Science in China Series D: Earth Sciences 2006 Vol.49 Supp. II 110—118

DOI: 10.1007/s11430-006-8110-z

Seasonal drought effects on carbon sequestration of a mid-subtropical planted forest of southeastern China

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Received October 27, 2005; accepted March 10, 2006

Abstract Continuous measurement of carbon dioxide exchange using the eddy covariance (EC) technique is made at the Qianyanzhou mid-subtropical planted forest as part of the ChinaFLUX network. Qianyanzhou planted forest is affected by typical subtropical continental monsoon climate. It has plentiful water and heat resource but is in inconsistency of its seasonal distribution in the mid-subtropical region, thus seasonal drought frequently occurs in this planted forest. In this study, seasonal drought effect on ecosystem carbon sequestration was analyzed based on net ecosystem productivity (NEP), ecosystem respiration (RE) and gross ecosystem productivity (GEP) at the month scale in 2003 and 2004. In this drought-stressed planted forest, ecosystem carbon sequestration showed a clear seasonality, with low rates during seasonal drought and in winter. The declining degree of ecosystem carbon sequestration under the seasonal drought condition was determined by the accumulation of soil moisture deficits and a co-occurrence of high temperatures. Different drought effects are expected for RE and GEP. The net effect of ecosystem carbon balance depends on how these two quantities are affected relatively to each other. Summer drought and heat wave are two aspects of weather that likely play an important part in the annual NEP of forest in this region.

Keywords: seasonal drought, subtropical planted forest, eddy covariance, ecosystem respiration, gross ecosystem productivity.

Both atmospheric CO_2 concentration and air temperature of lower atmosphere are rising that have been widely perceived[1,2]. A consensus exits that ecosystem water balance is changing due to altered precipitation and evaporation patterns[3,4]. As Rambal and Debussche[5] pointed out, enhanced drought may not only result from low annual precipitation, but more likely from a different rainfall distribution. In the future warmer climate with increased mean temperatures, it seems that heat waves would become more intense, longer lasting, and/or more frequent[6]. For example, gross primary productivity was reduced by 30% over Europe during 2003 Europe-wide heat and drought, which resulted in a strong anomalous net source of carbon dioxide (0.5 Pg C/a) to the atmosphere[7], and reversed the effect of four years' net ecosystem carbon sequestration[8]. The impacts of drought effects on forest carbon sequestration were emphasized in the global climate change since the forest is taken as the largest carbon sequestration pool[9—11].

At present, China's forest area is 175 million hectares, and the forest coverage rate is about 18.21%.

The planted forest area is 53 M ha, ranking No.1 in the world. At present stock volume of the forest is increasing and net increase of stock volume of the forest is 889 Mm^3 in China, and the stock volume of the planted forest is 490 Mm^3, occupying 55.07% of the total forest stock volume. Fang *et al.*[12] pointed out that the planted forest (afforestation and reforestation) absorbed 0.45 Pg C, which was the main reason of the increase of carbon absorption in China. However, although evidences from different aspects show that the planted forest exactly absorbs carbon dioxide from the atmosphere, direct proof is very scattered and scarce[12,13].

The planted forest is the major component of forest in South China, which occupies 54.3% of the total planted forest area and 52.6% of stock volume of the planted forest in China[14]. Due to the effect of subtropical continental monsoon climate, the min-subtropical region in China is rich in water and heat resources. However, subtropical high controls the progress of summer low atmosphere in this region, which results in summer and autumn droughts frequently. Baldocchi[10] pointed out that it was very important to explore the drought effect on the ecosystem carbon sequestration based on the natural drought conditions. Up to now, few researches have focused on seasonal drought effects on ecosystem carbon sequestration and their control mechanisms.

Continuous measurement of carbon dioxide exchange using the eddy covariance (EC) technique was made at the Qianyanzhou mid-subtropical planted forest as part of the ChinaFLUX network. Yu *et al.*[15], Liu *et al.*[16] and Wen *et al.*[17] indicated that Qianyanzhou planted forest carbon uptake and release were controlled by the light, temperature and soil moisture at hour scale, but there was few studies on seasonal drought effect on ecosystem carbon sequestration. Therefore, seasonal drought effect on ecosystem carbon sequestration was analyzed based on net ecosystem productivity (NEP), ecosystem respiration (RE) and gross ecosystem productivity (GEP) of Qianyanzhou planted forest at month scale in 2003 and 2004. The obtained results will be used to model the change of carbon sink/source of China's mid-subtropical forest in future climate change, and to evaluate the role of planted forest in the carbon balance of the mid-subtropical region in China.

1 Materials and methods

1.1 Site description

The study site, established in late August of 2002, is located at Qianyanzhou Experimental Station of Chinese Ecosystem Research Network (CERN) and ChinaFLUX network in southeastern China (26°44′52″N, 115°03′47″E, elevation 102 m). The plantation, which was planted in 1985, around the site is on gently undulating terrain with slopes between 2.8° and 13.5°. The plantation is dominated by *Pinus elliottii*, *Pinus massoniana* and *Cunninghamia lanceolata*. The average annual air temperature was 17.9℃, and annual precipitation was 1485.1 mm during 1985—2004. The minimum precipitation was 944.9 mm in 2003, and the maximum was 2410.4 mm in 2002. More extensive description of the site can be found in Liu *et al.* [16] and Wen *et al.* [17].

1.2 Flux calculation and correction

The above-canopy flux system mounted at 39.6 m on a tower consists of model CSAT-3 3-axis sonic anemometer (Campbell Scientific Inc., Logan, UT) and model LI-7500 fast response CO_2/H_2O infrared gas analysers (Licor Inc., Lincoln, NB). The signals of these instruments were recorded at 10 Hz by a CR5000 datalogger (Model CR5000, Campbell Scientific) and then block-averaged over 30 min for analysis and archiving. The planar fit method was applied to the wind components to remove the effect of instrument tilt or irregularity on the airflow[18]. Correction was made for the effect of fluctuations of air density on the fluxes of CO_2 and water vapour[19]. Instrumentation in detail referred to related literatures[16,17].

Net ecosystem CO_2 exchange (F_{NEE}, NEE, mg $CO_2 \cdot m^{-2} \cdot s^{-1}$) between the atmosphere and planted forest was calculated with

$$F_{NEE} = \overline{w'\rho_c'(z_r)} + \int_0^{z_r} \frac{\partial \overline{\rho}_c}{\partial t} dz , \quad (1)$$

where the first term on the right-hand side is the eddy flux for carbon dioxide, the second term is the storage below the height of observation (z_r). Note that positive sign represents CO_2 release into the atmosphere, and *vice versa*. The value of net ecosystem CO_2 exchange (NEE) is equal to net ecosystem CO_2 productivity (NEP) except for the sign, ie. NEP= –NEE.

Spurious data were removed from the dataset if the instrument performance and experimental condition were abnormal. The problems were largely related to rainfall, water condensation, or system failure. To avoid possible underestimation of the fluxes under stable conditions during the night, the effect of friction velocity u_* was examined. When the value of u_* was less than 0.2 $m \cdot s^{-1}$, a decreasing trend in the flux was observed. In this case, the values observed in the night (global radiation < 1 $W \cdot m^{-2}$) were excluded[20], since storage and advection were likely to reduce gas fluxes through the measurement plane of the EC instruments under these conditions. Likewise, negative fluxes at night (i.e. apparent photosynthesis) were also taken out of the database. More extensive description of data gap-filling strategy during daytime and nighttime can be found in Liu *et al.*[16].

1.3 Ecosystem respiration and gross ecosystem productivity

To estimate the gross ecosystem CO_2 exchange (F_{GEE}, GEE, mg $CO_2 \cdot m^{-2} \cdot s^{-1}$), it is necessary to achieve the daytime ecosystem respiration ($R_{eco,d}$, mg $CO_2 \cdot m^{-2} \cdot s^{-1}$) and nighttime ecosystem respiration ($R_{eco,n}$, mg $CO_2 \cdot m^{-2} \cdot s^{-1}$). Herein, the daytime ecosystem respiration was obtained based the extrapolation of the function relationship between the nighttime ecosystem respiration and soil temperature and moisture. Therefore, ecosystem respiration (F_{RE}, RE, mg $CO_2 \cdot m^{-2} \cdot s^{-1}$) was defined as

$$F_{RE} = R_{eco.n} + R_{eco,d} . \quad (2)$$

Thus, gross ecosystem CO_2 exchange (F_{GEE}, GEE, mg $CO_2 \cdot m^{-2} \cdot s^{-1}$) was defined as

$$F_{GEE} = F_{NEE} - F_{RE} . \quad (3)$$

The value of gross ecosystem CO_2 exchange (GEE) is equal to gross ecosystem CO_2 productivity (GEP) except for the sign, ie. GEP= –GEE. At the ecosystem level, it is considered that gross ecosystem CO_2 productivity (GEP) is right equal to gross primary productivity (GPP). Here, the unit of NEP, RE and GEP could be g $C \cdot m^{-2} \cdot mon^{-1}$ at the month scale.

1.4 Modeling canopy conductance

The bulk canopy conductance g_c ($m \cdot s^{-1}$) is derived from the measurement through the big-leaf approach of Penman-Monteith by inverting latent heat fluxes[21].

$$g_c = \left[r_a \left(\frac{\Delta}{r} \left(\frac{A}{\lambda E} - 1 \right) - 1 \right) + \frac{\rho_a D_a \varepsilon}{E} \right]^{-1} , \quad (4)$$

where Δ is the slope of the saturation curve ($Pa \cdot K^{-1}$), r the psychrometer constant ($Pa \cdot K^{-1}$), ρ_a the air density ($Kg \cdot m^{-3}$), D_a the air saturation deficit ($mmol \cdot mol^{-1}$), ε the ratio of the molecular weights of water and dry air and r_a the aerodynamic resistance ($s \cdot m^{-1}$). The latter was deduced from turbulence measurement as

$$r_a = \frac{u}{u_*^2} + 6.2 u_*^{-2/3} . \quad (5)$$

The first term on the right hand represents the aerodynamic resistance and the second term, the addition boundary layer resistance that takes the difference between the transport process of momentum and water vapour into account[21].

2 Results and discussions

2.1 Characteristic of climate in Qianyanzhou planted forest

Qianyanzhou planted forest lies in typical subtropical continental monsoon climate region. Based on the meteorological data of Qianyanzhou station during 1985—2004, the annual average air temperature was 17.9℃, and annual precipitation in average was 1485.1 mm. The precipitation in 2003 was 944.9 mm, and the precipitation in 2004 was 1404.5 mm. As Fig. 1 showed that precipitations in June and July of 2003 were lower than the averages of precipitation ± 1 standard deviation during 1985—2004, and the averages of air temperature in July, August and September of 2003 were higher than that of air temperature ± 1 standard deviation during 1985—2004.

As we know, there is plentiful water and heat resources but inconsistency of its seasonal distribution in the mid-subtropical region, thus seasonal droughts frequently occur in this planted forest. The intensity of seasonal drought was determined by the accumulation of soil moisture deficits and a co-occurrence of high

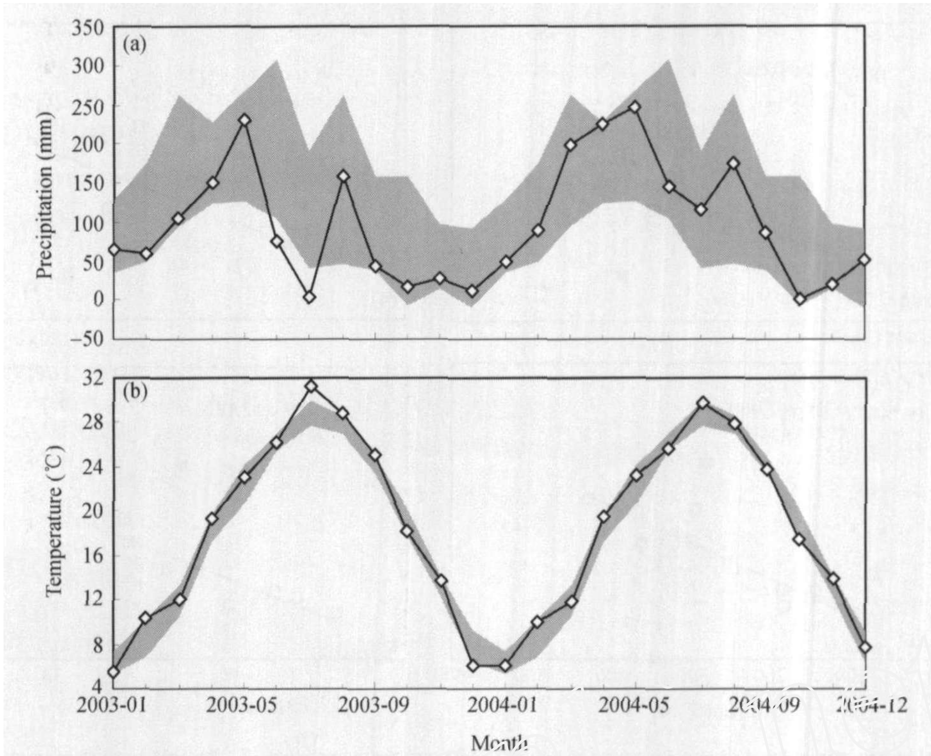

Fig. 1. Seasonal variation of precipitation (a) and mean air temperature (b) at the month scale in 2003 and 2004 at Qianyanzhou mid-subtropical planted forest. Gray region indicated precipitation (a) and mean air temperature (b) ± 1 standard deviation based on the monthly meteorological data of Qianyanzhou station during 1985—2004.

temperatures.

2.2 *Environmental control over ecosystem sequestration*

First of all, the effect of light, temperature, VPD and soil moisture on net ecosystem carbon productivity (NEP) was analyzed at the month scale in Qianyanzhou planted forest. The impacts of photosynthetically active radiation and air temperature on the NEP between 2003 and 2004 (Fig. 2) were different, although the regression analysis showed that photosynthetically active radiation and air temperature were the dominant factors on the NEP. Fig. 2(a) and (b) demonstrated that the NEP declined in July and August in 2003 because of higher temperature and lower precipitation. However, Fig. 2(c) and (d) showed that the NEP increased in October in 2004 because there was little precipitation (0.6 mm) during the later period of summer drought. Fig. 3 also indicated that soil water content at the soil surface was also a dominant factor on the NEP in July and August in 2003.

We suggested that it is obviously different for the way and degree that the NEP was affected by the seasonal drought in this planted forest. The enhancement or decrement of ecosystem carbon sequestration was determined by the coupled effect of summer drought and heat wave on the eco-physiological characteristic of this planted forest.

2.3 *Coupling relationship of RE and GEP*

Net ecosystem productivity (NEP) is the result of carbon balance of ecosystem respiration (RE) and gross ecosystem productivity (GEP). The NEP can be directly determined based on the eddy covariance technique, and RE and GEP are also estimated indirectly[22]. Here, the relationship between NEP, RE and GEP were synthetically investigated. Fig. 4 showed that there was a significantly positive relationship between NEP and RE in 2003 and 2004. However, it is of departure from the relationship between NEP and RE in July and August in 2003 and in October in 2004. Fig. 5 presented that there was also significantly positive relationship betwenn NEP and GEP in 2003 and 2004. However, it is also of departure from the relationship between NEP and GEP in July and August in 2003 and in October in 2004. Obviously the coupling

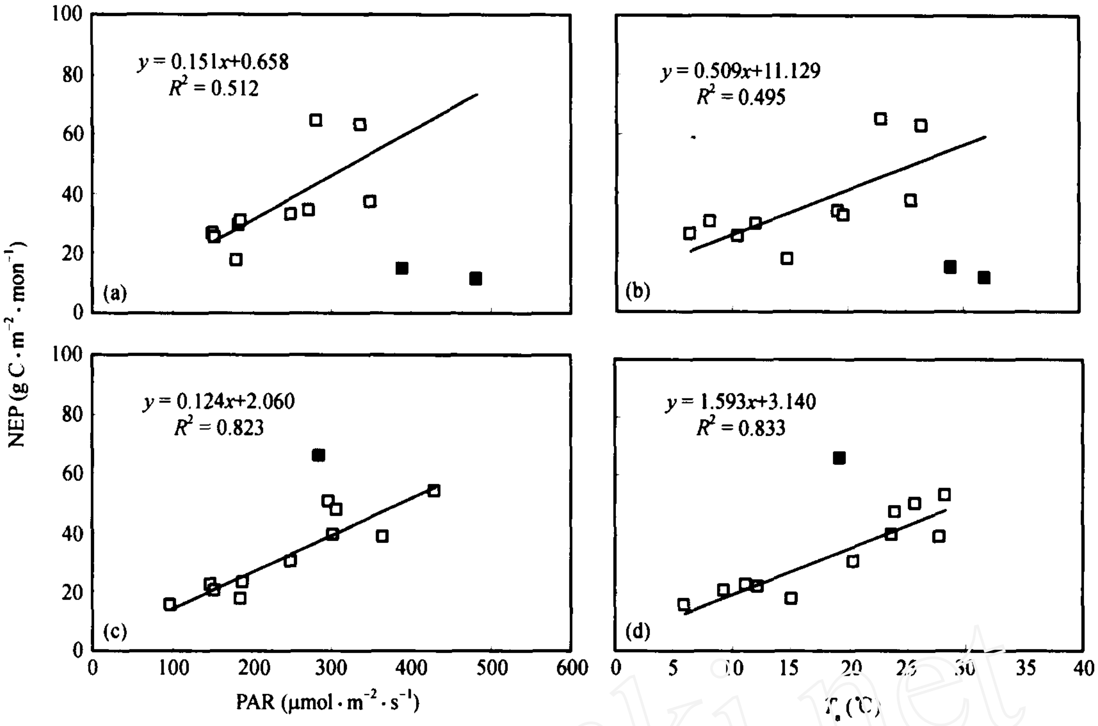

Fig. 2. The relationship between photosynthetically active radiation (PAR) and air temperature (T_a) and net ecosystem productivity (NEP) at the month scale in 2003 and 2004 at Qianyanzhou mid-subtropical planted forest. (a) and (b) are referred to the data in 2003, solid square referred to the data in July and August of 2003, (c) and (d) are referred to the data in 2004, solid square referred to the data in October of 2004. The solid line represents line regression not including solid square data.

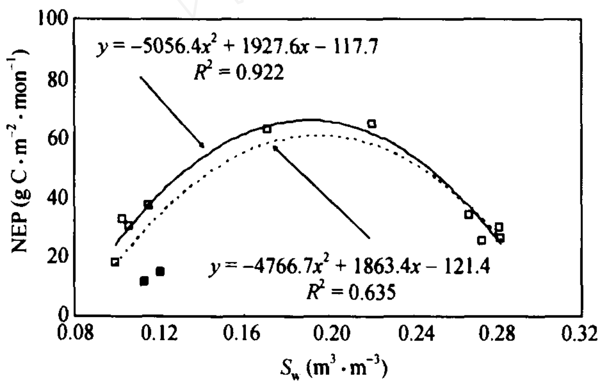

Fig. 3. The relationship between soil water content at the surface soil (S_w) and net ecosystem productivity (NEP) at the month scale in 2003 at Qianyanzhou mid-subtropical planted forest. Solid squares are referred to the data in July and August in 2003; the solid line represents line regression not including solid square data, while the dash line represents line regression including solid square data.

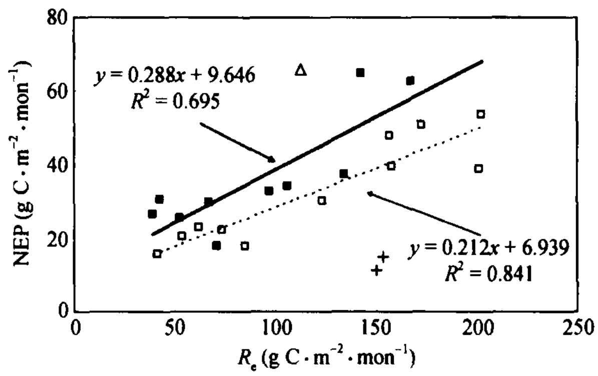

Fig. 4. The relationship between net ecosystem productivity (NEP) and ecosystem respiration (RE) at the month scale in 2003 and 2004 at Qianyanzhou mid-subtropical planted forest. The crosses mean the data in July and August of 2003, and solid squares mean the data in other month in 2003. The triangle means the data in October of 2004, and blank squares mean the data in other month of 2004. The solid line represents line regression not including the data in July and August of 2003, while dash line represents line regression not including the data in October of 2004.

relationship between NEP and RE, GEP was changed during summer time due to the seasonal drought at Qianyanzhou planted forest.

As Fig. 6 indicated there exited significantly positive relationship between ecosystem respiration (RE) and gross ecosystem productivity (GEP), while the relationship was kept fixable proportion between 2003 and 2004. The ecosystem carbon sequestration was determined by the coupling relationship of GEP and RE. Janssens[23] and Högberg *et al.*[24] also reported similar results. However, we also noticed the departure

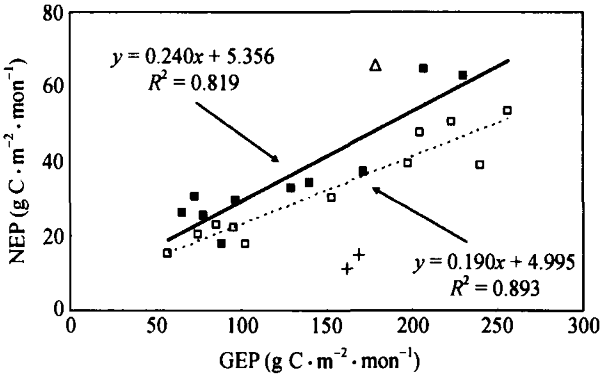

Fig. 5. The relationship between net ecosystem productivity (NEP) and gross ecosystem productivity (GEP) at the month scale in 2003 and 2004 at Qianyanzhou mid-subtropical planted forest. The symbols and lines in this figure are the same as Fig. 4.

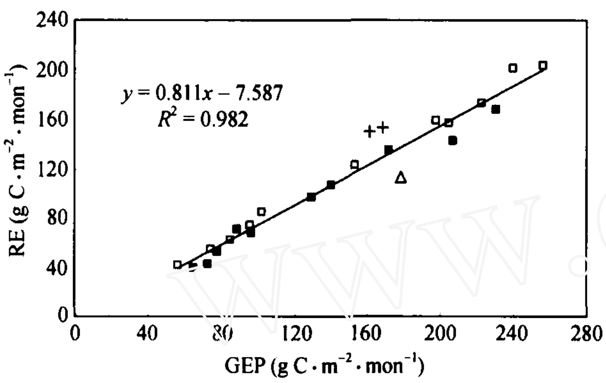

Fig. 6. The relationship between ecosystem respiration (RE) and gross ecosystem productivity (GEP) at the month scale in 2003 and 2004 at Qianyanzhou mid-subtropical planted forest. The symbols in this figure are the same as Fig. 4. The solid line represents line regression in 2003 and 2004, not including the data in July and August of 2003 and in October of 2004.

from the relationship between RE and GEP in July and August of 2003 and in October of 2004 because of seasonal drought effects.

2.4 *Seasonal drought effect on ecosystem carbon sequestration*

Seasonal variation of net ecosystem productivity (NEP), ecosystem respiration (RE) and gross ecosystem productivity (GEP) in 2003 and 2004 at Qianyanzhou planted forest was shown in Fig. 7. Fig. 7 indicated that ecosystem carbon sequestration showed a clear seasonality in 2003 and 2004, with low rates during seasonal drought and in winter. The NEP in July and August of 2003 was lower than the average of 2003. The NEP in August and September of 2004 also declined, but the NEP in October of 2004 reached the highest value.

Fig. 7 showed that seasonal patterns of RE and GEP were different with that of NEP. Although RE and GEP both showed a declining trend during the summer drought of 2003, there exited very different declining trend. Contrastively, RE and GEP did not show a declining trend during the summer drought of 2004. This was mainly because GEP was largely dependent on radiation, air temperature, VPD and amount of total soil water accessible by roots, ecosystem respiration was likely to be more dependent on top-soil water content and temperature[25].

Fig. 8(a) showed that canopy conductance began to

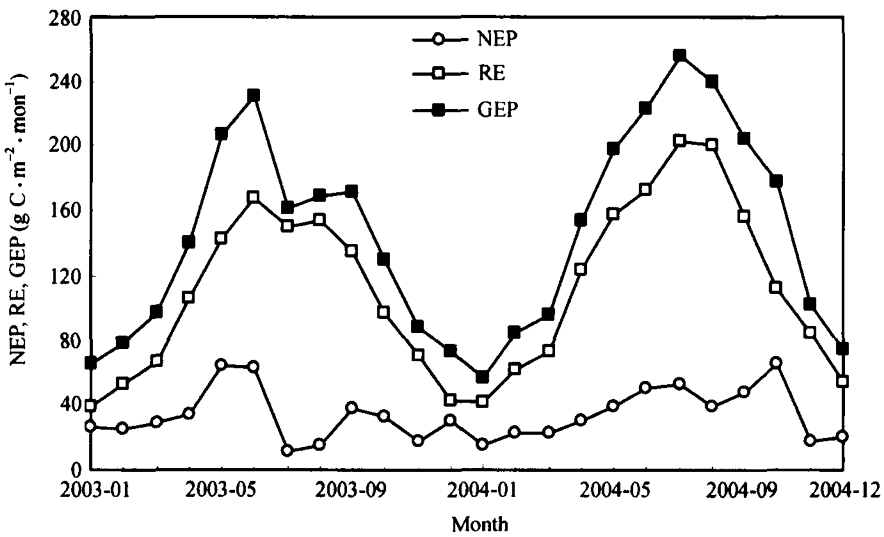

Fig. 7. Seasonal variation of net ecosystem productivity (NEP), ecosystem respiration (RE) and gross ecosystem productivity (GEP) at the month scale in 2003 and 2004 at Qianyanzhou mid-subtropical planted forest.

decline in May of 2003, while gross ecosystem productivity (GEP) still increased a little. Due to the accumulation of soil moisture deficits and a co-occurrence of high temperatures, GEP also began to decline sharply during summertime in 2003. Contrastively, although canopy conductance showed a decline during the seasonal drought in 2004, GEP did not show a decline trend. It was obvious whether GEP declined or not during the summer drought rested with the coupling effects of higher temperature and lower precipitation. Fig. 8(b) showed that temperature was the dominant factor over ecosystem respiration (RE), although the RE declined obviously during the summer of 2003 since the accumulation of soil moisture deficits and a co-occurrence of high temperatures.

Seasonal variation of relative change of GEP and RE at the month scale in 2003 and 2004 was shown in Fig. 8(c). It was evident that the relative increase of GEP was larger than that of RE in May of 2003, thus the NEP increased clearly. It was noticed that the relative decrease of GEP was higher than that of RE in July of 2003, thus the NEP decreased clearly. Contrastively, the NEP in August in 2004 decreased because of the GEP decrease, but the RE kept relatively no change. It showed that the NEP enhanced in October in 2004 because the decline of the GEP was quicker than the decline of the RE. This suggested that different drought effects could be expected on RE and GEP.

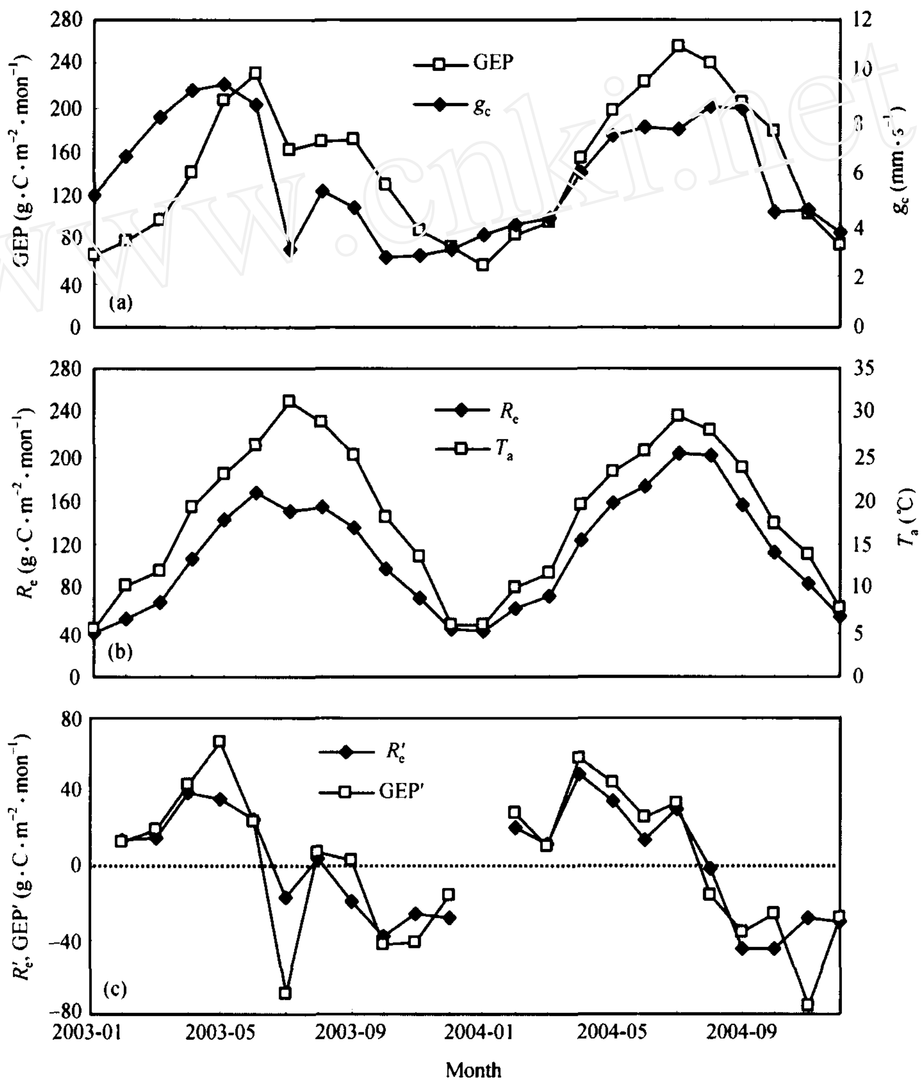

Fig. 8. Seasonal variation of gross ecosystem productivity (GEP) and canopy conductance(g_c) (a), ecosystem respiration (RE) and air temperature (T_a) (b), and relative change of GEP (GEP') and RE (RE') (c) at the month scale in 2003 and 2004 at Qianyanzhou mid-subtropical planted forest.

The net effect of ecosystem carbon balance depends on how these two quantities are affected relatively to each other. Summer drought and heat wave are two aspects of weather that likely play an important part in the annual NEP of forest in this region. Therefore, it is necessary to determine the mechanism of abiotic and biotic control over RE and GEP when quantifying the ecosystem carbon sequestration. In future, we must consider how summer drought and heat wave conspire to affect short-term physiological and long-term ecological process[10].

3 Conclusions

As part of the ChinaFLUX network, continuous measurement of carbon dioxide exchange using the eddy covariance (EC) technique was made at Qianyanzhou mid-subtropical planted forest. In this drought-stressed planted forest, ecosystem carbon sequestration showed a clear seasonality with low rates during drought and in winter.

The decline degree of ecosystem carbon sequestration under seasonal drought condition was determined by the coupled effects of the accumulation of soil moisture deficits and a co-occurrence of high temperatures. Different drought effects are expected for RE and GEP. The net effect of ecosystem carbon balance depends on how these two quantities are affected relatively to each other. We suggested that natural drought experiments be an alternative approach to studying how ecosystems may response to warming. Summer drought and heat wave are two aspects of weather that likely play an important part in the annual NEP of forest in this region.

Acknowledgements This research was supported by the Ministry of Science and Technology of China (Grant No. 2002CB412501) and Chinese Academy of Sciences (Grant No. KZCX1-SW-01-01A). It was also supported by the National Natural Science Foundation of China (Grant No. 30225012). We also thank two anonymous reviewers for their valuable suggestions.

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