

Underestimated effects of low temperature during early growing season on carbon sequestration of a subtropical coniferous plantation

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Abstract. The impact of air temperature in early growing season on the carbon sequestration of a subtropical coniferous plantation was discussed through analyzing the eddy flux observations at Qianyanzhou (QYZ) site in southern China from 2003 to 2008. This site experienced two cold early growing seasons (with temperature anomalies of 2–5 °C) in 2005 and 2008, and a severe summer drought in 2003.

Results indicated that the low air temperature from January to March was the major factor controlling the inter-annual variations in net carbon uptake at this site, rather than the previously thought summer drought. The accumulative air temperature from January to February showed high correlation ($R^2 = 0.970$, $p < 0.001$) with the annual net ecosystem production (NEP). This was due to the controls of early-month temperature on the plant phenology developing and the growing season length at this subtropical site. The cold spring greatly shortened the growing season length and therefore reduced the carbon uptake period. The eddy flux observations showed a carbon loss of 4.04 g C m^{-2} per growing-season day at this coniferous forest site. On the other hand, the summer drought also reduced the net carbon uptake strength because the photosynthesis was more sensitive to water deficit stress than the ecosystem respiration. However, the impact of summer drought occurred within a relatively shorter period and the carbon sequestration went back to the normal level once the drought was relieved.

1 Introduction

The influences of air temperature (T_a) upon ecosystem carbon uptake vary widely with biomes and climate regimes (Baldocchi et al., 2005; Falge et al., 2002). Air temperature has been widely regarded as one of the major environmental factors controlling CO_2 exchanges of boreal and temperate forests (Chen et al., 2009; Powell et al., 2006; Yuan et al., 2008). In temperate and boreal regions, warmer temperature in early spring is often associated with high level of net ecosystem production (NEP) (Teklemariam et al., 2009). The NEP and the length of carbon uptake period are found linearly correlated over 28 US and European flux sites (Churkina et al., 2005). Seasonal NEP patterns of the eastern Asian temperate forests are sensitive to high spring T_a and summer solar radiation, while the net carbon sequestered by tropical seasonal forest is under the control of dry season length (Saigusa et al., 2008). However, water availability also plays a major role in regulating the inter-annual and intra-annual variabilities of net carbon uptake in the boreal and temperate forests. Spring T_a together with late summer water availability is reported to regulate the inter-annual variability in carbon balance of Canada Douglas-fir stands (Krishnan et al., 2009). At this boreal site, the increase in spring T_a has positive effects on annual gross ecosystem production (GEP) and ecosystem respiration (RE), but causes slight decrease in annual NEP flux due to further stress of soil water availability.

Different from boreal and temperate plants, most native subtropical ones are thermophilic, and fail to be or become chill tolerant (Allen et al., 2001; Ross et al., 2009). Chilling



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temperature can disturb or even disrupt major photosynthesis components, including the carbon reduction cycle and the control of stomatal conductance (Allen, 2001). Therefore, ecosystem photosynthesis is inevitably exposed to the damping effect of chilling. In tropical and subtropical regions, the influences of cold temperature are more discussed in screening cultivar species (Ismail et al., 2002), refrigeratedly storing crop product (Collins et al., 1995), alleviating agronomic chilling injury (Alia-Tejacal et al., 2007) and exploring eczonal acclimation to warming (Ross et al., 2009). However, the possible disturbances of chill to subtropical forest ecosystem have been rarely reported probably because of the low frequency of subtropical chill.

The possible influences of low temperatures on natural subtropical ecosystem are often underestimated, partly because of the low frequency of chilling incursion events in subtropics. Instead, the water availability was thought as the major factor influencing the carbon sequestration for most subtropical ecosystems and has been extensively discussed (Christopher et al., 2010; Migliavacca et al., 2009; Wen et al., 2010; Yu et al., 2008). Southern China, dominated by subtropical eastern-Asian monsoon, is sometimes exposed to cold surge in late winter and early spring (Lu et al., 2010). The responses of subtropical coniferous plantation CO_2 exchanges to low temperature may be quite different from those of other biomes, and the effects of low temperature on carbon sequestration during early growing season are still open to discussions.

The objective of this study was to investigate how low temperatures during early growing season influence the carbon sequestration strength of a subtropical coniferous plantation in southern China. The responses of ecosystem photosynthesis and respiration to cold early growing season were examined using the eddy covariance observations from 2003 to 2008 at Qianyanzhou (QYZ) site located in southern China. This site experienced unusual cold early growing season in year 2005 and 2008. To evaluate the impacts of cold early growing season and summer drought on carbon sequestration, the responses of net ecosystem CO_2 exchanges to temperature and precipitation anomalies were also discussed. In addition, the remotely sensed vegetation index was used to explore the possible dependency of plant developing on early growing-season temperature and its relation with carbon sequestration capability.

2 Data and methodology

2.1 Site description

Qianyanzhou site ($26^\circ44'29''$ N, $115^\circ03'29''$ E) locates in Jiangxi Province of southern China, a typical red soil hilly region, with a subtropical monsoon climate. The prevailing wind direction of this climate regime is respectively north-northwest in winter and south-southeast in summer. The

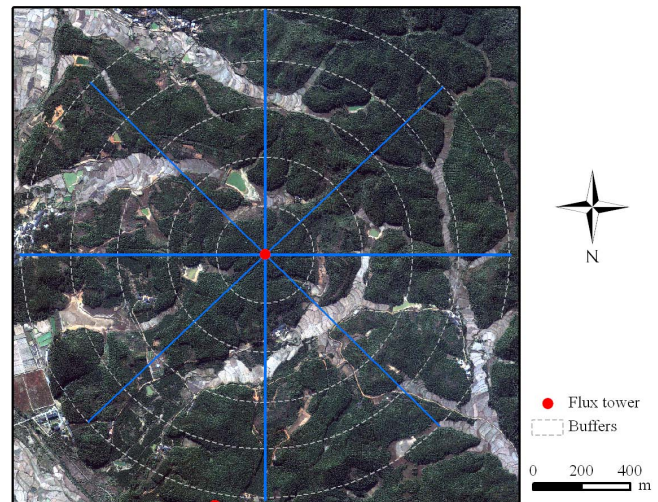


Fig. 1. The IKONOS image (Nov. 7, 2003) around the QYZ flux tower (red point). The interval between buffer circles is 200 m.

coniferous trees were planted around 1985 on gently undulating terrain (Fig. 1). The dominated species are Slash pine (*Pinus elliottii*), Masson pine (*Pinus massoniana*) and Chinese fir (*Cunninghamia lanceolata*), with a tree density of about $1460 \text{ stems ha}^{-1}$ and total biomass of 106 t ha^{-1} . The maximum leaf area index (LAI) is around 5.6 and the mean canopy height is about 13 m. The mean tree height, diameter at breast height and density for Slash pine are about 12.0 m, 15.8 cm and $809 \text{ stems ha}^{-1}$ respectively, for Masson pine are about 9.5 m, 13.1 cm and $444 \text{ stems ha}^{-1}$ respectively, and for Chinese fir are about 10.9 m, 13.2 cm and $210 \text{ stems ha}^{-1}$ respectively. This evergreen needle-leaf plantation shows physiological seasonality, with obvious reviving stage occurring at the rise of spring air temperature. The red soil is weathered from red sand rock, and soil texture is divided into 2.0–0.05 mm (17%), 0.05–0.002 mm (68%) and $< 0.002 \text{ mm}$ (15%). Further details of QYZ site can be referred to Wen et al. (2006).

According to local climate records of 1989–2008, annual T_a of QYZ site varies between 17.35 and 18.94°C (standard deviation (SD) 0.37°C), and annual accumulative air temperature ($> 5^\circ\text{C}$, T_{AC}) fluctuates slightly between 4592 and 5152°C (SD 126°C). In February, daily T_a rises gradually from year valley (averagely 4.66°C) to above 10°C . During this period when local ecosystem was sensitive to air temperature, T_{AC} shows great variation between 41.7 and 217.3°C (SD 64.3°C). Annual precipitation (PPT) varies between 945 and 2144 mm (SD 12 mm), with 24%, 41%, 23% and 12% of the total precipitation occurs in four quarters in turn. The rainfall scarcity and high temperature in late summer often result in seasonal drought at QYZ site (Wen et al., 2010).

2.2 Observation and instrumentation

The eddy flux observation system was established at QYZ site in late 2002. The above-canopy flux was observed at a height of 39.6 m with instruments loaded on a ventilated tower. Wind velocity was detected by a 3-D sonic anemometer (Model CSAT3, Campbell Scientific Inc., USA (Campbell for short)), and concentrations of CO₂ and water vapor were measured using an LI7500 open-path CO₂/H₂O analyzer (Model LI-7500, Licor Inc., USA). All raw data were sampled at 10 Hz by a CR5000 datalogger (Model CR5000, Campbell).

Air temperature and relative humidity sensors (Model HMP45C, Campbell) were mounted in ventilated shield 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), while soil water contents were recorded with three TDR probes (Model CS615-L, Campbell) at depths of 5, 20 and 50 cm. Radiation measurements were made using a four-component net radiometer (Model CNR-1, Kipp & Zonen, The Netherlands), a pyranometer (Model CM11, Kipp & Zonen) and a quantum sensor of photosynthetically active radiation (Model LI190SB, Licor Inc.). Rainfall was monitored with a rain gauge (Model 52203, RM Young Inc., USA). Meteorological variables were sampled at 1 Hz with 30 min averages calculated by three CR10X dataloggers (Model CR10XTD, Campbell) and a CR23X datalogger (Model CR23XTD, Campbell) with a 25-channel solid-state multiplexer (Model AM25T, Campbell).

As showed in Fig. 1, over 96 % of the 200 m adjacent region around QYZ flux tower was dominated by forest, while the fraction of forest cover within the 1000 m neighboring region was a little lower (83 %). The rest landscapes other than coniferous tree were largely orange orchard and cultivated field in the valley areas. Under the moderate wind environment of QYZ site (0–4 m s⁻¹), the cover of dense tree around the flux tower accounted for main fraction of the source area of QYZ eddy covariance system. The contribution of non-forest covers to the whole CO₂ footprint was estimated below 5 %.

2.3 Flux correction and gap filling

The carbon dioxide exchange (mg CO₂ m⁻² s⁻¹) between the biosphere and the atmosphere was calculated,

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

where the first term on right-hand side is the eddy flux for carbon dioxide and the second is the storage below the height of observation (z_r). All advective terms in the mass conservation equation are ignored.

The methods of flux calculation and correction for carbon dioxide and water vapor in Wen et al. (2010) were adopted

in this study. A brief description of the methodology was given below. Spurious data were removed from the dataset if the instrument performance and experimental conditions were abnormal. Averagely, about 50–60 % of the half-hourly NEP dataset was excluded. The instrument characteristics and the quality and reliability of flux measurements were examined by power- and co-spectra. Firstly, half-hour fluxes were calculated from the 10 Hz raw data. For flux correction, planar fit rotation was applied to the wind components to remove the effects of instrument tilt or irregularity on the airflow at monthly intervals (Wilczak et al., 2001). The instrument effects that damped the high-frequency fluctuations were corrected (Aubinet et al., 1999), and adjustment was also made for the effect of air density fluctuations on CO₂ and water vapor fluxes (Webb et al., 1980). The CO₂ storage effect below the observation height was corrected with the temporal change in CO₂ concentration above the canopy measured by an LI7500 open-path CO₂/H₂O analyzer (Yu et al., 2008). To avoid possible underestimation of the fluxes under stable conditions during night, these observed NEP values during night (solar elevation angle < 0°) were excluded when the value of friction velocity (u_*) was less than 0.19 m s⁻¹, which was the maximum u_* threshold among 2003–2008 at QYZ site. Further measures of spike detecting and weak turbulence elimination followed the processes of Wen et al. (2006).

The widely-used nonlinear regressions method (Moffat et al., 2007; Richardson et al., 2007) was utilized to fill long data gaps (> 2 h). With the quality control measures at half-hourly interval, there were about 28–35 % and 80–90 % missing data in daytime and nighttime observations, respectively. The missing daytime NEP values were estimated using the Michaelis-Menten equation within a 10-day window,

$$\text{NEP} = \frac{\alpha N_{\text{es}} Q_p}{N_{\text{es}} + \alpha Q_p} - \text{RE}_{\text{day}} \quad (2)$$

where α is ecosystem apparent quantum yield (mg CO₂ μmol⁻¹), Q_p is photosynthetic photon flux density (μmol m⁻² s⁻¹), N_{es} is the asymptotic gross ecosystem photosynthesis (mg CO₂ m⁻² s⁻¹) at saturating light, and RE_{day} is the average daytime RE (mg CO₂ m⁻² s⁻¹). Because the measurements of photosynthetic photon flux density at QYZ site were subject to temporal attenuation effect, the observed direct solar radiation was used instead to examine the inter-annual variation in radiation rather than photosynthetically active radiation (PAR). However, within a 10-day window, this systematic attenuation would not weaken the gap-filling of Eq. (2).

For the nighttime, NEP was defined as ecosystem respiration (RE_{night} , mg CO₂ m⁻² s⁻¹). The missing RE_{night} was estimated using the relationship of RE with soil temperature and soil water content within a yearly window (Reichstein et al., 2002; Wen et al., 2010),

$$\text{RE}_{\text{night}} = \text{RE}_{\text{ref}} (b_1 + b_2 S_W)^{\frac{T_{\text{soil}} - T_{\text{ref}}}{10}} \quad (3)$$

where R_{ref} , b_1 and b_2 are fitted parameters, R_{ref} is the RE rate ($\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) at reference temperature T_{ref} (set as 15°C here), S_w and T_{soil} are the soil water content ($\text{m}^3 \text{ m}^{-3}$) and soil temperature, respectively. To estimate 24 h NEP value, the daytime ecosystem respiration (RE_{day}) was estimated by extrapolating the nighttime relationship function of ecosystem respiration (RE_{night}) with soil temperature and soil water content.

2.4 Vegetation index

The temporal series of Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index (EVI) was utilized in this study to examine the growth of above-ground plantation. As temporal curve of remotely sensed vegetation index can reflect the seasonal and annual variations in above-ground biomass, the effects of water/heat anomalies on ecosystem is likely to be indicated by the vegetation index time series (Churkina et al., 2005). Compared with the widely used Normalized Difference Vegetation Index (NDVI), EVI is more resistant to soil background, less susceptible to atmospheric disturbance and less sensitive to vegetation saturation (Huete et al., 2002). The 16-day MODIS EVI used in the study was available at a spatial resolution of 500 m, and can be acquired from NASA Gateway (NASA, 2009). The quality layer of the MODIS VI product records the reliability of each EVI pixel, ranging from level 1 (the best) to level 13 (the worst) (LPDAAC, 2010).

The temporal series of EVI from 2003 to 2008 were extracted within a region of 10 km by 10 km centered on the flux tower. This region was similar as QYZ site in the terms of forest cover fraction and forest composition. The MODIS land cover (MCD12Q1) product was used to identify the forest pixels. To reduce the impact of cloud contamination and topography, only the pixels with quality above level 3 and with altitude below 400 m were chosen. The EVI averages respectively during the whole year and the early growing season (from January to March) were calculated to examine the response of canopy density to the temperature and moisture anomalies.

2.5 Data analysis

The daily deviations of environmental factors and fluxes from corresponding normal levels were summed over days to indicate the accumulative temporal variations. Specially, the accumulative deviation to normal levels of daily T_a (T_{AD}) was also calculated for critical phenological phases to detect possible heat anomalies. The linear relationships between carbon fluxes and T_a at 10-day scale during January through March were calculated to evaluate the sensitivity of carbon fluxes to temperature.

Four T_a related indices were chosen to detect possible temperature anomalies in late winter and early spring, i.e., the T_{AC} during January through February ($T_{\text{AC}-12}$) and during

January through March ($T_{\text{AC}-13}$), the growing season length (GSL) during January through February (GSL_{12}) and during whole year (GSL_{Yr}). GSL in the study was defined as the number of days during certain period with daily T_a above 5°C . The linear and quadratic relationships between annual and the first half year carbon fluxes and above four indices were estimated to examine the sensitivity of this ecosystem to low temperature.

The relationships between CO_2 fluxes and air temperature were examined at 10-day, monthly and annual scales. The correlation of EVI with growing season length and carbon fluxes was also utilized to see how plant growth responded to the climate variations and its relationship with carbon sequestration activity.

3 Results

3.1 Seasonal and inter-annual variation of environmental factors

The air temperature and precipitation at QYZ site showed strong seasonal and inter-annual variations (Fig. 2), which were controlled by the eastern Asian subtropical monsoon. The trends of temperature and soil water content generally followed those of solar radiation and precipitation, respectively. Both the years of 2005 and 2008 experienced cold early springs, which were shown in very low T_a from January to February (Fig. 2b). One ice storm in early 2008 caused T_a about 5°C below normal level during January 10 through February 20. However, less than 5 % of QYZ trees were damaged by the ice storm and the influences on trees were partially compensated by the rapid understory growth because of the improved radiation condition of forest gaps. The daily T_a anomaly in early 2005 ($\sim -2^\circ\text{C}$) was smaller than that in early 2008 ($\sim -5^\circ\text{C}$), but the period of low T_a in 2005 (~ 60 days) persisted 20 days longer than that in 2008 (~ 40 days). In the both years, the growing season length reduced by about 20 days. From January to March, T_a ($P = 0.001$), T_{AC} ($P = 0.025$) and GSL_{13} ($P = 0.008$) were significantly below normal levels, but in the rest months did not markedly deviate from normal (Table 1).

The cold early growing season in 2005 corresponded with low level of solar radiation, but the case in 2008 was somewhat different (Table 1). The level of R_s was far below normal during January 10 through February 20 in 2008, but in the rest period of January through March the R_s level did not significantly deviate (Fig. 2a). In early months of year 2006, the level of R_s was also below normal level, but the deviation was not in the continuous manner as that of 2005 (Fig. 2a). About 40 % variation of spring air temperature could be explained by solar radiation at 10-day scale during 2003–2008, and only 18.4 % variation of annual air temperature was associated with solar radiation. Low solar radiation is not always correspondent with low temperatures. Though air temperature and solar radiation showed similar seasonalities in

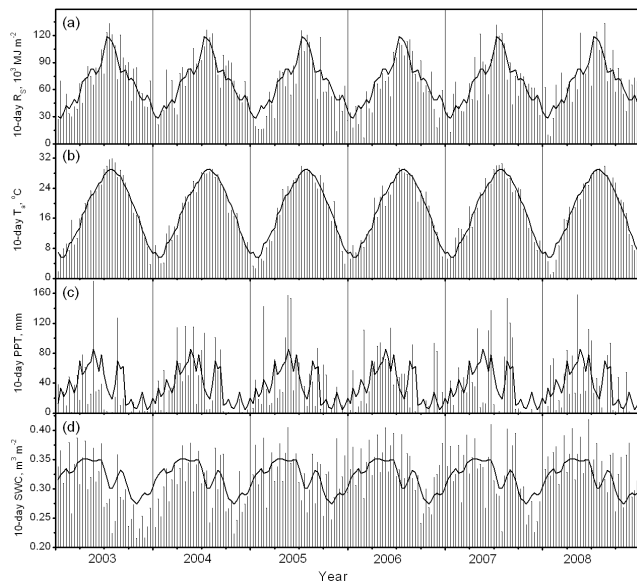


Fig. 2. The 10-day environmental conditions of QYZ site from 2003 to 2008: **(a)** downward solar radiation (R_s , $\times 10^3 \text{ MJ m}^{-2}$), **(b)** air temperature (T_a , $^\circ\text{C}$), **(c)** precipitation (PPT, mm) and **(d)** soil water content (SWC, $\text{m}^3 \text{ m}^{-3}$). The drop lines and curves were the 10-day measurements and corresponding multi-year averages respectively.

Fig. 2a and 2b, the anomalies of radiation were not necessarily consistent with those of temperature in terms of timing and magnitude, such as in the springs and autumns of 2005 and 2006.

In addition, the asynchronism of precipitation and air temperature, an important characteristic of eastern Asian monsoon climate, often results in summer droughts in southern China. The summer T_a of 2003 was markedly ($1\text{--}3^\circ\text{C}$) above normal, while the concurrent precipitation was about 50% ($\sim 280 \text{ mm}$) below average. The extreme water deficit with the high summer T_a resulted in the decades-unprecedented drought in 2003 (Wen et al., 2010).

3.2 Responses of plant growth to environmental variation

The changes in the EVI time series in the spring were closely related to the concurrent air temperature and effectively indicated the plant phenology (Fig. 3). The averaged EVI values during January to March in 2005 and 2008 were significantly lower than the other years ($P < 0.01$), and EVI of the two years did not reach normal level until late April (DOY 110). The cold early months in 2005 and 2008 caused phase lags in the EVI time series, which indicated the postponing of vegetation reviving stage and resulted in shorter growing season lengths. The year 2007 had an extremely warmer early growing season (averagely 1.6°C above normal during January to March), which was responded by the abnormally high EVI values before May.

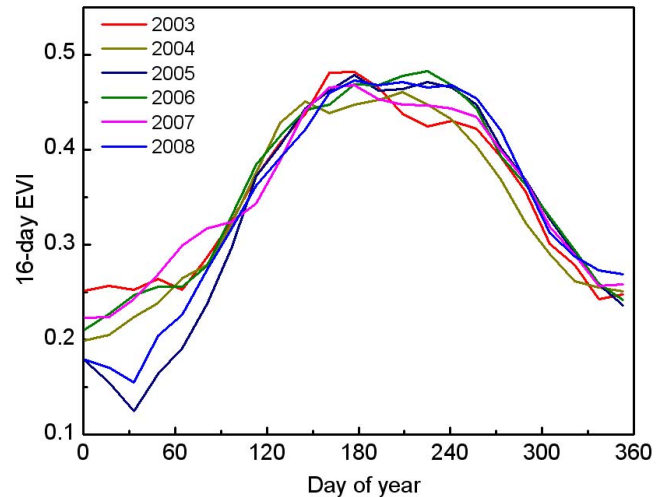


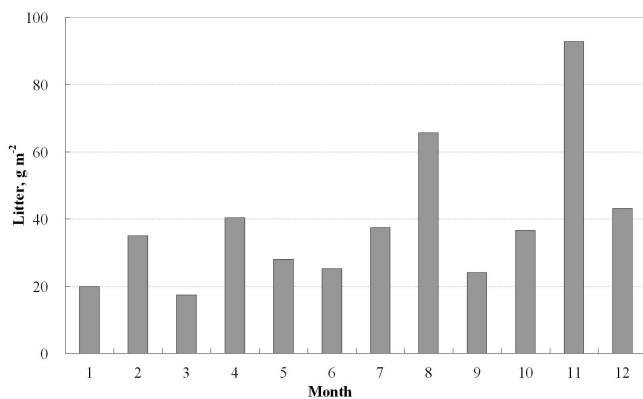
Fig. 3. Temporal curves of 16-day MODIS EVI for the coniferous plantation covered region around QYZ site. The EVI value was the average of forest pixels in this region (10 km by 10 km).

However, the response of EVI to summer droughts was relatively weaker, and the EVI drop in summer 2003 was small compared with that in spring 2005 and 2008. This may be because EVI was more like an indicator of above-ground green biomass, and the influence of water stress was difficult to observe by this greenness index if the water stress was not causing leaf drop or other severe damages to the trees. The EVI time series also disclosed strong seasonality of QYZ ecosystem. The seasonal EVI variation of this evergreen coniferous forest could be attributed to the strong seasonality-characterized monsoon climate and the possible uncertainties of MODIS product at 1-km resolution in terms of mixed pixel and cover classification (Huete et al., 2002). The seasonality of heat and water conditions may cause the seasonal variations of local ecosystem. The monthly measurements of litter during 2004–2007 confirmed this, with highest litter fall in November (as shown in Fig. 4). This fact agreed with the low EVI level in winter at QYZ site.

The early-month EVI showed high correlation with the growing season length (Fig. 5). About 80% variation in spring GSL could be explained by the averaged EVI of early months ($P = 0.017$) at QYZ site (Fig. 5a). The time of vegetation reviving and budding in spring basically indicated the starting and the length of the growing season, so the EVI of early months was also closely associated with annual GSL ($R^2 = 0.789$, $P = 0.018$) (Fig. 5b). The year 2007 had the highest spring temperature and therefore the longest growing season length, while the cold springs in 2005 and 2008 shortened the growing season length by almost 20 days comparing with the other years (Table 1). Therefore, the EVI curves were likely to reflect the variations in growing phase and even above-ground biomass in a sense (Churkina et al., 2005).

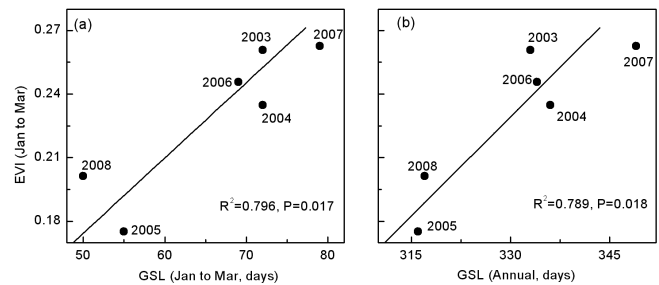
Table 1. Air temperature (T_a), accumulative T_a (T_{AC} , $\geq 5^\circ\text{C}$), growing season length (GSL, $T_a \geq 5^\circ\text{C}$, in days) and precipitation (PPT, mm) at QYZ site during 2003–2008.

Factor	Period	2003	2004	2005	2006	2007	2008
T_a	Jan–Mar	9.90	9.10	6.89	9.20	10.46	7.77
	Apr–Dec	21.30	20.76	21.27	21.02	21.02	21.20
$T_{AC} (\geq 5^\circ\text{C})$	Jan–Mar	427	415	246	423	515	373
	Apr–Dec	4501	4360	4510	4415	4402	4478
GSL ($\geq 5^\circ\text{C}$)	Jan–Mar	72	72	55	69	79	50
	Apr–Dec	261	264	261	265	270	267
R_S (MJ m^{-2})	Jan–Mar	678.4	666.8	436.0	512.5	668.8	707.3
	Apr–Dec	4022.6	3943.4	3542.4	3540.4	3650.0	3843.0
PPT (mm)	Jun–Sep	279.3	522.9	475.3	490.2	723.1	530.2
	Jan–Dec	944.9	1404.5	1455.4	1485.3	1318.7	1332.9

**Fig. 4.** The monthly measured litter of QYZ ecosystem during 2004–2007.

3.3 Seasonal and inter-annual variations of CO_2 flux

Figure 6 showed the time series of daily GEP, RE and NEP fluxes from 2003 to 2008. For the purpose of comparison, the differences between daily CO_2 fluxes and corresponding averages during 2003–2008 were accumulated for each year (i.e., the accumulative daily flux deviation) and showed as Fig. 6d–f. The daily fluxes showed strong seasonal and inter-annual variabilities due to water and heat anomalies. Daily GEP and RE fluxes increased gradually from 1.8 and $1.6 \text{ g C m}^{-2} \text{ day}^{-1}$ respectively in January, reached the maximums (respectively 7.6 and $5.9 \text{ g C m}^{-2} \text{ day}^{-1}$) in July, and then gradually decreased till December. The cold early springs in 2005 and 2008 resulted in low levels of GEP fluxes in the first half year, while the summer drought in 2003 caused an abrupt drop in the GEP fluxes. The low photosynthetic flux in 2005 may be also partially related to low solar radiation in this year. Compared with the photosynthetic flux, the ecosystem respiration peaked later and was less sensitive to the summer drought.

**Fig. 5.** Relations of the averaged MODIS EVI from January to March with the concurrent growing season length (GSL) and the annual GSL during 2003–2008 at QYZ site.

The NEP fluxes showed stronger intra-annual variability than the GEP and RE fluxes. The two years with cold early spring had the lowest annual NEP fluxes due to the more reduced photosynthetic activity than ecosystem respiration. The favorable water and heat conditions in 2002 brought the high levels of photosynthesis and growth of this evergreen plantation, which provided beneficial carbon sequestration basis for the followed year 2003. Therefore, the GEP kept at high level during the warmer first half year of 2003, while less precipitation in the second half year of 2003 constrained the ecosystem respiration and almost counteracted the effect of warmer condition in the first half year. The exceptionally high GEP flux and relatively low RE flux in the first half year of 2003 resulted in the high carbon uptake during this period. The sharp decrease in the NEP during the summer period of 2003 was caused by the different responses of GEP and RE fluxes to drought. However, due to the relatively high carbon uptake strength during the first half year, the annual NEP in 2003 was slightly higher than the multi-year average. The water deficit also caused a reduction in the carbon uptake in 2007 but with much less magnitude.

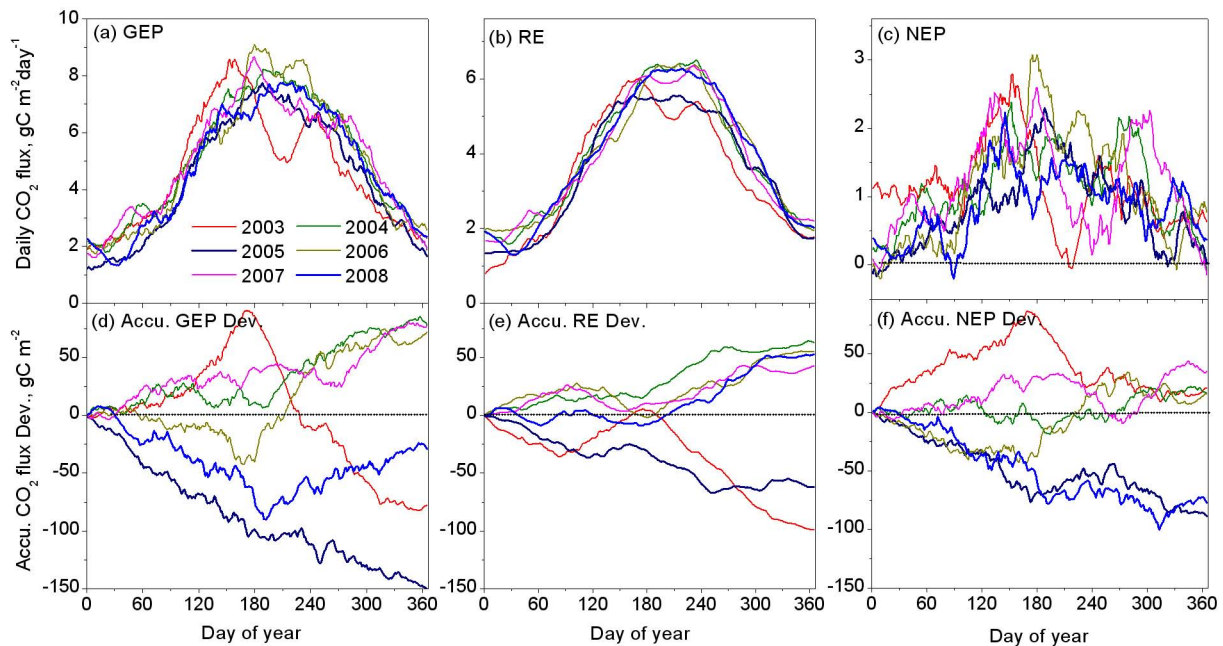


Fig. 6. The 30-day slide-averaged CO₂ fluxes (a–c) and the accumulative flux deviations (d–f) during 2003–2008. These deviation curves reflected the varying processes of CO₂ fluxes over years.

Figure 6d also showed low GEP level in the first half year of 2006, while the concurrent RE flux was basically at normal level. This was likely caused by the low solar radiation in early 2006. The low GEP level during this period caused the NEP flux negatively deviated from normal level. However, the annual net carbon uptake reached the level of normal years, due to the strong photosynthesis under the favorable environmental conditions of the second half 2006. In addition, the year 2006 did not experience the phenological lag as that caused by cold early springs in 2005 and 2008 (Fig. 3).

The annual GEP flux of QYZ site ranged from 1629 to 1856 g C m⁻² (coefficient of variance (CV) 5.4 %) during 2003–2008, while annual RE flux varied between 1286 and 1446 g C m⁻² (CV 5.1 %). Table 2 suggested that the QYZ ecosystem was a stable carbon sink during 2003–2008 at annual scale, varying between 306 and 430 g C m⁻² year⁻¹ (CV 14 %). The annual fluxes of GEP and RE hold strong linear consistency ($R^2 = 0.683$, $P = 0.043$). However, great annual GEP did not necessarily correspond to great annual NEP, and only 48.7% variation of annual NEP could be explained by annual GEP ($P = 0.123$). In addition, annual NEP showed little variation with ecosystem respiration during 2003–2008 ($R^2 = 0.030$, $P = 0.743$).

Table 2. Annual CO₂ fluxes of QYZ site during 2003–2008 (g C m⁻² yr⁻¹).

	2003	2004	2005	2006	2007	2008	mean	CV
GEP	1702	1856	1629	1851	1857	1754	1779	5.4 %
RE	1286	1446	1323	1440	1427	1437	1384	5.1 %
NEP	416	411	306	412	430	316	395	14.0 %

3.4 Responses of CO₂ fluxes to low temperature

Generally, both ecosystem photosynthesis and respiration showed close relation with air temperatures of early months at 10-day scale, while the response of net carbon uptake to temperatures was comparatively weak (Table 3). During the whole period from January to March, over 70% variation of the GEP and RE fluxes can be explained by 10-day T_a ($P < 0.001$). However, the March GEP was not so sensitive to temperature ($R^2 = 0.228$, $P = 0.045$) as that in the two previous months. The RE flux showed the gradually stronger dependency of temperature from January to March. The possible influences of radiation on CO₂ fluxes were also examined (Table 3). The 10-day fluxes of RE and NEP showed weaker associations with solar radiation than with air temperature during January to March. However, the GEP varied with solar radiation a little more than with air temperature.

At half-year and annual scale, the early growing season length and temperature showed close relationship with GEP and NEP (Table 4). The January and February T_{AC} (T_{AC-12})

Table 3. The relationships between the CO₂ fluxes and T_a /solar radiation at 10-day scale during 2003–2008.

		GEP		RE		NEP	
		R^2	P	R^2	P	R^2	P
T_a	Jan	0.151	0.111	0.201	0.062	0.649	0.000
	Feb	0.528	0.001	0.611	0.000	0.806	0.000
	Mar	0.082	0.249	0.768	0.000	0.295	0.020
	Jan–Mar	0.188	0.001	0.659	0.000	0.791	0.000
R_d	Jan	0.583	0.000	0.010	0.693	0.580	0.000
	Feb	0.452	0.002	0.261	0.030	0.493	0.001
	Mar	0.179	0.081	0.023	0.545	0.390	0.006
	Jan–Mar	0.436	0.000	0.157	0.003	0.540	0.000

was most efficient to reflect the ecological impacts of low temperature among the four heat indices, i.e., the accumulative air temperatures (of both Jan–Feb and Jan–Mar, $\geq 5^\circ\text{C}$) and the growing season lengths (of both Jan–Feb and whole year) (Table 4). Generally, the GEP and RE fluxes of the first half year varied with T_{AC} and GSL more than those of the annual fluxes varied with, while the NEP flux was in the contrary case. Annual NEP flux was more sensitive to these indices than annual GEP and RE were. As Table 4 showed, annual net carbon uptake increased with the Jan–Feb accumulative temperature (T_{AC-12}) ($R^2 = 0.970$, $P < 0.001$) more than with the Jan–Mar one (T_{AC-13}) ($R^2 = 0.736$, $P = 0.029$). This fact implied that it was possibly the T_a of January and February that has the year-long influences on carbon uptake at QYZ site. In addition, the net carbon uptake of whole year related to T_{AC-12} much more closely than that of the first half year related to T_{AC-12} ($R^2 = 0.657$, $P = 0.050$). It suggested that the influence period of cold early growing season on carbon uptake persisted beyond the early months itself. As the 6 years under discussion as concerned, the larger the T_{AC-12} (i.e., the warmer early months) was, the larger the annual net carbon uptake was. The close correlation between annual NEP and GSL_{Yr} ($R^2 = 0.870$, $P = 0.007$) suggested that the GSL decline induced by cold growing season regulated the depressions of annual NEP in both 2005 and 2008 to a large extent. Cold spring in the two years caused an about 20-day decrease in annual GSL, which corresponded with a loss of about one fourth of annual net carbon uptake ($\sim 79\text{ g C m}^{-2}$).

The CO₂ fluxes during the early months were not closely associated with the accumulative solar radiation as with the accumulative air temperature (Table 4). The NEP flux in the first half year could be explained a little more by accumulative radiation (77.2%) in January and February than by accumulative temperature (65.7%). However, this fact was not true for the accumulative variables during January to March. Only about 48% variation of annual carbon uptake could be explained by accumulative radiation in the January and February, and the carbon uptake during January to March varied even less with accumulative radiation ($R^2 = 0.123$).

Table 4. The relationships of CO₂ fluxes with accumulative air temperature, solar radiation and growing season length during 2003–2008.

		First half year			Whole year		
		GEP	RE	NEP	GEP	RE	NEP
T_{AC-12}	R^2	0.819	0.787	0.657	0.488	0.034	0.970
	P	0.013	0.018	0.050	0.123	0.726	0.000
T_{AC-13}	R^2	0.582	0.719	0.434	0.620	0.164	0.736
	P	0.078	0.033	0.155	0.063	0.426	0.029
R_{d-12}	R^2	0.745	0.305	0.772	0.030	0.095	0.477
	P	0.027	0.256	0.021	0.744	0.551	0.129
R_{d-13}	R^2	0.314	0.505	0.251	0.149	0.062	0.123
	P	0.248	0.113	0.312	0.450	0.635	0.496
GSL_{12}	R^2	0.712	0.497	0.606	0.318	0.001	0.912
	P	0.035	0.118	0.068	0.244	0.963	0.003
GSL_{yr}	R^2	0.605	0.621	0.461	0.547	0.080	0.870
	P	0.069	0.063	0.138	0.093	0.587	0.007

3.5 Association of EVI with carbon uptake

Annual net carbon uptake was closely correlated with the EVI of early growing season (from January to March, EVI_{13}) as shown in Fig. 7 ($R^2 = 0.922$, $P = 0.002$). The high correlation between annual NEP and EVI_{13} can be attributed to the high correlation between the EVI and the growing season length, as showed in Fig. 5. The early (or later) starting of growing season due to high (or low) temperatures of early months can be effectively captured by the remote sensing vegetation index, and the growing season length largely determined the length of carbon uptake period at this site. However, annual NEP flux only showed moderate association with yearly averaged EVI ($R^2 = 0.315$, $P = 0.246$). In addition, annual ecosystem photosynthesis had relatively stronger links with both early-months and annual EVI, respectively with $R^2 = 0.420$ ($P = 0.164$) and $R^2 = 0.620$ ($P = 0.063$). As heterotrophic respiration did not directly

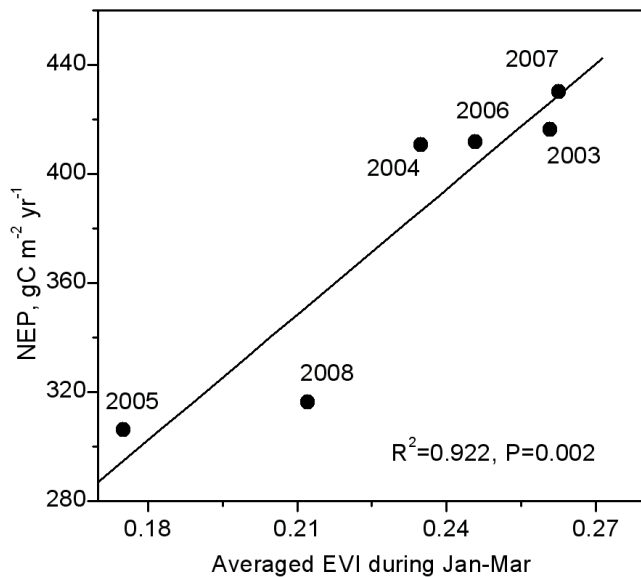


Fig. 7. Relation between the EVI of January through March and annual net ecosystem production.

depend on above-ground biomass which determined EVI, ecosystem respiration showed slight variations with early-months or annual EVI ($R^2 < 0.050$).

4 Discussion

The somewhat different carbon flux responses of subtropical ecosystem to cold early growing season may be attributed to the physiological properties of subtropical plantation. Generally, boreal and temperate plants have adapted to the stress of low temperature, while subtropical and tropical ecosystems are comparatively vulnerable to chilling injury. Most low temperature related discussions of carbon sequestration mainly focused on boreal and temperate forests (Baldocchi, 2008; Gu et al., 2009; Krishnan et al., 2009; Saigusa et al., 2008; Teklemariam et al., 2009). Annual NEP flux of an eastern Asian temperate forest held similar inter-annual variation as that of GEP flux because of early leaf expansion related to unusually warm spring (Saigusa et al., 2005).

Native subtropical plants are vulnerable to low temperature at the stage of early growing season, the period when enough heat is necessary for vegetation reviving and budding. Therefore, persisting extreme low temperature can lead to severe ecosystem disturbances or damages. The length of low temperature period in 2008 (~40 days) was only two thirds length of that in 2005 (~60 days), but the reduction of annual carbon uptake in 2008 (~79 g C m⁻² below average) was nearly at the depression level in 2005 (~89 g C m⁻² below average). As Fig. 2b showed, the early months of 2008 (~5 °C below average) was even colder than that of 2005 (~2 °C below average), the chilling weather in 2008 caused

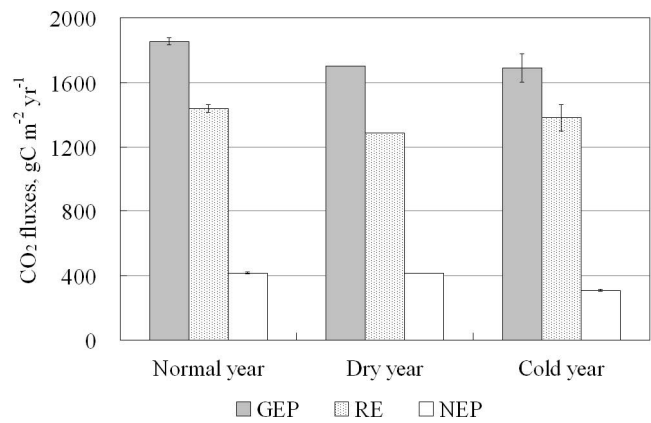


Fig. 8. Averaged annual CO₂ fluxes (g C m⁻²) of normal years (2004, 2006 and 2007), dry year (2003) and cold years (2005 and 2008) at QYZ site.

severe physiological and physical damages to local ecosystems.

The previous researches (Yu et al., 2008; Wen et al., 2010) concluded that the water availability primarily controlled the inter-annual variability of net carbon uptake. However, the Fig. 8 showed a greater impact of the cold early-months air temperature on the annual net carbon uptake strength than the summer drought. The annual NEP in the cold years (averagely 311 g C m⁻², 2005 and 2008) was significantly lower than that in normal years (averagely 417.3 g C m⁻², 2004, 2006 and 2007) and dry year (416 g C m⁻², 2003). Averagely, the depressing effects of water and heat anomalies on annual GEP showed no significant difference (respectively 153 and 162 g C m⁻²), while the annual RE in dry year deviated negatively more to normal level (151 g C m⁻²) than that in cold years (58 g C m⁻²). Therefore, cold early months caused a larger loss (107 g C m⁻²) in annual net carbon uptake at QYZ site compared with normal years, but the annual NEP of drought years was basically at the level of normal years.

The fact that the cold early months and summer drought have different influences on the net carbon uptake could be explained by the different responses of ecosystem photosynthesis and respiration. At this subtropical evergreen needle-leaf forest site, the growing season length was largely determined by the accumulative temperature of early months ($R^2 = 0.885$, $p < 0.005$), which influenced the timing of plant phenology. Cold springs usually postponed the vegetation reviving and budding, and even caused chilling injuries to tree leaves and other organs, which had the significant influence on the ecosystem photosynthesis. This could be seen from the consistently low EVI values in early months and low GEP fluxes in the first half year in 2005 and 2008. The growing season length and the carbon uptake period were therefore greatly shortened (see Fig. 9). For this subtropical site, an amount of 4.04 g C m⁻² ($R^2 = 0.912$, $P = 0.011$) in net

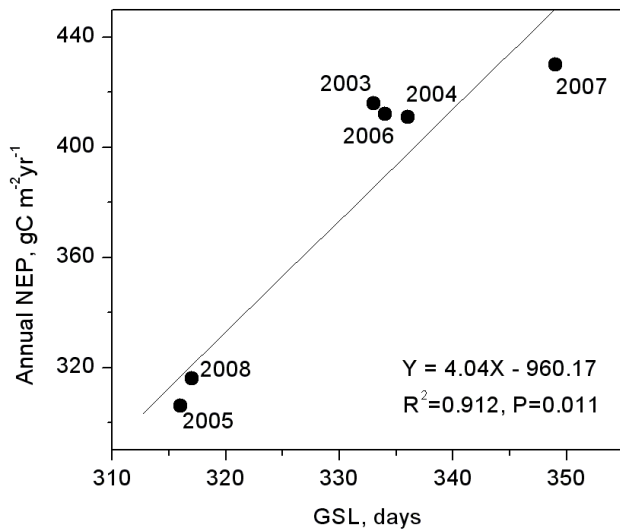


Fig. 9. Relation of annual NEP flux (gC m^{-2}) with the growing season length ($\geq 5^\circ\text{C}$, days). The line was regressed with the data of non-drought years by excluding the year 2003.

carbon uptake was gained per additional growing-season day in terms of the regression slope of annual NEP to GSL. This coniferous forest site showed a less sensitivity of net carbon uptake strength to growing season length than the temperate and boreal deciduous forests (5.57 gC m^{-2} , $R^2 = 0.686$, $N > 40$) (Baldocchi, 2008), but greater than the evergreen broadleaf forest of $3.70 \text{ gC m}^{-2} \text{ day}^{-1}$ (Leuning et al., 2005) and the evergreen needle-leaf forest of $3.40 \text{ gC m}^{-2} \text{ day}^{-1}$ (Churkina et al., 2005). On the other hand, though photosynthesis was more sensitive to drought than ecosystem respiration, the depression in net carbon uptake occurred within a relatively shorter period. The influence of summer drought on carbon uptake efficiency was generally confined within the drought period itself if the water stress was not beyond the ecosystem tolerance, and trees could quickly restore to normal assimilation level when water stress was relieved. For the year 2003, the summer drought reduced the ecosystem fluxes with a stronger depression in photosynthesis than ecosystem respiration, but only within a shorter period. Moreover, the relatively high photosynthetic flux in spring helped the annual NEP in 2003 to keep at a relatively high level.

Though a longer record would be helpful to verify that the low temperature rather than the summer drought is the major factor influencing the inter-annual variations of carbon sink strength at this subtropical conifer site, a variety of environment conditions were indeed included in the relative shorter study period to enhance the conclusion of this study. Years 2005 and 2008 have exceptionally shorter growing season due to low temperatures in early months, year 2007 has a longer growing season due to warmer spring, and year 2003 is a year suffering summer drought.

5 Conclusions

This study explored how the carbon uptake of a subtropical coniferous plantation responded to low temperatures in late winter and early spring. The annual net carbon uptake at QYZ site was highly correlated ($R^2 = 0.970$, $p < 0.001$) with the effective accumulative temperature ($> 5^\circ\text{C}$) from January to February. An amount of $\sim 85 \text{ gC m}^{-2}$, about one fourth of annual carbon sequestration of this ecosystem, was lost in two years (2005 and 2008), which experienced cold springs with daily temperature anomaly larger than 2°C from January and February.

The low temperature outweighed the summer drought in regulating the inter-annual variability of annual net carbon uptake at this subtropical site. The cold spring postponed vegetation budding and markedly reduced growing season length. The photosynthesis was greatly depressed by the cold early growing season and its effects persisted beyond the low temperature period itself. As a result, the early-month EVI could be used as an effective indicator of the plant phenology and the annual NEP ($R^2 = 0.922$, $p < 0.005$). The low air temperatures of early months in 2005 and 2008 reduced the growing season length by above 20 days and a carbon uptake loss of 4.04 gC m^{-2} per additional growing-season day was observed.

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