Effects of drought and ice rain on potential productivity of a subtropical coniferous plantation from 2003 to 2010 based on eddy covariance flux observation

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Abstract

Increasing occurrences of climate extreme events urge us to study their impacts on terrestrial carbon sequestration. Ecosystem potential productivity deficits could characterize such impacts and display the ecosystem vulnerability and resilience to the extremes in climate change, whereas few studies have analyzed the yearly dynamics of forest potential productivity deficits. Based on a perfect-deficit approach, we used in situ eddy covariance flux data and meteorological observation data at Qianyanzhou station from 2003 to 2010 to explore the relationship between potential productivity and climate extremes, such as droughts in 2003 and 2007, ice rain in 2005, and an ice storm in 2008. We found (1) the monthly canopy photosynthetic capacity (CPC) deficits could be mainly explained by air temperature (Ta) deficits ($R^2 = 0.45$, $p < 0.0001$); (2) a significant correlation was noted between seasonal CPC deficits and co-current Ta deficits ($R^2 = 0.45$, $p < 0.0001$), especially in winter ($R^2 = 0.79$, $p = 0.003$); (3) drought in summer exerted a negatively lagged effect on potential productivity ($R^2 = 0.59$, $p = 0.02$), but at a short time scale; and (4) annual CPC deficits captured the impacts of climate extremes on the forest ecosystem potential productivity, and the two largest potential productivity deficits occurred in 2003 (relative CPC deficits = 0.34) and in 2005 (relative CPC deficits = 0.35), respectively. With the perfect-deficit approach, the forest ecosystem vulnerability to extremes was analyzed in a novel way.

Keywords: climate extreme events, forest, potential productivity, drought, ice rain

1. Introduction

With China becoming the largest emitter of fossil fuel CO$_2$ in the world (1.5 Pg C yr$^{-1}$ in 2006) (Gregg et al 2008), there is a strong impetus to increase the terrestrial ecosystem carbon sink to mitigate greenhouse gas (GHG) emission in China. Forests play a significantly important role in the global carbon cycle, and it is necessary to get a clear understanding of carbon (C) sequestration of forests in the international GHG reduction negotiation (Pan et al 2011). According to the 7th National Forest Resource Inventory Report from the State Forestry Administration (www.forestry.gov.cn), forests cover ~20.36% of China. And more than 65% of the carbon sink of China is located in southern China due to climate change,
shrub recovery and large-scale afforestation programs since the 1980s (Fang et al 2001, Piao et al 2009, Wang et al 2011). Plantations are the major component of forest in southern China, occupying 54.3% of the total planted forest area and 52.6% of the stock volume of plantations in the whole of China (Sun et al 2006). In addition, the rapid increase in plantation area resulting from national afforestation programs contributes to about 10% of the terrestrial ecosystem carbon sink in China, which was estimated to mitigate 28–37% of its fuel carbon emission in the past two decades (Piao et al 2009, Xu et al 2012). The planted forests in southern China have an important effect on the pattern of the global carbon sink. Nevertheless, the planted forests can be vulnerable to ecosystem disturbance, such as deforestation, fire, extreme events, etc (Lugo 1997). Also these disturbances may turn the plantation ecosystem into a carbon source in certain years, thus the impact of disturbances on the carbon sink capacity of planted forests in southern China is of great concern.

The trend is that an increase in climatic extreme events will appear in the future (Easterling et al 2000). Also extreme climate events (e.g., heat waves, droughts, ice storms) have been observed in many areas, such as the USA, Europe and China (Zhao and Running 2010, Stone 2008, Gu et al 2012). Ciais et al (2005, Meehl and Tebaldi 2004). With observation data and the VEGAS model, the biological productivity across much of the Northern Hemisphere was found to decline by 0.9 Pg C yr$^{-1}$, or 5%, compared to the average of the past twenty years due to a rare drought occurring from 1998 to 2002 (Zeng et al 2005). A 30% reduction in gross primary productivity over Europe due to the unprecedented drought in 2003 was estimated by the ORCHIDEE biosphere model and eddy covariance flux observation, which resulted in a strong anomalous net source of carbon dioxide (0.5 Pg C yr$^{-1}$) (Ciais et al 2005). In particular, southern China has also suffered from ice storms, ice rain and drought in recent decades (Zhou et al 2011a, Pei et al 2013). The extent of damage to plantations in southern China caused by ice rain during the spring of 2008 varied among the tree species through two field transect surveys across Jiangxi province, in which slash pine suffered the most (Shao et al 2011). Ying et al (2012) found that a nonlinear relationship existed between the greenness rebound time and ice rain impact severity through enhanced vegetation index and ground visits, and 80% of the forests in southern China returned to normal status within one year after the ice rain. The spring drought occurring in southwestern China reduced regional annual gross primary productivity and net primary productivity in 2010 by 65 and 46 Tg C yr$^{-1}$, respectively (Zhang et al 2012). The sustainability of forest carbon sinks is greatly influenced by the frequency and intensity of large extreme events (Frolking et al 2009, Turner and Dale 1998) and depends on how quickly the forests recover their capacity for photosynthesis (Amiro et al 2010, Ying et al 2012).

The subtropical coniferous plantation ecosystem at Qianyanzhou Ecological Experimental Station (QYZ, 26°44′29″N, 115°03′29″E, and elevation 102 m) is located in Jiangxi Province of southern China (humid climate zone), a part of the ChinaFLUX network, which was established in late August of 2002. The mean annual air temperature is 17.9 °C, whereas the highest and lowest extreme temperatures are 39.5 °C and −5.8 °C, respectively (Wen et al 2006). During the investigated period, an extremely cold early growing season and freezing rain occurred in 2005 and 2008. Also, mean annual precipitation is 1542 mm, along with a dry period from July to August (Wang et al 2011). This coniferous forest was planted around 1985, with a tree density of about 1460 stems ha$^{-1}$ and total biomass of 106 t ha$^{-1}$. The prevailing species are slash pine (Pinus elliottii), Masson pine (Pinus massoniana) and Chinese fir (Cunninghamia lanceolata). This plantation is on gently undulating terrain with slopes between 2.8° and 13.5° (Wen et al 2006). The soil parent material consists of red sandstone and mud stone, and soils are mainly red earth, which is weathered from red sand rock (Wang et al 2004). In addition, an inconsistency of precipitation and temperature often results in a late summer drought (e.g., 2003) at QYZ station, southern China. Further details of the Qianyanzhou site are available in the literature (Wang et al 2011, Wen et al 2006, Yu et al 2008).
2.2. Flux and meteorological data

CO₂ and H₂O fluxes in this study were measured from 1 January 2003 to 31 December 2010 using the eddy covariance (EC) technique (Baldocchi et al. 1988). The above-canopy flux was observed at a height of 39.6 m by an open-path eddy covariance system located on a ventilated tower. All original data were sampled at 10 Hz by a CR5000 datalogger (Model CR5000, Campbell) and then scaled to 30 min mean fluxes. Synchronous meteorological observation data include photosynthetically active radiation (PAR), air temperature, soil temperature, soil humidity, radiation and precipitation, which were sampled at 1 Hz, from which 30 min averages were calculated.

The flux of net ecosystem CO₂ exchange (NEE, mg CO₂ m⁻² s⁻¹) or evapotranspiration (ET, gH₂O m⁻² s⁻¹) between the ecosystem and the atmosphere was calculated using equation (1), the net ecosystem productivity (NEP) was assigned as –NEE.

\[
\text{NEP} = - \left( \frac{\mu \rho \epsilon}{\delta t} + \int_0^z \frac{\delta \rho}{\delta t} \, dz \right),
\]

where the first term on right-hand side is the eddy flux for carbon dioxide or water vapor below the height of observation (z₁), and all advective terms in the mass conservation equation were ignored.

The methods of flux calculation and correction for CO₂ and water vapor in this study were consistent with those in Wen et al. (2010). To avoid possible underestimation of fluxes under stable conditions during night, these observed NEE and ET 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 in the years 2003–2010 at QYZ station. Further measures of spike detection and weak turbulence elimination followed the process of Wen et al. (2006).

Missing values of NEE and ET resulting from equipment failure were inevitable in long-term measurements. The present study utilized the prevailing nonlinear regression method (Moffat et al. 2007, Richardson and Hollinger 2007) to fill larger gaps (>2 h), while the small gaps (<2 h) were linearly interpolated. The daytime missing NEE values of large gaps were estimated by the Michaelis–Menten equation with a ten-day window:

\[
\text{NEP} = \frac{\alpha Q_\rho N_{\text{es}}}{\alpha Q_\rho + N_{\text{es}}} - \text{RE}_{\text{day}},
\]

where α is the ecosystem apparent quantum yield (mg CO₂ μmol⁻¹), Q_\rho is the photosynthetic photon flux density (μmol m⁻² s⁻¹), N_{\text{es}} is the asymptotic gross ecosystem photosynthesis (GEP; mg CO₂ m⁻² s⁻¹) at saturating light, and RE_{\text{day}} is the average value of daytime respiration (RE; mg CO₂ m⁻² s⁻¹) (Zhang et al. 2011a).

For the nighttime data, NEP was defined as the ecosystem respiration (RE_{\text{night}}; mg CO₂ m⁻² s⁻¹). The missing RE_{\text{night}} values were filled by employing a function of soil temperature and soil water content with a yearly interval (Reichstein et al. 2002, Wen et al. 2010):

\[
\text{RE}_{\text{night}} = \text{RE}_{\text{ref}}(b_1 + b_2 S_w) \frac{T_{\text{soil}} - T_{\text{ref}}}{T_{\text{ref}}},
\]

where RE_{\text{ref}}, b₁, b₂ are the fitted parameters, RE_{\text{ref}} is the RE rate (mg CO₂ m⁻² s⁻¹) at reference temperature T_{\text{ref}} (set as 15°C here), and S_w and T_{\text{soil}} stand for soil water content (m³ m⁻³) at 5 cm depth and the soil temperature (°C) at 5 cm depth, respectively. To estimate gross ecosystem photosynthesis, the daytime ecosystem respiration (RE_{\text{day}}) was estimated by extrapolating the relationship function of nighttime respiration with soil temperature and soil water content.

Additionally, the missing ET data were linearly interpolated for small gaps (<2 h). For large gaps, the missing ET values were filled by mean diurnal variation methods in combination with a look-up table (Reichstein et al. 2005).

2.3. Canopy photosynthetic capacity (CPC)

The canopy photosynthetic capacity (CPC) was defined as the daily maximum potential carbon storage capacity of an ecosystem (Yi et al. 2012). For a specified year, the daily CPC of ecosystems observed by eddy flux towers was termed as the maximum GEP derived from half-hourly CO₂ eddy covariance flux data (Gu et al. 2009). The daily observation data comprised a yearly CPC curve smoothed with the algorithm in Yi et al. (2012). This CPC curve formed an upper boundary line for the scatter plot of instantaneous canopy photosynthesis rate against time (red curve in figure 1). The area between the curve and the time axis (red area in figure 1) denoted the ecosystem’s carbon assimilation potential in an individual year (Gu et al. 2009).

2.4. Perfect CPC and deficit CPC

A perfect CPC (PCPC) curve was defined as a measure of the maximum carbon assimilation for a site given ‘perfect’ climate conditions for a specified day of the year, over the years for which data were available (Yi et al. 2012). The eddy covariance data of the present study at QYZ site ranged from 2003 to 2010 (>4 years), which was adequate to construct PCPC for a single site (Lauenroth and Sala 1992). The perfect CPC values were estimated for each day of the year as the maximum CPC recorded on that day across all the accessible years of flux data at each site. Similarly, a perfect CPC curve (black line in figure 1) which represented the maximized carbon assimilation potential could be constructed and smoothed with the same algorithm as the CPC. The CPC deficit (blue area in figure 1) which represented the maximized carbon assimilation potential could be constructed and smoothed with the same algorithm as the CPC. The CPC deficit (blue area in figure 1) was defined as the difference between the CPC and the perfect CPC on a particular day (Yi et al. 2012). Apart from CPC deficits, the air temperature (Tₐ) deficits and net radiation (Rn) deficits were analyzed with this perfect-deficit approach.

We will focus on the relationship between deficits of the ecosystem potential productivity and deficits of the climate factors (maximum Tₐ and Rn), as the perfect-deficit method is capable of identifying extreme climate events and their impacts on ecosystem productivity (Yi et al. 2012).
2.5. Water balance index

The daily precipitation data (P; mm) was observed near the flux tower simultaneously. The ratio of P to ET measured by the EC flux tower was adopted as a simple water balance index (P/ET; mm). In this analysis, a monthly water balance index (drought index) was used to illustrate the severity of summer droughts in the QYZ plantation ecosystem. Previous studies have shown that the QYZ plantation ecosystem suffered frequent summer drought caused by an inconsistent distribution of precipitation and temperature, generally with net water gains during the preseason (June) and net water losses during midseason (July) and postseason (August) (Wen et al. 2010). Therefore, we will put an emphasis on the impacts of drought on CPC deficits in summer, which was indicated by this simple water balance index (P/ET) used in summer.

3. Results and discussion

We found the CPC deficits of a subtropical coniferous plantation ecosystem at QYZ station were significant in relation to air temperature deficits (Ta deficits) rather than deficits of Rn. Figure 1 demonstrated that the distribution of CPC deficits (blue area) differed from one year to another and large CPC deficits existed in 2003 (drought year), 2005 and 2008 (both ice rain years), except for 2007 (moderate drought year). Meanwhile, the fact that no obvious fluctuations of summer CPC deficits were observed from 2006 to 2008 (blue line in figure 4(a)) also supported that conclusion. This might be explained by the fact that less rain in association with fewer clouds increased the available light duration and led to an increase of GEP (Wen et al. 2010). Figure 2 showed the relative monthly CPC deficits almost consistently varied with the relative monthly Ta deficits. To a large extent, the relative CPC deficits increased with relative Ta deficits. Figure 3(b) showed that the relative CPC deficits were mostly negatively associated with relative Ta deficits in July ($R^2 = 0.65, p = 0.009$). In contrast, figure 3(c) showed that the relative CPC deficits were positively associated with relative Ta deficits in February (especially for 2005 and 2008). This was partly because of the lack of water in July, whereas the extremely low air temperature (large Ta deficits) dominated the CPC
deficits in February. The precipitation anomalies of July 2003 and July 2007 were −0.9611 and −0.9635, respectively, which were the two lowest precipitations in July among the 8 years. But the relative CPC deficits in July were not sensitive to the corresponding precipitation ($R^2 = 0.12, p = 0.2$) and water balance index ($p = 0.27$). Meanwhile, subtropical ecosystems became more vulnerable to low temperature and freezing, whereas boreal and temperate plants adapted to the low temperature (Gu et al 2008, Teklemariam et al 2009, Zhang et al 2011b). As illustrated in figures 1(c), (f), 2(c) and (f), the largest relative Ta deficits (>0.65) and relative CPC deficits (>0.6) happened in February of 2005 and 2008. These reflected the moderate freezing (−2°C below average) in the winter of 2005 and the extreme freezing (−5°C below average) in the winter of 2008 caused by ice storms in southern China (Shao et al 2011, Zhou et al 2011a). Figure 3(a) showed that about 45% of the variation in relative monthly CPC deficits could be explained by relative monthly Ta deficits. This fact verified that the determiner of relative CPC deficits was air temperature at the monthly time scale all year round. The more air temperature deficits there were, the more CPC deficits we found at the monthly time scale.

Moreover, large CPC deficits were noted during the summer in 2003, which identified that extreme drought inhibited the forest ecosystem potential productivity. Figure 3(d) demonstrated that the drought in July influenced the CPC deficits in August significantly, which might be ascribed to a time-lag effect of drought. However, no significant relationships were found between relative monthly CPC deficits and the simultaneous water balance index during summer. Generally, precipitation at QYZ site decreased in July followed, to some extent, by an increment in August, while Ta reached the highest value in July (Wen et al 2010). Previous studies that a lagged response of plant growth to drought was observed in humid forests highlighted the point in figure 3(d) (Breda et al 2006, Vicente-Serrano et al 2013). Table 1 showed that the lagged effect of summer drought on CPC deficits only existed between drought stress in July and CPC deficits in August, which further confirmed the potential productivity response lag to drought was around one month. The summer could be divided into three parts: June (preseason), July (midseason) and August (postseason). Generally, precipitation at QYZ site decreased in July followed, to some extent, by an increment in August, while Ta reached the highest value in July (Wen et al 2010).
Table 1. The relationship between relative CPC deficits in a specific month and P/ET in previous months. In general, summer droughts lasted from June to August, and we will focus only on the monthly CPC deficits in those three months.

| P/ET         | June       | July   | August  |
|--------------|------------|--------|---------|
| Previous one month | $R^2 = 0.39$, $p = 0.057$ | $R^2 = 0.233$, $p = 0.020$ | $R^2 = 0.59$, $p = 0.020$ |
| Previous two months | $R^2 = 0.01$, $p = 0.374$ | $R^2 = 0.606$, $p = 0.14$ | $R^2 = 0.704$, $p = 0.003$ |
| Previous three months | $R^2 = 0.16$, $p = 0.937$ | $R^2 = 0.421$, $p = 0.16$ | $R^2 = 0.827$, $p = 0.003$ |

Meanwhile, the soil water contents at different depths showed obviously declining trends during the midseason or postseason. The water balance index (P/ET) usually reached a minimum in July. That was in agreement with the lagged effect of drought shown in table 1. Despite the significantly negative influence of air temperature deficits on CPC deficits in summer, the trend of both two lines came back to positive correlation in latter months.

In addition, relative seasonal CPC deficits were found to some extent to be determined by relative seasonal Ta deficits ($R^2 = 0.45$, $p < 0.00001$). The variation trend of winter was sharper than the other three seasons in terms of relative CPC deficits from 2003 to 2010 (figure 4(a)). Also, figure 4(b) confirmed that the CPC deficits in winter were the largest among the four seasons (mean = 0.38), so was the variation magnitude (SD = 0.064). The trend of mean relative seasonal CPC deficits totally followed that of the mean relative seasonal Ta deficits. Specifically, figure 5(b) demonstrated that most of the variation of relative CPC in winter could be explained by the air temperature deficits ($R^2 = 0.79$, $p = 0.003$). Also the significant correlation existing between CPC deficits and Ta deficits further confirmed that CPC deficits in winter were the most vulnerable to extreme low temperature and freezing (large Ta deficits). We found that CPC deficits in winter (black line in figure 4(a)) were almost largest among the four seasons in each year, especially in 2005 and 2008. Long-term extreme ice rain lasting for about 60 days in early 2005 made the daily Ta anomaly drop to $-2^\circ$C at QYZ site (Zhang et al 2011b). Also southern and central China (including the QYZ site) suffered heavily from the 2008 Great Chinese Ice Storm from 10 January to 6 February in 2008 (Zhou et al 2011b). Both of these two extreme climate events were reflected as two sharp increases of winter CPC deficits (black line, figure 4(a)). Additionally, figure 5(a) showed that
Figure 4. Seasonal dynamics of: (a) relative CPC deficits at QYZ station from 2003 to 2010; (b) mean relative CPC and Ta deficits. Error bars denote the standard deviation of deficits in each season. The subtropical coniferous forest ecosystem at Qianyanzhou station was divided into four seasons: spring (March, April and May); summer (June, July and August); autumn (September, October and November); winter (December, January and February) in regard to episodic summer drought attributable to the Asian monsoon climate.

Figure 5. Relationship between relative seasonal CPC deficits and relative seasonal Ta deficits. (a) Relative deficits of all the 4 seasons; (b) relative deficits of winter.
a 45% variation of relative seasonal CPC deficits could be explained by relative seasonal Ta deficits. Evidence showed the vegetation of humid biomes mostly responded at short drought time scales and recovered to its previous state in a short period, which was ascribed to the mechanisms affecting the resistance and resilience of vegetation to drought stress (Vicente-Serrano et al 2013). This fact implied it was possible that the constraint of the episodic summer drought on CPC deficits at QYZ site was restricted within summer itself due to rapid recovery of the forest ecosystem from the short time scale droughts. The positive correlation between CPC deficits in September and Ta deficits in September also verified that ($R^2 = 0.41$, $p = 0.041$).

Figure 6 showed that the annual CPC deficits were high in 2005 and 2008. Generally, the trend was in agreement with the inhibition of extreme events against forest potential productivity, although there was a reduction of CPC deficits due to more available incoming solar radiation in 2007. The two largest potential productivity deficits occurred in 2003 (relative CPC deficits = 0.34) and in 2005 (relative CPC deficits = 0.35), respectively, which verified the effects of extreme drought in 2003 and extreme ice rain in 2005 on the potential productivities. But the annual CPC deficits were not significantly associated with annual Ta deficits ($R^2 = 0.16$, $p = 0.3$). This was partly because the forest ecosystem was more complex and of greater diversity than grassland ecosystems typically stressed by water availability. The perfect CPC denoted the essential characteristics of the local system, and the increase in CPC deficits reflected the impacts of the disturbance and climate change (i.e., extreme climate events) on the potential productivity of the local ecosystem (Yi et al 2012). The forest system was more capable of adjusting itself to the extreme climate disturbance and recovery from it, so that the CPC deficits were not determined by a single occasional extreme event (i.e., low temperature in early year) at an annual time scale.

4. Conclusion

This study explored the response of subtropical coniferous forest ecosystem potential productivity to climate extreme events occurring in southern China with in situ EC flux observation during 8 years (2003–2010). The annual forest ecosystem potential productivity was significantly reduced by extreme drought and ice rain. In particular, the plantation potential productivity in winter was most severely reduced by the extreme freeze events. Also, our analysis indicated the lag time of ecosystem potential productivity response to drought was approximately one month. Nevertheless, with the increase in frequency and intensity of extreme climatic events (Easterling et al 2000, Meehl and Tebaldi 2004, Min et al 2011), the planted forest ecosystems which play an important role in terrestrial carbon sink will possibly become more vulnerable to extreme events and act as a net carbon source. Uncertainties resulting from the forest ecosystem seasonality and complexity existed in the feedback between the potential productivity and extreme climate. Furthermore, eddy covariance flux observation in collaboration with remote sensing and ground field surveys are highly desired in any future research.

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References

Amiro B D et al 2010 Ecosystem carbon dioxide fluxes after disturbance in forests of North America J. Geophys. Res.—Biogeosci. 115 G00K02

Baldocchi D D, Hicks B B and Meyers T P 1988 Measuring biosphere–atmosphere exchanges of biologically related gases with micrometeorological methods Ecology 69 1331–40

Breda N, Huc R, Granier A and Dreyer E 2006 Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences Ann. Forest Sci. 63 625–44

Ciais P et al 2005 Europe-wide reduction in primary productivity caused by the heat and drought in 2003 Nature 437 529–33

Easterling D R, Meehl G A, Parmesan C, Changnon S A, Karl T R and Mearns L O 2000 Climate extremes: observations, modeling, and impacts Science 289 2006–74

Fang J Y, Chen A P, Peng C H, Zhao S Q and G L 2001 Changes in forest biomass carbon storage in China between 1949 and 1998 Science 292 2320–2

Frolking S, Palace M W, Clark D B, Chambers J Q, Shugart H H and Hurr G C 2009 Forest disturbance and recovery: a general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure J. Geophys. Res.—Biogeosci. 114 G00E02

Gregg J S, Andres R J and Marland G 2008 China: emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production Geophys. Res. Lett. 35 L08806

Gu L, Hanson P J, Post W M, Kaiser D P, Yang B, Nemani R, Pallardy S G and Meyers T 2008 The 2007 eastern US spring freeze: increased cold damage in a warming world? Bioscience 58 253–62

Gu L, Post W, Baldocchi D, Black T A, Suyker A, Verma S, Vesala T and Wofsy S 2009 Characterizing the seasonal dynamics of plant community photosynthesis across a range of vegetation types Phenol. Ecosystem Processes ed A Noormets (New York: Springer) pp 35–58

Lauenroth W K and Sala O E 1992 Long-term forage production of North-American shortgrass steppe Ecol. Appl. 2 397–403

Lugo A E 1997 The apparent paradox of reestablishing species richness on degraded lands with tree monocultures Forest Ecol. Manag. 99 9–19

Meehl G A and Tebaldi C 2004 More intense, more frequent, and longer lasting heat waves in the 21st century Science 305 994–7

Min S K, Zhang X, Zwiers F W and Hegerl G C 2011 Human contribution to more-intense precipitation extremes Nature 470 378–81

Moffat A M et al 2007 Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes Agric. Forest Meteorol. 147 209–32

Pan Y D et al 2011 A large and persistent carbon sink in the world’s forests Science 333 988–93

Pei F S, Li X, Liu X P and Lao C H 2013 Assessing the impacts of droughts on net primary productivity in China J. Environ. Manag. 114 362–71

Piao S L, Fang J Y, Ciais P, Pei Y, Huang Y, Sitch S and Wang T 2009 The carbon balance of terrestrial ecosystems in China Nature 458 1009–13

Reichstein M et al 2005 On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm Glob. Change Biol. 11 1424–39

Reichstein M, Tenhunen J D, Rousset O, Oechel C W, Rambal S, Dore S and Valentini R 2002 Ecosystem respiration in two mediterranean evergreen holm oak forests: drought effects and decomposition dynamics Funct. Ecol. 16 27–39

Richardson A D and Hollinger D Y 2007 A method to estimate the additional uncertainty in gap-filled net canopy fluxes resulting from long gaps in the CO2 flux record Agric. Forest Meteorol. 147 199–208

Shao Q Q, Huang L, Liu J Y, Kuang W H and Li J 2011 Analysis of forest damage caused by the snow and ice chaos along a transect across southern China in spring 2008 J. Geogr. Sci. 21 219–34

Stone R 2008 Natural disasters—ecologists report huge storm losses in China’s forests Science 319 1318–9

Sun X M, Wen X F, Yu G R, Liu Y F and Liu Q J 2006 Seasonal drought effects on carbon sequestration of a mid-subtropical planted forest of southeastern China Sci. China D 49 110–8

Teklemariam T, Staebler R M and Barr A G 2009 Eight years of carbon dioxide exchange above a mixed forest at borden, ontario Agric. Forest Meteorol. 149 2040–53

Turner M G and Dale V H 1998 Comparing large, infrequent disturbances: what have we learned? Ecosystems 1 493–6

Vicente-Serrano S M et al 2013 Response of vegetation to drought time-scales across global land biomes Proc. Natl Acad. Sci. USA 110 52–7

Wang S Q, Liu J Y, Yu G R, Pan Y Y, Chen Q M, Li K R and Li J Y 2004 Effects of land use change on the storage of soil organic carbon: a case study of the qianyanzhou forest experimental station in China Clim. Change 67 247–55

Wang S Q, Liu J Y, Zhang C, Yi C X and Wu W X 2011 Effects of afforestation on soil carbon turnover in China’s subtropical region J. Geogr. Sci. 21 118–34

Wen X F, Wang H M, Wang J L, Yu G R and Sun X M 2010 Ecosystem carbon exchanges of a subtropical evergreen coniferous plantation subjected to seasonal drought, 2003–2007 Biogeosciences 7 357–69

Wen X F, Yu G R, Sun X M, Li Q K, Liu Y F, Zhang L M, Ren C Y, Fu Y L and Li Z Q 2006 Soil moisture effect on the temperature dependence of ecosystem respiration in a subtropical pinus plantation of southeastern China Agric. Forest Meteorol. 137 166–75

Xu X T, Piao S L, Wang X H, Chen A P, Ciais P and Myneni R B 2012 Spatio-temporal patterns of the area experiencing negative vegetation growth anomalies in China over the last three decades Environ. Res. Lett. 7 035701

Yi C X et al 2012 Climate extremes and grassland potential productivity Environ. Res. Lett. 7 035703

Ying S, Lianhong G, Robert E D and Benzhi Z 2012 Forest greening after the massive 2008 Chinese Ice Storm: integrated effects of natural processes and human intervention Environ. Res. Lett. 7 035702

Yu G R et al 2008 Environmental controls over carbon exchange of three forest ecosystems in eastern China Glob. Change Biol. 14 2555–71

Zeng N, Qian H, Roedenbeck C and Heimann M 2005 Impact of 1998–2002 midlatitude drought and warming on terrestrial ecosystem and the global carbon cycle Geophys. Res. Lett. 32 L22709

Zhang W J, Wang H M, Wen X F, Yang F T, Ma Z Q, Sun X M and Yu G R 2011a Freezing-induced loss of carbon uptake in a
subtropical coniferous plantation in southern China. *Ann. Forest Sci.* 68 1151–61

Zhang W J, Wang H M, Yang F T, Yi Y H, Wen X F, Sun X M, Yu G R, Wang Y D and Ning J C 2011b Underestimated effects of low temperature during early growing season on carbon sequestration of a subtropical coniferous plantation *Biogeosciences* 8 1667–78

Zhang L, Xiao J F, Li J, Wang K, Lei L P and Guo H D 2012 The 2010 spring drought reduced primary productivity in southwestern China *Environ. Res. Lett.* 7 045706

Zhao M S and Running S W 2010 Drought-induced reduction in global terrestrial net primary production from 2000 through 2009 *Science* 329 940–3

Zhou B Z, Li Z C, Wang X M, Cao Y H, An Y F, Deng Z F, Letu G R, Wang G and Gu L H 2011a Impact of the 2008 ice storm on moso bamboo plantations in southeast China *J. Geophys. Res.—Biogeosci.* 116 G00H06

Zhou B Z et al 2011b The Great 2008 Chinese Ice Storm its socioeconomic-ecological impact and sustainability lessons learned *Bull. Am. Meteorol. Soc.* 92 47–60