DOI: 10.1007/s11430-006-8099-3

Seasonal dynamics of CO_2 fluxes from subtropical plantation coniferous ecosystem

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Received October 27, 2005; accepted March 10, 2006

Abstract As one component of ChinaFLUX, the measurement of CO_2 flux using eddy covariance over subtropical planted coniferous ecosystem in Qianyanzhou was conducted for a long term. This paper discusses the seasonal dynamics of net ecosystem exchange (NEE), ecosystem respiration (RE) and gross ecosystem exchange (GEE) between the coniferous ecosystem and atmosphere along 2003 and 2004. The variations of NEE, RE and GEE show obvious seasonal variabilities and correlate to each other, i.e. lower in winter and drought season, but higher in summer; light, temperature and soil water content are the main factors determining NEE; air temperature and water vapor pressure deficit (VPD) influence NEE with stronger influence from VPD. Under the proper light condition, drought stress could decrease the temperature range for carbon capture in planted coniferous, air temperature and precipitation controlled RE; The NEE, RE, and GEE for planted coniferous in Qianyanzhou are –387.2 g C·m^{-2} a^{-1}, 1223.3 g C·m^{-2} a^{-1}, –1610.4 g C·m^{-2} a^{-1} in 2003 and –423.8 g C·m^{-2} a^{-1}, 1442.0 g C·m^{-2} a^{-1}, –1865.8 g C·m^{-2} a^{-1} in 2004, respectively, which suggest the intensive ability of plantation coniferous forest on carbon absorbing in Qianyanzhou.

Keywords: plantation, eddy covariance, photosynthesis, respiration, drought stress.

Global climatic changing has been a focus for a long time in many fields, the increasing CO_2 concentration in atmosphere was considered as one main driving force for global warming[1]. However, there is great discrepancy for all kinds of measurements in carbon cycling. Many researches concluded that the terrestrial ecosystem uptakes CO_2 from the atmosphere, but the direct observation was scarce. Forest ecosystem is the most important carbon-absorbing pool in the terrestrial ecosystem for plant growth, which resulted in the focus on carbon up taking and in environmental controlling[2–4]. Planted forest is one important part in China for its carbon-fixing ability [5,6]. From the 1970s, forestation has been one important activity in China, which leads to the yearly increasing of forest area, and forest biomass. In Southern China, there is a magnitude of planted forest area, which accounts for 54.3% of forestation and 52.6% of carbon storage in China mainland.

The carbon up taking of planted forest was approbated in Kyoto Protocol. Meanwhile, the forestation and reforestation could be calculated in the country's CO_2 budgets from 1990. In the past 20 years, carbon storage in the forests of China increased 0.4 PgC, with annual increasing 0.011−0.035 PgC, which mainly resulted from forestation[5,6]. Although the potential of carbon fixation in planted forest was paid attention to for a long time, there is disputation for the quantitative estimation[7,8]. Eddy covariance (EC) was an advanced technique that could be used for observation under a high temporal frequency and for a long time. Eddy covariance could show the daily seasonal and intra annual dynamics and its correlation to environmental factors. To accurately understand the carbon absorbing ability of the terrestrial ecosystem, it is necessary to observe carbon exchange for a long time with high frequency[11]; meanwhile, studying the influence of environmental and physiological factors on CO_2 fluxes over canopy could provide dataset for carbon balance validation[9,10,12,13].

The paper analyzed the daily, seasonal dynamics of NEE, RE and GEE and their environmental factors using eddy covariance in Qianyanzhou, and estimated the carbon budgets in the studied site.

1 Materials and methods

1.1 Site description

The meteorological tower is located in the Qianyanzhou (115°04′13″E, 26°44′48″N, 110.8 m) station, situated on the typical red earth hilly region in the mid-subtropical monsoon landscape zone of South China. The altitude for the whole experiment station is around 100 m, so the footprint is relative plat. Around the tower, the forest cover reaches 90% in 1 km^2 region, and 70% in 100 km^2. The vegetation mainly includes *Pinus massoniana, Pinus elliottii Engelm,* and *Cunninghamia lanceolata* (Fig. 1). The shrub under canopy mainly includes *Loropetalum chinense* and *Lyonia compta*. The soil is red soil, which is weathered from red sand rock. According to the statistics of 1985−2004 meteorological data, at this site, the mean annual temperature was 17.9℃; positive accumulation temperature is 6543.8℃, and ≥10℃ accumulation temperature is 5948.2℃. The annual precipitation

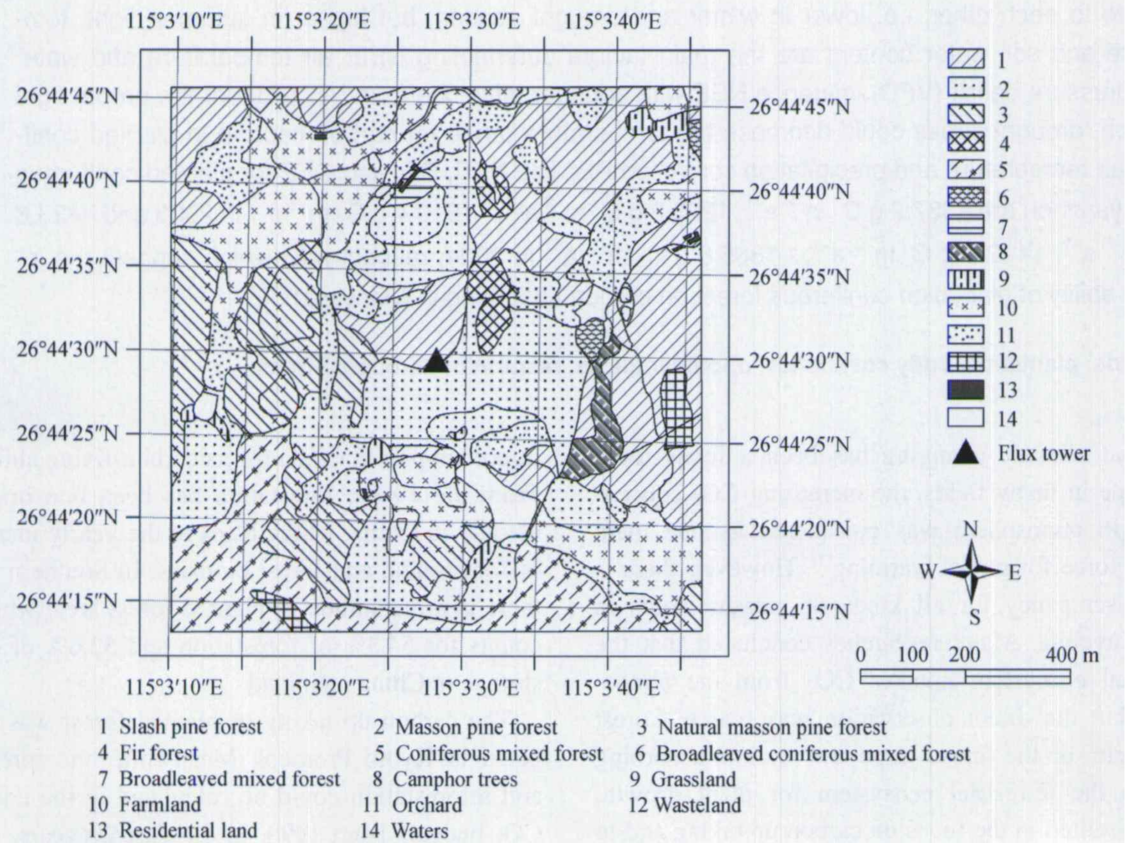

Fig. 1. The vegetation map around tower in Qianyanzhou station.

1485.1 mm, annual evaporation 1302.8 mm, mean relative humidity 84%. It is a typical sub tropical monsoon climate. The drought period analyzed in this paper was performed during the 2003 growth season. This season was warm and dry relative to the average climatic conditions; the whole year cumulative precipitation was about 63% of the long term average in this site, especially, during June and July. Both months it was only 23%, and the averaged temperature was higher by 1.0℃ than the mean annual temperature, and the July temperature was higher by 3℃ (Table 1 and Fig. 1).

1.2 Data logging and processing

The EC was used for measuring CO_2 flux between vegetation and atmosphere. The three-dimensional sonic anemometers (Model CSAT-3, Campbell Scientific) were used for measuring wind speed and temperature fluctuation, the infrared gas analyzer (Model LI-7500, Licor Inc.) was used for measuring CO_2 and H_2O. The EC systems were described in detail in references 14 and 15. Data were digitally logged continuously over 30 min intervals at a 10 Hz frequency with data logger (Model CR5000, Campbell Scientific). In addition, there are seven level CO_2 profile system and routine meteorological measurement system, installed for measuring net radiation, temperature, and humidity; correspondingly, the photosynthesis, respiration, letter fall, and LAI were measured.

In order to eliminate the items of horizontal and vertical advection in the equation of conservation of mass, the raw of 30 min flux data were reformed by three-dimension coordinate rotation [16] that aligned the vertical velocity measurement normal to mean wind streamlines and brought the mean lateral and vertical velocity to zeros. The effect of fluctuation in air density on the flux data also was corrected[17].

The NEE (F_{NEE}, mg CO_2 m^{-2} s^{-1}) was defined as

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

On the right hand side, the first term is CO_2 fluctuation flux; the second item is storage of CO_2. Eq. (1) is the fundamental equation for NEE, the positive mean the CO_2 emission to atmosphere, and the negative means carbon capture. NEE is equal to NEP with denotation in converse.

During data analyzing, eliminating the abnormity related to precipitation and dew could get credible observations. To get credible EC measurements on nighttime (gross radiation < 1 $W \cdot m^{-2}$), we deleted the data when friction velocity less than 0.2 m s^{-1} to avoid the underestimation from storage and advection.

1.3 Gap filling

We divided the daytime data (total radiation ≥ 1 $W \cdot m^{-2}$) in every 10 days to fill the missing data with the Michaelis–Menten[19] equation;

$$F_{\mathrm{NEE}} = -\left(\frac{\alpha Q_{\mathrm{P}} N_{\mathrm{es}}}{N_{\mathrm{es}} + \alpha Q_{\mathrm{P}}} \right) + R_{\mathrm{eco,d}} , \qquad (2)$$

where α is the apparent quanta yield, N_{es} is total ecosystem exchange, it is potential NEE (when PAR is abundance), and $R_{\mathrm{eco,d}}$ is the non-light respiration (when the PAR is zero).

Daytime NEE is from ecosystem respiration, so we interpolate the missing data with the Lloyd and Taylor equation[4,20].

$$F_{\mathrm{NEE}} = R_{\mathrm{eco,n}} = R_{\mathrm{eco,ref}} e^{E_0 \left(\frac{1}{T_{\mathrm{ref}} - T_0} - \frac{1}{T_{\mathrm{K}} - T_0} \right)} , \qquad (3)$$

where $R_{\mathrm{eco,ref}}$ is the ecosystem respiration (mg m^{-2} s^{-1}) at reference temperature (T_{ref}); T_{k} is air temperature, and E_0 is the activation energy in J mol^{-1}.

Table 1 The parameters for planted coniferous around tower in Qianyanzhou station (observed in 2005)

Vegetation	Diameter at breast height (cm)			Height (m)			Mean canopy (m)		Max canopy (m)		Min canopy (m)		Density (trees · hm^{-2})
	mean	max	min	mean	max	min	west to east	south to north	west to east	south to north	west to east	south to north	
Slash Pine	16.97	28.60	4.00	12.60	20.00	4.70	3.00	2.90	7.30	5.90	1.20	0.90	745
Chinese red pine	13.40	32.60	3.80	10.50	16.00	3.90	2.90	2.80	9.00	7.60	0.90	1.00	880
China fir	13.52	20.80	4.10	10.80	15.00	4.00	2.70	2.80	5.00	4.90	1.30	1.40	102
Broad-leaves	7.57	17.80	2.90	7.40	16.50	3.50	2.90	2.70	9.70	5.80	1.60	1.20	46
Mean/sum	13.82	22.33	5.65	10.97	14.48	5.38	3.08	2.99	5.13	4.75	1.60	1.58	1773

T_0 is a fitted temperature parameter.

For the ecosystem under drought stress, data lacking in nighttime could be utilized as Q_{10} to filling[15,21]. In the Q_{10} model, ecosystem respiration was described with the Van't Hoff function.

$$F_{\mathrm{NEE}} = R_{\mathrm{eco,n}} = R_{\mathrm{eco,refs}} e^{\ln(Q_{10})(T_k - T_{\mathrm{ref}})/10}. \quad (4)$$

In the Q_{10} model, Q_{10} is negatively correlated to temperature, and its relationship to water content could be described with quadratic equation.

$$Q_{10} = a - bT_a + cS_{\mathrm{w}} + dS_{\mathrm{w}}^2, \quad (5)$$

where $R_{\mathrm{eco,refs}}$ is the ecosystem respiration under reference temperature and proper water content. S_w ($m^3 \cdot m^{-3}$) is the water content in soil surface. *a*, *b*, *c* and *d* are constants, in which $b \geqslant 0$ and $d \leqslant 0$.

1.4 Ecosystem respiration and total CO_2 exchange

To estimate the gross ecosystem exchange (F_{GEE}, mg CO_2 $m^{-2} \cdot s^{-1}$), we need the daytime ecosystem respiration ($R_{\mathrm{eco,d}}$, mg CO_2 $m^{-2} \cdot s^{-1}$). We extrapolated the night respiration to obtain the respiration in daytime. Therefore, the RE (RE, FRE, mg CO_2 $m^{-2} \cdot s^{-1}$) was defined as the following:

$$F_{\mathrm{RE}} = R_{\mathrm{eco.n}} + R_{\mathrm{eco,d}}. \quad (6)$$

Therefore, the GEE (F_{GEE}, mg CO_2 $m^{-2} \cdot s^{-1}$) was defined as

$$F_{\mathrm{GEE}} = F_{\mathrm{NEE}} - F_{\mathrm{RE}}. \quad (7)$$

GEE is rightly negative to GEP, on the ecosystem level, and it could be considered that GEP is right equal to GPP, on the temporal scale of hour. The unit is mg CO_2 $m^{-2} \cdot s^{-1}$, on the temporal scale of day or year, and the unit could be g C $m^{-2} \cdot d^{-1}$ and g C $m^{-2} \cdot a^{-1}$.

2 Results

2.1 The climate condition in 2003 and 2004

The climate in Qianyanzhou is characterized as a sub-tropical monsoon climate; the PAR, air temperature, VPD, precipitation and soil water content show obvious seasonal dynamics in 2003 and 2004 (Fig. 2). The PAR were 267.7 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 249.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 2003 and 2004, respectively. The air temperature dynamics are similar for 2003 and 2004 (Fig. 2(b)), the annual mean air temperature are 18.9℃ and 18.6℃ for 2003 and 2004, respectively. The air temperatures of July, August and September in 2003 are 3.7℃, 1.2℃, and 1.6℃, higher than those in 2004. The VPD also are different for 2003 and 2004, which was caused by the decreasing of precipitation in June and July and high temperature in July, August and September in 2003 (Fig. 2(b), (c)). The difference also provides us a nice opportunity for studying the effect of drought stress on carbon cycling in a planted forest.

There is a significant negative correlation between summer temperature and soil volume water content (Fig. 2(b), (c)). The water volume content varied similar to that of precipitation (Fig. 2(c)). The precipitation is 944.9 mm in 2003, lower than historical archives; it is 1404.5 mm in 2004. Soil water content in summer showed an obvious decrease in 2003 for the drought, but kept stable in 2004, which also showed us the lag of influence of drought on ecosystem processes. Meanwhile, the drought and high temperature stress occur jointly and synchronously.

2.2 Diurnal variation of carbon fixation

Fig. 3 compares and analyzes the NEE measured on 3 times height of planted ecosystem in 2003 and 2004. There is an obvious seasonality variation of monthly diurnal variation for 2003 and 2004, lower in winter and drought season, and higher in summer. During the growing season (May and June), the carbon fixation in 2004 is little less than that of 2003, because in the former part of 2003, the adequate water content did not influence the ecosystem processes in 2003, but the drought stress in 2003 play a lag effect on ecosystem processes in 2004. From July to October, carbon fixation in 2004 is higher than that of 2003; the precipitation plays the role in the differences. The obvious differences of monthly diurnal variation also proved that the necessity of observation on carbon exchange between atmosphere and terrestrial ecosystem for a long term.

Meanwhile, the photosynthesis of single leaf is very important to understanding the photosynthesis on the ecosystem level. We also compared the monthly diur-

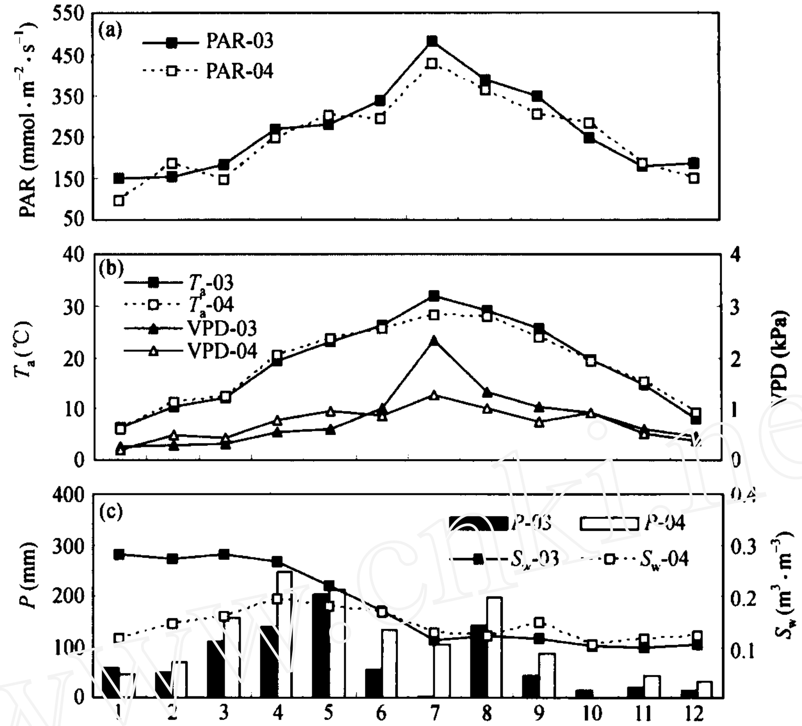

Fig. 2. Seasonal dynamics of PAR, air temperature (39.6 m), VPD (39.6 m), precipitation and soil water content (5 cm) in 2003 and 2004.

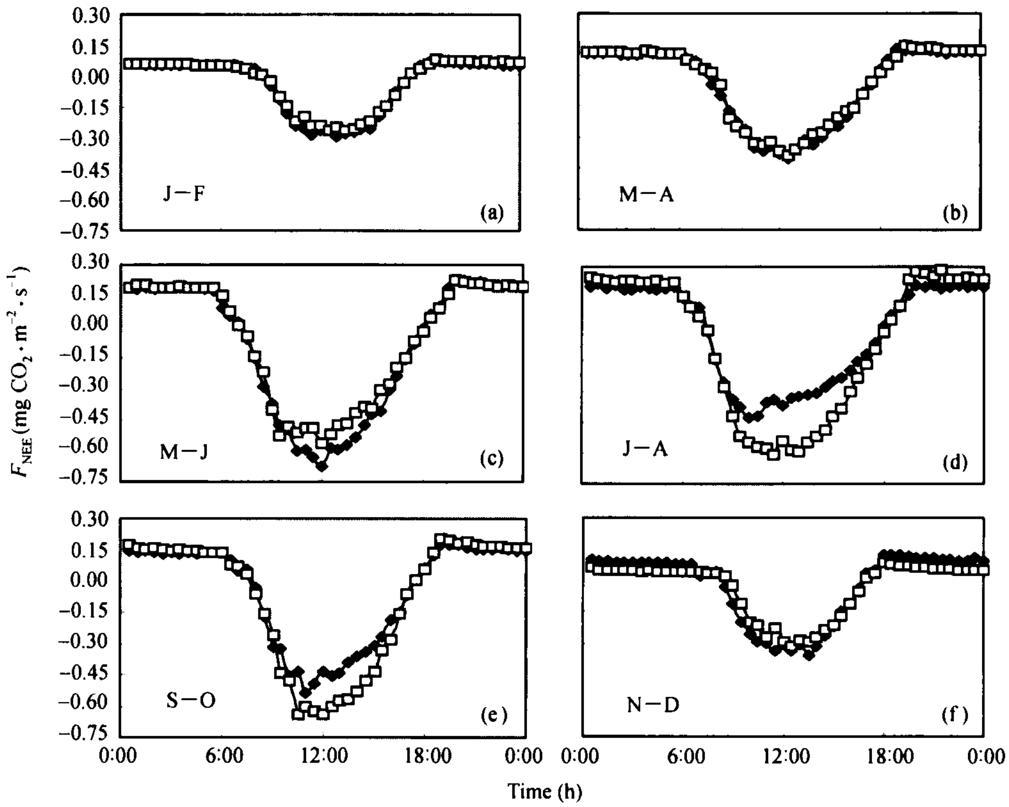

Fig. 3. The monthly diurnal variation of F_{NEE} for planted forest in 2003 and 2004 (Solid square stands for the observation in 2003, open square stands for 2004).

nal variation of NEE with photosynthesis on single leaf scale (Fig. 4). After 6:00, along with the increasing of PAR, CO_2 was captured more and more via photosynthesis, and at the same time, the negative NEP supported the point. The photosynthesis of single leaf reaches its peak around 11:00; however, NEE reaches its peak around 12:30, and when the PAR is lower than light compensation point around 18:00, the photosynthesis cease and NEE became positive, which suggests its role of carbon sources.

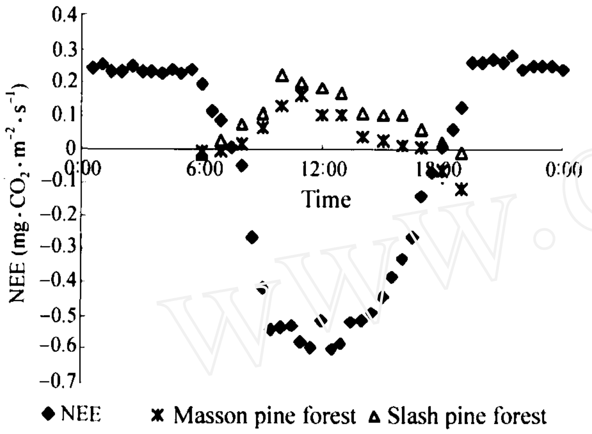

Fig. 4. Comparison of monthly diurnal variation of NEE with diurnal variation of single leaf photosynthesis (NEE: net ecosystem exchange, Masson pine forest: Masson pine forest single leaf photosynthesis rate, Slash pine forest: Slash pine forest single leaf photosynthesis rate).

2.3 *Seasonal dynamics of ecosystem carbon fixation*

The main advantage of EC is its contribution of capturing seasonal variation of carbon flux. We also analyzed the NEE, RE and GEE in 2003 and 2004 (Fig. 5). NEE is determined by the difference of RE and GEE, all of them showed obvious seasonality, lower in drought season and higher in summer. The decreasing RE during drought season in 2003, along with the decreasing of NEE, totally shows carbon sources.

One of the purposes of CO_2 measurement in long term using EC is to estimate the carbon fixation accurately. Our study showed that the planted forest will be a carbon sink in two years; the NEE, RE, and GEE are –387.2, 1223.3 and –1610.4 g C $m^{-2} \cdot a^{-1}$ in 2003, and –423.8, 1442.0 and –1865.9 g C $m^{-2} \cdot a^{-1}$ for 2004. Meanwhile, the carbon fixation is different for 2003 and 2004. The carbon fixation in 2004 is higher than that of 2003, which suggests that the influence of drought on carbon fixation could be 9.5%.

3 Discussion

3.1 *The influence of high temperature stress on photosynthesis*

The synchronous occurring of drought and high temperature is the law for planted forest in Qianyanzhou. Figs. 6 and 7 show that response of daytime NEE to PAR is significantly correlated to temperature. The proper temperature range for photosynthesis is 24—28℃ (Fig. 6), and 20—32℃ (Fig. 7). Drought stress limited the temperature range for photosynthesis. When the temperature is higher than 32℃, NEE will decreases, which results from the increased ecosystem respiration and decreased total

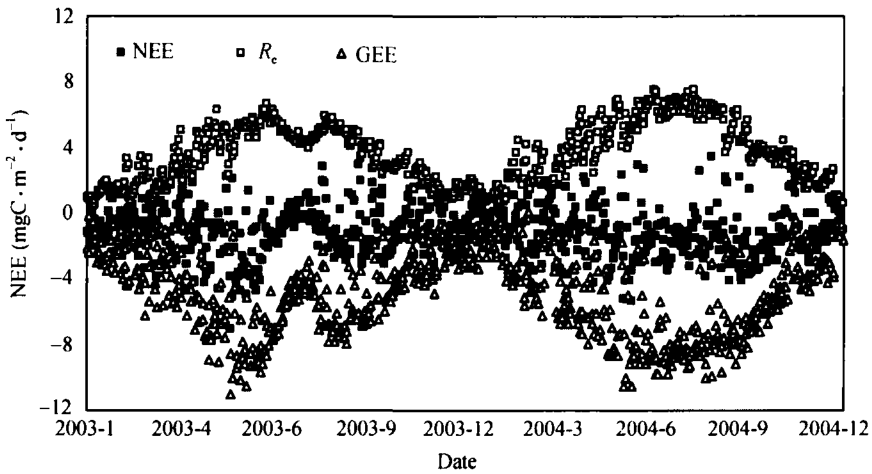

Fig. 5. Seasonal variation of NEE, RE and GEE for 2003 and 2004.

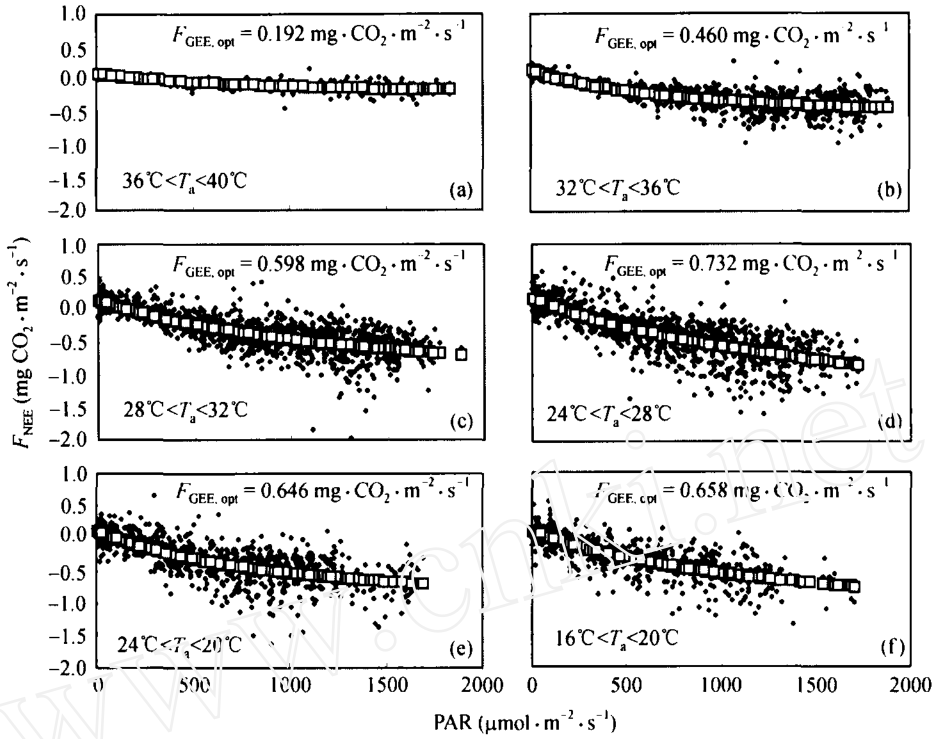

Fig. 6. The relationship of PAR to NEE under high temperature stress in 2003 (Open square stands for the results from Michalis-Menten model, F_{GEE},opt means the potential GEE with PAR being 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$).

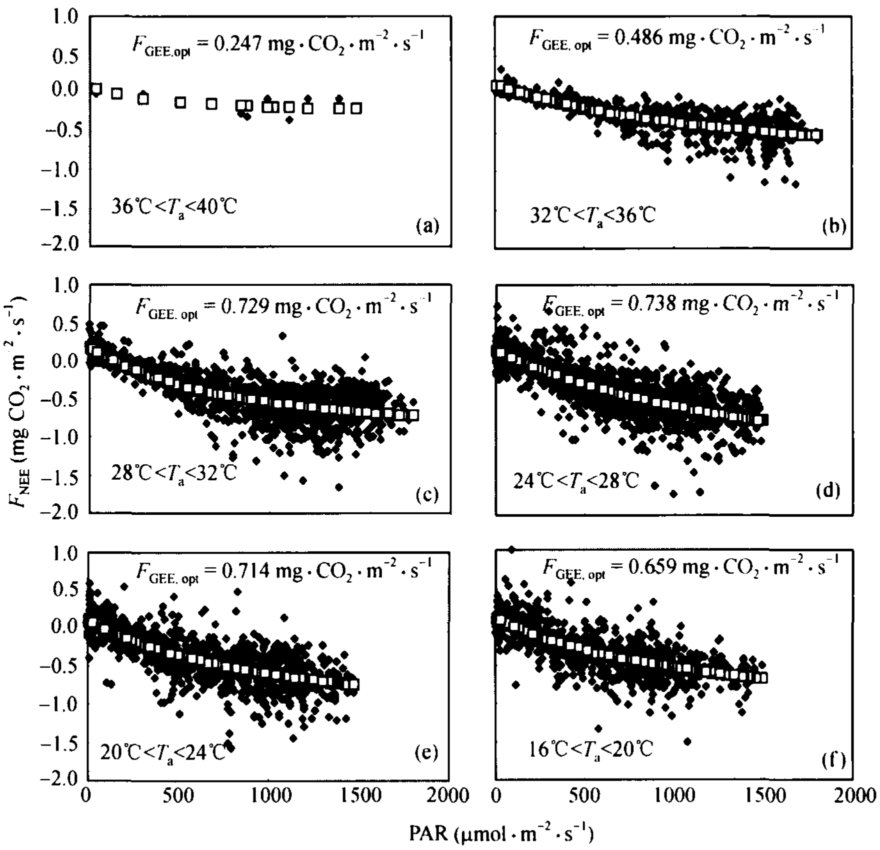

Fig. 7. The relationship of PAR to NEE under high temperature stress in 2004 (open square stands for the results from Michalis-Menten model, $F_{GEE,opt}$ means the potential GEE with PAR being 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$).

ecosystem exchange[22]. High temperature leads to high water pressure, so it is hard to separate the high temperature stress and drought stress on the decreasing of carbon fixation. We used residual analysis to determine the role of temperature and water vapor pressure on ecosystem exchange. NEE was influenced by PAR, it is negatively correlated to PAR, which could be described by the Michaelis-Menten model (Fig. 8(a), (b)). When the air temperature is higher than 30℃, residual is correlated to temperature significantly (Fig. 9(a), (b)). The residual is correlated to water vapor pressure significantly when water vapor pressure is higher than 1kPa (Fig. 10(a), (b)). Through the above analysis, we knew that the VPD influences carbon fixation on the ecosystem level much more, for high VPD could induce Stomatal closing, and thus inhibit photosynthesis on the ecosystem level[23].

3.2 The influence of temperature and soil water content on RE

Fig. 11 shows the response of RE to air temperature in 2003 and 2004; on the ecosystem level, temperature is the dominant factor on carbon emission from planted forest. Yu *et al.*[21] and Wen *et al.*[15] reported that under the drought stress, water condition

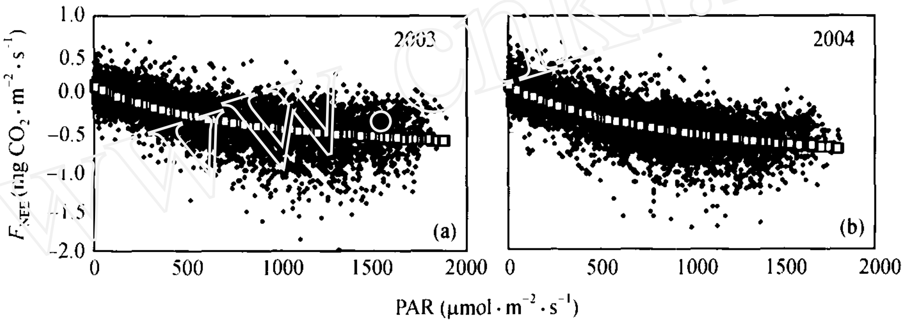

Fig. 8. The relationship of PAR to the difference between estimated and observed daytime F_{NEE} (open square stands for the results from Michalis-Menten model).

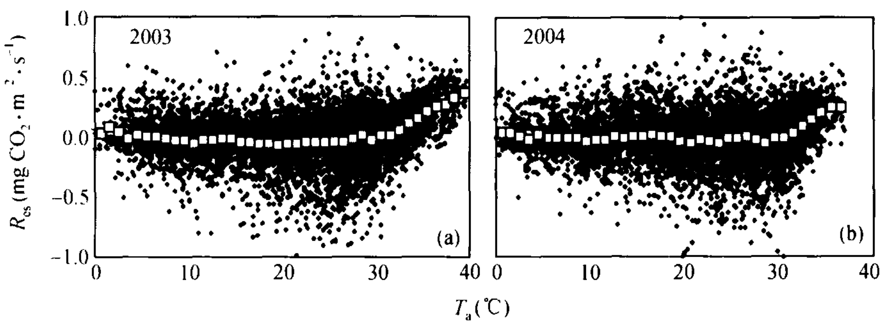

Fig. 9. The relationship of air temperature to the difference between estimated and observed daytime F_{NEE} (open square stands for the mean F_{NEE} for every 1℃).

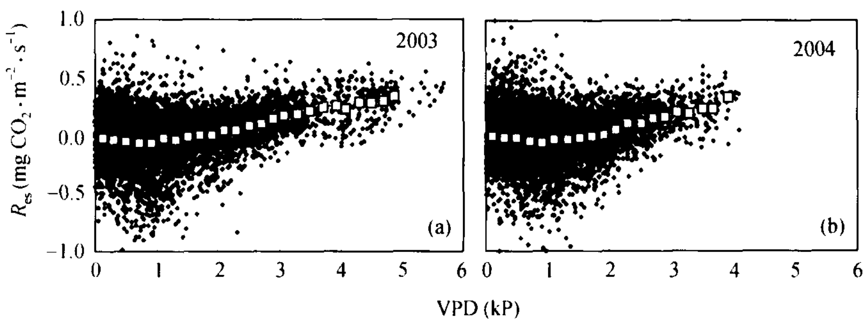

Fig. 10. The relationship of VPD to the difference between estimated and observed daytime F_{NEE} (open square stands for the mean F_{NEE} for every 0.2 kPa).

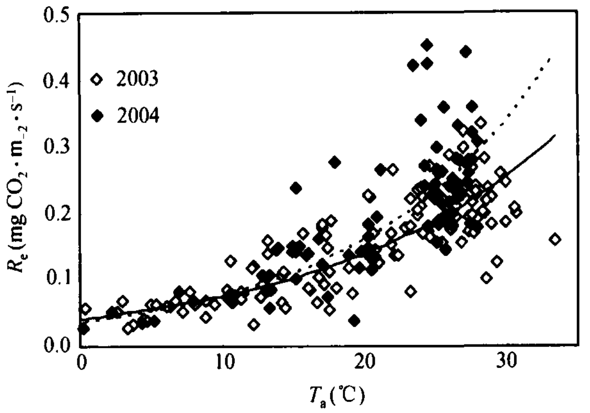

Fig. 11. The response of RE to air temperature variation for planted forest in 2003 and 2004 (to decrease the error in data processing, we averaged the daily data (n>3)).

could be the dominant factor on RE in Qianyanzhou; temperature and water content influence the RE together. In our study (Fig. 11), the response of RE to temperature is lower in 2003 than 2004, which results from the drought in 2003. Under the drought stress, soil water content influence RE and its sensitivity to temperature, i.e. Q_{10}, for the Q_{10} is very low under drought stress[15].

3.3 Contribution of soil respiration to ecosystem respiration for planted forest

It is still a disputed issue on how much contribution will plant respiration and soil respiration play on ecosystem carbon balance[24−26]. Some studies reported that soil autotrophic respiration and heterotrophic respiration could reach 75% of ecosystem respiration[27,28]. We measured the soil surface CO_2 emission 50 away from our flux tower (in same vegetation) with static chamber equipped GC in the study period. The results show that the soil respirations in the studied site are lower than other reports[27,28] whether the litter fall was removed or not. The soil respiration on bare soil account for 42.5% of ecosystem respiration, and soil respiration from litter fall-covered soil reaches 58.9% of ecosystem respiration (Fig. 12). The mean reason lies in the young forest in Qian Yanzhou, so the growing lead to the intensive respiration of plant, so the relative proportion of soil respiration will be low; meanwhile, the low pH value (4.6) and organic matter (2.6%) also contributed to the low proportion of soil respiration in ecosystem respiration.

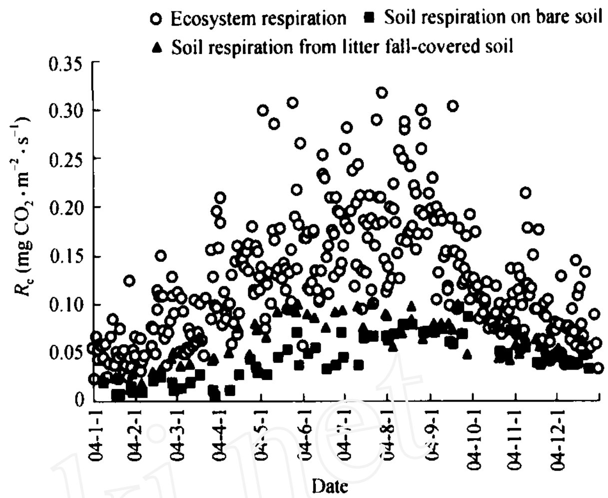

Fig. 12. The contribution of soil respiration to ecosystem respiration over planted forest in 2004.

3.4 Comparison with other studies

Using EC to measure CO_2 flux in a long term could accurately estimate the carbon fixation of plantation ecosystem in Qianyanzhou. Through the study for two years, the planted coniferous showed a carbon sink along the whole period, whatever drought of 2003 or normal condition of 2004, which suggests the important role of planted coniferous in carbon cycling. The carbon fixation in 2004 is higher than that of 2003, which means that effect of drought stress on carbon fixation is large, even 9.5%. Comparing with other studies sited in similar latitude (Table 3), our estimation is very close to other observations. However, the NEE in our study is higher than other studies of natural forest, even more than 10 times, but the reason maybe lies in the growing of a panted forest, which leads to high carbon fixation. Meanwhile, the growing for the whole in sub-tropical leads to a strong carbon sink. Some investigation also shows that the planted forest will decrease the grow rate after 20 years, and thus modify the forest stand and density; meanwhile, reducing mixed forest of coniferous and broad leaves will be a better choice for forest management and carbon policy. In the case of the lack in observation on the same vegetation, the comparison is a preliminary job; further study on the same tree and their comparison will be a future point.

Table 3 Comparison with other studies in similar latitude

Characteristics	This study	Sky Oaks Biological Field Station	Gainesville-cypress wetland	Gainesville (Mize)-slash pine
Longitude	26°44′N	33°22′N	29°46′N	29°45′N
Latitude	115°03′E	116°37′W	82°12′W	82°14′W
Vegetation	planted coniferous	Jungle	Wetland cypress	planted pine
Climate	subtropical	Mediterranean	subtropical	subtropical
NEE/g C m^{-2} a^{-1}	−483.58−−519.45	−56.7−−76.3	−37−−84	−740−−610
Reference	this paper	Baldocchi, 2004 (www.fluxnet.ornl.gov)	Clarke, 1999 (www.fluxnet.ornl.gov)	Clarke, 1999 (www.fluxnet.ornl.gov)

4 Conclusions

On the ecosystem level, the diurnal variation of NEE for planted coniferous in 2003 and 2004 changes along seasons, i.e. lower in winter and higher in summer. For May and June, the carbon fixation in drought condition is little higher than that in the normal condition, which maybe results from the previous adequate water before the drought stress in 2003, but the drought in 2003 left a lag effect on the ecosystem in 2004. For the growing season, i.e. from July to October, carbon fixation in 2004 is higher than 2003, and it may be due to the effect of the combined impact of high temperature and drought.

The NEE, RE, and GEE of 2003 and 2004 for plantation ecosystem in Qian Yanzhou show obvious seasonal variability, i.e. lower in winter and drought condition, higher in summer. Light is the main controlling factor for NEE over plantation, and both temperature and VPD influence NEE with stronger impact of VPD. Under the condition with proper light, drought could decrease the temperature range for carbon absorbing over plantation, while temperature and precipitation jointly dominate the RE.

The NEE, RE, and GEE for planted coniferous in Qianyanzhou are –387.2 g C · m^{-2} a^{-1}, 1223.3 g C · m^{-2} a^{-1}, –1610.4 g C · m^{-2} a^{-1} in 2003 and –423.8 g C · m^{-2} a^{-1}, 1442.0 g C · m^{-2} a^{-1}, –1865.8 g C · m^{-2} a^{-1} in 2004, respectively; meanwhile, the soil respiration accounts for 42.5% and 58.9% of the ecosystem respiration for these two years, which suggests the intensive carbon absorbing ability of planted coniferous in Qianyanzhou.

Acknowledgements This work was supported by the Chinese Academy of Sciences (Grant No. KZ-CX1-SW-01-01A2, KZ-CX-SW-01-01B-02) and the Ministry of Science and Technology of China (Grant No.2002CB412501), and Institute Geography Science Natural Resource Research, CAS, the Knowledge Innovation Engineering Backbone Science Plan (CX10G-E01-03-05), respectively. We also appreciate the technical assistance provided by Campbell Scientific Inc, USA, and its representative, the Tempo company in China.

References

1 Global Carbon Project. Science Framework and Implementation. Earth System Science Partnership (IGBP, IHDP, WCRP, DIVERSITAS) Report No.1: Global Carbon Project Report No. 1 Canberra, 2003, 22—23
2 Goulden M L, Wofsy S C, Harden J W, et al. Sensitivity of boreal forest carbon balance to soil thaw. Science, 1998, 279: 214—217
3 Twine T E, Kustas W P, Norman J M, et al. Correcting eddy-covariance flux underestimates over a grassland. Agricultural and Forest Meteorology, 2000, 103: 279—300
4 Fang C, Moncrieff J B. The dependence of soil CO_2 efflux on temperature. Soil Biology & Biochemistry, 2001, 33: 155—165
5 Zhang P C, Shao G F, Zhao G, et al. China's forest policy for the 21st century. Science, 2000, 288: 2135—2136
6 Fang J Y, Chen A P, Peng C, et al. Changes in forest biomass carbon storage in China between 1949 and 1998. Science, 2001, 292: 2320—2322
7 Valentini R, De Angells P, Matteucci G, et al. Seasonal net carbon dioxide exchange of a beech forest with the atmosphere. Global Change Biology, 1996, 2: 199—207
8 Massman W J, Lee X. Eddy Covariance Flux corrections and uncertainties in long term studies of carbon and energy exchanges. Agricultural and Forest Meteorology, 2002, 113: 121—144
9 Baldocchi D D, Falge E, Gu L, et al. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bulletin of the American Meteorological Society, 2001, 82: 2415—2434
10 Baldocchi D D. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future. Global Change Biology, 2003, 9: 479—492
11 Cao M K, Yu G R, Liu J Y, et al. Multi-scale observation and cross-scale mechanistic modeling on terrestrial ecosystem carbon cycle. Sci China Ser. D-Earth Sci, 2005, 48 (Supp I): 17—32
12 Greco S, Baldocchi D D. Seasonal variations of CO_2 and water

vapour exchange rates over a temperate deciduous forest. Global Change Biology, 1996, 2: 183−197

13 Law B E, Falge E, Gu L, et al. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agricultural and Forest Meteorology, 2002, 113: 97−120

14 Liu Y F, Song X, Sun X M, et al. Seasonal variation of CO_2 flux and its environmental factors in evergreen coniferous plantation. Sci China Ser D-Earth Sci, 2005, 48 (Supp I): 123−132

15 Wen X F, Yu G R, Sun X M, et al. Soil moisture effects on the temperature dependence of ecosystem respiration in a subtropical pinus plantation of southeastern China. Agricultural and Forest Meteorology, 2006a (in press)

16 Wilczak J M, Oncley S P, Stage S A. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorology, 2001, 99: 127−150

17 Webb E K, Pearman G L, Leuning R. Correction of flux measurements foe density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society, 1980, 106: 85−100

18 Wen X F, Yu G R, Sun X M, et al. Turbulence flux measurement above the overstory of a subtropical Pinus plantation over the hilly region in southeastern China. Sci China Ser D-Earth Sci, 2005, 48(Supp. I): 63−73

19 Michaelis L, Menten M L. Die Kinetik der Invertinwirkung. Biochem Z, 1913, 49: 333

20 Lloyd J, Taylor J A. On the temperature dependence of soil respiration. Functional Ecology, 1994, 8: 315−323

21 Yu G R, Wen X F, Sun X M, et al. Seasonal patterns of environmental control of ecosystem respiration in subtropical and temperate forests in China. Sci China Ser D-Earth Sci, 2005, 48(Supp I): 93−105

22 Carrara1 A, Janssens I A, Yuste J C, et al. Seasonal changes in photosynthesis, respiration and NEE of a mixed temperate forest. Agricultural and Forest Meteorology, 2004, 126: 15−31

23 Farquhar G D, Sharkey T D. Stomatal conductance and photosynthesis. Annual Review of Plant Physiology, 1982, 33: 317−345

24 Valentini R, Matteucci G, Dolman A J, et al. Respiration as the main determinant of carbon balance in European forests. Nature, 2000, 404: 861−865

25 Giardina C P, Ryan M G. Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. Nature, 2000, 404: 858−861

26 Grace J, Rayment M. Respiration in the balance. Nature, 2000, 404: 819−820

27 Goulden M L, Munger J W, Fan S M, et al. Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. Science, 1996, 271: 1576−1578

28 Law B E, Kelliher F M, Baldocchi D D, et al. Carbon storage and fluxes in ponderosa pine forests at different developmental stages. Global Change Biology, 2001, 6: 613−630