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**Ecosystem carbon  
exchange subjected  
to seasonal drought**

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# Ecosystem carbon exchange of a subtropical evergreen coniferous plantation subjected to seasonal drought, 2003–2007

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## Abstract

The behavior of whole ecosystems in humid climate zone in response to drought is less well documented. Continuous measurements of carbon dioxide and water vapor exchange using the eddy covariance technique during 2003–2007 were made above a subtropical evergreen coniferous plantation in Southeast China. Seasonal distribution of precipitation and temperature was out of step during the summer, which resulted in droughts frequently. Gross ecosystem photosynthesis (GEP), ecosystem respiration (RE) and net ecosystem production (NEP) showed clear seasonality, with low rates during seasonal drought and in winter. The exponential response of monthly GEP and RE to air temperature provided us an implication that monthly NEP was less sensitive and only increased linearly. However, the function response of monthly NEP and its components (GEP and RE) disappeared under high temperature and low moisture. Monthly and year RE showed a linear and positive dependence on the corresponding GEP, with statistically significant. Annual NEP varied among years from 306 to 430 g C m<sup>-2</sup> (mean 395, SD 50). Interannual variability in NEP was controlled primarily by air temperature and the ratio of precipitation and evapotranspiration that affected the RE/GEP ratio, which varied between 0.76 and 0.81 (mean 0.78, SD 0.02).

## 1 Introduction

Although not as commonly recognized, it is evident that ecosystem water balances are changing due to altered rainfall and evaporation patterns (Rambal and Debussche, 1995; Waple and Lawrimore, 2003; Reichstein et al., 2007). Enhanced drought may not only result from low annual rainfall, but more likely from a different rainfall distribution (Rambal and Debussche, 1995). There is growing evidence of a higher frequency of climatic extremes as a result of global climate change in recent years (e.g. Karl et al., 1995; Beniston, 2004). In the future warmer climate with increased air temperatures, it seems that heat waves would become more intense, longer lasting, and/or more

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frequent (Meehl and Tebaldi, 2004). The changing precipitation regime accompanying with increased air temperatures has a profound impact on ecosystem carbon fluxes (e.g. Ciais et al., 2005; Niu et al., 2008). For example, a 30% reduction in gross ecosystem photosynthesis (GEP) occurred during 2003 Europe-wide heat and drought, which resulted in a strong anomalous net source of carbon dioxide ( $0.5 \text{ Pg C yr}^{-1}$ ) to the atmosphere, and reversed the effect of four years of net ecosystem carbon sequestration (Ciais et al., 2005).

It's possible to measure the net carbon and water fluxes between ecosystems and the atmosphere based on the eddy covariance technique, which enable us to evaluate the seasonal and interannual variability in their exchanges and climatic controls (Baldocchi et al., 2003, 2008; Yu et al., 2006). However, the carbon balance at the ecosystem level (net ecosystem production, NEP) is the difference between gross ecosystem photosynthesis (GEP), which is carbon uptake by photosynthesis, and ecosystem respiration (RE), which is carbon losses by autotrophic and heterotrophic respiration (Schulze et al., 2000). The ecosystem carbon balance depended on how GEP and RE were affected relatively to each other. Moreover, it's possible to statistically partition the NEP into GEP and RE, which allows a better interpretation of the fluxes in terms of ecosystem carbon processes (e.g. Reichstein et al., 2005). Many flux records are just now long enough to allow analysis of the complex, interacting biotic and abiotic controls on the carbon cycle of terrestrial ecosystems. Recently, some flux studies at least 5 years in duration have been published (e.g. Goulden et al., 1996; Barford et al., 2001; Hollinger et al., 2004; Haszpra et al., 2005; Saigusa et al., 2005; Barr et al., 2007; Beringer et al., 2007; Dunn et al., 2007; Grünwald et al., 2007; Ma et al., 2007; Schwalm et al., 2007; Urbanski et al., 2007; Hirara et al., 2008). Such kinds of long-term flux measurements enable us to quantify how temperature fluctuations and drought conditions affect NEP and its components (Baldocchi, 2008). Droughts are relatively unpredictable in timing, duration and intensity in humid climate zones; therefore, the behavior of whole ecosystems in response to drought is less well documented (Baldocchi, 2008). It is a very important way to explore the drought effects on the

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ecosystem carbon exchange based on the natural drought conditions (e.g. Baldocchi, 2005).

The objective of our study was to evaluate the magnitude and cause of both seasonal and interannual variation in GEP, RE, and NEP between the atmosphere and a subtropical evergreen coniferous plantation subjected to seasonal drought during 2003–2007 in Southeast China. The inconsistent distribution of precipitation and temperature allows summer droughts frequently (Wen et al., 2006; Yu et al., 2008a, 2008b). There is a pronounced spectral gap in ecosystem carbon and water exchange at the monthly scale, which makes it appropriate time step to capture seasonal and phenological change (Baldocchi et al., 2001).

## 2 Materials and methods

### 2.1 Site description

As a part of the ChinaFLUX network, the eddy fluxes of carbon dioxide and water vapor were measured at Qianyanzhou site (26°44′52″ N, 115°03′47″ E, and elevation 102 m) in Southeast China. The site is located in the subtropical continental monsoon region. According to the long-term records of the adjacent weather station (1985–2007, data source: database of Chinese Ecosystem Research Network), the mean annual air temperature is 17.9°C, the mean annual precipitation is 1475 mm. Generally, the area is subject to episodic summer droughts; during the investigated period, extremely dry summers occurred in 2003 and 2007. The main wind directions are north-northwest during the winter, and south-southeast during the summer. This plantation, planted in 1985, around the site is on undulating terrain with slopes between the crest and valley of the hill from 2.8 to 13.5 degrees. The topography map around the tower is shown in Fig. 1.

The tree density is 1463 stems ha<sup>-1</sup>, the biomass is 106 t ha<sup>-1</sup>, the leaf area index is 5.6 and the mean canopy height is about 13 m. The plantation is dominated by Slash

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pine (*Pinus elliottii*), Masson pine (*Pinus massoniana*) and Chinese fir (*Cunninghamia lanceolata*). A survey made in 2004 around the flux tower indicates that the mean tree height, diameter at breast height, and density of Slash pine were about 12.0 m, 15.8 cm and 809 stems ha<sup>-1</sup>, respectively, and were about 9.5 m, 13.1 cm and 444 stems ha<sup>-1</sup> for Masson pine, respectively, and were about 10.9 m, 13.2 cm and 210 stems ha<sup>-1</sup> for Chinese fir, respectively. The soil is red soil weathered from red sand rock. Soil texture is divided into 2.0–0.05 mm (17%), 0.05–0.002 mm (68%) and <0.002 mm (15%). Further details were available in the literatures (Wen et al., 2006; Huang et al., 2007; Yu et al., 2008a, 2008b).

## 2.2 Measurements and instrumentation

The above-canopy flux system at 39.6 m on a tower consisted of a 3-D sonic anemometer (Model CSAT3, Campbell Scientific Inc., Logan, UT, USA) and an LI7500 open-path CO<sub>2</sub>/H<sub>2</sub>O analyzer (Model LI-7500, Licor Inc., Lincoln, NE, USA). The LI7500 was calibrated twice or thrice in every year by pure nitrogen gas, CO<sub>2</sub> standard gas and dew point generator (Model LI-610, Licor Inc., Lincoln, NE, USA). Flux variables were sampled at 10 Hz by a CR5000 datalogger (Model CR5000, Campbell Scientific Inc.) with 30 min mean fluxes calculated.

Routine radiation measurements were made using a four-component net radiometer (Model CNR-1, Kipp & Zonnen, Delft, The Netherlands), a pyranometer (Model CM11, Kipp & Zonen) and a quantum sensor of photosynthetically active radiation (Model LI190SB, Licor Inc.). Air temperature and relative humidity sensors (Model HMP45C, Campbell Scientific Inc.) were mounted in ventilated mounts at heights of 1.6, 7.6, 11.6, 15.6, 23.6, 31.6 and 39.6 m above the ground. Soil temperatures were measured at five depths (2, 5, 20, 50 and 100 cm) with thermocouples (105T and 107-L, Campbell Scientific Inc.). Soil water contents were recorded with three TDR probes (Model CS615-L, Campbell Scientific Inc.) at depths of 5, 20 and 50 cm. Rainfall was monitored with a rain gauge (Model 52203, RM Young, Inc., Michigan, USA). Meteorological variables were sampled at 1 Hz by three CR10X dataloggers (Model CR10XTD,

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Campbell Scientific Inc.) and a CR23X datalogger (Model CR23XTD, Campbell Scientific Inc.) with a 25-channel solid-state multiplexer (Model AM25T, Campbell Scientific Inc.) with 30 min averages calculated.

### 2.3 Flux calculation and correction

5 Carbon dioxide and water vapor fluxes were measured since late August 2002 using the eddy covariance technique. The flux of NEP ( $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) and evapotranspiration (ET,  $\text{g H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) between the biosphere and the atmosphere was calculated,

$$F_c = - \left( \overline{w' \rho'_c(z_r)} + \int_0^{z_r} \frac{\partial \bar{\rho}_c}{\partial t} dz \right) \quad (1)$$

10 where the first term on right-hand side is the eddy flux for carbon dioxide or water vapour, the second term is the storage of carbon dioxide or water vapour below the height of observation ( $z_r$ ), and all advective terms in the mass conservation equation were ignored.

Spurious data were removed from the dataset if the instrument performance and experimental conditions were abnormal. Generally, 56.3% of the study site half-hourly NEP dataset was excluded. The problems were largely related to rainfall, water condensation, system failure, or turbulent mixing during the night (Wen et al., 2006). In this study, the detailed protocols of flux calculation and correction for carbon dioxide and water vapour were described as following. First of all, for the raw time series, physically not possible values could be excluded for the calculation of averages, variance and covariance in half-hour intervals. A spike detection algorithm on the raw time series followed the paper by Vickers and Mahrt (1997). Any values, which exceed 5.5 times standard deviations in a window of 10 values, were labeled as spikes. Values, which were detected as spikes, could be excluded for later calculations. The raw time series would be shortened by the number of missing values in this case. It was important that the proportion of real measurements in the raw time series was large enough to be representative. Herein, we adopted at least 90% real measurements in a half-hour

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interval. The characteristics of the instrument and the quality and reliability of flux measurements were examined by calculation of power- and co-spectra (Wen et al., 2005; Sun et al., 2006). Secondly, for the time series at half-hour intervals, planar fit rotation was applied to the wind components to remove the effect of instrument tilt or irregularity on the airflow at the monthly intervals (Wilczak et al., 2001). The instrument effects that damp the high-frequency fluctuations including the dynamic frequency response of the sonic anemometer and the IRGA, the scalar path averaging, and the sensor separation were corrected (Kaimal et al., 1972; Moore, 1986; Aubinet et al., 2000). Correction was made for the effect of fluctuations of air density on the fluxes of CO<sub>2</sub> and water vapor (Webb et al., 1980; Leuning, 2004). The effect of the CO<sub>2</sub> storage below the height of observation was corrected using the temporal change in CO<sub>2</sub> concentration above the canopy measured with an LI7500 open-path CO<sub>2</sub>/H<sub>2</sub>O analyzer (Yu et al., 2008b). The effect of the water vapour storage below the height of observation was corrected using the air temperature and relative humidity profile measurements. An overall quality flag was created for NEP and ET fluxes according the steady state test and integral turbulence characteristics test (Foken and Wichura, 1996). In addition, the algorithm used to detect the spikes of NEP is based on the method of Papale et al. (2006), and it was applied to blocks of 13 days and separately for daytime and nighttime CO<sub>2</sub> flux data. Lastly, to avoid possible underestimation of the fluxes under stable conditions during the night, the effect of friction velocity  $u^*$  was examined (Reichstein et al., 2005). When the value of  $u^*$  was less than  $0.19 \text{ m s}^{-1}$ , the values observed of NEP and ET in the night (global radiation  $< 1 \text{ W m}^{-2}$ ) were excluded. Likewise, positive NEP fluxes at night (i.e. apparent photosynthesis) were also taken out of the database.

## 2.4 Gap filling and flux partitioning

Data gaps are unavoidable in long-term and continuous measurements. The data gaps of NEP were filled mainly by the nonlinear regressions method (Falge et al., 2001). For small gaps (<2 h), the missing data was linearly interpolated. For larger gaps, the missing daytime NEP was estimated using the Michaelis-Menten equation with a 10-

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day window,

$$NEP = \frac{\alpha Q_p GEP_{sat}}{\alpha Q_p + GEP_{sat}} - RE_{day} \quad (2)$$

where  $\alpha$  is ecosystem apparent quantum yield ( $\text{mg CO}_2 \text{ mol}^{-1}$ ),  $Q_p$  is photosynthetic photon flux density ( $\text{mol m}^{-2} \text{ s}^{-1}$ ),  $GEP_{sat}$  is the asymptotic GEP at saturating light, and  $RE_{day}$  is the average daytime RE (both  $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ).

The nighttime NEP was defined as nighttime ecosystem respiration ( $RE_{night}$ ,  $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ). The missing  $RE_{night}$  were estimated as a function of soil temperature and soil moisture (Reichstein et al., 2002),

$$RE_{night} = R_{ref}(b_1 + b_2 S_w) \frac{T_{soil} - T_{ref}}{10}, \quad (3)$$

where  $R_{ref}$ ,  $b_1$  and  $b_2$  are fitted parameters, and  $T_{ref}$  is fixed to  $15^\circ\text{C}$ ,  $R_{ref}$  stands for the ecosystem respiration rate ( $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) at the reference temperature,  $S_w$  is the soil water content ( $\text{m}^3 \text{ m}^{-3}$ ) at 5 cm depth, and  $T_{soil}$  is the soil temperature ( $^\circ\text{C}$ ) at 5 cm depth.

To estimate the gross ecosystem photosynthesis (GEP,  $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), the daytime ecosystem respiration ( $RE_{day}$ ,  $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) was estimated by the extrapolation of the function relationship between the nighttime ecosystem respiration ( $RE_{night}$ ,  $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) and soil temperature and water content.

In addition, for small gaps of ET (<2 h), the missing data was linearly interpolated. For larger gaps, the missing ET was filled by the combined look-up table and mean diurnal variation method (Reichstein et al., 2005).

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### 3 Results

#### 3.1 Seasonal and interannual variations of environmental conditions

Figure 2 demonstrates the seasonal variations of monthly air temperature, vapour pressure deficit (VPD), precipitation and soil water content. The air temperature showed single peak variation with the maximum more than 28°C in July, corresponding with the VPD more than 1.2 kPa (Fig. 2a). However, rainfall variability was obvious due to annual rainfall and altered rainfall patterns (Fig. 2b). Generally, precipitation decreased in the midseason (July), to some degree, whereas the air temperature reached the maximum. The asynchronous seasonality between temperature and precipitation during the midseason offered a possibility of frequently seasonal droughts. The seasonal variations of soil water content in different depths were closely related to the rainfall variability. They showed strong seasonal patterns, generally with net water gains during the pre-season and net water losses during the mid-season and post-season. The soil water content in different depths showed obvious decline trends during the mid-season or post-season.

Table 1 lists the annual net radiation, air temperature, precipitation (P), evapotranspiration (ET), and water balance index (P-ET, and P/ET). The annual precipitation in 2003 was the lowest among the 5-year records accompanying with the lowest water balance index, and the second lowest in 2007. Meanwhile, the annual air temperature in 2003 and 2007 were highest. In comparison, the annual precipitation in 2004, 2005 and 2006 were similar, with the higher water balance index, but the lowest annual air temperature and net radiation in 2005.

In general, this plantation was subject to episodic summer droughts; during the investigated period, extremely dry summers occurred in 2003 and 2007. Carbon assimilation and plant growth rate were suppressed by this environmental stress. Under such conditions, some plants even appeared senescence in 2003 (Wen et al., 2006). Increased rainfall variability due to low annual rainfall and altered rainfall and evaporation patterns could be likely to have complicated effects on ecosystem carbon exchange of

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this subtropical plantation.

### 3.2 Seasonality and interannual variability of GEP, RE and NEP

Monthly and seasonal anomalies reflect primarily weather and climate variations (Goulden et al., 1996; Barford et al., 2001). Figure 3 shows the seasonal and interannual variations of 30-day running-mean GEP, RE and NEP. Note that NEP and its components (GEP and RE) showed clear seasonality, with low rates varying with drought severity and history during summer and in winter. In 2003 and 2007, it was obvious that the reduction of GEP, RE and NEP occurred during the midseason or postseason (Fig. 3). In 2003, this plantation even reversed the effect of net ecosystem carbon sequestration during the summer. The reduction of NEP in 2003 and 2007 was induced by droughts resulting from higher temperature (Fig. 2a) and lower soil water content (Fig. 2b). Especially, the NEP also decreased in 2004, 2005 and 2006 with episodic summer droughts.

Table 2 gives the annual GEP, RE and NEP totals and the RE/GEP ratios. Annual GEP varied from 1629 to 1857 g C m<sup>-2</sup> (mean 1779, SD 107), annual RE varied from 1286 to 1447 g C m<sup>-2</sup> (mean 1384, SD 75), and annual NEP varied from 306 to 430 g C m<sup>-2</sup> (mean 395, SD 50). The annual RE/GEP ratio ranged from 0.755 to 0.812 (mean 0.779, SD 0.021). The NEP was the lowest in 2005 because of the lowest air temperature and net radiation (Table 1). The NEP in 2003 and 2007 didn't show a clear decline even with extremely dry summer. Ma et al. (2008) reported that the observed NEP in 2004 and 2005 was 497.1 and 374.7 g C m<sup>-2</sup> yr<sup>-1</sup>, respectively, though biometric measurements in adjacent plot of our flux tower. They were comparable, but higher than our NEP results by the eddy covariance technique, with 416.1 and 306.0 g C m<sup>-2</sup> yr<sup>-1</sup> in 2004 and 2005 (Table 2).

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### 3.3 Response of GEP, RE and NEP to temperature

Figure 4 illustrates the response of monthly and yearly GEP, RE, NEP to air temperature. As Fig. 4a showed that monthly GEP and RE increased exponentially with air temperature while air temperature was lower than 28°C, accompanying with relatively higher soil moisture. The average of soil water content was 0.168 m<sup>3</sup> m<sup>-3</sup>. More importantly, NEP was less sensitive to air temperature than GEP and RE. NEP only increased linearly with air temperature. However, such kinds of function relationship failed when air temperature was higher than 28°C, accompanying with relatively lower soil moisture. The average of soil water content was 0.125 m<sup>3</sup> m<sup>-3</sup>. As Fig. 4b showed that it was held that yearly NEP increased linearly with air temperature. Annual air temperature was almost sufficiently high during 2003–2007, varying only from 17.9 to 18.9°C (mean 18.5, SD 0.4) (Table 1). Although the interannual variation of air temperature was within 1°C, this linear relationship was statistically significant. Air temperature dominated the processes of NEP at the monthly and yearly scales (Fig. 4). However, there were no statistically significant relationship between yearly GEP and RE and air temperature.

### 3.4 Response of GEP, RE and NEP to soil water content

Figure 5 illustrates the response of monthly GEP, RE and NEP to soil water content. There are two distinct groups of data. In the first group for air temperature larger than 16°C, the correlations of soil water content with GEP and RE were quadratic function. Both relationships were statistically significant. However, the correlation of soil water content with NEP was not statistically significant. In the second group for air temperature less than 16°C, there were no obviously correlations between soil water content and GEP, RE and NEP. Especially, there were also no statistically significant relationships between yearly GEP, RE, NEP and soil water content.

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## 4 Discussions

### 4.1 Effects of drought on GEP, RE and NEP

Due to the influence of Asian monsoon climate, the site for this study is frequently subject to extreme heat stress in the summer. The variation of NEP is complex, because NEP integrates two interactive processes, GEP and RE, both of which respond uniquely (e.g. Reichstein et al., 2002; Barr et al., 2007). RE is controlled by temperature and soil water content, while GEP is mainly controlled by radiation, air temperature, water vapor deficit, and the water amount of root uptake (Reichstein et al., 2002). The interactions with the components of NEP (i.e. GEP and RE) were more important.

The effect of drought on NEP varied with drought severity and history. In general, the depletion of water near the soil surface apparently reduced soil respiration, while water remaining deep in the soil column supported photosynthesis during the early days of drought. The water in the deep soil would be exhausted with the process of the intensified drought. Severe and persistent drought suppressed NEP by suppressing GEP to a degree that equaled or exceeded the large suppression in RE during the seasonal drought period (Fig. 3). Carbon assimilation by the canopy decreases remarkably as soil dries up, and consequently supply of the carbohydrates to the below-ground bio-community is reduced accordingly (Reichstein et al., 2002). The declining degree of NEP was determined by the accumulation of soil moisture deficits and a co-occurrence of high temperatures (Wen et al., 2006). In addition, during the postseason, the decrease in RE was more than the simultaneous decrease in GEP, which also resulted in the recovery of carbon uptake to some degree resting with the degree of drought during the midseason.

The seasonal drought altered the parallel exponential response of GEP and RE to air temperature in some degrees, and NEP was less sensitive to air temperature than GEP and RE (Fig. 4a). The exponential response of GEP to air temperature resulted from a logarithm relationship between air temperature and photosynthetic photon flux density. Note that the GEP at half-hourly intervals could be described using the Michaelis–

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Menten equation. Reichstein et al. (2007) pointed out that NEP was less sensitive to climate than expected if climate-driven increases or decreases in GEP or RE are met with compensatory behavior in the other term.

The optimum for GEP and RE were usually found at intermediate water contents and the GEP and RE decreases at water contents either higher or lower than the optimum during higher temperature (Fig. 5). Since water contents of most soils are not in their optimal ranges under most natural conditions, consideration of soil water effect in the relationships between GEP, RE and NEP and environmental elements was critical for accurate prediction of global climate change scenarios.

## 4.2 Coupling relationship between GEP and RE

The RE/GEP ratio is useful diagnostics in studies of interannual variability (Valentini et al., 2000; Law et al., 2002). Table 2 gives the ratios of RE to GEP from 2003 to 2007. Table 3 also gives the ratios of RE to GEP among different ecosystems with at least 5 years records. The standard deviation showed significant interannual variability in NEP, resulting from the differential effects of climatic variability or disturbance on GEP and RE (Table 3). The RE/GEP ratio in this study was mostly lower than other ecosystems (Table 3) with higher carbon uptake capacity at Qianyanzhou site. Law et al. (2002) reported a range in RE/GEP across a broad diversity of terrestrial ecosystems from 0.55 to 1.2, with means of 0.82 for deciduous broadleaf forest and 0.85 for coniferous forest. Many of the boreal and northern temperate forests had RE/GEP ratios that exceeded 1.0. Valentini et al. (2000) found a strong dependence of RE/GEP on latitude across a north–south transect of European forests, ranging from 0.50 for southern forests to 0.90 for northern forests.

Figure 6 demonstrates the relationships between monthly and yearly RE and GEP. In comparison, the dataset cited in Table 3 are also shown. They showed closely positive correlation between RE and GEP at the monthly and yearly scales. It can be argued that year-to-year changes in NEP are associated with simultaneous increases or decreases in GEP and RE (Reichstein et al., 2007; Richardson et al., 2007; Baldocchi,

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2008). Even though this ecosystem had experienced significant disturbance of seasonal drought, the slope between GEP and RE was very similar to the regression on the basis of data from the European (Janssens et al., 2001) and FLUXNET network (Baldocchi, 2008). However, on the annual time scale, the slope between GEP and RE in this study was more impressible to the severe drought year (2003) and the water excess year (2005).

### 4.3 Water balance controls over interannual variations in GEP, RE and NEP

Although any statistically significant relationship was not found between yearly GEP, RE, NEP and soil water content, annual GEP, RE and NEP totals were linked to the site water balance. Figure 7 demonstrates the relationships between yearly GEP and RE and site water balance (P-ET), and between yearly NEP and site water balance index P/ET. The results highlighted that a quadratic function best described the dependence of ecosystem carbon exchange on factors related to water balance in this humid climate zone. The optimum for GEP, RE and NEP were found at intermediate water balances, and they decreased at water balances either higher or lower than the optimum. P-ET is a reasonable estimate of water balance (Law et al., 2002), but it could underestimate the intensity of water stress because runoff components could be the potential errors resources. In comparison, it was only held that yearly NEP increased linearly with air temperature (Fig. 5). Carbon assimilation and plant growth were suppressed while the water consumption was much larger or smaller than that of water supply. For example, lower net carbon uptake in 2005 was caused that the reduced photosynthesis exceeded the reduced respiration due to low temperatures and excess cloudiness. Severe drought (e.g. in 2003) caused a little reduction in annual NEP mainly due to higher NEP during the pre-season resulting from higher water availability. Moderate drought in 2007 led to an additional carbon uptake because of increasing GEP and retarding RE during the post-season. This unexpected result occurred because less rain was associated with fewer clouds, which made more available light and increased GEP.

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Figure 8 demonstrates the relationships between the ratio of yearly RE to GEP and air temperature and site water balance index P/ET. Interannual variability in the RE/GEP ratio was controlled primarily by air temperature, and by factors related to the site water balance. Our results suggested that factors related to the water balance might override the effects of temperature on annual ecosystem carbon balance. Ecosystem water balances are changing due to altered rainfall and evaporation patterns (Rambal and Debussche, 1995; Waple and Lawrimore, 2003). This result also highlighted the possibility that with respect to changing climate the variations in rainfall and evaporation patterns might affect ecosystem carbon balance complexly. Thus, special attention should be given to the coupling of the carbon and water cycles. Most predictions of the response of terrestrial ecosystem to climatic warming focus on the increase in temperature, but ignore the possibility that ecosystem carbon exchange may be especially sensitive to seasonal distribution of precipitation (e.g. drought) during specific intervals of the year (Goulden et al., 1996; Reichstein et al., 2007). The longer-term ecosystem water balance was clearly important, and might explain much of the observed interannual variability and trend. Nonetheless, the factors related to the ecosystem water balance may have key implications for ecosystem resistance and resilience in the face of changes in climate or climate variability (e.g. Dunn et al., 2007).

#### 4.4 Comparison of ecosystem carbon exchange with other forests

Some flux studies with at least 5 years data had been published. Table 3 lists the interannual variation of ecosystem carbon exchange among different ecosystems with at least 5 years records. There were relative few studies in the subtropical humid zone. Ecosystem carbon sequestration of this subtropical evergreen coniferous plantation was similar to that of the temperate coniferous forest at Fujiyoshida site, and the subtropical savanna at Howard Springs site. Year to year variability was lower than that of Fujiyoshida and Howard Springs. Note that there was obviously different in yearly GEP and RE among the three sites. Yearly GEP and RE of this subtropical plantation were higher than that of Fujiyoshida and Howard Springs mainly because of the

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whole year growing season. The maximum LAI was 5.6, varying less than 1.5 during the whole year growing season (Huang et al., 2007). In addition, ecosystem carbon sequestration of this subtropical plantation was higher than that of other ecosystems except for that of the temperate coniferous forest at Tharandt site. These differences may be related to climate type, ages, structure, and plant ecophysiological characteristics of different forests (e.g. Law et al., 2002; Griffis et al., 2003), which suggested the complexity and uncertainty in the evaluation of ecosystem carbon balance. Baldocchi (2008) pointed that evergreen mid-age forest, year-round growing seasons and small pool of decomposing detritus on the soil would result in the maximum amounts of net carbon sequestration, and maximum amounts occur when the forests are between 50 and 100 years. It indicated that more carbon uptake would be possible because this subtropical coniferous plantation was planted in 1985.

## 5 Conclusions

The asynchronous seasonality between temperature and precipitation during the summer period occurred in the 5-year study period (2003–2007) that enabled us evaluate the magnitude and cause of both seasonal and interannual variations in GEP, RE and NEP subjected to seasonal drought. NEP and its components (i.e. GEP and RE) showed clear seasonality, with low rates during seasonal drought and in winter. Seasonal variability in NEP was controlled by factors that affected GEP and RE differently. The response of monthly GEP and RE to air temperature was exponential, but monthly NEP only increased linearly with air temperature. Note that the function response of monthly NEP and its components (GEP and RE) disappeared under extremely summer drought. Monthly and yearly RE showed a linear and positive dependence on the corresponding GEP, with statistically significant. Although drought suppressed both RE and GEP, the net impact on NEP varied among years. Annual NEP varied from 306 to 430 g C m<sup>-2</sup> (mean 395, SD 50). Yearly GEP and RE were statistically significant with site water balance (P-ET), and yearly NEP with the related water balance index P/ET.

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Interannual variability in NEP was controlled primarily by air temperature and the ratio of precipitation and evapotranspiration that affected the RE/GEP ratio, which varied between 0.76 and 0.81 (mean 0.78, SD 0.02).

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**Table 1.** Interannual variability in annual net radiation ( $R_n$ ), air temperature ( $T$ ), total precipitation ( $P$ ), evapotranspiration ( $ET$ ), and water balance ( $P - ET$ ,  $P/ET$ ) from 2003 to 2007 at Qianyanzhou site.

Year	$R_n$ $\text{MJ m}^{-2} \text{yr}^{-1}$	$T$ $^{\circ}\text{C}$	$P$ $\text{mm yr}^{-1}$	$ET$ $\text{mm yr}^{-1}$	$P-ET$ $\text{mm yr}^{-1}$	$P/ET$ dimensionless
2003	2849.3	18.9	855.0	761.4	93.6	1.123
2004	2865.8	18.6	1324.8	860.4	464.4	1.540
2005	2621.0	17.9	1329.9	550.6	779.3	2.415
2006	2657.9	18.4	1310.3	694.1	616.2	1.888
2007	2776.6	18.9	1106.6	867.5	239.1	1.276
2003–2007	2754.1	18.5	1185.3	746.8	438.6	1.648
Mean $\pm$ SD	$\pm 110.7$	$\pm 0.4$	$\pm 206.9$	$\pm 131.3$	$\pm 277.1$	$\pm 0.518$

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**Table 2.** Interannual variability in annual gross ecosystem photosynthesis (GEP), ecosystem respiration (RE), net ecosystem production (NEP), and the RE/GEP ratios from 2003 to 2007 at Qianyanzhou site.

Year	GEP g C m <sup>-2</sup> yr <sup>-1</sup>	RE g C m <sup>-2</sup> yr <sup>-1</sup>	NEP g C m <sup>-2</sup> yr <sup>-1</sup>	RE/GEP dimensionless
2003	1701.7	1285.6	416.1	0.755
2004	1857.6	1447.2	410.4	0.779
2005	1628.8	1322.8	306.0	0.812
2006	1851.5	1439.7	411.8	0.778
2007	1857.1	1426.9	430.2	0.768
2003–2007	1779.3	1384.4	394.9	0.779
Mean ± SD	±107.3	±74.8	±50.3	±0.021

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**Table 3.** Comparison of ecosystem carbon exchange ( $\text{g C m}^{-2} \text{ yr}^{-1}$ ) among different ecosystems with greater than or equal to 5 years records. The values in the bracket indicate the standard deviation.

Site	Latitude	Longitude	Vegetation	GEP	RE	NEP	RE/GEP	Temperature (°C)	Precipitation (mm)	Age (yr)	LAI	Period	Literatures
NOBS site	55.88 N	98.48 W	Deciduous and evergreen boreal forest	706 (57)	713 (79)	-2 (41)	1.009 (0.060)	-3.2	420	160	4.2	1994–2004	Dunn et al., 2007
SOA site	53.63 N	106.20 W	Deciduous and evergreen boreal forest	1255 (135)	1083 (103)	182 (94)	0.866 (0.063)	1.3	484	73	5.8	1994–2003	Barr et al., 2007
Tharandt	50.96 N	13.57 E	Temperate coniferous forest	1845 (154)	1295 (95)	550 (87)	0.703 (0.031)	8.5	833	122	7.6	1996–2005	Grünwald et al., 2007
Hegyhátsál	49.95 N	16.65 E	Herbaceous/shrubland	1096 (180)	1061 (35)	35 (59)	0.975 (0.056)	9.9	679	-	-	1997–2004	Haszpra et al., 2005
Western hemlock	49.87 N	125.29 W	Clearcut	521 (258)	1097 (234)	-577 (75)	2.521 (1.128)	8.9	1241	5	0.8	2001–2005	Schwalm et al., 2007
Harvard Forest	42.54 N	72.17 W	Temperate coniferous forest	2076 (122)	1784 (155)	293 (61)	0.859 (0.032)	8.4	1293	56	8.4	1998–2005	
			Temperate deciduous forest	1166 (79)	962 (118)	224 (56)	0.823 (0.053)	-	-	-	-	1991–1995	Goulden et al., 1996
				1297 (99)	1099 (91)	201 (36)	0.847 (0.026)	-	-	-	-	1992–2000	Barford et al., 2001
Howland Forst	45.25 N	68.73 W	Deciduous and evergreen boreal forest	1343 (95)	1168 (80)	174 (45)	0.871 (0.028)	6.7	1040	100	4.7	1996–2002	Hollinger et al., 2004
			Temperate deciduous forest	978 (120)	742 (36)	237 (92)	0.759 (-)	-	-	-	-	1994–2002	Saigusa et al., 2005
Takayama	36.13 N	137.42 E		1328 (260)	1214 (290)	112 (36)	0.907 (0.046)	6.6	2033	50	3.5	2000–2004	Hirara et al., 2008
			Temperate coniferous forest	1634 (149)	1274 (96)	360 (86)	0.781 (0.038)	9.6	2055	90	5.5	2000–2004	
Fujiyoshida	35.45 N	135.98 E	Herbaceous/shrubland	1070 (193)	972 (51)	98 (51)	0.907 (0.050)	16.5	562	-	0.6	2002–2006	Ma et al., 2007
Tonzi Ranch	38.43 N	120.96 W	Herbaceous	926 (230)	963 (151)	-38 (118)	1.065 (0.146)	16.5	562	-	2.4	2001–2006	
Vaira Ranch Qianyanzhou	26.75 N	115.06 E	Subtropical coniferous plantation	1779 (107)	1384 (75)	395 (50)	0.779 (0.021)	18.5	1185.3	23	5.6	2003–2007	This study
			Subtropical Savanna	1378 (87)	1022 (43)	358 (78)	0.743 (0.039)	27.1	1824	-	1.0	2001–2005	Beringer et al., 2007

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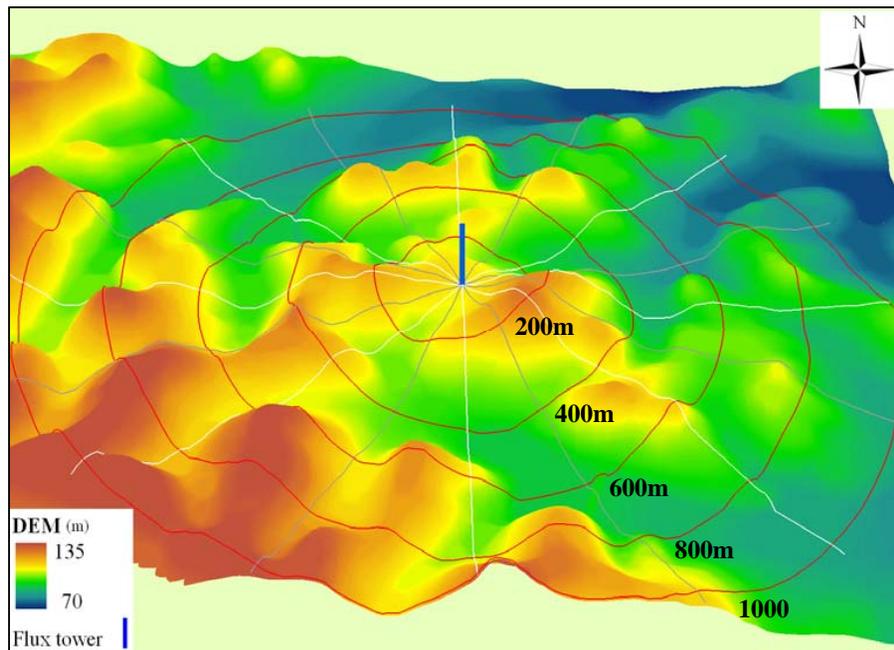
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**Fig. 1.** Area relief map of the Qianyanzhou site based on Digital Elevation Model (DEM). The tower is located in the middle of the map, with 200 m equidistance lines.

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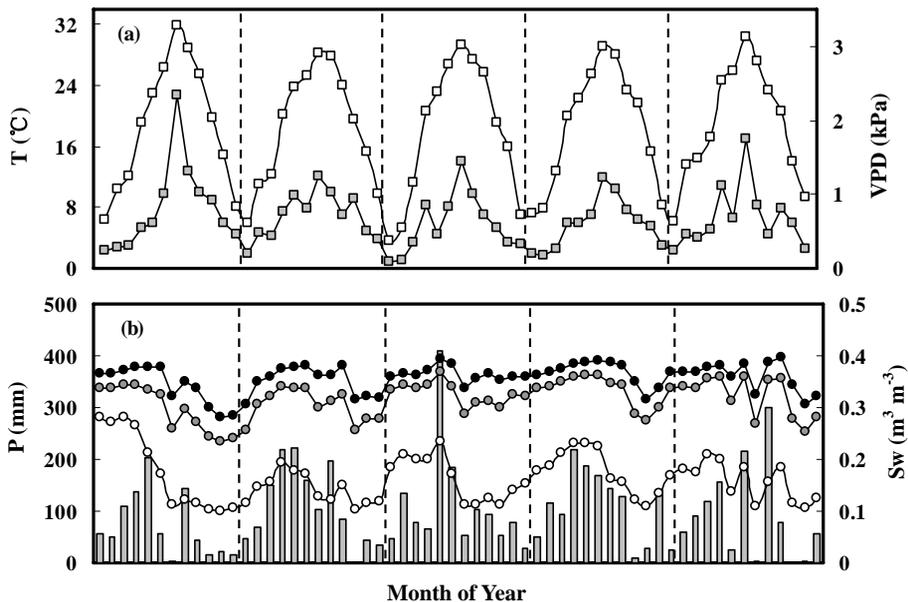
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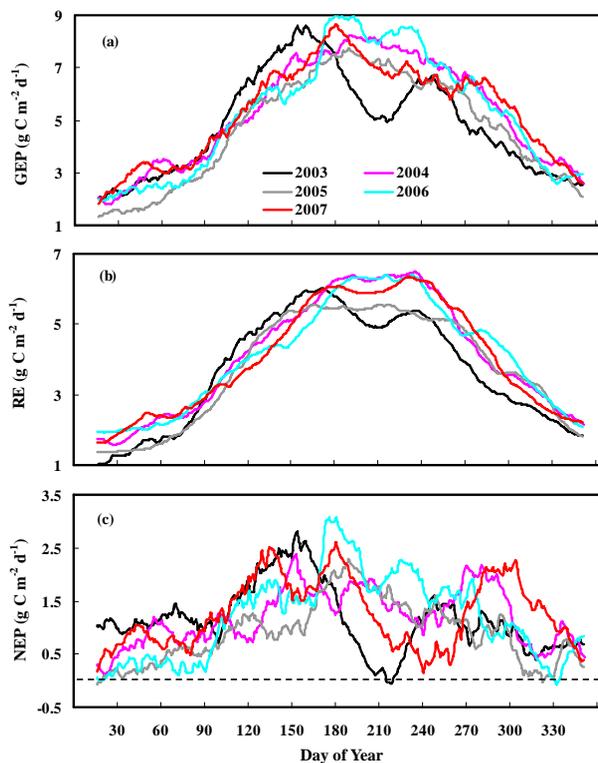


**Fig. 2.** Seasonal and interannual variations of monthly (a) air temperature ( $T$ , blank squares) and vapour pressure deficit (VPD, gray squares) at the height of the eddy covariance system, and (b) precipitation ( $P$ , gray bars) and soil water content (5 cm: blank circles; 20 cm: gray circles; 50 cm: black circles) from 2003 to 2007 at Qianyanzhou site.

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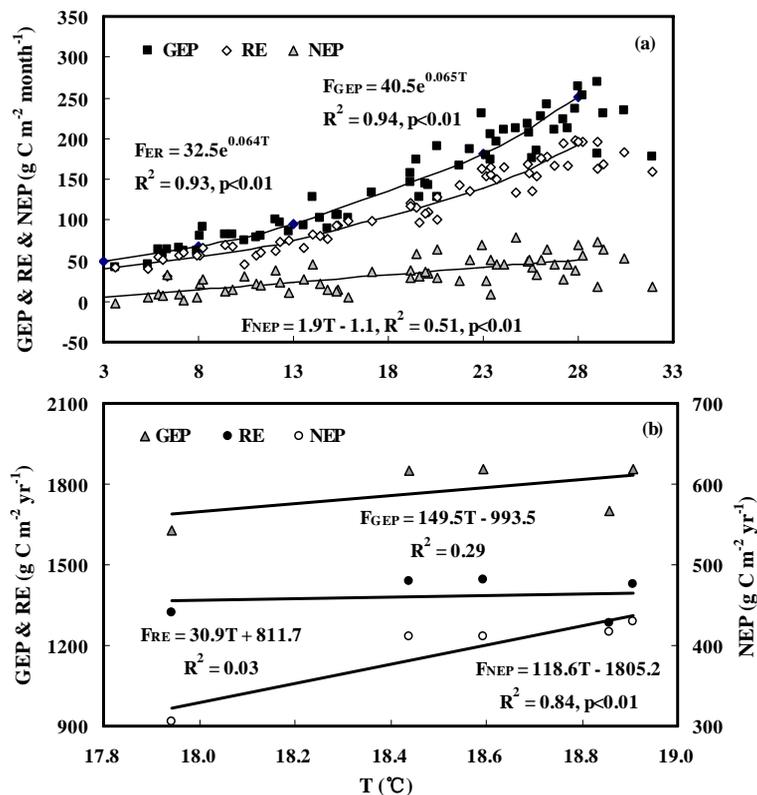


**Fig. 3.** Seasonal and interannual variations of 30-day running-mean (a) gross ecosystem photosynthesis (GEP), (b) ecosystem respiration (RE), and (c) net ecosystem production (NEP) from 2003 to 2007 at Qianyanzhou site.

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**Fig. 4.** Response of (a) monthly and (b) yearly gross ecosystem photosynthesis (GEP), ecosystem respiration (RE), net ecosystem production (NEP) to air temperature ( $T$ ) during 2003 to 2007 at Qianyanzhou site.

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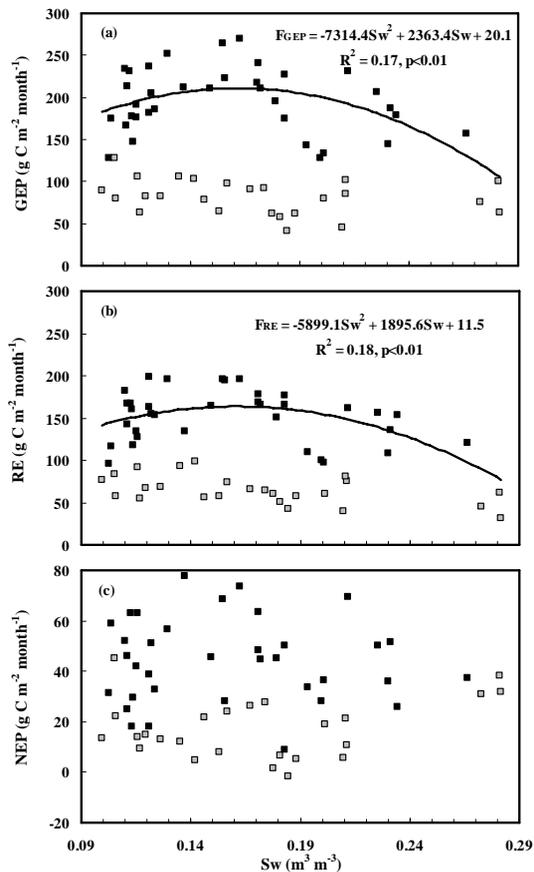
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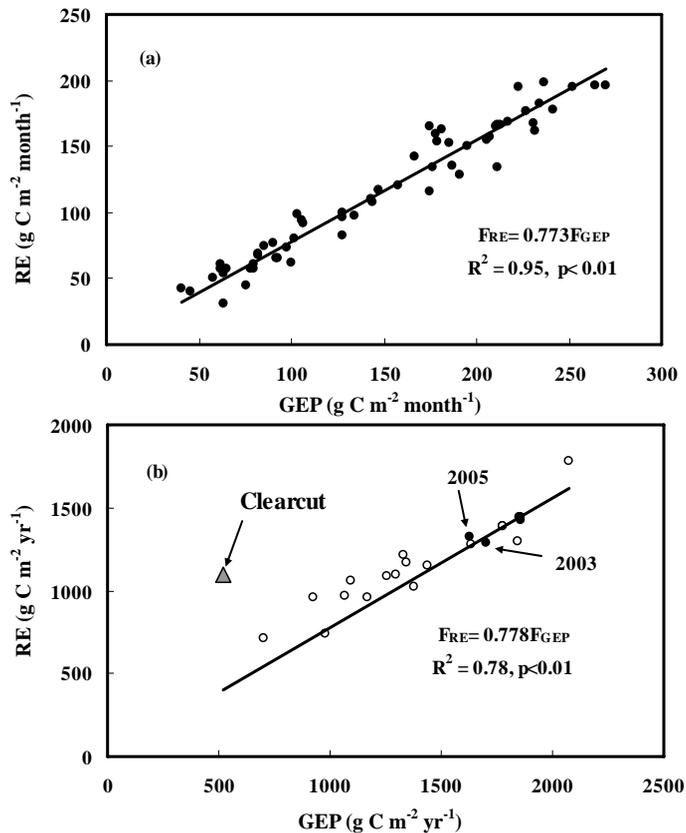
## Ecosystem carbon exchange subjected to seasonal drought

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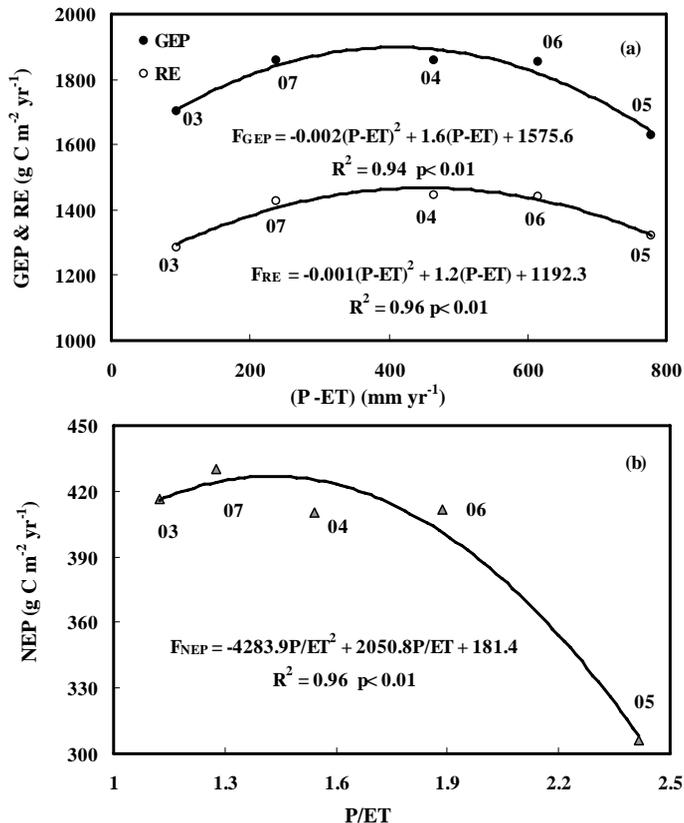
**Fig. 5.** Response of monthly gross ecosystem photosynthesis (GEP), ecosystem respiration (RE) and net ecosystem production (NEP) to soil water content (Sw, 5 cm) during 2003 to 2007 at Qianyanzhou site. GEP, RE and NEP were marked by black squares while air temperature was larger than 16°C, and gray squares while temperature less than 16°C.

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**Fig. 6.** The dependence (a) monthly and (b) yearly ecosystem respiration (RE) on gross ecosystem photosynthesis (GEP) during 2003 to 2007 at Qianyanzhou site. The linear regression lines were shown. The dataset cited in Table 3 are shown as triangle (clearcut) and blank circles for comparison.

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**Fig. 7.** The relationships **(a)** between yearly gross ecosystem photosynthesis (GEP), ecosystem respiration (RE) and water balance (P-ET), and **(b)** between yearly net ecosystem production (NEP) and water balance index (P/ET) during 2003 to 2007 at Qianyanzhou site.

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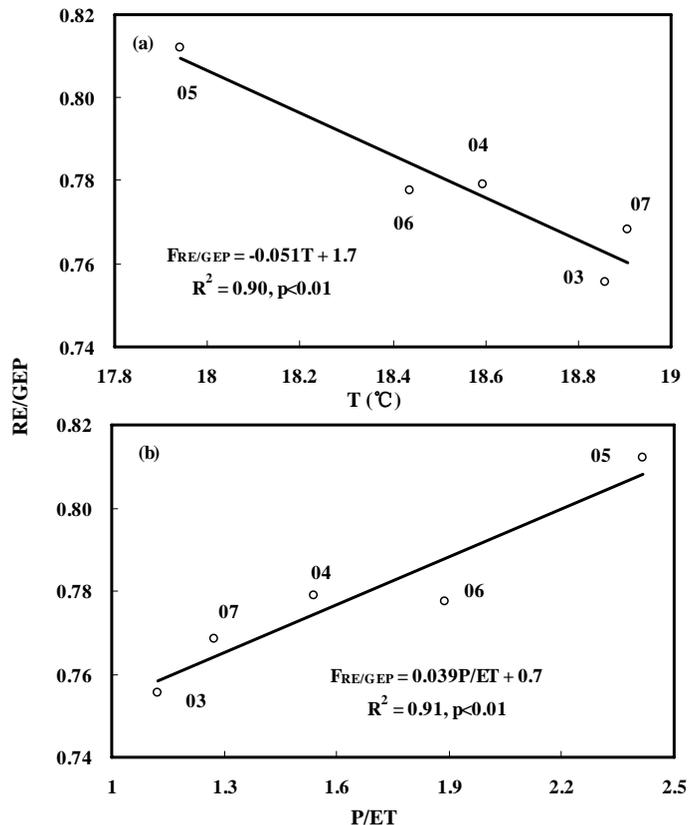
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**Fig. 8.** The dependence of the ratio of yearly ecosystem respiration (RE) to gross ecosystem photosynthesis (GEP) on **(a)** air temperature ( $T$ ) and **(b)** water balance index ( $P/ET$ ) during 2003 to 2007 at Qianyanzhou site.

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