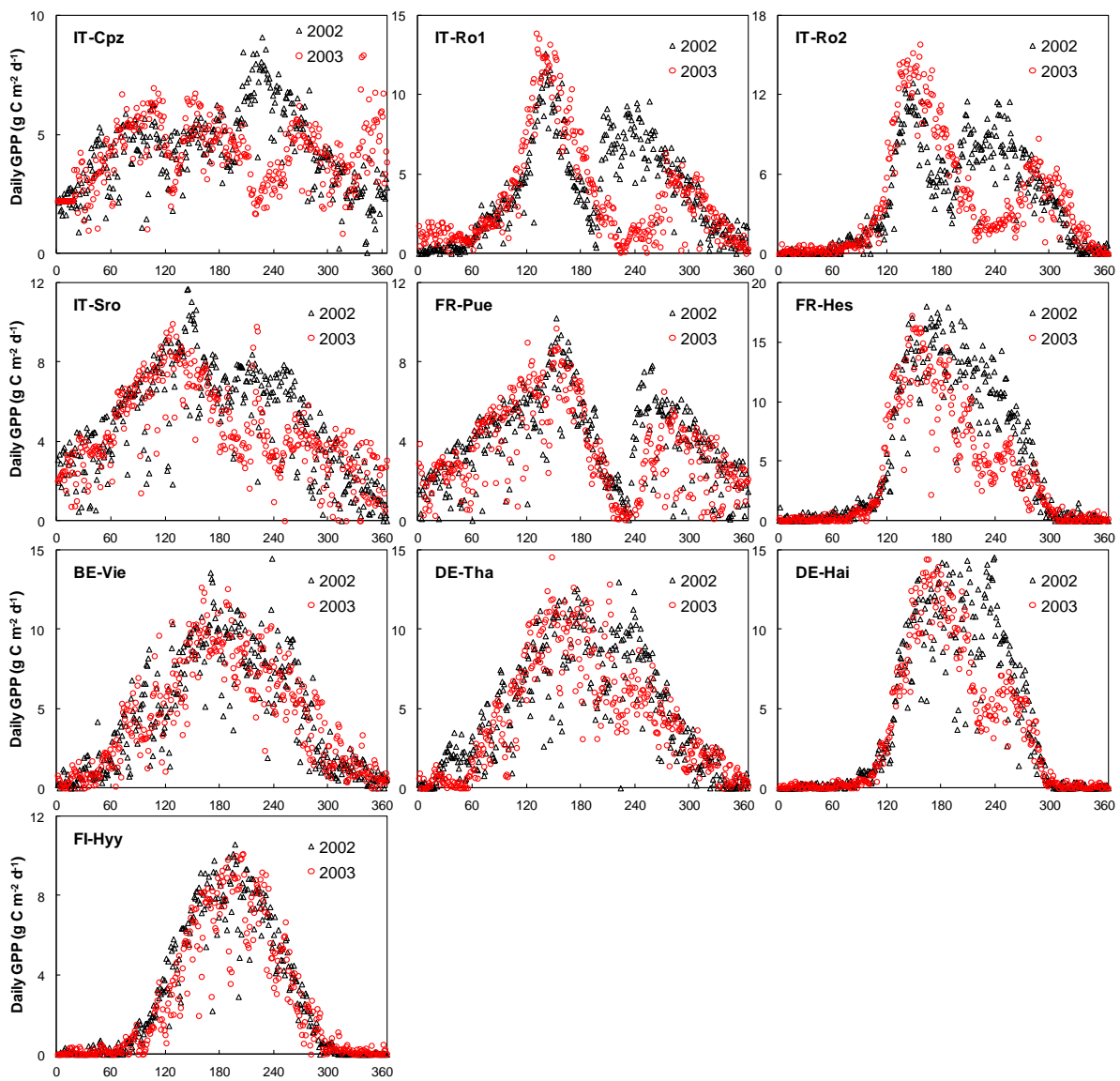
553

554 **Figure S8.** (a) Global distribution of averaged CUP over 2000-2010 derived from the daily  
555 records of landscape freeze/thaw (F/T) data with the spatial resolution of 25km by 25km. (b)  
556 Comparison between the MODIS- and F/T-derived CUP in North America. More details of  
557 the data and method are provided in S1.9. The F/T data were firstly re-gridded into 0.1 ° by  
558 0.1 °, and then both the MODIS- and F/T-derived were averaged along latitude with a 0.5 °  
559 interval.  
560



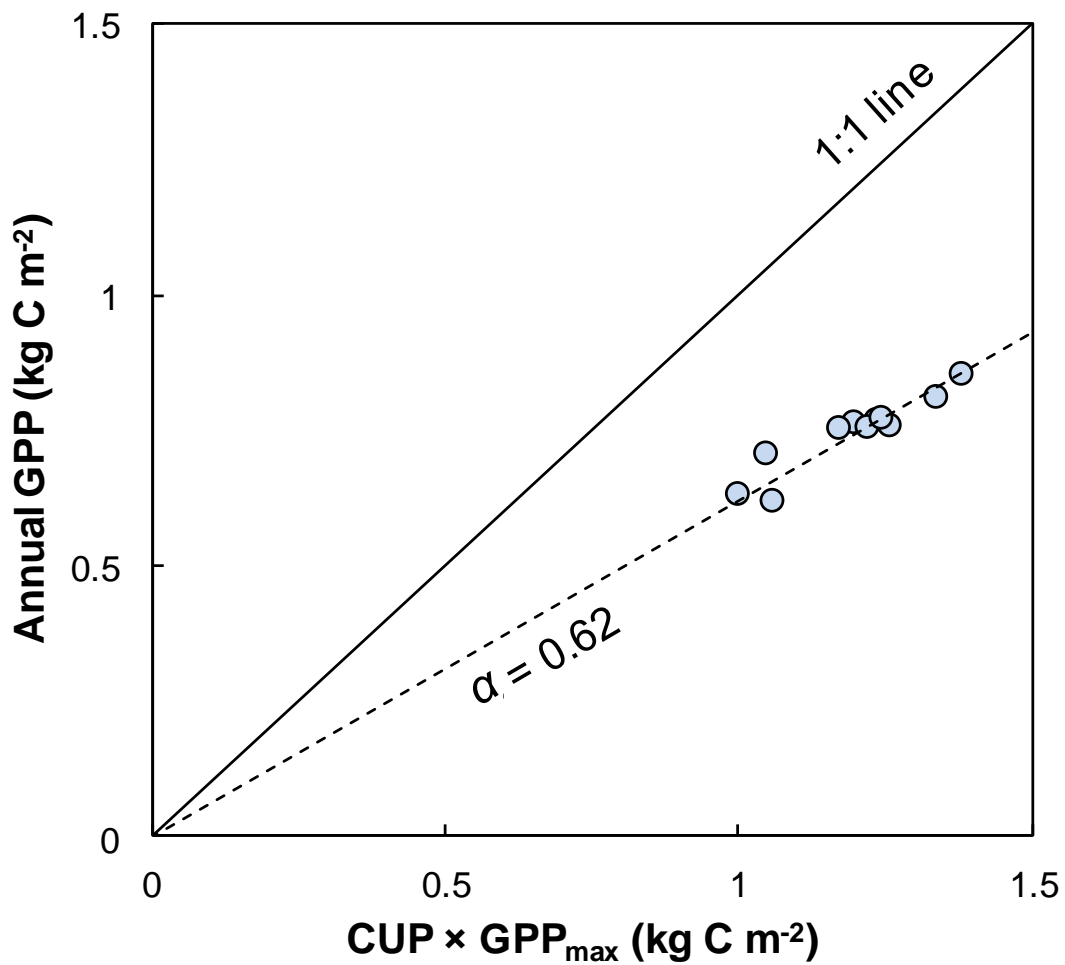
561

562 **Figure S9.** GPP dynamics in 2002 and 2003 at 10 FLUXNET sites in Europe. The year 2003  
 563 was extremely hot and dry, with July temperature up to 6 °C above and annual precipitation  
 564 about 50% below the long-term averages(155). The selection of sites is based on the ref  
 565 (149), which analyzed the impacts of the 2003 heatwave on European primary productivity.  
 566 According to that study, GPP in 2002 (black triangle) was chosen as a reference and the  
 567 impact of 2003 heatwave was calculated as the relative changes in 2003 (red circle) from  
 568 those in 2002. The site information can be found in Table S1.  
 569



570

571 **Figure S10.** Relationship between annual GPP and the product of CUP and  $GPP_{max}$  in the  
572 Black Hills National Forest, South Dakota, USA. Each circle represents a year from 2000 to  
573 2010. The results were obtained from the MODIS GPP observations in a  $0.1 \times 0.1^\circ$  grid pixel  
574 ( $43.85^\circ N$ ,  $103.95^\circ W$ ) which located in the burned area in the Black Hills National Forest.  
575 More information about the fire disturbance and the following recovery of vegetation  
576 greenness can be found in Xiao *et al.*(154) .



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578

579 **Supporting References**

- 580 1. Baldocchi D, et al. (2001) FLUXNET: a new tool to study the temporal and spatial  
581 variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities.  
582 *Bulletin of the American Meteorological Society* 82(11):2415-2434.
- 583 2. Gu L, et al. (2003) Phenology of vegetation photosynthesis. *Phenology: An integrative*  
584 *environmental science*, (Springer), pp 467-485.
- 585 3. Reichstein M, et al. (2005) On the separation of net ecosystem exchange into  
586 assimilation and ecosystem respiration: review and improved algorithm. *Global Change*  
587 *Biol* 11(9):1424-1439.
- 588 4. Papale D, et al. (2006) Towards a standardized processing of Net Ecosystem Exchange  
589 measured with eddy covariance technique: algorithms and uncertainty estimation.  
590 *Biogeosciences* 3(4):571-583.
- 591 5. Beer C, et al. (2010) Terrestrial gross carbon dioxide uptake: global distribution and  
592 covariation with climate. *Science* 329(5993):834-838.
- 593 6. Moncrieff JB, Malhi Y, & Leuning R (1996) The propagation of errors in long-term  
594 measurements of land-atmosphere fluxes of carbon and water. *Global Change Biol*  
595 2(3):231-240.
- 596 7. Moffat AM, et al. (2007) Comprehensive comparison of gap-filling techniques for eddy  
597 covariance net carbon fluxes. *Agr Forest Meteorol* 147(3-4):209-232.
- 598 8. Desai AR, et al. (2008) Cross-site evaluation of eddy covariance GPP and RE  
599 decomposition techniques. *Agr Forest Meteorol* 148(6-7):821-838.
- 600 9. Heinsch FA, et al. (2003) GPP and NPP (MOD17A2/A3) Products NASA MODIS Land  
601 Algorithm. *MOD17 User's Guide*:1-57.
- 602 10. Zhao MS, Heinsch FA, Nemani RR, & Running SW (2005) Improvements of the  
603 MODIS terrestrial gross and net primary production global data set. *Remote Sens*  
604 *Environ* 95(2):164-176.
- 605 11. Zhao MS & Running SW (2010) Drought-induced reduction in global terrestrial net  
606 primary production from 2000 Through 2009. *Science* 329(5994):940-943.
- 607 12. Running SW, et al. (2004) A continuous satellite-derived measure of global terrestrial  
608 primary production. *Bioscience* 54(6):547-560.
- 609 13. Sjöstrom M, et al. (2011) Exploring the potential of MODIS EVI for modeling gross  
610 primary production across African ecosystems. *Remote Sens Environ* 115(4):1081-1089.
- 611 14. Gu L, et al. (2009) Characterizing the seasonal dynamics of plant community  
612 photosynthesis across a range of vegetation types. *Phenology of Ecosystem Processes*,  
613 (Springer), pp 35-58.
- 614 15. Jönsson P & Eklundh L (2004) TIMESAT—a program for analyzing time-series of  
615 satellite sensor data. *Computers & Geosciences* 30(8):833-845.
- 616 16. Gilmanov TG, et al. (2007) Partitioning European grassland net ecosystem CO<sub>2</sub>  
617 exchange into gross primary productivity and ecosystem respiration using light response  
618 function analysis. *Agr Ecosyst Environ* 121(1-2):93-120.

- 619 17. Fischer ML, Billesbach DP, Berry JA, Riley WJ, & Torn MS (2007) Spatiotemporal  
620 variations in growing season exchanges of CO<sub>2</sub>, H<sub>2</sub>O, and sensible heat in agricultural  
621 fields of the Southern Great Plains. *Earth Interact* 11, 10.1175/EI231.1
- 622 18. Liu XJ, Ju XT, Zhang FS, Pan JR, & Christie P (2003) Nitrogen dynamics and budgets  
623 in a winter wheat-maize cropping system in the North China Plain. *Field Crop Res*  
624 83(2):111-124.
- 625 19. Eklundha L & Jönssonb P (2012) Timesat 3.1 Software Manual.
- 626 20. Giorgi F & Lionello P (2008) Climate change projections for the Mediterranean region.  
627 *Global Planet Change* 63(2-3):90-104.
- 628 21. Grunzweig JM, Lin T, Rotenberg E, Schwartz A, & Yakir D (2003) Carbon  
629 sequestration in arid-land forest. *Global Change Biol* 9(5):791-799.
- 630 22. Bates DM & Watts DG (1988) Nonlinear regression: iterative estimation and linear  
631 approximations (Wiley Online Library).
- 632 23. Fox J (2002) Nonlinear regression and nonlinear least squares. appendix to an R and S-  
633 PLUS companion to applied regression. (Sage Publications, Ca).
- 634 24. Xu L, et al. (2013) Temperature and vegetation seasonality diminishment over northern  
635 lands. *Nature Climate Change* 3(6):581-586.
- 636 25. Kim Y, Kimball JS, Zhang K, & McDonald KC (2012) Satellite detection of increasing  
637 Northern Hemisphere non-frozen seasons from 1979 to 2008: Implications for regional  
638 vegetation growth. *Remote Sens Environ* 121:472-487.
- 639 26. Zhang K, Kimball JS, Kim Y, & McDonald KC (2011) Changing freeze-thaw seasons in  
640 northern high latitudes and associated influences on evapotranspiration. *Hydrol Process*  
641 25(26):4142-4151.
- 642 27. Wohlfahrt G, et al. (2008) Seasonal and inter-annual variability of the net ecosystem CO<sub>2</sub>  
643 exchange of a temperate mountain grassland: Effects of weather and management. *J*  
644 *Geophys Res-Atmos* 113, D08110, doi:10.1029/2007JD009286.
- 645 28. Carrara A, Janssens IA, Yuste JC, & Ceulemans R (2004) Seasonal changes in  
646 photosynthesis, respiration and NEE of a mixed temperate forest. *Agr Forest Meteorol*  
647 126(1-2):15-31.
- 648 29. Moureaux C, Debacq A, Bodson B, Heinesch B, & Aubinet M (2006) Annual net  
649 ecosystem carbon exchange by a sugar beet crop. *Agr Forest Meteorol* 139(1-2):25-39.
- 650 30. Aubinet M, et al. (2001) Long term carbon dioxide exchange above a mixed forest in the  
651 Belgian Ardennes. *Agr Forest Meteorol* 108(4):293-315.
- 652 31. Tota J, et al. (2008) Amazon rain forest subcanopy flow and the carbon budget:  
653 Santarem LBA-ECO site. *J Geophys Res-Bioge* 113, G00B02,  
654 doi:10.1029/2007JG000597.
- 655 32. Huete AR, et al. (2006) Amazon rainforests green-up with sunlight in dry season.  
656 *Geophys Res Lett* 33, L06405, doi:10.1029/2005GL025583.
- 657 33. da Rocha HR, et al. (2009) Patterns of water and heat flux across a biome gradient from  
658 tropical forest to savanna in Brazil. *J Geophys Res-Bioge* 114, G00B12,  
659 doi:10.1029/2007JG000640.



- 660 34. Humphreys ER, et al. (2006) Carbon dioxide fluxes in coastal Douglas-fir stands at  
661 different stages of development after clearcut harvesting. *Agr Forest Meteorol* 140(1-  
662 4):6-22.
- 663 35. McCaughey JH, Pejam MR, Arain MA, & Cameron DA (2006) Carbon dioxide and  
664 energy fluxes from a boreal mixedwood forest ecosystem in Ontario, Canada. *Agr Forest*  
665 *Meteorol* 140(1-4):79-96.
- 666 36. Flanagan LB & Adkinson AC (2011) Interacting controls on productivity in a northern  
667 Great Plains grassland and implications for response to ENSO events. *Global Change*  
668 *Biol* 17(11):3293-3311.
- 669 37. Dunn AL, Barford CC, Wofsy SC, Goulden ML, & Daube BC (2007) A long-term  
670 record of carbon exchange in a boreal black spruce forest: means, responses to  
671 interannual variability, and decadal trends. *Global Change Biol* 13(3):577-590.
- 672 38. Lafleur PM, Roulet NT, Bubier JL, Frolking S, & Moore TR (2003) Interannual  
673 variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog.  
674 *Global Biogeochemical Cycles* 1036, doi:10.1029/2002GB001983, 2.
- 675 39. Goulden ML, et al. (2004) Diel and seasonal patterns of tropical forest CO<sub>2</sub> exchange.  
676 *Ecol Appl* 14(4):S42-S54.
- 677 40. Black TA, et al. (2000) Increased carbon sequestration by a boreal deciduous forest in  
678 years with a warm spring. *Geophys Res Lett* 27(9):1271-1274.
- 679 41. Howard EA, Gower ST, Foley JA, & Kucharik CJ (2004) Effects of logging on carbon  
680 dynamics of a jack pine forest in Saskatchewan, Canada. *Global Change Biol*  
681 10(8):1267-1284.
- 682 42. Giasson MA, Coursolle C, & Margolis HA (2006) Ecosystem-level CO<sub>2</sub> fluxes from a  
683 boreal cutover in eastern Canada before and after scarification. *Agr Forest Meteorol*  
684 140(1-4):23-40.
- 685 43. Bergeron O, et al. (2007) Comparison of carbon dioxide fluxes over three boreal black  
686 spruce forests in Canada. *Global Change Biol* 13(1):89-107.
- 687 44. Mkhabela MS, et al. (2009) Comparison of carbon dynamics and water use efficiency  
688 following fire and harvesting in Canadian boreal forests. *Agr Forest Meteorol*  
689 149(5):783-794.
- 690 45. Zha T, et al. (2009) Carbon sequestration in boreal jack pine stands following harvesting.  
691 *Global Change Biol* 15(6):1475-1487.
- 692 46. Peichl M & Arain MA (2007) Allometry and partitioning of above- and belowground  
693 tree biomass in an age-sequence of white pine forests. *Forest Ecol Manag* 253(1-3):68-  
694 80.
- 695 47. Yuan FM, et al. (2008) Modeling analysis of primary controls on net ecosystem  
696 productivity of seven boreal and temperate coniferous forests across a continental  
697 transect. *Global Change Biol* 14(8):1765-1784.
- 698 48. Flanagan LB & Syed KH (2011) Stimulation of both photosynthesis and respiration in  
699 response to warmer and drier conditions in a boreal peatland ecosystem. *Global Change*  
700 *Biol* 17(7):2271-2287.
- 701 49. Adkinson AC, Syed KH, & Flanagan LB (2011) Contrasting responses of growing  
702 season ecosystem CO<sub>2</sub> exchange to variation in temperature and water table depth in two

- 703 peatlands in northern Alberta, Canada. *J Geophys Res-Biogeosci* 116, G01004,  
704 doi:10.1029/2010JG001512.
- 705 50. Ammann C, Flechard CR, Leifeld J, Neftel A, & Fuhrer J (2007) The carbon budget of  
706 newly established temperate grassland depends on management intensity. *Agr Ecosyst*  
707 *Environ* 121(1-2):5-20.
- 708 51. Dietiker D, Buchmann N, & Eugster W (2010) Testing the ability of the DNDC model to  
709 predict CO<sub>2</sub> and water vapour fluxes of a Swiss cropland site. *Agr Ecosyst Environ*  
710 139(3):396-401.
- 711 52. Li X, et al. (2012) Estimation of evapotranspiration over the terrestrial ecosystems in  
712 China. *Ecohydrology*. 7: 139–149.
- 713 53. Guan DX, et al. (2006) CO<sub>2</sub> fluxes over an old, temperate mixed forest in northeastern  
714 China. *Agr Forest Meteorol* 137(3-4):138-149.
- 715 54. Yan Y, et al. (2008) Closing the carbon budget of estuarine wetlands with tower-based  
716 measurements and MODIS time series (vol 14, pg 1690, 2008). *Global Change Biol*  
717 14(10):2469-2471.
- 718 55. Chen SP, et al. (2009) Energy balance and partition in Inner Mongolia steppe ecosystems  
719 with different land use types. *Agr Forest Meteorol* 149(11):1800-1809.
- 720 56. Kato T, et al. (2006) Temperature and biomass influences on interannual changes in CO<sub>2</sub>  
721 exchange in an alpine meadow on the Qinghai-Tibetan Plateau. *Global Change Biol*  
722 12(7):1285-1298.
- 723 57. Sun G, et al. (2011) A general predictive model for estimating monthly ecosystem  
724 evapotranspiration. *Ecohydrology* 4(2):245-255.
- 725 58. Sulkava M, Luysaert S, Zaehle S, & Papale D (2011) Assessing and improving the  
726 representativeness of monitoring networks: The European flux tower network example. *J*  
727 *Geophys Res-Biogeosci* 116, G00J04, doi:10.1029/2010JG001562.
- 728 59. Staudt K & Foken T (2007) Documentation of reference data for the experimental areas  
729 of the bayreuth centre for ecology and environmental research (bayceer) at the waldstein  
730 site, Tech. Rep (University of Bayreuth).
- 731 60. Anthoni PM, et al. (2004) Forest and agricultural land-use-dependent CO<sub>2</sub> exchange in  
732 Thuringia, Germany. *Global Change Biol* 10(12):2005-2019.
- 733 61. Knohl A, Schulze ED, Kolle O, & Buchmann N (2003) Large carbon uptake by an  
734 unmanaged 250-year-old deciduous forest in Central Germany. *Agr Forest Meteorol*  
735 118(3-4):151-167.
- 736 62. Schindler D, Turk M, & Mayer H (2006) CO<sub>2</sub> fluxes of a Scots pine forest growing in  
737 the warm and dry southern upper Rhine plain, SW Germany. *Eur J Forest Res*  
738 125(3):201-212.
- 739 63. Don A, Reibmann C, Kolle O, Scherer-Lorenzen M, & Schulze ED (2009) Impact of  
740 afforestation-associated management changes on the carbon balance of grassland. *Global*  
741 *Change Biol* 15(8):1990-2002.
- 742 64. Grunwald T & Bernhofer C (2007) A decade of carbon, water and energy flux  
743 measurements of an old spruce forest at the Anchor Station Tharandt. *Tellus B*  
744 59(3):387-396.

- 745 65. Rebmann C, et al. (2010) Treatment and assessment of the CO<sub>2</sub>-exchange at a complex  
746 forest site in Thuringia, Germany. *Agr Forest Meteorol* 150(5):684-691.
- 747 66. Pilegaard K, et al. (2003) Field measurements of atmosphere-biosphere interactions in a  
748 Danish beech forest. *Boreal Environ Res* 8(4):315-333.
- 749 67. Gockede M, et al. (2008) Quality control of CarboEurope flux data - Part 1: Coupling  
750 footprint analyses with flux data quality assessment to evaluate sites in forest  
751 ecosystems. *Biogeosciences* 5(2):433-450.
- 752 68. Suni T, et al. (2003) Long-term measurements of surface fluxes above a Scots pine forest  
753 in Hyytiala, southern Finland, 1996-2001. *Boreal Environ Res* 8(4):287-301.
- 754 69. Laurila T, et al. (2001) Seasonal variations of net CO<sub>2</sub> exchange in European Arctic  
755 ecosystems. *Theor Appl Climatol* 70(1-4):183-201.
- 756 70. Aurela M, et al. (2007) CO<sub>2</sub> exchange of a sedge fen in southern Finland - The impact of  
757 a drought period. *Tellus B* 59(5):826-837.
- 758 71. Tanja S, et al. (2003) Air temperature triggers the recovery of evergreen boreal forest  
759 photosynthesis in spring. *Global Change Biol* 9(10):1410-1426.
- 760 72. Hibbard KA, Law BE, Reichstein M, & Sulzman J (2005) An analysis of soil respiration  
761 across northern hemisphere temperate ecosystems. *Biogeochemistry* 73(1):29-70.
- 762 73. Granier A, et al. (2000) The carbon balance of a young Beech forest. *Funct Ecol*  
763 14(3):312-325.
- 764 74. Berbigier P, Bonnefond JM, & Mellmann P (2001) CO<sub>2</sub> and water vapour fluxes for 2  
765 years above Euroflux forest site. *Agr Forest Meteorol* 108(3):183-197.
- 766 75. Rambal S, Joffre R, Ourcival JM, Cavender-Bares J, & Rocheteau A (2004) The growth  
767 respiration component in eddy CO<sub>2</sub> flux from a *Quercus ilex mediterranean* forest.  
768 *Global Change Biol* 10(9):1460-1469.
- 769 76. Bonal D, et al. (2008) Impact of severe dry season on net ecosystem exchange in the  
770 Neotropical rainforest of French Guiana. *Global Change Biol* 14(8):1917-1933.
- 771 77. Nagy Z, et al. (2007) The carbon budget of semi-arid grassland in a wet and a dry year in  
772 Hungary. *Agr Ecosyst Environ* 121(1-2):21-29.
- 773 78. Pinter K, et al. (2008) Interannual variability of grasslands' carbon balance depends on  
774 soil type. *Community Ecol* 9:43-48.
- 775 79. Hirano T, et al. (2007) Carbon dioxide balance of a tropical peat swamp forest in  
776 Kalimantan, Indonesia. *Global Change Biol* 13(2):412-425.
- 777 80. Peichl M, Leahy P, & Kiely G (2011) Six-year stable annual uptake of carbon dioxide in  
778 intensively managed humid temperate grassland. *Ecosystems* 14(1):112-126.
- 779 81. Morales P, et al. (2005) Comparing and evaluating process-based ecosystem model  
780 predictions of carbon and water fluxes in major European forest biomes. *Global Change*  
781 *Biol* 11(12):2211-2233.
- 782 82. Kutsch WL, et al. (2010) The net biome production of full crop rotations in Europe. *Agr*  
783 *Ecosyst Environ* 139(3):336-345.
- 784 83. Scartazza A, et al. (2004) Comparisons of  $\delta^{13}C$  of photosynthetic products and  
785 ecosystem respiratory CO<sub>2</sub> and their responses to seasonal climate variability. *Oecologia*  
786 140(2):340-351.

- 787 84. Garbulsky MF, Penuelas J, Papale D, & Filella I (2008) Remote estimation of carbon  
788 dioxide uptake by a Mediterranean forest. *Global Change Biol* 14(12):2860-2867.
- 789 85. Marcolla B, Pitacco A, & Cescatti A (2003) Canopy architecture and turbulence  
790 structure in a coniferous forest. *Bound-Lay Meteorol* 108(1):39-59.
- 791 86. Marcolla B & Cescatti A (2005) Experimental analysis of flux footprint for varying  
792 stability conditions in an alpine meadow. *Agr Forest Meteorol* 135(1-4):291-301.
- 793 87. Vaccari FP, et al. (2012) Land use change and soil organic carbon dynamics in  
794 Mediterranean agro-ecosystems: The case study of Pianosa Island. *Geoderma* 175:29-36.
- 795 88. Migliavacca M, et al. (2009) Modeling gross primary production of agro-forestry  
796 ecosystems by assimilation of satellite-derived information in a process-based model.  
797 *Sensors-Basel* 9(2):922-942.
- 798 89. Montagnani L, et al. (2009) A new mass conservation approach to the study of CO<sub>2</sub>  
799 advection in an alpine forest. *J Geophys Res-Atmos* 114, D07306,  
800 doi:10.1029/2008JD010650.
- 801 90. Rey A, et al. (2002) Annual variation in soil respiration and its components in a coppice  
802 oak forest in Central Italy. *Global Change Biol* 8(9):851-866.
- 803 91. Tedeschi V, et al. (2006) Soil respiration in a Mediterranean oak forest at different  
804 developmental stages after coppicing. *Global Change Biol* 12(1):110-121.
- 805 92. Chiesi M, et al. (2005) Modelling carbon budget of Mediterranean forests using ground  
806 and remote sensing measurements. *Agr Forest Meteorol* 135(1-4):22-34.
- 807 93. Saito M, Miyata A, Nagai H, & Yamada T (2005) Seasonal variation of carbon dioxide  
808 exchange in rice paddy field in Japan. *Agr Forest Meteorol* 135(1-4):93-109.
- 809 94. Ito A, et al. (2006) Seasonal variation in leaf properties and ecosystem carbon budget in  
810 a cool-temperate deciduous broad-leaved forest: simulation analysis at Takayama site,  
811 Japan. *Ecol Res* 21(1):137-149.
- 812 95. Takagi K, et al. (2009) Change in CO<sub>2</sub> balance under a series of forestry activities in a  
813 cool-temperate mixed forest with dense undergrowth. *Global Change Biol* 15(5):1275-  
814 1288.
- 815 96. Hirano T, et al. (2003) CO<sub>2</sub> and water vapor exchange of a larch forest in northern Japan.  
816 *Tellus B* 55(2):244-257.
- 817 97. Choi M, Lee SO, & Kwon H (2010) Understanding of the Common Land Model  
818 performance for water and energy fluxes in a farmland during the growing season in  
819 Korea. *Hydrol Process* 24(8):1063-1071.
- 820 98. Kang M, Kwon H, Cheon JH, & Kim J (2012) On estimating wet canopy evaporation  
821 from deciduous and coniferous forests in the Asian monsoon climate. *J Hydrometeorol*  
822 13(3):950-965.
- 823 99. Jacobs CMJ, et al. (2007) Variability of annual CO<sub>2</sub> exchange from Dutch grasslands.  
824 *Biogeosciences* 4(5):803-816.
- 825 100. Dolman AJ, Moors EJ, & Elbers JA (2002) The carbon uptake of a mid latitude pine  
826 forest growing on sandy soil. *Agr Forest Meteorol* 111(3):157-170.
- 827 101. Moors EJ, et al. (2010) Variability in carbon exchange of European croplands. *Agr*  
828 *Ecosyst Environ* 139(3):325-335.

- 829 102. Chojnicki B, Urbaniak M, Józefczyk D, Augustin J, & Olejnik J (2007) Measurements of  
830 gas and heat fluxes at Rzecin wetland. *Wetlands: Monitoring, Modeling and*  
831 *Management*, edited by Okruszko, T., Maltby, E., Szatylowicz, J., Mirosław-Swiątek, D.,  
832 and Kotowski, W:125-131.
- 833 103. Pital G, Rodrigues A, Mateus J, & Pereira J (2011) Reversing of seasonal patterns of  
834 carbon uptake in an eucalyptus stand in Portugal after drought and felling. *Forest Syst*  
835 *20(3):475-484.*
- 836 104. Pereira J, et al. (2007) Net ecosystem carbon exchange in three contrasting  
837 Mediterranean ecosystems—the effect of drought. *Biogeosciences* 4:791-802.
- 838 105. Merbold L, et al. (2009) Artificial drainage and associated carbon fluxes (CO<sub>2</sub>/CH<sub>4</sub>) in a  
839 tundra ecosystem. *Global Change Biol* 15(11):2599-2614.
- 840 106. van der Molen MK, et al. (2007) The growing season greenhouse gas balance of a  
841 continental tundra site in the Indigirka lowlands, NE Siberia. *Biogeosciences* 4(6):985-  
842 1003.
- 843 107. Kurbatova J, Li C, Varlagin A, Xiao X, & Vygodskaya N (2008) Modeling carbon  
844 dynamics in two adjacent spruce forests with different soil conditions in Russia.  
845 *Biogeosciences* 5(4):969-980.
- 846 108. Marchesini LB, et al. (2007) Carbon balance assessment of a natural steppe of southern  
847 Siberia by multiple constraint approach. *Biogeosciences* 4(4):581-595.
- 848 109. Sagerfors J, et al. (2008) Annual CO<sub>2</sub> exchange between a nutrient-poor, minerotrophic,  
849 boreal mire and the atmosphere. *J Geophys Res-Biogeophys* 113, G01001,  
850 doi:10.1029/2006JG000306.
- 851 110. Eklundh L, Jin HX, Schubert P, Guzinski R, & Heliasz M (2011) An optical sensor  
852 network for vegetation phenology monitoring and satellite data calibration. *Sensors-*  
853 *Basel* 11(8):7678-7709.
- 854 111. Lindroth A, Klemetsson L, Grelle A, Weslien P, & Langvall O (2008) Measurement of  
855 net ecosystem exchange, productivity and respiration in three spruce forests in Sweden  
856 shows unexpectedly large soil carbon losses. *Biogeochemistry* 89(1):43-60.
- 857 112. Lagergren F, et al. (2008) Biophysical controls on CO<sub>2</sub> fluxes of three Northern forests  
858 based on long-term eddy covariance data. *Tellus B* 60(2):143-152.
- 859 113. Hargreaves K, Milne R, & Cannell M (2003) Carbon balance of afforested peatland in  
860 Scotland. *Forestry* 76(3):299-317.
- 861 114. Soussana JF, et al. (2007) Full accounting of the greenhouse gas (CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>)  
862 budget of nine European grassland sites. *Agr Ecosyst Environ* 121(1-2):121-134.
- 863 115. Rebmann C, et al. (2005) Quality analysis applied on eddy covariance measurements at  
864 complex forest sites using footprint modelling. *Theor Appl Climatol* 80(2-4):121-141.
- 865 116. Wilkinson M, Eaton EL, Broadmeadow MSJ, & Morison JIL (2012) Inter-annual  
866 variation of carbon uptake by a plantation oak woodland in south-eastern England.  
867 *Biogeosciences* 9(12):5373-5389.
- 868 117. Acreman MC, Harding RJ, Lloyd CR, & McNeil DD (2003) Evaporation characteristics  
869 of wetlands: experience from a wet grassland and a reedbed using eddy correlation  
870 measurements. *Hydrol Earth Syst Sc* 7(1):11-21.

- 871 118.Kwon HJ, Oechel WC, Zulueta RC, & Hastings SJ (2006) Effects of climate variability  
872 on carbon sequestration among adjacent wet sedge tundra and moist tussock tundra  
873 ecosystems. *J Geophys Res-Bioge* 111, G03014, doi:10.1029/2005JG000036.
- 874 119.Jenkins JP, et al. (2007) Refining light-use efficiency calculations for a deciduous forest  
875 canopy using simultaneous tower-based carbon flux and radiometric measurements. *Agr*  
876 *Forest Meteorol* 143(1-2):64-79.
- 877 120.Gilmanov TG, et al. (2005) Integration of CO<sub>2</sub> flux and remotely-sensed data for primary  
878 production and ecosystem respiration analyses in the Northern Great Plains: potential for  
879 quantitative spatial extrapolation. *Global Ecol Biogeogr* 14(3):271-292.
- 880 121.Goldstein AH, et al. (2000) Effects of climate variability on the carbon dioxide, water,  
881 and sensible heat fluxes above a ponderosa pine plantation in the Sierra Nevada (CA).  
882 *Agr Forest Meteorol* 101(2-3):113-129.
- 883 122.Liu HP, Randerson JT, Lindfors J, & Chapin FS (2005) Changes in the surface energy  
884 budget after fire in boreal ecosystems of interior Alaska: An annual perspective. *J*  
885 *Geophys Res-Atmos* 110, D13101, doi:10.1029/2004JD005158.
- 886 123.Meyers TP & Hollinger SE (2004) An assessment of storage terms in the surface energy  
887 balance of maize and soybean. *Agr Forest Meteorol* 125(1-2):105-115.
- 888 124.Oechel WC, et al. (2000) Acclimation of ecosystem CO<sub>2</sub> exchange in the Alaskan Arctic  
889 in response to decadal climate warming. *Nature* 406(6799):978-981.
- 890 125.Pataki DE & Oren R (2003) Species differences in stomatal control of water loss at the  
891 canopy scale in a mature bottomland deciduous forest. *Adv Water Resour* 26(12):1267-  
892 1278.
- 893 126.Heinsch FA, et al. (2004) Carbon dioxide exchange in a high marsh on the Texas Gulf  
894 Coast: effects of freshwater availability. *Agr Forest Meteorol* 125(1-2):159-172.
- 895 127.Urbanski S, et al. (2007) Factors controlling CO<sub>2</sub> exchange on timescales from hourly to  
896 decadal at Harvard Forest. *J Geophys Res-Bioge* 112, G02020,  
897 doi:10.1029/2006JG000293.
- 898 128.Hollinger DY, Aber J, & Dail B (2004) Spatial and temporal variability in forest-  
899 atmosphere CO<sub>2</sub> exchange (vol 10, pg 1689, 2004). *Global Change Biol* 10(11):1961-  
900 1961.
- 901 129.Allison VJ, Miller RM, Jastrow JD, Matamala R, & Zak DR (2005) Changes in soil  
902 microbial community structure in a tallgrass prairie chronosequence. *Soil Sci Soc Am J*  
903 69(5):1412-1421.
- 904 130.Powell TL, et al. (2006) Environmental controls over net ecosystem carbon exchange of  
905 scrub oak in central Florida. *Agr Forest Meteorol* 141(1):19-34.
- 906 131.Borken W, Savage K, Davidson EA, & Trumbore SE (2006) Effects of experimental  
907 drought on soil respiration and radiocarbon efflux from a temperate forest soil. *Global*  
908 *Change Biol* 12(2):177-193.
- 909 132.Law BE, Thornton PE, Irvine J, Anthoni PM, & Van Tuyl S (2001) Carbon storage and  
910 fluxes in ponderosa pine forests at different developmental stages. *Global Change Biol*  
911 7(7):755-777.
- 912 133.Schmid HP, Grimmerd CSB, Cropley F, Offerle B, & Su HB (2000) Measurements of  
913 CO<sub>2</sub> and energy fluxes over a mixed hardwood forest in the mid-western United States.  
914 *Agr Forest Meteorol* 103(4):357-374.

- 915 134.Sun G, et al. (2010) Energy and water balance of two contrasting loblolly pine  
916 plantations on the lower coastal plain of North Carolina, USA. *Forest Ecol Manag*  
917 259(7):1299-1310.
- 918 135.Noormets A, et al. (2010) Energy and water balance of two contrasting loblolly pine  
919 plantations on the lower coastal plain of North Carolina, USA (vol 259, pg 1299, 2010).  
920 *Forest Ecol Manag* 260(1):169-169.
- 921 136.Verma SB, et al. (2005) Annual carbon dioxide exchange in irrigated and rainfed maize-  
922 based agroecosystems. *Agr Forest Meteorol* 131(1-2):77-96.
- 923 137.Monson RK, et al. (2002) Carbon sequestration in a high-elevation, subalpine forest.  
924 *Global Change Biol* 8(5):459-478.
- 925 138.DeForest JL, et al. (2006) Phenophases alter the soil respiration-temperature relationship  
926 in an oak-dominated forest. *Int J Biometeorol* 51(2):135-144.
- 927 139.Davis KJ, et al. (2003) The annual cycles of CO<sub>2</sub> and H<sub>2</sub>O exchange over a northern  
928 mixed forest as observed from a very tall tower. *Global Change Biol* 9(9):1278-1293.
- 929 140.Lipson DA, Wilson RF, & Oechel WC (2005) Effects of elevated atmospheric CO<sub>2</sub> on  
930 soil microbial biomass, activity, and diversity in a chaparral ecosystem. *Appl Environ*  
931 *Microb* 71(12):8573-8580.
- 932 141.Powell TL, et al. (2008) Carbon exchange of a mature, naturally regenerated pine forest  
933 in north Florida. *Global Change Biol* 14(11):2523-2538.
- 934 142.Clark KL, Gholz HL, & Castro MS (2004) Carbon dynamics along a chronosequence of  
935 slash pine plantations in north Florida. *Ecol Appl* 14(4):1154-1171.
- 936 143.Potts DL, Scott RL, Cable JM, Huxman TE, & Williams DG (2008) Sensitivity of  
937 Mesquite Shrubland CO<sub>2</sub> Exchange to Precipitation in Contrasting Landscape Settings.  
938 *Ecology* 89(10):2900-2910.
- 939 144.Desai AR, Bolstad PV, Cook BD, Davis KJ, & Carey EV (2005) Comparing net  
940 ecosystem exchange of carbon dioxide between an old-growth and mature forest in the  
941 upper Midwest, USA. *Agr Forest Meteorol* 128(1-2):33-55.
- 942 145.Ma SY, Baldocchi DD, Xu LK, & Hehn T (2007) Inter-annual variability in carbon  
943 dioxide exchange of an oak/grass savanna and open grassland in California. *Agr Forest*  
944 *Meteorol* 147(3-4):157-171.
- 945 146.Gough CM, Vogel CS, Schmid HP, Su HB, & Curtis PS (2008) Multi-year convergence  
946 of biometric and meteorological estimates of forest carbon storage. *Agr Forest Meteorol*  
947 148(2):158-170.
- 948 147.Wilson KB & Baldocchi DD (2001) Comparing independent estimates of carbon dioxide  
949 exchange over 5 years at a deciduous forest in the southeastern United States. *J Geophys*  
950 *Res-Atmos* 106(D24):34167-34178.
- 951 148.Cook BD, et al. (2004) Carbon exchange and venting anomalies in an upland deciduous  
952 forest in northern Wisconsin, USA. *Agr Forest Meteorol* 126(3-4):271-295.
- 953 149.Noormets A, Chen J, & Crow TR (2007) Age-dependent changes in ecosystem carbon  
954 fluxes in managed forests in northern Wisconsin, USA. *Ecosystems* 10(2):187-203.
- 955 150.Sun G, Noormets A, Chen J, & McNulty SG (2008) Evapotranspiration estimates from  
956 eddy covariance towers and hydrologic modeling in managed forests in Northern  
957 Wisconsin, USA. *Agr Forest Meteorol* 148(2):257-267.

- 958 151.Scott RL, Hamerlynck EP, Jenerette GD, Moran MS, & Barron-Gafford GA (2010)  
959 Carbon dioxide exchange in a semidesert grassland through drought-induced vegetation  
960 change. *J Geophys Res-Bioge* 115, G03026, doi:10.1029/2010JG001348.
- 961 152.Falk M, Wharton S, Schroeder M, Ustin S, & U KTP (2008) Flux partitioning in an old-  
962 growth forest: seasonal and interannual dynamics. *Tree Physiol* 28(4):509-520.
- 963 153.Navarro M, et al. (2008) Fruit development, not GPP, drives seasonal variation in NPP in  
964 a tropical palm plantation. *Tree Physiol* 28(11):1661-1674.
- 965 154.Xiao X, Biradar C, Wang A, Sheldon S, & Chen Y (2011) Recovery of Vegetation  
966 Canopy After Severe Fire in 2000 at the Black Hills National Forest, South Dakota,  
967 USA. *Journal of Resources and Ecology* 2(2):106-116.
- 968 155.Ciais P, et al. (2005) Europe-wide reduction in primary productivity caused by the heat  
969 and drought in 2003. *Nature* 437(7058):529-533.
- 970