

1 **Biophysical controls on net ecosystem CO<sub>2</sub> exchange over a semiarid shrubland in**  
2 **northwest China**

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4 X. Jia<sup>1,2</sup>, T. S. Zha<sup>1,2\*</sup>, B. Wu<sup>1,2</sup>, Y. Q. Zhang<sup>1,2</sup>, J. N. Gong<sup>3</sup>, S. G. Qin<sup>1,2</sup>, G. P. Chen<sup>4</sup>, [D. Qian<sup>1,2</sup>](#), S. Kellomäki<sup>3</sup>, H.  
5 Peltola<sup>3</sup>

6  
7 <sup>1</sup> Yanchi Research Station, School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

8 <sup>2</sup> [Key Laboratory of soil and Water Conservation and Desertification Combating, Ministry of Education, Beijing Forestry University,](#)  
9 [Beijing 100083, China](#)

10 <sup>3</sup> School of Forest Sciences, University of Eastern Finland, PO Box 111, FIN-80101 Joensuu, Finland

11 <sup>4</sup> Institute of Forest Sciences, Bailongjiang Forestry Management Bureau, Wudu, Gansu 746010, China

12  
13 **Correspondence to:** T. S. Zha (tianshazha@bjfu.edu.cn)

## 1 **Abstract**

2 The carbon (C) cycling in semiarid and arid areas remains largely unexplored, despite the wide distribution of  
3 drylands globally. Rehabilitation practices have been carried out in many desertified areas, but information on the  
4 C sequestration capacity of recovering vegetation is still largely lacking. Using the eddy-covariance technique, we  
5 measured the net ecosystem CO<sub>2</sub> exchange (NEE) over a recovering shrub ecosystem in northwest China  
6 throughout 2012 in order to (1) quantify NEE and its components, (2) examine the dependence of C fluxes on  
7 biophysical factors at multiple timescales. The annual budget showed a gross ecosystem productivity (GEP) of  
8 456 g C m<sup>-2</sup> yr<sup>-1</sup> (with a 90% prediction interval of 449-463 g C m<sup>-2</sup> yr<sup>-1</sup>) and an ecosystem respiration (*R<sub>e</sub>*) of 379 g  
9 C m<sup>-2</sup> yr<sup>-1</sup> (with a 90% prediction interval of 370-389 g C m<sup>-2</sup> yr<sup>-1</sup>), resulting in a net C sink of 77 g C m<sup>-2</sup> yr<sup>-1</sup> (with a  
10 90% prediction interval of 68-87 g C m<sup>-2</sup> yr<sup>-1</sup>). The maximum daily NEE, GEP and *R<sub>e</sub>* were -4.7, 6.8 and 3.3 g C  
11 m<sup>-2</sup> day<sup>-1</sup>, respectively. Both the maximum C assimilation rate (i.e., at optimum light intensity) and the quantum  
12 yield varied over the growing season, being higher in summer and lower in spring and autumn. At the half-hourly  
13 scale, water deficit exerted a major control over daytime NEE, and interacted with other stresses (e.g., heat and  
14 photoinhibition) in constraining C fixation by the vegetation. Low soil moisture also reduced the temperature  
15 sensitivity of *R<sub>e</sub>* (*Q*<sub>10</sub>). At the synoptic scale, rain events triggered immediate pulses of C release from the  
16 ecosystem, followed by peaks of CO<sub>2</sub> uptake 1-2 days later. Over the entire growing season, leaf area index  
17 accounted for 45 and 65% of the seasonal variation in NEE and GEP, respectively. There was a linear  
18 dependence of daily *R<sub>e</sub>* on GEP, with a slope of 0.34. These results highlight the role of abiotic stresses and their  
19 alleviation in regulating C cycling in the face of an increasing frequency and intensity of extreme climatic events.  
20

## 1 Introduction

Drylands (semiarid and arid areas) cover over 40% of the Earth's land surface, and are rapidly expanding as a result of climate change and human activities (Asner et al., 2003). Although dryland ecosystems are characterized by low precipitation, soil fertility and productivity, they are important to the global carbon (C) budget as they account for approximately 20% of total terrestrial net primary productivity (Whittaker, 1975) and 15% of total soil organic carbon (Lal, 2004). The C cycling in desert ecosystems is particularly sensitive to climate and land-use changes, and may feed back to the climate system (Li et al., 2005). In order to accurately predict global C cycling under changing climate, it is necessary to understand how CO<sub>2</sub> exchange in dry areas responds to variations in climatic conditions (Gao et al., 2012). Currently, the C dynamics of desert shrub ecosystems and their responses to environmental factors are less-well-known compared to those of forests and grasslands (Gao et al., 2012).

Whether a dryland ecosystem is a net sink or source of CO<sub>2</sub> is affected by the way it responds to climatic variability (Liu et al., 2012). In semiarid and arid ecosystems, moisture related factors such as precipitation, soil water content (SWC) and vapor pressure deficit (VPD) usually exert strong influences on diurnal, seasonal and interannual variations in the net ecosystem CO<sub>2</sub> exchange (NEE) (Fu et al., 2006; Gao et al., 2012). Water deficit may depress gross ecosystem productivity (GEP) by limiting plant physiological processes (e.g., stomatal closure) and altering plant phenology (e.g., delayed leaf emergence) and canopy structure (e.g., reduced leaf area index, LAI) (Zhou et al., 2013). Low water availability may also limit ecosystem respiration ( $R_e$ ) by reducing root activity, suppressing microbial decomposition of organic matters and restricting the diffusion of extra-cellular enzymes and C substrates in the soil (Wang et al., 2014). Moreover, the effects of water availability on GEP and  $R_e$  depend not only on the sensitivity of related biotic processes and the magnitude of water stress, but also on the temporal pattern of water supply. For example, NEE in dryland ecosystems showed complex and inconsistent responses to rainfall events (Liu et al., 2011; Gao et al., 2012), indicating our lack of understanding on how dryland ecosystems respond to water stress and its relief.

Besides water availability, NEE in arid and semiarid ecosystems is also affected by other abiotic and biotic factors. Drought stress often accompanies thermal and irradiation stresses, as the cloudiness is usually low and the soil is readily heated up by solar radiation during dry periods. High leaf temperature can deactivate photosystem II, enhance the evaporative demand for plants and stimulate respiration (Fu et al., 2006). Strong irradiation is common in arid and semiarid areas, and is likely to induce midday photosynthetic depression (Fu et al., 2006). In many ecosystems, canopy development (e.g., changes in LAI) is critical to the seasonal evolution of CO<sub>2</sub> fluxes (Xu and Baldocchi, 2004; Li et al., 2005). However, the large stochasticity of precipitation and variability of soil moisture in arid and semiarid ecosystems can obscure the effects of LAI (Wang et al., 2008). Considering the inconsistent effects of these environmental stresses and biotic factors on CO<sub>2</sub> fluxes (e.g., Fu et al., 2006; Aires et al., 2008; Wang et al., 2008), it is needed to examine the relative importance of these biophysical controls and their interactions in desert shrub ecosystems.

China is one of the most threatened countries by desertification. Extensive revegetation and conservation practices have been carried out in northern China (Li et al., 2004). However, little has been done to quantify the C sequestration potential of the recovering vegetation (Gao et al., 2012). Shrubland ecosystems at the south edge of the Mu Us desert ([also referred to as the Mu Us sandland](#)) lie in a critical geographic transition zone between arid and semiarid climates, and between agricultural and pastoral land uses. Overgrazing on the natural shrublands and steppes caused severe desertification in this region (Chen and Duan, 2009). Grazing of natural vegetation has been prohibited since the late 1990s. Thus, the vegetation has been recovering for over ten years. The rehabilitation of desertified lands has been evidenced by the increasingly fine soil texture, increased nutrient contents and biodiversity, and reduced wind erosion (Chen and Duan, 2009). The ability of the recovering ecosystems to sequester CO<sub>2</sub> has not yet been assessed. This information, however, is essential to adaptive management under changing climate.

Using the eddy-covariance technique, we measured NEE over a shrub ecosystem at the south edge of the Mu Us

1 desert throughout 2012. Our objectives were (1) to quantify NEE and its partitioning into GEP and  $R_e$  at diurnal,  
2 seasonal and annual scales, (2) to examine the dependence of NEE and its components on abiotic and biotic  
3 factors at multiple timescales. We hypothesized that soil water shortage is dominant over other stresses in  
4 controlling NEE of dryland ecosystems, and could modify the responses of NEE to other environmental factors.  
5 We also proposed that the seasonal dynamics of LAI is an important determinant of productivity over the growing  
6 season, whereas at shorter timescales (e.g., hourly) abiotic stresses could impose critical constraints on  $\text{CO}_2$   
7 fluxes.

## 8 **2 Materials and methods**

### 9 **2.1 Study site**

10 NEE measurements were made at the Yanchi Research Station (37°42.51'N, 107°13.62'E, 1530 m a.s.l.),  
11 Ningxia, northwest China. [The area lies in the southern edge of the Mu Us desert and is characterized by a](#)  
12 [mid-temperate semiarid continental monsoon climate](#). The mean annual temperature (1954-2004) is 8.1 °C and  
13 the frost-free season lasts for 165 days on average (Chen and Duan, 2009; Wang et al., 2014). The mean annual  
14 precipitation is 287 mm, 62% of which falls from July to September (Feng et al., 2013). The mean annual potential  
15 evapotranspiration is 2024 mm. The soil is sandy and has a bulk density of  $1.54 \pm 0.08 \text{ g cm}^{-3}$  (mean  $\pm$  standard  
16 deviation (SD),  $n = 16$ ) in the upper 10 cm of the soil profile. The area is dominated by a mixture of deciduous  
17 shrub species including *Artemisia ordosica*, *Hedysarum mongolicum* and *Hedysarum scoparium*, and also has  
18 sparsely distributed patches of *Salix psammophila* and *Agropyron cristatum*. The canopy height is about 1.4 m.  
19 Water deficit is a limiting factor for plant photosynthesis and soil respiration ( $R_s$ ) at the study site (Feng et al.,  
20 2013; Wang et al., 2014).

### 21 **2.2 Eddy flux measurements**

22 The eddy-covariance instrument was mounted at a height of 6.2 m on a scaffold tower and oriented in the  
23 prevailing wind direction (northwest). A 3D ultrasonic anemometer (CSAT3, Campbell Scientific Inc., USA) was  
24 used to measure fluctuations in wind speed, direction and sonic temperature. A closed-path fast response  
25 infrared gas analyzer (LI-7200, LI-COR Inc., USA) was used to measure fluctuations in  $\text{CO}_2$  and water vapor  
26 concentrations. The tube between the air inlet and the LI-7200 was 100 cm, the tube flow rate was  $15.0 \text{ L min}^{-1}$ .  
27 The tube inlet was situated about 14 cm south of, 16 cm east of, and 8 cm below the anemometer sampling  
28 volume. We calibrated the LI-7200 every three months, using 99.99% nitrogen gas to calibrate zeros for both  $\text{CO}_2$   
29 and water vapor, and a 650 ppm  $\text{CO}_2$  standard and a dew point generator (LI-610, LI-COR Inc., USA) to calibrate  
30 the span for  $\text{CO}_2$  and water vapor, respectively. A data logger (LI-7550, LI-COR Inc., USA) was used to store 10  
31 Hz real-time data. The underlying surface of the shrubland was flat and extended over 250 m in all directions.  
32 Footprint analysis using the flux source area model (FASM) (Schmid, 1997) showed that  $> 90\%$  of the fluxes  
33 originated from within 200 m of the tower. The  $\text{CO}_2$  storage term was not added in estimating NEE because of the  
34 short canopy (1.4 m) that usually makes the term negligible (Zhang et al., 2007). In addition,  $\text{CO}_2$  storage term  
35 tends to be close to zero when summed to daily and annual timescales (Baldocchi, 2003).

### 36 **2.3 Meteorological measurements**

37 Incident photosynthetically active radiation (PAR) was measured using a quantum sensor (PAR-LITE, Kipp &  
38 Zonen, The Netherlands). Net radiation ( $R_n$ ) was measured using a four-component radiometer (CNR-4, Kipp &  
39 Zonen, The Netherlands). Air temperature ( $T_a$ ) and relative humidity were measured with a thermohygrometer  
40 (HMP155A, Vaisala, Finland). All these meteorological sensors were mounted on the tower at 6 m aboveground.  
41 Soil temperature ( $T_s$ ) and water content (SWC) profiles were monitored adjacent to the tower using ECH<sub>2</sub>O-5TE  
42 sensors (Decagon Devices, USA) at four depths (0.1, 0.3, 0.7 and 1.2 m). Five soil heat plates (HFP01, Hukseflux  
43 Thermal Sensors, The Netherlands) were placed at 10 cm below the soil surface, within about 5 m of the tower  
44 base. [Rainfall was measured from 15 May 2012. The measurements were done with a manual rain bucket before](#)

22 July, and thereafter with a tipping bucket rain gauge (TE525WS, Campbell Scientific Inc., USA) at a distance of about 50 m from the tower. All micrometeorological variables were measured every 10 s and then averaged or summed to the 30 min resolution before being stored on data loggers (CR200X for rainfall, CR3000 for all others, Campbell Scientific Inc., USA).

## 2.4 LAI measurements

For measuring LAI, we deployed a 4 × 4 grid of 16 quadrats (10 m × 10 m each) within a 100 m × 100 m plot centered on the flux tower in late March 2012. LAI was measured at roughly weekly intervals. The starting and ending dates for LAI measurements were specified for each species based on phenological observations. The plot-level LAI was calculated as the sum over all component species. The methods for LAI measurements were detailed in the Supplementary Material.

## 2.5 Data processing and analysis

### 2.5.1 Flux calculation

Raw data were processed using the EddyPro 4.0.0 software (LI-COR Inc., USA). Processing steps included spike removal, tilt correction (double axis rotation), correction for sensor separation, spectral correction, detrending (Reynolds averaging) and flux computation (Burba and Anderson, 2010). Correction for density fluctuations (WPL terms) was not used, however, as LI-7200 is capable of outputting CO<sub>2</sub> mixing ratios, i.e., thermal expansion and water dilution of the sampled air have already been accounted for (Burba and Anderson, 2010). Half-hourly fluxes were rejected if missing records, removed spikes and absolute limit violations together exceeded 10% of the total records of any of the three components of wind velocity and/or CO<sub>2</sub> concentration. CO<sub>2</sub> fluxes were also excluded from analyses when turbulent mixing was low during calm nights (friction velocity  $u^* < 0.18 \text{ m s}^{-1}$ ). The  $u^*$  threshold was estimated following the ChinaFLUX standard method (Zhu et al., 2006). Half-hourly CO<sub>2</sub> fluxes were despiked following Papale et al. (2006). Instrument malfunction, power failure and sensor calibration together led to 3% missing of half-hourly flux data in 2012, while the data quality control procedure rejected 26% of the annual dataset. Eighty-seven percent of all the missing and rejected NEE values occurred during nighttime. For estimating annual sums of C fluxes, only 7% of all daytime data needed to be gap-filled, compared to a proportion of 52% at nighttime. Downward fluxes are counted as negative and upward fluxes as positive. The overall performance of the eddy flux measurement system was evaluated by the degree of energy balance closure (Li et al., 2005), which was 78% in 2012 when taking into account the heat stored in the soil above soil heat plates.

### 2.5.2 Gap-filling and partitioning NEE into GEP and R<sub>e</sub>

Linear interpolation was used to fill small gaps ( $\leq 2 \text{ h}$ ). For larger gaps during daytime (i.e.,  $\text{PAR} \geq 5 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ), NEE-PAR relationships were used for gap-filling. A light response model (Eq. 1) which incorporates photoinhibition at high radiation (Ye, 2007) was used to estimate missing daytime data because net CO<sub>2</sub> uptake declined at high PAR, especially in summer (Fig. 2).

$$\text{NEE}_{\text{day}} = \alpha \frac{1 - \beta Q}{1 + \gamma Q} (Q - Q_c) \quad (1)$$

where  $\text{NEE}_{\text{day}}$  is daytime NEE ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ),  $Q$  is incident PAR in units of  $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ,  $Q_c$  is the light compensation point, and  $\alpha$ ,  $\beta$ ,  $\gamma$  are fit values for the following calculations (Ye, 2007; see also Appendix A for a list of parameters and abbreviations).

$$Q_m = \frac{\sqrt{(\beta + \gamma)(1 + \gamma Q_c)} / \beta - 1}{\gamma} \quad (2)$$

$$\text{NEE}_{\text{max}} = \alpha \frac{1 - \beta Q_m}{1 + \gamma Q_m} (Q_m - Q_c) \quad (3)$$

$$\varphi_0 = \text{NEE}'_{\text{day}}(Q=0) = \alpha[1 + (\gamma + \beta)Q_c] \quad (4)$$

$$\varphi_c = \text{NEE}'_{\text{day}}(Q=Q_c) = \alpha \frac{1 + (\gamma - \beta)Q_c - \beta\gamma Q_c^2}{(1 + \gamma Q_c)^2} \quad (5)$$

$$R_d = -\text{NEE}_{\text{day}}(Q=0) = -\alpha Q_c \quad (6)$$

In Eqs. 2-6,  $Q_m$  is the PAR intensity at the maximum rate of net CO<sub>2</sub> uptake ( $\text{NEE}_{\text{max}}$ ),  $\varphi_0$  and  $\varphi_c$  are the quantum yield at  $Q = 0$  and  $Q = Q_c$ , respectively,  $R_d$  is the model-derived bulk ecosystem respiration. For the estimation of missing  $\text{NEE}_{\text{day}}$ , Eq. (1) was fit to consecutive windows of 500 non-missing daytime data points to obtain seasonally-varying parameter values.

The  $Q_{10}$  model was used for filling nighttime gaps (Zha et al., 2004):

$$\text{NEE}_{\text{night}} = R_{e10} Q_{10}^{(T_s - 10)/10} \quad (7)$$

where  $\text{NEE}_{\text{night}}$  is nighttime NEE,  $T_s$  the soil temperature at 10-cm depth,  $R_{e10}$  the  $R_e$  at  $T_s = 10$  °C,  $Q_{10}$  the temperature sensitivity of ecosystem respiration. Equation (7) was only fit to the annual dataset because short-term data points were too scattered to establish any valid  $\text{NEE}_{\text{night}}-T_s$  relationships.  $T_s$  at 10-cm depth was selected because it produced a higher coefficient of determination ( $R^2$ ) than  $T_s$  at other depths and  $T_a$ . In order to estimate annual CO<sub>2</sub> fluxes, missing  $T_s$  values were gap-filled with the mean diurnal variation (MDV) method (Moffat et al., 2007), while missing PAR values were gap-filled using an empirical relationship to half-hourly PAR data from a meteorological tower about 3 km east.

Daytime  $R_e$  during the growing season was extrapolated from the temperature response function for  $\text{NEE}_{\text{night}}$  (Eq. 7). Off-season  $R_e$  was considered as 24-h NEE fluxes. GEP was estimated as:

$$\text{GEP} = R_e - \text{NEE} \quad (8)$$

### 2.5.3 Statistical analysis

Equation (1) was fit monthly from May to October to evaluate the seasonal variation in light response of NEE. The regressions were conducted on bin-averaged data using 50  $\mu\text{mol m}^{-2} \text{s}^{-1}$  PAR intervals. In order to test the dependency of the  $\text{NEE}_{\text{day}}-\text{PAR}$  relationship on abiotic factors and exclude the confounding effects of plant phenology, we compiled  $\text{NEE}_{\text{day}}$  during the peak growing season (Jun - Aug) into multiple groups according to VPD ( $\text{VPD} \leq 1$  kPa,  $1 \text{ kPa} < \text{VPD} \leq 2$  kPa,  $\text{VPD} > 2$  kPa),  $T_a$  ( $T_a \leq 20$  °C,  $20$  °C  $< T_a \leq 25$  °C,  $T_a > 25$  °C) and SWC at 30-cm depth ( $\text{SWC} \leq 0.1 \text{ m}^3 \text{ m}^{-3}$ ,  $\text{SWC} > 0.1 \text{ m}^3 \text{ m}^{-3}$ ). The  $\text{NEE}_{\text{day}}$  values were then bin-averaged before parameters were fit for each group. These threshold values were chosen to most clearly show the differences between levels, and to avoid having too few data points in a certain group. In addition, the values were equal or close to those used by previous studies in dryland areas. To evaluate the relative importance of different abiotic factors, Eq. (1) was fit to all half-hourly  $\text{NEE}_{\text{day}}$  values during June - August, and the residuals were then subjected to least-square regressions and a stepwise multiple linear regression against VPD,  $T_a$  and SWC (Z-transformed data were used in the stepwise regression). In order to test  $\text{NEE}_{\text{day}}-T_a$  and  $\text{NEE}_{\text{day}}-\text{VPD}$  relationships, as well as their dependence on SWC,  $\text{NEE}_{\text{day}}$  was compiled with respect to SWC at 30-cm depth ( $\text{SWC} \leq 0.1 \text{ m}^3 \text{ m}^{-3}$ ,  $\text{SWC} > 0.1 \text{ m}^3 \text{ m}^{-3}$ ), and then bin-averaged into 1 °C  $T_a$  and 0.2 kPa VPD intervals, respectively.  $\text{NEE}_{\text{day}}-T_a$  and  $\text{NEE}_{\text{day}}-\text{VPD}$  relationships were fit with the quadratic model.

For examining the effects of SWC on the  $R_e-T_s$  (10-cm depth) relationship, we classified  $\text{NEE}_{\text{night}}$  when  $T_s > 0$  °C into two groups with respect to SWC at 30-cm depth ( $\text{SWC} \leq 0.1 \text{ m}^3 \text{ m}^{-3}$ ,  $\text{SWC} > 0.1 \text{ m}^3 \text{ m}^{-3}$ ), and then bin-averaged  $\text{NEE}_{\text{night}}$  into 1 °C  $T_s$  intervals.  $R_{e10}$  and  $Q_{10}$  in Eq. (7) were estimated separately for each SWC group. A minimum of ten data points were required for a valid bin for all abovementioned bin-averages. The following surface fitting ( $T_s$ -REW model) was then used to further examine the interaction between temperature



1 and water availability in regulating half-hourly  $NEE_{\text{night}}$ :

$$2 \quad NEE_{\text{night}} = (a + bREW)(c + dREW)^{(T_s - 10)/10} \quad (9)$$

3 where  $a$ ,  $b$ ,  $c$  and  $d$  are fit parameters ( $R_{e10} = a + bREW$ ;  $Q_{10} = c + dREW$ ). REW means relative extractable water  
4 content (Zhou et al., 2013), which was calculated as:

$$5 \quad REW = \frac{SWC - SWC_{\min}}{SWC_{\max} - SWC_{\min}} \quad (10)$$

6 where  $SWC_{\max}$  and  $SWC_{\min}$  are the minimum and maximum SWC during the period of  $T_s > 0$  °C, respectively.  
7 Linear regressions were used to compare measured vs. predicted half-hourly  $NEE_{\text{night}}$  values and to examine the  
8 dependence of  $NEE_{\text{night}}$  residuals on REW for both the  $Q_{10}$  model (Eq. 7) and the  $T_s$ -REW model (Eq. 10). SWC  
9 at 30-cm depth was chosen for both daytime and nighttime analyses because its effects were most pronounced  
10 among SWC at different layers.

11 Linear regressions were used to examine the seasonal relationships between GEP and  $R_e$ , and the responses of  
12 NEE and GEP to seasonal changes in LAI. For this purpose, daily-integrated values were calculated for C fluxes,  
13 and daily LAI was derived by linear interpolation between measurements.

14 We evaluated the cumulative effect of random measurement uncertainty on annual NEE with the so-called  
15 successive days approach (Hollinger and Richardson, 2005; Dragoni et al., 2007). This method infers the  
16 statistical properties of the random error from the difference between half-hourly NEE measurements made  
17 exactly 24 h apart. The effects of imperfect environmental similarity between the successive days were controlled  
18 for following Dragoni et al. (2007). A Monte Carlo approach was then used to generate a random error for each  
19 measured half-hourly NEE. The simulation was repeated 2000 times and the uncertainty of the measured annual  
20 NEE was estimated by calculating the 90% prediction limits of all simulated annual NEE values. Similarly, we  
21 evaluated the random uncertainty for annual GEP and  $R_e$  following a Monte Carlo algorithm detailed by Hagen et  
22 al. (2006). The algorithm infers the statistical properties of the random error from the residuals of the model for  
23 gap-filling and flux partitioning. Again, the 90% prediction limits of all ( $N = 2000$ ) simulated annual GEP and  $R_e$   
24 values were calculated. The resulting GEP and  $R_e$  uncertainties encompass sources from both measurement  
25 error and model parameterization (Hagen et al., 2006).

## 27 3 Results

### 28 3.1 Seasonal variation in environmental conditions

29 Environmental variables showed clear seasonal patterns (Fig. 1). The daily mean  $T_a$  ranged from -8.5 on 23  
30 January to 23.4 °C on 11 July (Fig. 1a).  $T_s$  had a minimum of -12.1 °C on 8 February and a maximum of 25.8 °C  
31 on 22 June (Fig. 1a). The daily PAR reached a maximum of 61.5 mol m<sup>-2</sup> day<sup>-1</sup> on 15 June, and was < 30 mol m<sup>-2</sup>  
32 day<sup>-1</sup> during winter (Fig. 1b). Daily mean VPD reached a maximum of 2.2 kPa on 9 June, and was lower than <  
33 0.5 kPa during winter (Fig. 1c). Rainfall summed to 304.9 mm from mid-May to December, > 60% of which fell  
34 between June and August. There were three rain events larger than 20 mm day<sup>-1</sup>, among which the largest  
35 occurred on 27 June (49.8 mm day<sup>-1</sup>) (Fig. 1d). Snowmelt and soil thaw in early spring resulted in a relatively wet  
36 soil (Fig. 1d). During the growing season, SWC (except for that at 120-cm depth) followed the pattern of rainfall,  
37 and SWC in deeper layers (30 and 70 cm) only responded to large rainfall events (Fig. 1d).

### 39 3.2 Seasonal variation in NEE and its biophysical controls

40 Daily NEE ranged from -4.71 g C m<sup>-2</sup> day<sup>-1</sup> (largest net CO<sub>2</sub> uptake) on 30 June to 1.63 g C m<sup>-2</sup> day<sup>-1</sup> on 30 July  
41 (Fig. 1f). GEP reached a maximum of 6.78 g C m<sup>-2</sup> day<sup>-1</sup> on 30 June. Maximum  $R_e$  was 3.26 g C m<sup>-2</sup> day<sup>-1</sup> on 25  
42 July. Annual net ecosystem productivity (NEP = -NEE) was 77 g C m<sup>-2</sup> yr<sup>-1</sup> (with a 90% prediction interval of 68-87  
43 g C m<sup>-2</sup> yr<sup>-1</sup>).  $R_e$  contributed 379 g C m<sup>-2</sup> yr<sup>-1</sup> (with a 90% prediction interval of 370-389 g C m<sup>-2</sup> yr<sup>-1</sup>) to NEP,  
44 leading to an annual GEP of 456 g C m<sup>-2</sup> yr<sup>-1</sup> (with a 90% prediction interval of 449-463 g C m<sup>-2</sup> yr<sup>-1</sup>).

1 PAR had strong influences on  $NEE_{day}$  during the growing season (Fig. 2), accounting for > 80% of the variability in  
2  $NEE_{day}$  in most months (except for October) (Table 1). A third-order polynomial pattern was observed for the  
3  $NEE_{day}$ -PAR relationship in summer months (Figs. 2b, c and 3). The absolute values of  $NEE_{max}$ ,  $\varphi_0$ ,  $\varphi_c$  and  $R_d$   
4 were all highest in July, while lower in spring and autumn (Table 1). The effect of PAR was modified by other  
5 environmental factors (Table 2; Fig. 3). The magnitude of  $NEE_{max}$  and  $\varphi_c$  decreased, whereas  $Q_m$  increased, with  
6 increasing VPD and  $T_a$ . In addition,  $R_d$  increased with  $T_a$ . The magnitude of  $NEE_{max}$ ,  $Q_m$  and  $R_d$  were all lower  
7 under dry soil conditions. The  $NEE_{day}$  residuals were positively correlated with VPD and  $T_a$ , and negatively  
8 correlated with SWC (Fig. 3d-f). The stepwise regression produced the following relationship: Residual =  
9  $-0.30SWC + 0.17T_a + 0.11VPD$  ( $R^2 = 0.16$ ,  $P < 0.01$ ).

10  $NEE_{day}$  first decreased (towards higher  $CO_2$  uptake), and then increased, with increasing  $T_a$  and VPD (Fig. 4).  
11 Moreover,  $NEE_{day}$  was more responsive to  $T_a$  and VPD, and showed higher maximum  $CO_2$  uptake rates under  
12 wetter soil conditions ( $SWC \geq 0.1 \text{ m}^3 \text{ m}^{-3}$ ). For most of the VPD range,  $NEE_{day}$  was more negative under higher  
13 soil water availability (Fig. 4b).

14  $NEE_{night}$  related positively with  $T_s$  at 10-cm depth for both SWC groups (Fig. 5). However,  $Q_{10}$  was much larger,  
15 with  $R_{e10}$  slightly smaller, for the higher SWC group. The surface fitting showed that  $Q_{10}$  increased from 1.9 to 3.2,  
16 and  $R_{e10}$  increased with from 0.73 to 0.83  $\mu\text{mol } CO_2 \text{ m}^{-2} \text{ s}^{-1}$ , as REW increased from 0 to 1 (Fig. 6). The  $T_s$ -REW  
17 model fit the measured half-hourly values better than the  $Q_{10}$  model (Fig. 7). Half-hourly  $NEE_{night}$  residuals  
18 showed a positive correlation with REW (Fig. 7b). However, the pattern disappeared after incorporating REW into  
19 the model (Fig. 7d).

20 There was a linear dependence of daily  $R_e$  on GEP ( $R^2 = 0.65$ ), with a slope of 0.34 (Fig. 8a). Both daily GEP and  
21 NEE responded linearly to the seasonal variation of LAI ( $R^2 = 0.65$  and 0.45, respectively), with a slope of 4.12 for  
22 GEP, and -2.03 for NEE (Fig. 8b and c).

### 23 24 **3.3 Synoptic variation in NEE as related to rain pulses**

25 Pulses of NEE were observed during the growing season when rainfall occurred (Fig. 9a). In order to examine the  
26 effects of rain events and related environmental factors on NEE, half-hourly measurements around the largest  
27 rainfall event (DOY 179-180, 61 mm) were scrutinized (Fig. 9b and c). NEE during daytime was markedly  
28 depressed on DOY 179-180 compared to the day before rain (DOY 178), and NEE during nighttime was slightly  
29 higher on DOY 179-180 than on days without rain (DOY 181-184). As a result, a positive pulse in daily NEE was  
30 observed on DOY 179-180 (Fig. 9a). The positive NEE pulse was accompanied by a sharp increase in SWC, but  
31 decreases in  $T_a$ ,  $T_s$  and PAR (Fig. 9b and c). Daytime NEE was dramatically stimulated by high PAR,  
32 temperatures and SWC on days immediately following the rain event (DOY 181-182), leading to a clear post-rain  
33 peak in  $CO_2$  uptake.

### 34 35 **3.4 Diurnal variations in NEE and meteorological factors**

36 The monthly mean diurnal variations of non-rainy days showed that the diel amplitude of NEE varied dramatically  
37 over the growing season, being largest in July and smallest in October (Fig. 10a). NEE during nighttime was  
38 relatively low in magnitude in comparison to that during daytime in most months (except for October). The  
39 ecosystem was a C sink on non-rainy days from May to September. Net  $CO_2$  uptake peaked before noon (at  
40 09:30 - 10:00 LST, LST = GMT + 8) on summer (June - August) days, leading to an asymmetric distribution of  
41 NEE around noon. PAR did not show such an asymmetry, being highest between 12:30 and 13:30 LST (GMT + 8)  
42 (Fig. 10b). Both  $T_a$  and VPD were lowest in early morning, and peaked in late afternoon (Fig. 10c and d).

## 43 44 **4 Discussion**

### 45 **4.1 Magnitude of NEP**

46 Dryland ecosystems can vary from a net sink to source of  $CO_2$  on an annual basis, as mainly determined by the  
47 variations in water availability and the amount of primary producers (Liu et al., 2012). The total amount of C



1 sequestered by the studied shrubland in 2012 ( $NEP = 77 \text{ g C m}^{-2} \text{ yr}^{-1}$ ), with an annual rainfall of at least 305 mm  
2 and a peak LAI of 1.2, was generally lower than that sequestered by forests and grasslands in humid and  
3 subhumid areas (e.g., Suyker and Verma, 2001; Zha et al., 2004; Zhou et al., 2013). However, the NEP was  
4 higher than many reported values from semiarid and arid nonforest ecosystems (Wang et al., 2008; Gao et al.,  
5 2012). For example, a revegetated shrub ecosystem ~200 km west of our site dominated by *Caragana korshinskii*  
6 and *A. ordosica* had a NEP of 14–23  $\text{g C m}^{-2} \text{ yr}^{-1}$ , with an annual precipitation of < 150 mm (Gao et al., 2012). An  
7 semiarid steppe in central Mongolia showed a NEP of 41  $\text{g C m}^{-2} \text{ yr}^{-1}$ , an annual precipitation of 260 mm and a  
8 peak LAI of 0.57 (Li et al., 2005). Liu et al. (2012) reported that a salt desert shrubland (with LAI < 0.4) in  
9 northwest China was near C neutral in a dry year (17 mm annual precipitation), but a C sink of 40  $\text{g C m}^{-2} \text{ yr}^{-1}$  in a  
10 wet year (48 mm annual precipitation). The shrub ecosystem we studied has a wide regional distribution, thus  
11 represents a huge C fixation potential. At our site, precipitation in 2012 was at least 18 mm higher than the  
12 long-term mean, which calls for future studies that assess how semiarid shrub ecosystems respond to interannual  
13 variability in water availability.

## 14 15 **4.2 Effects of abiotic stresses on NEE**

16 The nature and relative importance of different biophysical factors in controlling NEE differ among ecosystems  
17 (Fu et al., 2006). Water stress, which varies significantly at the seasonal and interannual scales, is the most  
18 common limitation to vegetation growth in dryland ecosystems (Fu et al., 2006). Our study revealed the dominant  
19 role of low soil water content in limiting photosynthesis, which was also observed by Fu et al. (2006) in a semiarid  
20 steppe. However, they found that high temperature and strong solar radiation together contributed to a decrease  
21 of  $NEE_{\text{day}}$  in an alpine shrub. Our findings that low SWC and high VPD depressed the maximum rate of  $\text{CO}_2$   
22 uptake ( $NEE_{\text{max}}$ ) (Table 2; Fig. 3) were in agreement with previous studies in dryland ecosystems (Li et al., 2005;  
23 Wang et al., 2008; Yang et al., 2011). Both SWC and VPD affect plant hydraulic status, however, they reduce C  
24 assimilation through different mechanisms. Dry soil leads to reduced water supply for metabolism and cell  
25 expansion, while VPD affects  $\text{CO}_2$  supply for photosynthesis by regulating stomatal conductance and evaporative  
26 demand (Zhou et al., 2013). These two mechanisms did not act in isolation, but interacted to reduce  $\text{CO}_2$  uptake  
27 under water-stressed conditions (Fig. 4). Li et al. (2005) also suggested that the sensitivity of stomata to VPD  
28 becomes stronger once leaf water potential starts to drop because of the deficiency of water supply from the soil.  
29 Low soil water availability may aggravate VPD-induced stomatal closure.

30 Water limitation of  $R_e$  or  $R_s$  has been found in various types of ecosystems (Gao et al., 2012). Our results showed  
31 a marked decrease in both the magnitude and temperature sensitivity ( $Q_{10}$ ) of  $R_e$  under low SWC (Figs. 5 and 6).  
32 Wang et al. (2014) measured  $R_s$  in a nearby community dominated by *A. ordosica* (800 m north of the eddy-flux  
33 tower). They found that  $R_s$  was closely correlated with  $T_s$  when SWC at 10-cm depth was higher than  $0.08 \text{ m}^3 \text{ m}^{-3}$ ,  
34 whereas  $R_s$  was decoupled from temperature during dry periods. The reduction in  $Q_{10}$  of  $R_e$  under drought  
35 conditions was most likely associated with decreased C transportation to roots due to suppressed photosynthesis,  
36 deactivated rhizosphere and switched C pool being respired (e.g., from labile to recalcitrant) (Zhang et al., 2007;  
37 Wang et al., 2008; Gao et al., 2012). **Our result that the  $T_s$ -REW model over-performed the  $T_s$ -only model (Fig. 7)  
38 indicated the need to take water availability into account when modeling short-term (e.g., hourly) changes of  
39 respiration in dryland ecosystems.**

40 Air temperature is another factor affecting VPD besides humidity, which may explain the reduction in  $NEE_{\text{max}}$  at  
41 high temperatures (Fig. 3b). Alternatively, high  $T_a$  might have enhanced respiration and/or suppressed  
42 photosystem II, resulting in smaller  $NEE_{\text{max}}$ . The quadratic relationship between  $NEE_{\text{day}}$  and  $T_a$  was likely  
43 because that, C assimilation was limited by low PAR and temperature on cloudy and rainy days; whereas limited  
44 by heat and water stresses on clear days (Fu et al., 2006). Similar to Li et al. (2005), we found that  $NEE_{\text{day}}$   
45 became less responsive to  $T_a$  under drought conditions (Fig. 4a), reflecting drought limitations to both plant and  
46 microbial activities. A downward shift of optimum  $T_a$  of  $NEE_{\text{day}}$  under low SWC was attributable to different  
47 responses of GEP and  $R_e$  to water deficit (Fu et al., 2006). The asymmetric distribution of net photosynthesis

1 around noon, which we observed (Fig. 10a), is common in arid areas (Zhang et al., 2007). It can be ascribed to  
2 either temperature-induced increases in  $R_e$  or VPD-induced stomatal closure in the afternoon (Fig. 10c and d).  
3 In our study, the  $\text{CO}_2$  uptake decreased under strong solar radiation in summer months (Figs. 2 and 3). One  
4 possible explanation for this is the photoinhibition of  $\text{CO}_2$  assimilation, i.e., insufficient thermal dissipation of  
5 leaves and consequent damage to photosynthetic apparatus under excessive light (Fu et al., 2006). Alternatively,  
6 high VPD and temperature may have depressed  $\text{CO}_2$  uptake under high PAR. The third-order polynomial pattern  
7 in the light response of  $\text{NEE}_{\text{day}}$  (Figs. 2b, c and 3) was unexpected yet interesting. We propose that it may be  
8 related to confounding factors such as VPD and temperature. Although VPD and temperature covaried with PAR  
9 at the diurnal scale, they lagged PAR by 3-4 h (Fig. 10b-d). Therefore, their depression effects on NEE could be  
10 strongest when PAR is below its daily maximum. A detailed understanding of how these interacting environmental  
11 factors regulate ecophysiological processes is needed to develop mechanistic models suitable for arid and  
12 semiarid ecosystems, which is a focus of our ongoing research.

### 13 14 **4.3 Effects of rain pulses on NEE**

15 Rain events triggered pulsed dynamics of NEE in the shrub ecosystem during the growing period (Fig. 9a). Large  
16 positive daily NEE occurred immediately after the heavy rain on DOY 179-180 (61 mm), but the peak of  $\text{CO}_2$   
17 uptake lagged the pulse of  $\text{CO}_2$  release by 1-2 days (Fig. 9a and b). Similarly, Gao et al. (2012) found that a large  
18 precipitation event resulted in a rapid burst of positive C flux ( $\text{CO}_2$  release) before negative values set in 1-2 days  
19 later in a revegetated shrubland in northwest China. Wang et al. (2014) also reported immediate pulses of  $R_s$   
20 following rain events in an *A. ordosica* dominated community at our site. In a semiarid steppe in central Mongolia,  
21 the respiration enhancement effect was even higher during the rain period itself (Li et al., 2005). In contrast, Liu et  
22 al. (2011) found in a saline desert that NEE took 4-5 days to reach its peak of  $\text{CO}_2$  uptake after rain. The rapid  
23 stimulation of  $\text{CO}_2$  release by precipitation may arise from the rapid activation of microorganisms and  
24 decomposition of soil organic matter due to the “Birch effect”, which has been widely reported in regions with dry  
25 soils when a rainfall event occurs after a period of drought (Jarvis et al., 2007). Alternatively, soil water from  
26 rainfall may have degassed the  $\text{CO}_2$  stored in soil pores, considering the sandy soils with high porosity in desert  
27 areas (Lee et al., 2004). The lagged responses of photosynthesis may be associated with physiological  
28 acclimation and recovery of plants from the preceding dry period (Liu et al., 2011). It may also be related to the  
29 post-rainfall environmental conditions that are optimum for C assimilation (Fig. 9c). These results showed that  
30 fast and slow responses contribute together to the pulsed ecosystem behavior. [The asynchronous and differential](#)  
31 [responses of biotic processes to rainfall pulses may affect C sequestration capacity of arid and semiarid areas](#)  
32 [under the projected climate change scenarios associated with increased rainfall variability](#) (Chen et al., 2009).  
33 It is worthy of note that not all rain events caused an equal response of NEE (Fig. 9a). For example, NEE seemed  
34 relatively insensitive to a smaller rain event on DOY 202 (31 mm). This may be due to other biophysical factors  
35 that confound the NEE responses to sudden increases in water availability (Chen et al., 2009). Both temperature  
36 and radiation were much less affected over the DOY 202 rain event (data not shown) than over the DOY 179-180  
37 event (61 mm, Fig. 9b and c), which could partially explain the result that the DOY 202 rain event did not cause a  
38 large fluctuation in NEE. The behavior of NEE over a rain event also depends on the size and timing of water  
39 pulse, the environmental conditions prior to the rain, plant phenology, functional type and rooting depth, all of  
40 which affect the rainfall-response of NEE (Aires et al., 2008; Liu et al., 2011; Gao et al., 2012).

### 41 42 **4.4 Biotic controls on $\text{CO}_2$ fluxes**

43 Leaf area relates to both the amount of photosynthetic tissues and the amount of intercepted light by the  
44 vegetation (Yang et al., 2011). Our results that photosynthetic parameters varied seasonally (Table 1; Fig. 2) with  
45 canopy development (e.g., changes in LAI) has been reported previously for different vegetations (Zha et al.,  
46 2004; Yang et al., 2011). [The small magnitudes of  \$\text{NEE}\_{\text{day}}\$  and its weak response to PAR in October](#) (Table 1; Figs.  
47 [2f and 10](#)) resulted partially from senescent leaves and reduced LAI at the end of the growing season.

1 Temperature and radiation also decreased at the late season, contributing to reduced CO<sub>2</sub> uptake by the  
2 vegetation. Furthermore, we found that LAI accounted for 45 and 65% of the seasonal variation in NEE and GEP,  
3 respectively (Fig. 8b and c), indicating the importance of canopy development in controlling C balance. Similar  
4 GEP-LAI and NEE-LAI relationships have been reported for steppe, grassland and pasture ecosystems (e.g.,  
5 Tappeiner and Cernusca, 1998, Flanagan et al., 2002; Yang et al., 2011). The slope of the GEP-LAI relationship  
6 reported here (4.1 g C m<sup>-2</sup> leaf area day<sup>-1</sup>) was comparable to that in a semiarid steppe (3.1 g C m<sup>-2</sup> day<sup>-1</sup>) (Li et  
7 al., 2005) and two Mediterranean grasslands (3.9-4.1 g C m<sup>-2</sup> day<sup>-1</sup>, Xu and Baldocchi, 2004; Aires et al., 2008).  
8 However, it was much smaller than that found in a Canadian temperate grassland (7.5-8.7 g C m<sup>-2</sup> day<sup>-1</sup>,  
9 Flanagan et al., 2002). A small GEP-LAI slope may be indicative of water and nutrient limitations (Li et al., 2005).  
10 Canopy productivity was shown to have a shadowing effect on  $R_e$  as photosynthesis provides substrates to both  
11 autotrophic and heterotrophic respiration (Wan and Luo, 2003; Flanagan and Johnson, 2005). In our study, GEP  
12 accounted for 65% of the seasonal variation in  $R_e$ , with a slope of 0.34 (Fig. 8a). Li et al. (2005) reported a similar  
13 slope (0.33) for the  $R_e$ -GEP relationship in a semiarid steppe. Xu and Baldocchi (2004) and Aires et al. (2008)  
14 showed slopes of 0.47 and 0.53 in Mediterranean grasslands, respectively. However, Liu et al. (2011) reported a  
15 larger slope (0.8) in a saline desert shrub ecosystem, which may reflect greater C allocation to respiratory tissues  
16 (stems, branches and coarse roots) or functions (e.g., maintenance respiration).

## 18 **5 Conclusions**

19 In line with our hypotheses, we found in the semiarid shrub ecosystem that (1) water stress exerted a strong  
20 control over half-hourly changes in NEE during the peak growing season, and interacted with heat stress and  
21 photoinhibition in constraining C fixation; (2) rain pulses regulated NEE at the synoptic scale, highlighting the role  
22 of water supply in the alleviation of abiotic stresses; (3) canopy development largely determined NEE and GEP  
23 over the entire growing season. Climate modeling suggests a warmer and drier future climate in the semiarid and  
24 arid regions of Asia (McCarthy et al., 2001). Hence, more stressful environmental conditions in the future may  
25 lead to substantially lower carbon sequestration capacity in temperate semiarid areas. Also, the predicted higher  
26 variability in precipitation (Easterling et al., 2000), i.e., more extreme but less frequent rainfall events intervened  
27 by longer dry periods, accentuates the role of the temporal pattern of water availability in controlling NEE in the  
28 future.

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1 **Appendix A**2 **Table A1.** List of abbreviations.

| Variables/Parameters         | Description  |
|------------------------------|--|
| <b>Carbon fluxes</b>         |  |
| GEP                          | Gross ecosystem productivity   |
| NEP                          | Net ecosystem productivity   |
| NEE                          | Net ecosystem CO <sub>2</sub> exchange   |
| NEE <sub>day</sub>           | Daytime net ecosystem CO <sub>2</sub> exchange ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )                          |
| NEE <sub>night</sub>         | Nighttime net ecosystem CO <sub>2</sub> exchange ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )                        |
| $R_e$                        | Ecosystem respiration  |
| $R_s$                        | Soil respiration   |
| <b>Biophysical variables</b> |  |
| LAI                          | Leaf area index ( $\text{m}^2 \text{m}^{-2}$ )   |
| PAR                          | Photosynthetically active radiation  |
| Q                            | PAR intensity ( $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ )   |
| REW                          | Relative extractable water content   |
| $R_n$                        | Net radiation ( $\text{W m}^{-2}$ )  |
| $T_a$                        | Air temperature ( $^{\circ}\text{C}$ )   |
| $T_s$                        | Soil temperature ( $^{\circ}\text{C}$ )  |
| SWC                          | Soil water content ( $\text{m}^3 \text{m}^{-3}$ )  |
| SWC <sub>max</sub>           | Maximum SWC during the period when $T_s$ at 10-cm depth $> 0^{\circ}\text{C}$                                    |
| SWC <sub>min</sub>           | Minimum SWC during the period when $T_s$ at 10-cm depth $> 0^{\circ}\text{C}$                                    |
| <b>Model Parameters</b>      |  |
| $Q_c$                        | Light compensation point ( $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ )  |
| $Q_m$                        | PAR intensity at the maximum rate of net CO <sub>2</sub> uptake ( $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ ) |
| NEE <sub>max</sub>           | Maximum rate of net CO <sub>2</sub> uptake at $Q = Q_m$ ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )                 |
| $Q_{10}$                     | Sensitivity of ecosystem respiration to changes in temperature   |
| $R_d$                        | Bulk ecosystem respiration derived from Eq. (1) ( $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ )             |
| $R_{e10}$                    | $R_e$ at $T_s = 10^{\circ}\text{C}$ ( $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ )                         |
| $\varphi_0$                  | Quantum yield at $Q = 0$ ( $\mu\text{mol CO}_2 \mu\text{mol photons}^{-1}$ )                                     |
| $\varphi_c$                  | Quantum yield at $Q = Q_c$ ( $\mu\text{mol CO}_2 \mu\text{mol photons}^{-1}$ )                                   |
| $\alpha, \beta, \gamma$      | Fit parameters in Eq. (1)  |
| $a, b, c, d$                 | Fit Parameters in Eq. (9)  |

3

4

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1 **Table 1.** Parameter values describing the response of daytime NEE to incident PAR for each month and the entire  
 2 growing season (GS).

| Month | $\alpha$ ( $\times 10^3$ ) | $\beta$ ( $\times 10^4$ ) | $\gamma$ ( $\times 10^4$ ) | $Q_c$              | $Q_m$   | $NEE_{max}$ | $\varphi_0$ | $\varphi_c$ | $R_d$ | Adj. $R^2$ |
|-------|----------------------------|---------------------------|----------------------------|--------------------|---------|-------------|-------------|-------------|-------|------------|
| May   | -6.59 $\pm$ 1.65           | 4.01 $\pm$ 0.61           | -0.04 $\pm$ 3.14           | 186.94 $\pm$ 36.34 | 1344.19 | -3.54       | -0.0071     | -0.0061     | 1.23  | 0.82       |
| Jun   | -14.87 $\pm$ 2.18          | 3.04 $\pm$ 0.37           | 5.61 $\pm$ 2.97            | 141.22 $\pm$ 16.28 | 1340.05 | -6.03       | -0.0167     | -0.0132     | 2.10  | 0.93       |
| Jul   | -17.67 $\pm$ 2.56          | 3.12 $\pm$ 0.48           | 3.96 $\pm$ 2.86            | 154.99 $\pm$ 17.23 | 1395.40 | -7.98       | -0.0196     | -0.0158     | 2.74  | 0.94       |
| Aug   | -15.71 $\pm$ 3.01          | 3.69 $\pm$ 0.39           | 7.83 $\pm$ 4.47            | 146.00 $\pm$ 18.69 | 1105.94 | -4.79       | -0.0184     | -0.0133     | 2.29  | 0.86       |
| Sep   | -7.33 $\pm$ 1.92           | 2.31 $\pm$ 1.79           | 6.23 $\pm$ 8.04            | 159.79 $\pm$ 23.65 | 1629.61 | -3.33       | -0.0083     | -0.0064     | 1.17  | 0.90       |
| Oct   | -1.59 $\pm$ 0.93           | 6.59 $\pm$ 2.46           | 3.92 $\pm$ 18.90           | 324.98 $\pm$ 86.41 | 869.97  | -0.28       | -0.0021     | -0.0011     | 0.52  | 0.36       |
| GS    | -11.80 $\pm$ 1.41          | 1.10 $\pm$ 0.58           | 12.20 $\pm$ 4.08           | 150.06 $\pm$ 9.91  | 2281.00 | -4.98       | -0.0142     | -0.0098     | 1.77  | 0.96       |

3 Fit parameters in Eq. (1) ( $\alpha$ ,  $\beta$ ,  $\gamma$  and  $Q_c$ ) are presented as mean  $\pm$  SE. NEE ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), net ecosystem  
 4 CO<sub>2</sub> exchange; PAR ( $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ), photosynthetically active radiation;  $Q_c$  ( $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ), light  
 5 compensation point;  $NEE_{max}$  ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), the maximum magnitude of daytime NEE;  $Q_m$  ( $\mu\text{mol photons m}^{-2}$   
 6  $\text{s}^{-1}$ ), the PAR intensity corresponding to  $NEE_{max}$ ;  $\varphi_0$  and  $\varphi_c$  ( $\mu\text{mol CO}_2 \mu\text{mol photons}^{-1}$ ), the quantum yield when  
 7 PAR is equal to zero and  $Q_c$ , respectively;  $R_d$  ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), model-derived bulk ecosystem respiration; Adj.  
 8  $R^2$ , adjusted coefficient of determination.

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1 **Table 2.** Parameter values describing the response of daytime NEE to incident PAR during the peak growing  
 2 season (Jun-Aug) under different environmental conditions.

| Treatment          | $\alpha$ ( $\times 10^3$ ) | $\beta$ ( $\times 10^4$ ) | $\gamma$ ( $\times 10^4$ ) | $Q_c$              | $Q_m$   | $NEE_{max}$ | $\varphi_0$ | $\varphi_c$ | $R_d$ | Adj. $R^2$ |
|--------------------|----------------------------|---------------------------|----------------------------|--------------------|---------|-------------|-------------|-------------|-------|------------|
| VPD $\leq 1$       | -14.46 $\pm$ 1.58          | 5.18 $\pm$ 0.47           | -2.58 $\pm$ 1.46           | 152.80 $\pm$ 17.76 | 1184.57 | -8.30       | -0.0150     | -0.0139     | 2.21  | 0.96       |
| 1 < VPD $\leq 2$   | -15.33 $\pm$ 2.84          | 2.61 $\pm$ 0.55           | 6.28 $\pm$ 4.07            | 150.00 $\pm$ 20.32 | 1482.84 | -6.49       | -0.0174     | -0.0135     | 2.30  | 0.90       |
| VPD > 2            | -13.86 $\pm$ 6.81          | 0.89 $\pm$ 1.49           | 17.85 $\pm$ 17.80          | 150.20 $\pm$ 33.65 | 2332.48 | -4.64       | -0.0178     | -0.0108     | 2.08  | 0.80       |
| $T_a \leq 20$      | -16.10 $\pm$ 2.47          | 3.91 $\pm$ 0.63           | 1.48 $\pm$ 2.84            | 146.88 $\pm$ 19.01 | 1260.76 | -7.65       | -0.0174     | -0.0149     | 2.36  | 0.94       |
| 20 < $T_a \leq 25$ | -17.35 $\pm$ 3.27          | 2.99 $\pm$ 0.49           | 6.42 $\pm$ 4.11            | 150.83 $\pm$ 20.22 | 1334.66 | -6.64       | -0.0198     | -0.0151     | 2.62  | 0.89       |
| $T_a > 25$         | -13.96 $\pm$ 8.36          | 1.77 $\pm$ 1.17           | 12.00 $\pm$ 15.1           | 208.20 $\pm$ 50.47 | 1763.11 | -4.79       | -0.0180     | -0.0108     | 2.91  | 0.79       |
| SWC $\leq 0.1$     | -17.63 $\pm$ 3.13          | 3.06 $\pm$ 0.36           | 9.62 $\pm$ 4.39            | 129.53 $\pm$ 17.06 | 1204.58 | -5.54       | -0.0205     | -0.0151     | 2.28  | 0.88       |
| SWC > 0.1          | -16.61 $\pm$ 2.38          | 2.84 $\pm$ 0.48           | 4.05 $\pm$ 2.84            | 177.30 $\pm$ 17.22 | 1512.46 | -7.85       | -0.0186     | -0.0147     | 2.94  | 0.94       |

3 Fit parameters in Eq. (1) ( $\alpha$ ,  $\beta$ ,  $\gamma$  and  $Q_c$ ) are presented as mean  $\pm$  SE. NEE ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), net ecosystem  
 4 CO<sub>2</sub> exchange; PAR ( $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ), photosynthetically active radiation;  $Q_c$  ( $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ), light  
 5 compensation point;  $NEE_{max}$  ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), the maximum magnitude of daytime NEE;  $Q_m$  ( $\mu\text{mol photons m}^{-2}$   
 6  $\text{s}^{-1}$ ), the PAR intensity corresponding to  $NEE_{max}$ ;  $\varphi_0$  and  $\varphi_c$  ( $\mu\text{mol CO}_2 \mu\text{mol photons}^{-1}$ ), the quantum yield when  
 7 PAR is equal to zero and  $Q_c$ , respectively;  $R_d$  ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), model-derived bulk ecosystem respiration; Adj.  
 8  $R^2$ , adjusted coefficient of determination; VPD (kPa), vapor pressure deficit;  $T_a$  ( $^{\circ}\text{C}$ ), air temperature at 6 m  
 9 aboveground, SWC ( $\text{m}^3 \text{ m}^{-3}$ ), soil water content at 30-cm depth.

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## Figure Legends

**Fig. 1.** Seasonal variations of air temperature ( $T_a$ ) at 6 m aboveground and soil temperature ( $T_s$ ) at 10-cm depth (a), incident photosynthetically active radiation (PAR) (b), vapor pressure deficit (VPD) (c), soil water content (SWC) and rainfall (d), leaf area index (LAI) (e) and CO<sub>2</sub> fluxes (f) in 2012. NEE, net ecosystem CO<sub>2</sub> exchange; GEP, gross ecosystem productivity;  $R_e$ , ecosystem respiration. Daily means are shown for  $T_a$ ,  $T_s$ , VPD and SWC; Daily sums are shown for PAR, rainfall and CO<sub>2</sub> fluxes; interpolated daily values are shown for LAI. The vertical dashed lines separate each month, and the horizontal dashed lines in (a) and (f) represent  $y = 0$ .

**Fig. 2.** Daytime net ecosystem CO<sub>2</sub> exchange ( $NEE_{day}$ ) as a function of incident photosynthetically active radiation (PAR) for each month from May to October in 2012. Half-hourly  $NEE_{day}$  was bin-averaged into 50  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$  PAR increments. Bars indicate standard errors. Light response curves were fit with Eq. (1). The dashed lines represent  $y = 0$ .

**Fig. 3.** Daytime net ecosystem CO<sub>2</sub> exchange ( $NEE_{day}$ ) as a function of incident photosynthetically active radiation (PAR) under different environmental conditions (a-c) and the relationships between residuals of the light response curve and environmental factors (d-f). Only data from the peak growing season (Jun - Aug) were used to minimize the confounding effects of phenology. Half-hourly  $NEE_{day}$  was bin-averaged into 50  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$  PAR increments in a-c. Bars indicate standard errors. Light response curves were fit with Eq. (1). The horizontal dashed lines represent  $y = 0$ .

**Fig. 4.** Responses of daytime net ecosystem CO<sub>2</sub> exchange ( $NEE_{day}$ ) to air temperature ( $T_a$ ) (a) and vapor pressure deficit (VPD) (b) under different soil water contents (SWC) measured at 30-cm depth. Only data from the peak growing season (Jun - Aug) were used to minimize the confounding effects of phenology. Half-hourly  $NEE_{day}$  was bin-averaged into 1 °C  $T_s$  (a) and 0.2 kPa VPD (b) intervals, respectively. Bars indicate standard errors. Response curves were fit using the quadratic model. The horizontal dashed lines represent  $y = 0$ .

**Fig. 5.** Nighttime net ecosystem CO<sub>2</sub> exchange ( $NEE_{night}$ ) as a function of soil temperature ( $T_s$ ) at 10-cm depth under different soil water contents (SWC) measured at 30-cm depth. Only data when  $T_s > 0$  °C were used. Half-hourly  $NEE_{night}$  was bin-averaged into 1 °C  $T_s$  intervals. Error bars indicate standard errors.

**Fig. 6.** Nighttime net ecosystem CO<sub>2</sub> exchange ( $NEE_{night}$ ) as a function of soil temperature ( $T_s$ ) at 10-cm depth and relative extractable water content (REW, see Eq. 10). Only data when  $T_s > 0$  °C were used.

**Fig. 7.** Comparisons of measured and predicted half-hourly nighttime net ecosystem CO<sub>2</sub> exchange ( $NEE_{night}$ ) using the  $Q_{10}$  model (a) and the  $T_s$ -REW model (c); relationships between  $NEE_{night}$  residuals and REW for the  $Q_{10}$  model (b) and the  $T_s$ -REW model (d). REW means the relative extractable water content (see Eq. 10). Only data when  $T_s > 0$  °C were used. The dashed-lines in (a) and (c) represent  $y = x$ , and those in (b) and (d) represent  $y = 0$ . The fit line in (a):  $y = 1.08x - 0.14$ ,  $R^2 = 0.33$ ,  $P < 0.01$ ; the fit line in (c):  $y = 1.06x - 0.11$ ,  $R^2 = 0.39$ ,  $P < 0.01$ . The slope and intercept as well as their 95% confidence intervals (CI) are 1.27 (1.04, 1.50) and -0.40 (-0.48, -0.32) for the relationship between REW and the  $NEE_{night}$  residuals from the  $Q_{10}$  model (b), and are -0.21 (-0.43, 0.02) and 0.03 (-0.05, 0.11) for the relationship between REW and the  $NEE_{night}$  residuals from the  $T_s$ -REW model (d).

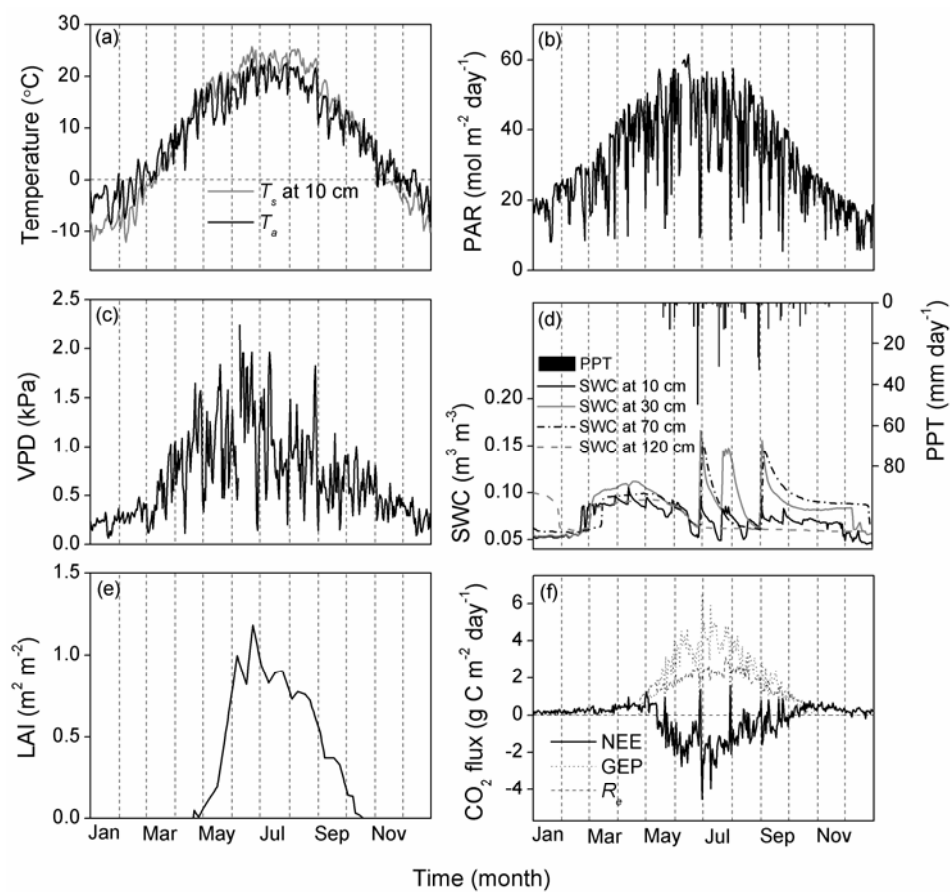
**Fig. 8.** Relationship between gross ecosystem productivity (GEP) and ecosystem respiration ( $R_e$ ) (a), and between leaf area index (LAI) and GEP (b) and net ecosystem CO<sub>2</sub> exchange (NEE) (c). Daily values are shown for the growing period when LAI > 0. The horizontal dashed line in (c) represents  $y = 0$ .

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**Fig. 9.** Pulses in daily net ecosystem CO<sub>2</sub> exchange (NEE) as related to [rainfall](#) events during the growing season (a), and synoptic variations of half-hourly NEE, soil water content (SWC) at 30-cm depth, air temperature ( $T_a$ ), soil temperature at 10-cm depth ( $T_s$ ) and incident photosynthetically active radiation (PAR) before and after a selected rainfall event (b-c). The horizontal dashed lines in (a) and (b) represent  $y = 0$ , and the vertical dashed lines in (b) and (c) separate each day. [The shadow areas in \(b\) and \(c\) indicate rainy days.](#) Rainfall was 50 mm on DOY 179 and 11 mm on DOY 180.

**Fig. 10.** Monthly mean diurnal cycles of net ecosystem CO<sub>2</sub> exchange (NEE) (a), incident photosynthetically active radiation (PAR) (b), air temperature ( $T_a$ ) at 6 m aboveground (c) and vapor pressure deficit (VPD) (d). The vertical dashed lines indicate noon, and the horizontal dashed line in (a) represents  $y = 0$ .

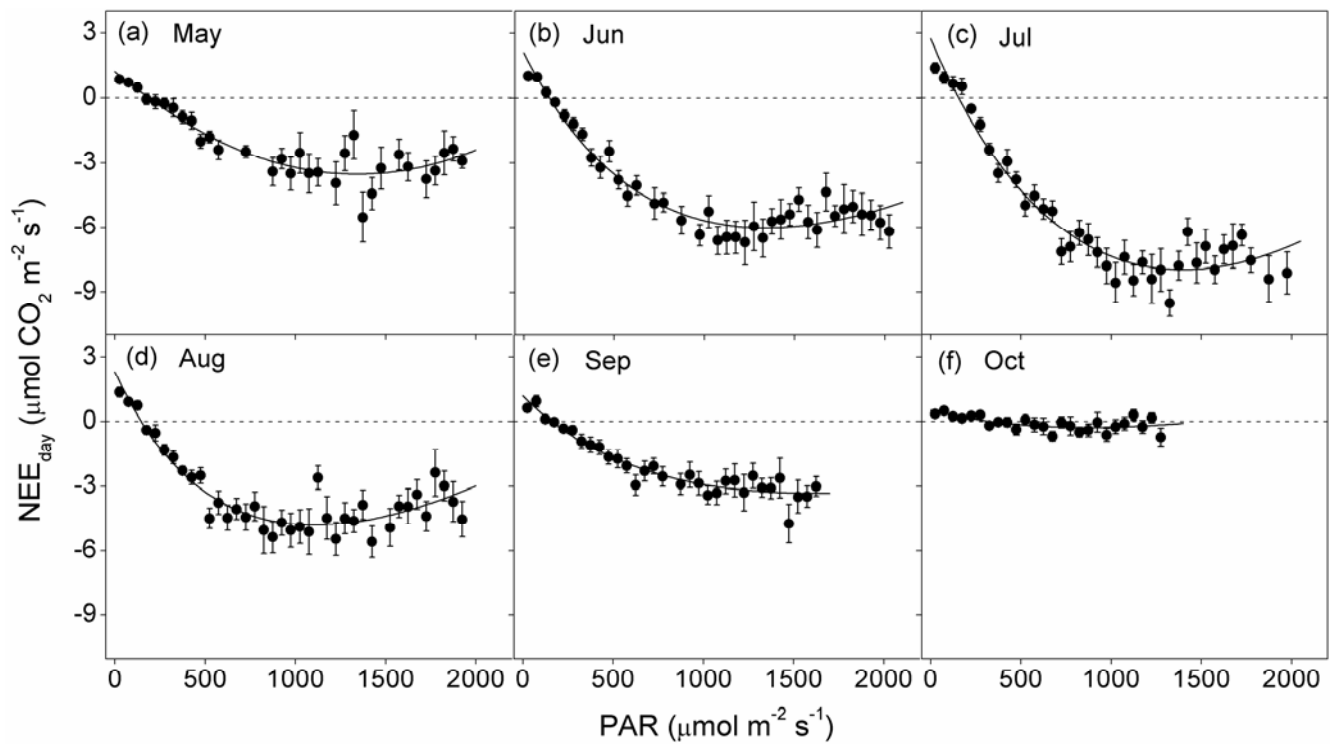
1 Fig. 1



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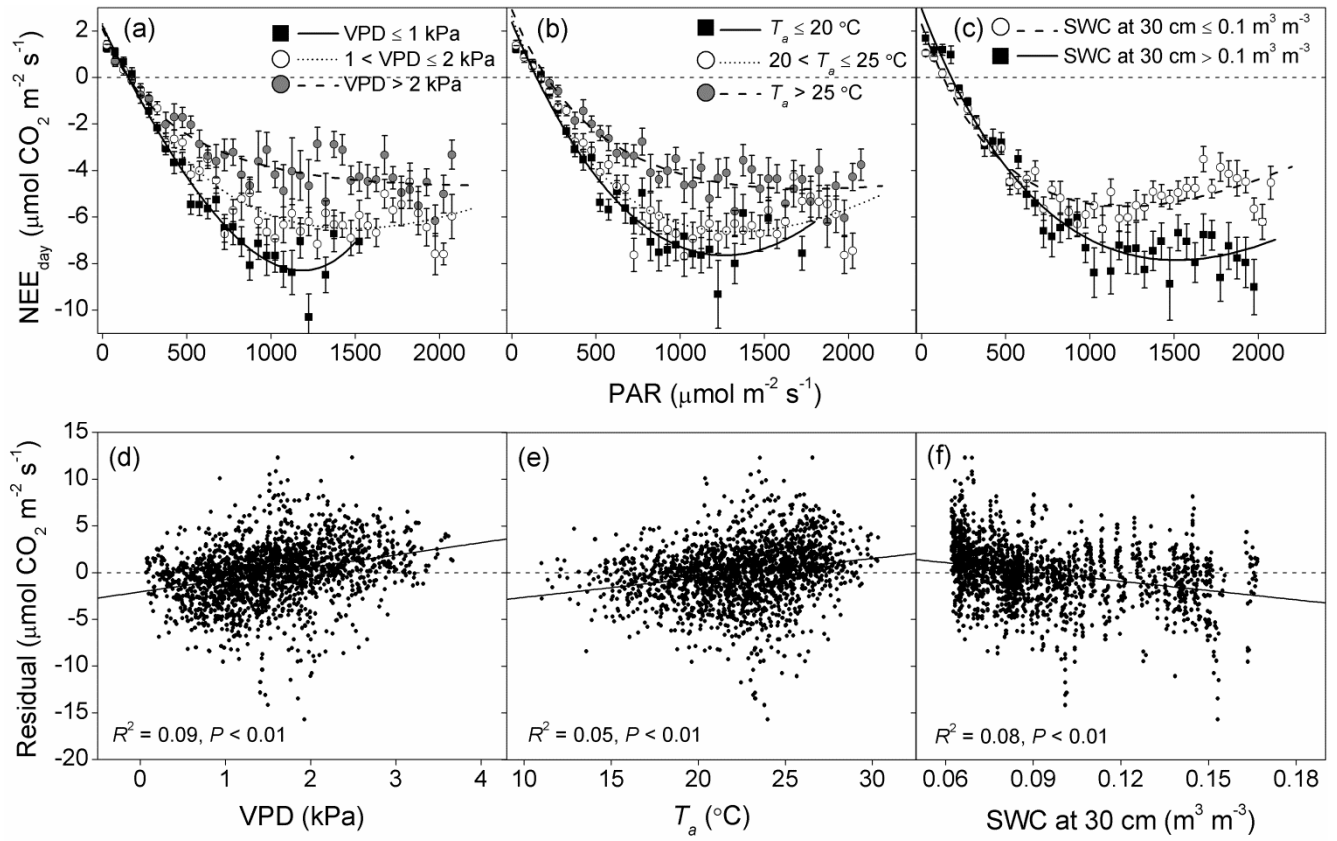
1 **Fig. 2**



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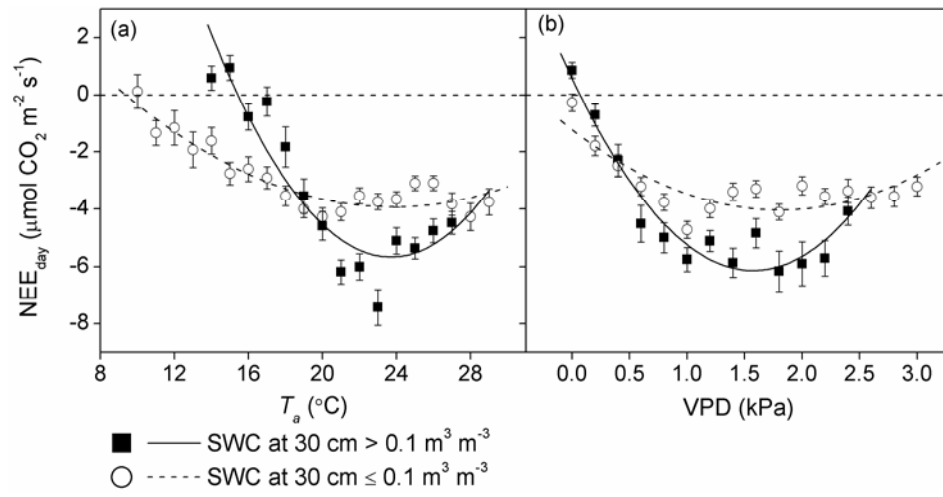
1 **Fig. 3**



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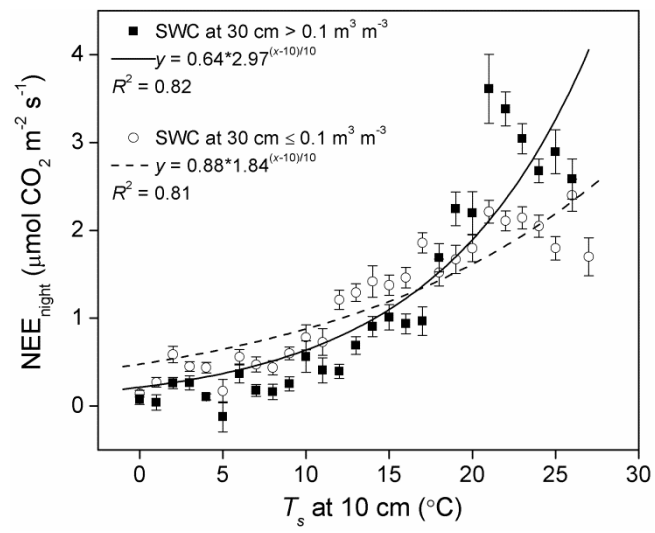
1 **Fig. 4**



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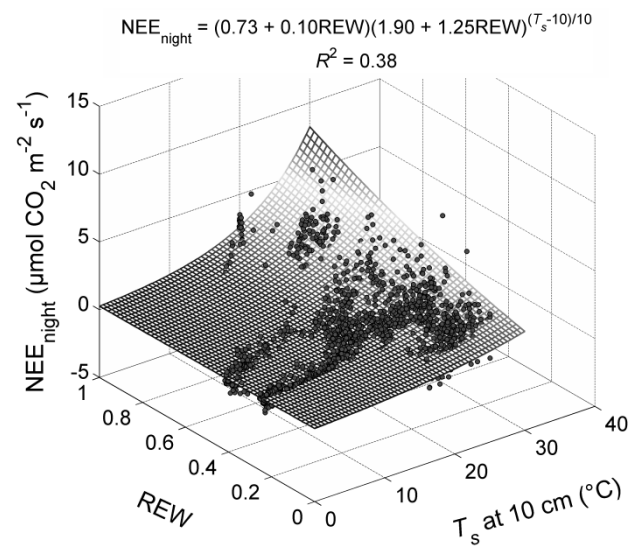
1 **Fig. 5**



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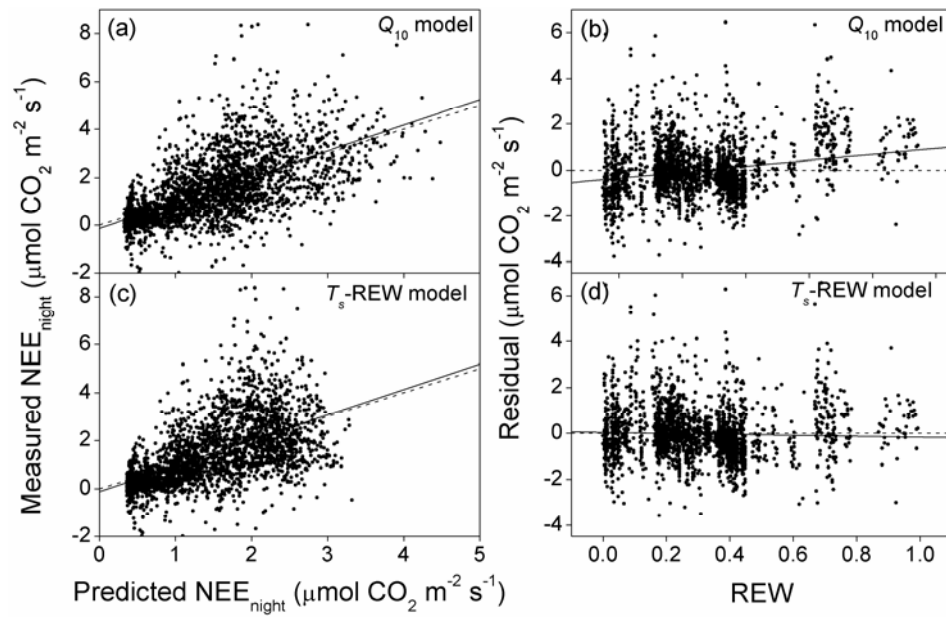
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1 **Fig. 6**



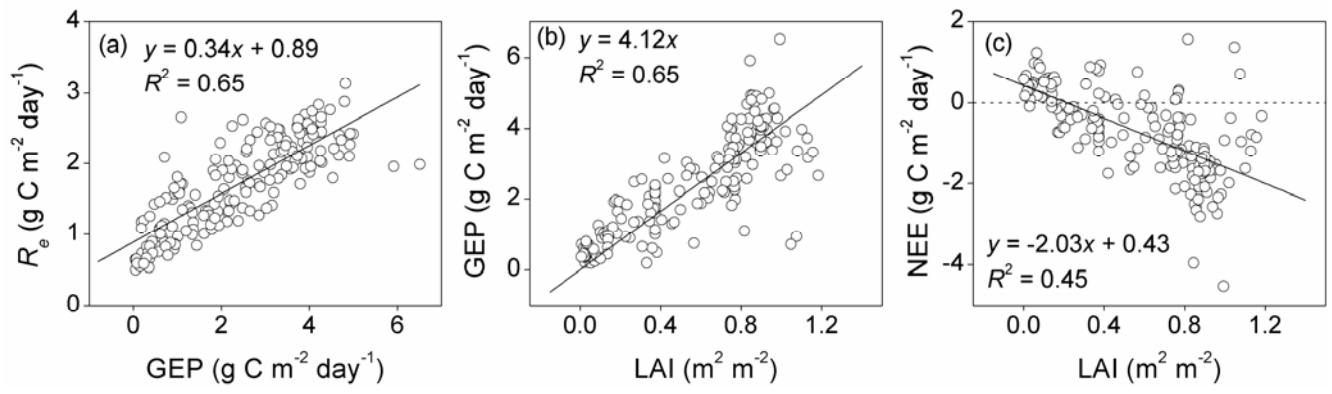
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1 **Fig. 7**



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1 **Fig. 8**

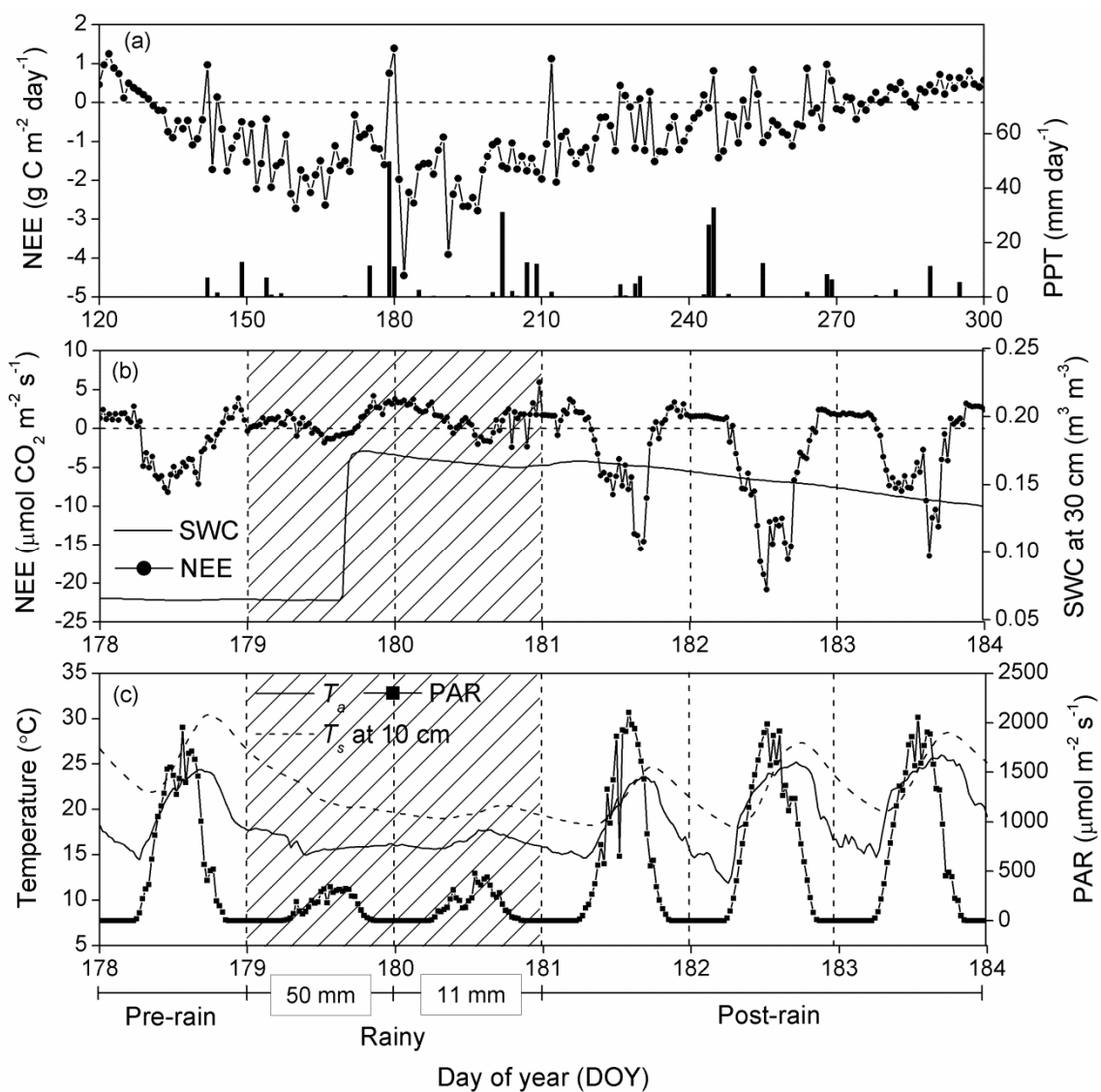


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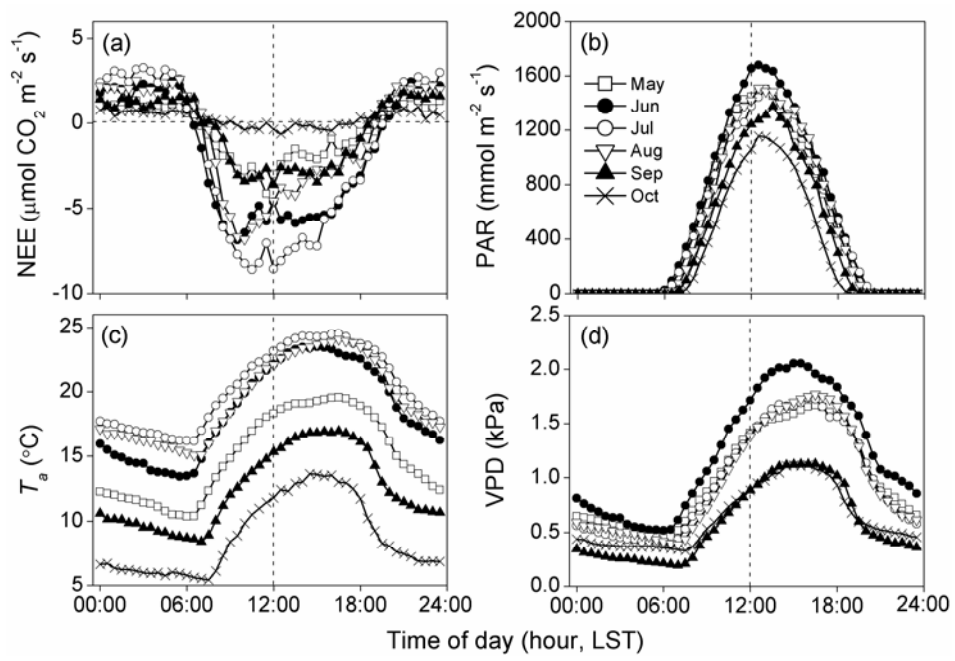
1 **Fig. 9**



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1 **Fig. 10**



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