WFL Publisher
Science and Technology
Meri-Rastilantie 3 B, FI-00980
Helsinki, Finland
e-mail: info@world-food.net

Journal of Food, Agriculture & Environment Vol.9 (3&4): 818-825. 2011
www.world-food.net

Carbon budget and its response to environmental factors in young and mature poplar plantations along the middle and lower reaches of the Yangtze River, China

Jinxing Zhou [1], Yuan Wei [1], Jun Yang [2], Xiaohui Yang [2*], Zeping Jiang [1], Jiquan Chen [3], Asko. Noormets [4] and Xiaosong Zhao [5]

*[1] Institute of Desertification Studies, Chinese Academy of Forestry, Beijing 100091, China. [2] Beijing Forestry University, Beijing 100083,China. [3] Department of Earth, Ecological and Environmental Science, The University of Toledo, Toledo, OH 43606,USA. [4] Department of Forestry and Environmental Resource, North Carolina State University, Raleigh, NC 27695,USA. [5] Nanjing Institute of Geography and Limnology, Chinese Academy of Science, Nanjing 210008, China. *e-mail: yangxh@caf.ac.cn*

Received 3 July 2011, accepted 9 October 2011.

Abstract

Although poplar forest is the dominant plantation type in China, there is uncertainty about the carbon budget of these forests across the country. The observations, performed in 2006, of two eddy covariance flux towers on a young poplar plantation (Yueyang, Hunan province) and a mature poplar plantation (Huaining, Anhui province) provide an opportunity to understand poplar CO_2 exchange at diurnal, seasonal and annual scales. The levels of net ecosystem carbon exchange (NEE) at these two sites are similar, but both ecosystem respiration (Reco) and gross ecosystem productivity (GEP) have significant differences, reflecting differences in climate and land management. Although more rain and lower photosynthetically active radiation (PAR) were recorded in the summer, the young plantation sequesters -476 g C m^{-2} yr^{-1}, compared to -465 g C m^{-2} yr^{-1} in the mature plantation. Daily maximum NEE values are also similar (9.98 g C m^{-2} d^{-1} vs. 9.75 g C m^{-2} d^{-1}). Differences in GEP and Reco between the two sites are greater. The young plantation assimilates 1629 g C m^{-2} yr^{-1} and releases 1153 g C m^{-2} yr^{-1} through respiration, while the corresponding values in the mature plantation are 1439 g C m^{-2} yr^{-1} and 976 g C m^{-2} yr^{-1}. Daily maximum GEP and daily maximum Reco of young plantation are 14.56 g C m^{-2} d^{-1} and 8.04 g C m^{-2} d^{-1}, which are 11% and 35% higher than the corresponding values of the mature plantation (13.10 g C m^{-2} d^{-1}, 5.97 g C m^{-2} d^{-1}). These two sites also had different parameters describing the responses of NEE on a half-hour time scale to PAR, but the responses of NEE, GEP and Reco to PAR and air temperature at daily and monthly scales do not differ among sites. These results suggest that a general parameterization could be sufficient at coarse time resolutions to model the response of carbon exchange to environmental factors in poplar forests from different climatic regions in China.

Key words: Net ecosystem carbon exchange, ecosystem respiration, gross ecosystem productivity, photosynthesis active radiation, air temperature.

Introduction

Poplar is one of the dominant plantation types in east Asia [1]. By 2003, poplar plantations occupied 7 million ha, with an annual carbon storage of about 6.2 t ha^{-1} yr^{-1} [2]. Poplar plantations are known to play an important role in carbon capture and are a potential source of bio-energy [3-6], however, there have been few studies on net carbon exchange and its response to environmental factors in poplar plantations [7-9]. The cumulative NEE during the growing season of a poplar plantation in Beijing, China, was -585 g C m^{-2} because of a shortage of groundwater [7]. A comparative study of evapotranspiration (ET) on two poplar plantations in northern China further demonstrates that an increase in ET is only possible if it is offset by an increased use of groundwater, which is replenished through rain or irrigation [9]. Drought stress on poplar trees could result in a sharp decrease in net photosynthetic rate and transpiration rate [10-12]. Although there have been studies on carbon flux values and the physiology of poplars experiencing annual precipitation less than 1000 mm [9, 13], there is a lack of detailed information on carbon exchange in poplar plantations with an annual precipitation close to 1500 mm and on the influence of flooding and climate on these systems.

Since the 1970s, the poplars have been the major tree species in plantation forestry and agroforestry systems in temperate China [14-15]. This study used eddy covariance measurements of CO_2 fluxes in 2006 along the middle and lower reaches of the Yangtze River, China, to test the hypothesis that young poplar plantations may have more positive effects on carbon sequestration than mature poplar plantations. The seasonal variability of net ecosystem exchange (NEE), gross primary production (GEP) and ecosystem respiration (Reco) during the growing season were analyzed and the responses of these factors to environmental factors further discussed.

Materials and Methods

Study site: Data were collected from two poplar plantations along the middle and lower reaches of the Yangtze River: Huaining in the southwestern Anhui province (33°N, 117°E, elevation 14-16.5 m) and Yueyang in the northern Hunan Province (29°31'40''N, 112°51'34'', elevation 31 m) (Table 1).

Huaining has a warm temperate climate with a mean annual precipitation of 1500 mm and mean annual air temperature of 16.7°C. The annual frost-free period is about 244 days long. This 260 ha poplar plantation has been managed for snail control and

Table 1. The basic conditions of the study sites and poplar plantations.

Sites	Huaining Anhui province	Yueyang, Hunan province
Location	33°N, 117°E	29°31′40″N, 112°51′34″
Elevation (m)	15	31
Topography	Flat	flat
Mean annual temperature (°C)	16.7	17
Annual precipitation (mm)	1500	1415
Stand age (years)	18	7
Canopy height (m)	18	16
Tree density (stems ha^{-1})	318	495
Height of the flux tower (m)	30	23

schistosomiasis prevention since 1989. The planting density is 318 trees ha^{-1} (3 m × 10 m). The examined poplar clones consisted of clone I-69 (*Populus deltoides* 'I-69') and clone I-72 (*Populus deltoides* 'I-72').

The Yueyang site is a flat area that floods for 20 to 50 days per year, and as long as 130 days under extreme conditions. This 650-ha poplar plantation has been managed for flood prevention since 2000. The climate is humid and subtropical, with a mean annual precipitation of 1415 mm and a mean annual air temperature of 17.0°C. The annual frost-free period is about 270 days. The examined clones consisted of clone 55/65 (*Populus deltoides* '55/65'), clone 2KEN8 (*Populus deltoides* '2KEN8') and clone NL-80121 (*Populus deltoides* 'nanlin 80121'). The spacing was 4 m × 5 m and the tree density 495 trees ha^{-1}.

Flux measurements: Two eddy covariance (EC) towers were established in 2005 to measure net ecosystem CO_2 flux at two plantation sites, and data were collected in 2006. A three-dimensional sonic anemometer-thermometer (CSAT3, Campbell Scientific) positioned at a height of 20 m was used to measure wind velocity and direction. CO_2 and water vapor fluctuations were measured simultaneously with a fast response open-path infrared gas analyzer (IRGA; LI-7500, LICOR). The LI-7500 was calibrated at regular 3-month intervals for CO_2 and water vapor using calibration gases and a dew point generator (LICOR 610, LICOR Inc., Lincoln, NE, USA). Output signals from the CSAT3 and IRGA were sampled at a frequency of 10 Hz by a programmed data logger (CR5000, Campbell Scientific) and recorded to a flash memory storage card. Eddy fluxes were calculated with a time step of 30 min according to EUROFLUX methodology [16]. A triple-coordinate rotation was performed to align the normal mean vertical velocity measurements to the mean wind streamlines prior to scalar flux calculations [17]. The WPL correction was used to eliminate the effect on flux [18]. A storage term was added to the calculated CO_2 fluxes to determine NEE; this term was estimated using the single-level measurements of CO_2 concentration with the open-path IRGA [19].

Meteorological measurements: Along with the flux measurements, meteorological variables were measured continuously in 2006 by a micro-meteorological tower. Precipitation was measured with a tipping bucket rain gauge (52203, RM Young, USA). Photosynthetic active radiation (PAR) and net radiation (Rn) were measured at 23 and 25 m above the ground, using a quantum sensor (LI190SB, LICOR, Lincoln, NE, USA) and a four-component net radiometer (CNR-1, Kipp & Zonen, Netherlands). Air temperature (Ta) and relative humidity (RH) were measured at 4 levels above ground level using 4 temperature/humidity sensors (Vaisala HMP45, Helsinki, Finland). Soil temperature (Ts) was measured using thermocouples at depths of 5, 10 and 20 cm. Soil volumetric water content was measured using a time domain reflectometer (TDR) probe at a depth of 15 cm. Two soil heat flux plates were placed 6 cm below the soil surface in two separate locations, 3 m away from the EC tower. All meteorological and soil data were recorded at half-hour intervals using a data logger (CR23XTD, Campbell Scientific Ltd., Edmonton, Alberta, Canada).

Quality control and gap-filling: Half-hourly flux data were rejected if they met the following criteria: (1) incomplete half-hour measurements, (2) rain events, (3) stable atmospheric condition (u*, friction velocity, 0.2 m s^{-1}) and (4) anomalous value for either three-dimensional wind velocities or scalars. Approximately 43-49% of the flux data were eliminated by the screening criteria listed above at two sites. The quality of the data were evaluated by the degree of energy closure, which averaged >85%.

Several strategies were introduced to compensate for missing data. Interpolated values were used to fill gaps < 2 h. For these gaps, NEE values were divided between day (NEE_{day} PAR > 10 ìmol m^{-2} s^{-1}) and night (NEE_{night} PAR < 10 µmol m^{-2} s^{-1}) to develop non-linear regressions for both gap filling and evaluating environmental effects on NEE. Light response functions were established by further dividing daytime data into half-monthly intervals and then fitting the relationships between NEE_{day} and PAR to the Michaelis–Menten function (Michaelis 1913) in the form [20]:

$$NEE_{day} = \frac{\alpha \times PAR \times NEE_{opt}}{\alpha \times PAR + NEE_{opt}} + R_d \quad (1)$$

where α (µmol C µmol $Photo^{-1}$) is the apparent quantum yield, NEE_{opt} (µmol C m^{-2} s^{-1}) is the optimum rate of NEE at saturation PAR, and R_d (µmol C m^{-2} s^{-1}) is a bulk estimate of dark ecosystem respiration. Missing data of NEE_{day} were filled using PAR and parameters fitted to Equation (1).

Reco may be underestimated under the stable conditions at night [21, 22]. To eliminate this possible uncertainty, the exponential function relating soil temperature (Ts, 5 cm) and nighttime data at high turbulence (u* > 0.2 m s^{-1}) was established:

$$Re_{night} = b_0 \exp(b_1 T_S) \quad (2)$$

where b_0 and b_1 are regression constants. This parameterization was used for both filling nighttime carbon flux data gaps and estimating daytime Re. Software OriginPro 7.5 was used to calculate regression parameters fitted to Equation (1) and Equation (2) and their significances.

In this study, positive Re values represent CO_2 release into the atmosphere and negative values indicate CO_2 entering the biosphere. Values of GEP were calculated as the difference between Re and NEE. For daily values of Re and GEP, the half-hourly results were summed [23, 24]. GEP was estimated according to Equation (3):

$$GEP=NEE-Reco \quad (3)$$

At the half-hour scale, the units of CO_2 flux were μmol m^{-2} s^{-1}, while at daily, monthly, and annual scales, the units were converted into g C m^{-2} day^{-1}, g C m^{-2} mon^{-1} and g C m^{-2} yr^{-1}, respectively.

Results and Discussion

Meteorological conditions: In general, weather and climate were very similar at these two sites. Fig. 1 shows the monthly values of PAR, Ta, LAI and precipitation during 2006. The seasonal variation in Ta and PAR at the two sites shows a similar one-peak pattern with the peak values achieved in the most active period. The maximum monthly Ta observed at Yueyang site, which is located at a lower altitude, was slightly higher than that observed at Huaining (29.5°C vs 28.4°C). Average annual Ta for both sites was 17.0°C, with the coldest temperatures in January (4.5°C, Huaining vs. 4.4°C, Yueyang). On an annual basis, the photosynthetically active radiation received by the two plantations was about 6500 mol m^{-2}, with Yueyang receiving 100 mol m^{-2} more than Huaining. Summer PAR was more stable at Yueyang, ranging from 783 to 858 mol m^{-2} mon^{-1}, while corresponding values at Huaining increased dramatically from 620 to 990 mol m^{-2} mon^{-1}.

LAI was greatest (2.8 m^2 m^{-2}) at Huaining; it was assumed to vary seasonally by about 20-30% (Fig. 1). In contrast, LAI in the younger stand increased significantly through the growing season until a maximum value was reached in late June. Maximum LAI in 2006 was approximately 3.5 m^2 m^{-2} at the Yueyang site, which was about 25% higher than that observed at Huangning. The monthly precipitation totals exhibited an asymmetrical distribution, with 54% of the precipitation at Huaining and 48% of the precipitation at Yueyang occurring between January and May. Maximum monthly precipitation in Huaining was 273 mm, which was slightly lower than that observed at Yueyang (280 mm). In the peak growing season, from June to September, Yueyang received only 258 mm of precipitation, which was less than that observed in May (280 mm). The corresponding values for Huaining were 453 and 273 mm. Such a large difference in precipitation between the two sites indicates that Yueyang site could capture carbon storage with more sunny days. In fact, Yueyang and Huaining experienced only 13 and 27 days, respectively, with >5 mm precipitation.

Response of NEE to PAR: PAR is the most critical environmental factor affecting stand daytime NEE. Daytime CO_2 fluxes (NEE) exhibited hyperbolic relationships with available PAR at both sites. Fig. 2 shows a comparison of mature (Huaining) vs. young (Yueyang) stands during growing season. In Yueyang, the value of NEE increased with PAR. During peak growth (May-August), NEE showed a strong response to PAR, with a peak value of about -37.7 μmol m^{-2} s^{-1}; with the onset of senescence in mid October, NEE decreased to -7 μmol m^{-2} s^{-1}. Compared to the NEE observed in Yueyang, the NEE in Huaining had a weaker response to PAR. NEE decreased under conditions of low radiation, but the relative rate of decrease in NEE per unit PAR began to decline when PAR exceeded 500; when PAR exceeded 1000, NEE reached a stable value of about -6.1 and -20.5 μmol m^{-2} s^{-1} in May and July. Huaining usually had weak carbon exchange rates; the peak NEE value recorded in August in Huaining was about -22 μmol m^{-2} s^{-1}, only 59% of the corresponding value in Yueyang.

In each month, there is little difference between the values of NEE for mature and young sites at low radiation levels. With increasing PAR, however, the mature site begins to show greatly reduced carbon uptake, with the exception of the values recorded in May. If a surrogate for apparent ecosystem light-use efficiency is defined as the ratio of a1/a2 or the initial slope of the light-response curve [25], it becomes evident that the young plantation is consistently more efficient in its use of PAR. Peak photosynthetic levels are consistently greater in the young plantation.

Seasonal trends in NEE-PAR response parameters are presented in Fig. 3 in terms of apparent quantum yield (α). These data demonstrate that the above description of daytime photosynthetic

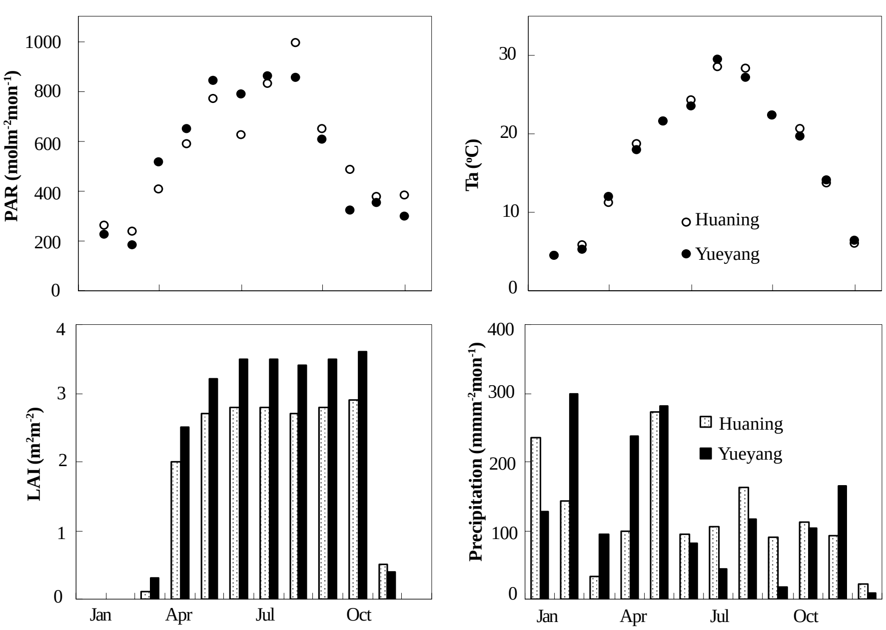

Figure 1. Monthly total photosynthetic active radiation (PAR), monthly average air temperature (Ta), Leaf Area Index (LAI) and monthly precipitation above-canopy.

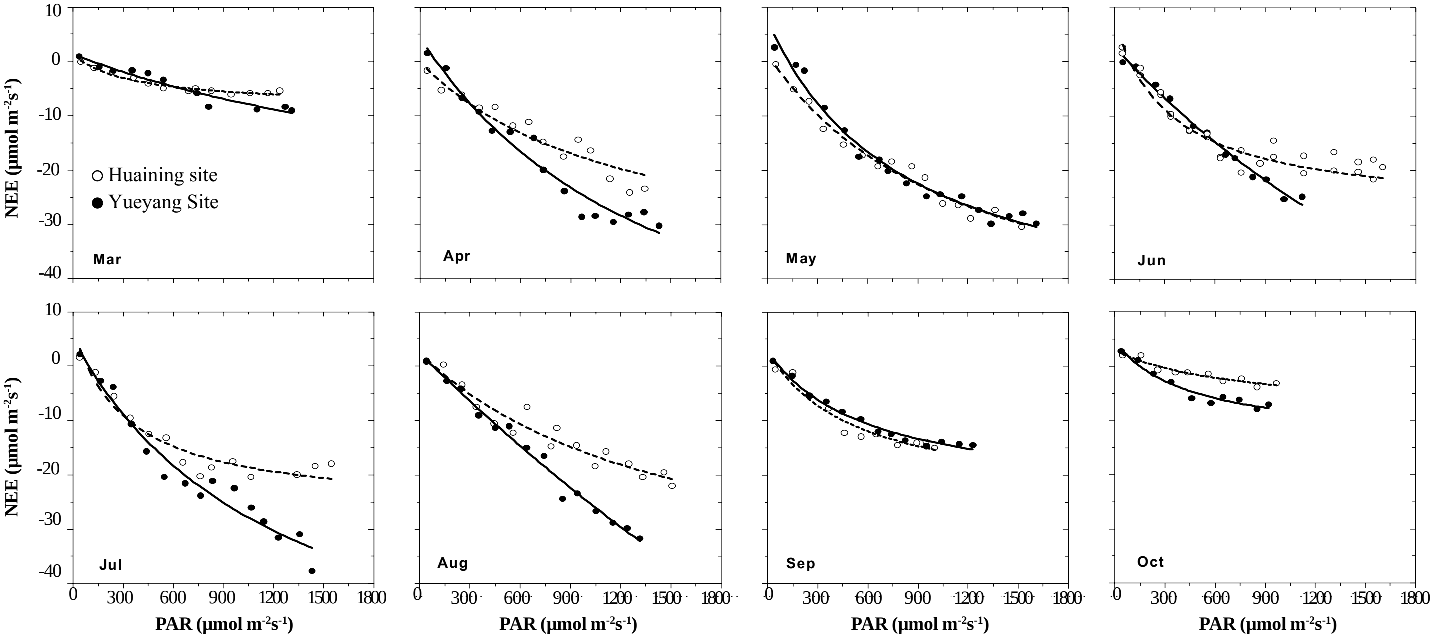

Figure 2. Comparison of NEE-PAR response curves during peak growth conditions.

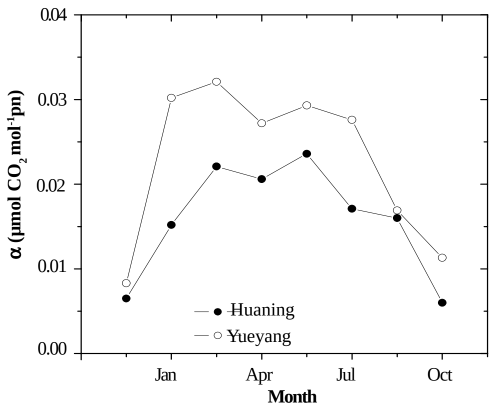

Figure 3. Seasonal pattern of apparent quantum yield (α).

capacity at mature and young plantation sites is generally applicable throughout the year. As expected, the young plantation consistently exhibits greater photosynthetic capacity than the mature site. When the trees put forth leaves in March, the apparent quantum yield was only 0.0065 and 0.0083 μmol CO_2 mol^{-1} photon. A sharp increase in α to 0.0302 μmol CO_2 mol^{-1} photon occurred in Yueyang in April, bringing α very close to the peak value (0.0321 μmol CO_2 mol^{-1} photon) recorded in Yueyang in May. The greatest and smallest differences in α between the two sites were 0.015 and 0.0009 μmol CO_2 mol^{-1} photon, recorded in April and September.

Diurnal patterns: For temperate forest ecosystems, the growth season and photosynthetic capacity were usually limited by temperature and the development of LAI [26]. PAR served as a direct, dominant influence on temperature increase and leaf area in such ecosystems. Seasonal variation in the mean diurnal pattern of NEE (3 days averaged) was also very similar to that found in this study (Fig. 4). CO_2 uptake started at 7:00-8:00 and responded linearly to increasing PAR because of the absence of water stress and a high light saturation point. In our study, peak CO_2 uptake

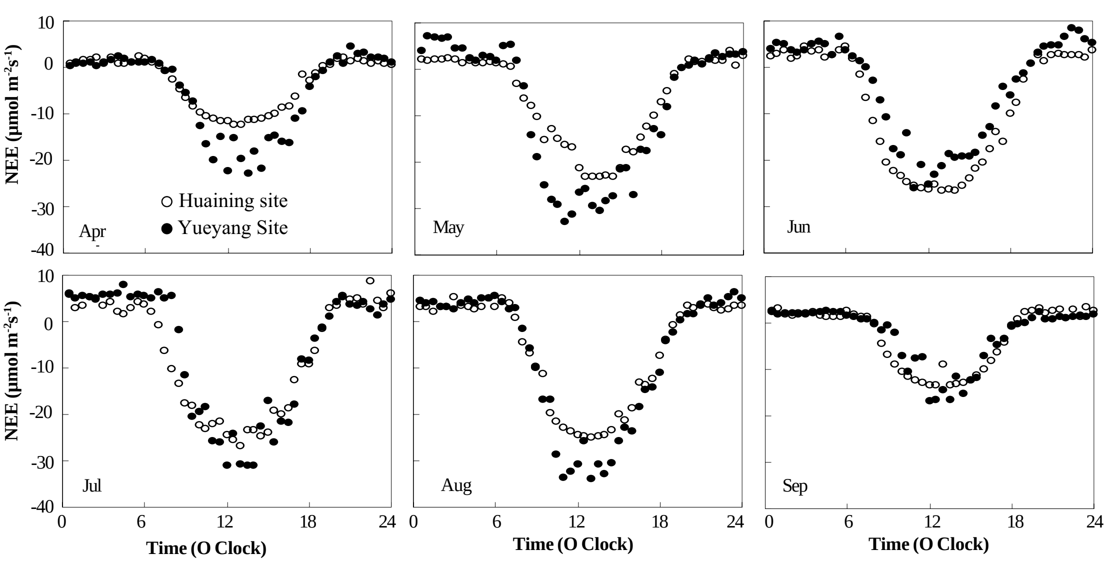

Figure 4. Three-day averaged diurnal course of net carbon exchange (NEE) during growing season.

occurred at noon, concurrent with the highest PAR. The symmetrical distribution of NEE values around noon was similar to the findings of another study in a poplar plantation on sandy soil in China .

The diurnal amplitude of NEE varied substantially across the growing season. At the beginning of the growing season in March, low temperature and rainy days limited carbon assimilation and respiration in ecosystems. With the development of forest canopy and rising temperature, NEE values were significantly elevated in April and May. In Huaining, the maximum half-hour daytime NEE decreased from -12.4 μmol m^{-2} s^{-1} in April to -23.1 μmol m^{-2} s^{-1} in May, then to about -26.5 μmol m^{-2} s^{-1} from June to August and -13.5 μmol m^{-2} s^{-1} in September. The same trend in the maximum half-hour daytime NEE was also found at Yueyang, but the values from April to September were slightly higher (-22.9, -32.9, -26, -30.9, -34 and -16.6 μmol m^{-2} s^{-1}). Overall, we found that half-hour NEE peaked at noon in all months at Huaining, while the daily maximum NEE occurred around 11:00 am in Yueyang.

Both sites reach their maximum carbon exchange rate in August; the value at Huaining was -26.8 μmol m^{-2} s^{-1},which was only 78.9% of the observed value at Yueyang (34.0 μmol m^{-2} s^{-1}). The maximum carbon exchange rate at Huaining was consistent with the findings at another poplar plantation in Beijing, where the maximum CO_2 exchange rate was -28 μmol m^{-2} s^{-1} [7]. Yueyang had a higher maximum CO_2 exchange, at -34.0 μmol m^{-2} s^{-1}. This value is close to that measured in a larch forest in Japan [27]. Overall, poplar plantations had more efficient carbon capture compared to the three typical forest ecosystems along the north-south transect in eastern China [28] as a subtropical coniferous plantation in Jiangxi Province [29], a temperate broad-leaved Korea pine mixed forest in northeastern China [30, 31] and a subtropical evergreen broadleaf forest in southern China [32]. A cultivated larch forest in Japan had the same peak CO_2 exchange rate as the Yueyang site [27], but maximum CO_2 uptake during day in most nature forest ecosystems in temperate zone is lower than that recorded on the poplar plantations[33-37]. This difference is the reason that poplar forest was selected as a source of bio-energy and material for the paper industry and as a carbon sink [6, 38, 39] .

Seasonal patterns: Seasonal patterns in carbon flux can be used to refine the response of vegetation to environmental controls, such as leaf area index, solar radiation, temperature, phenology, extreme weather events and photosynthetic capacity [34, 40]. In April, at the beginning of the growing season, low temperatures and young vegetation limited carbon flux in the poplar plantations. Particularly in respiration, the increase of soil temperature lagged behind canopy development and PAR; high groundwater water tables or spring floods aggravated this phenomenon. In winter, daily NEE values show that the poplar stands acted as a carbon source. Over the year, NEE decreased steadily and finally changed signs, from positive to negative, in March. Considerable daily variability in NEE was recorded and was attributed primarily to incident PAR. From May to August, NEE remained relatively stable and decreased with the onset of canopy senescence and lower temperatures.

The seasonal pattern in NEE at Huaining showed one peak in late May and one in early June (Fig. 5). As a result of increases in temperature and full development of vegetation, carbon assimilation and respiration were significantly elevated in June; however, carbon assimilation was severely limited by the limited supply of PAR and the large number of cloudy days in this period. Consequently, the seasonal pattern of NEE at Yueyang had two peaks: one in early May and one in July. This pattern was mainly the result of the variable PAR. As Fig. 1 demonstrates, there was a clear, deep through in PAR at Yueyang in June. The higher photosynthetic and respiratory capacities at the Yueyang site appear to offset each other, as both sites exhibited nearly identical maximum values: -9.8 g C m^{-2} d^{-1} in mid-June at Huaining and -9.9 g C m^{-2} d^{-1} at Yueyang. These values were similar to those recorded at another poplar plantation in Beijing but were slightly lower than those recorded at an Italian poplar plantation (10.95 g C m^{-2} d^{-1}).

Environmental influences on seasonal patterns of carbon flux include fire, unusually high temperatures, water shortage, plant diseases and extreme events [8, 41-46]. In late May and June, the Yueyang site experienced a natural disturbance caused by continuous rain. In this period, NEE and its components, Reco

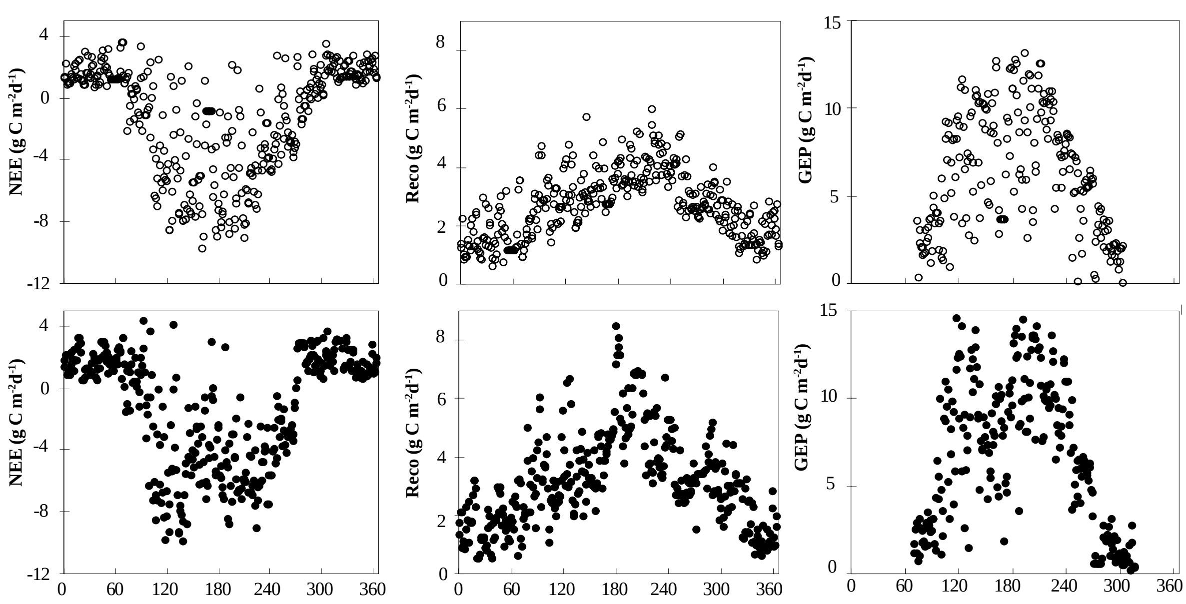

Figure 5. Seasonal patterns of net carbon exchange (NEE), ecosystem respiration (Reco) and gross ecosystem production(GEP) in 2006. ○ Huaining site, ●Yueyang Site.

and GEP, showed a rapid reduction (Fig. 5). By early and middle November, there was a net loss of carbon from Huaining and Yueyang. GEP showed patterns similar to NEE, suggesting a coupling between carbon flux and PAR; however, the maximum values of GEP were 13.1 and 14.6 g C m^{-2} d^{-1} for Huaining and Yueyang, respectively. The Huaining site was a low-productivity forest with an average GEP of about 6.2 g C m^{-2} d^{-1} and 230 growing days in 2006. Yueyang had a higher average GEP, 6.6 g C m^{-2} d^{-1} and a longer growing season of 248 days. For both sites, Reco showed a pattern of a single peak in July. More generally, Reco was high in the warm season and low in the cold season. Sudden increases in Reco due to heavy rain events were also observed in the spring and summer.

Monthly patterns: Both ecosystems release CO_2 from January to March, despite the small carbon uptake in late March. Most of the sink activity at both sites was limited to the period from April to September. Monthly NEE (Fig. 6) held relatively stable from May to August, with the exception of a sharp change in June due to low PAR. Carbon sink strength steadily declined starting in September, becoming positive in October. NEE in late fall was similar at both sites, but winter NEE was slightly greater (indicating a more significant carbon source source) at Yueyang than Huaining, especially in October. An additional 64 g C m^{-2} were released at Yueyang during the non-growing season. The Yueyang site was a slightly larger sink of CO_2 than the Huaining site in the months from April to October, with the exception of June. Maximum total monthly carbon capture for Huaining occurred in July (152 g C m^{-2}); this value was lower than the corresponding value recorded in May (170.7 g C m^{-2}). An additional 77.4 g C m^{-2} was sequestered by the Yueyang site during the growing season.

Monthly Reco (Fig. 6) was close to 50 g C m^{-2} in winter, increased in magnitude in spring and reached a maximum in July for Yueyang (189.7 g C m^{-2}) and August for Huaining (131.2 g C m^{-2}). Yueyang had a greater carbon release through respiration; a monthly Reco lower than that recorded in Huaining was seen only in September and December. The greatest difference in Reco between the two sites (80.8 g C m^{-2}) was recorded in July. Over the course of the year, values for CO_2 release through ecosystem respiration were 976.2 and 1150.4 g C m^{-2} for Huaining and Yueyang, respectively.

In spring (March to May), GEP increased more sharply than Reco at both sites; as a consequence, NEE rapidly decreased to negative values. GEP increased more rapidly at Yueyang than at Huaining (Fig. 6). The Yueyang site had a longer period of photosynthesis assimilation. The onset of GEP started at Yueyang in middle March and lasted into early November (Fig. 6). These differences were also apparent in the monthly GEP: both sites reached their maxima in July, but Yueyang had a value of -354.7 g C m^{-2}, 28.5% higher than the value at Huaining. Annual GEP values were 1404 g C m^{-2} and 1586.5 g C m^{-2} for Huaining and Yueyang, respectively.

Carbon budget: Stand age plays a major role in determining forest carbon fluxes and storage [47, 48]. A study of a Douglas fir chronosequence indicated that 20 years were needed for a switch from a source to a sink of C [49]. The clear-cut area was a source of carbon, but the 12-year-old Scots pine forest was turning from a source into a weak sink [50]. The carbon balance of plantations varies greatly over the course of stand development. In a previous study a 4-year poplar plantation had the greatest biomass productivity; the annual carbon storage increment decreased when the forest was older than 4 years [2]. The mean annual carbon storage increments from age 7 to 10 years were about 6.1 t C ha^{-1} yr^{-1}. An effect of age on annual GEP and Reco was clearly observed at 4 separate poplar plantations. The annual GEP of the 7-year-old plantation in the Yueyang site, measured by EC, was 1629 g C m^{-2} yr^{-1}; the annual GEP of the 18-year-old plantation in the Huaining site was 1450 g C m^{-2} yr^{-1}. An 11-year-old plantation in Beijing and a 12-year-old plantation in Italy had annual GEP values of about 1525 and 1522 g C m^{-2} yr^{-1}, respectively [7-8]. Annual Reco values were 976, 1063 and 1150 g C m^{-2} yr^{-1}, respectively, for poplar plantations aged 18, 11 and 7 years.

The vegetation of Yueyang demonstrated greater carbon assimilation and ecosystem respiration, but these two opposite carbon processed seemingly offset each other; an additional 190 g C m^{-2} in GEP and 174 g C m^{-2} in Reco resulted in 11 g C m^{-2} of additional carbon capture in Yueyang. Thus, in view of the uncertainties in measurement involved, the difference in annual carbon capture at these two poplar forest sites was not significant in 2006. There was little difference in annual NEE between the Huaining and Yueyang sites: NEE values were 4.6 and 4.8 t C ha^{-1} yr^{-1}. These values are much larger than the 2.6 t C ha^{-1} yr^{-1} recorded in a 200-year-old Korea pine in northern China or the 3.45 t C ha^{-1} yr^{-1} in a mature conifer plantation [31]. A poplar plantation in Beijing had nearly same annual NEE, at 4.62 t C ha^{-1} yr^{-1} [7]. These three sites were comparable in value to published reports from similar plantations in Italy (6.7-7.5 t C ha^{-1} in the growing season) [8]. Compared to other forests in Asia, North America and Europe, the poplar forest had a very high potential to capture CO_2 from the atmosphere [24, 34, 51, 52].

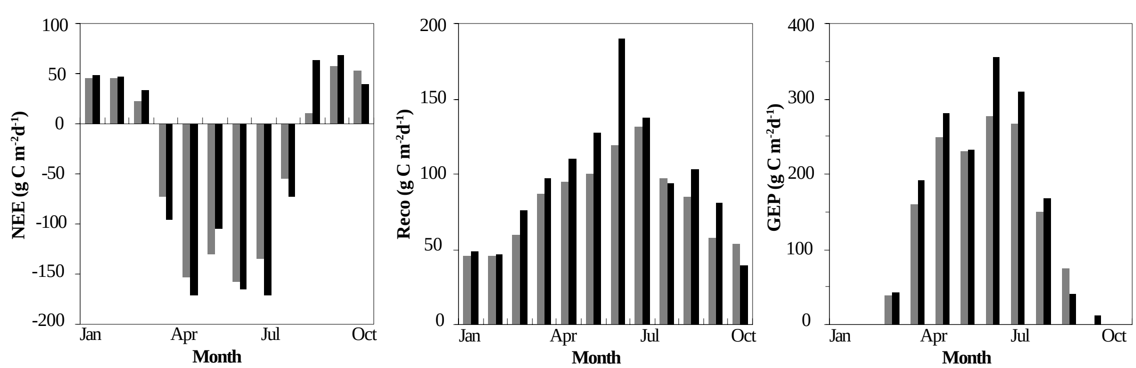

Figure 6. Monthly total net carbon exchange (NEE), ecosystem respiration (Reco) and gross ecosystem production (GEP) in 2006. □ Huaining site, ■Yueyang Site.

Conclusions

Our study encompassed observations of EC fluxes in 7-year-old and an 18-year-old poplar plantations along the middle and lower reaches of the Yangtze River. This study reinforces the importance of the carbon cycle in poplar plantations. We conclude that (a) annual NEE between the two sites was almost undistinguishable, given the degree of uncertainty. Both sites are strong carbon sinks, similar to other poplar plantations. Furthermore, age had no obvious effect on carbon budget; the difference in annual NEE between two sites was only 11 g C m^{-2} yr^{-1}. (b) The environmental analysis provided new insight into the importance of canopy duration as the dominant climatic influence on annual NEE in poplar forests. Seasonal variability in GEP was controlled primarily by canopy duration and secondarily by radiation, whereas seasonal variability in Reco was controlled primarily by temperature and secondarily by flooding events. GEP was lower at the Huaining site, at 88% of the value recorded at the Yueyang site. Both sites reach a maximum monthly GEP in July: 276 g C m^{-2} mon^{-1} at the Huaining and 354.7 g C m^{-2} mon^{-1} in the younger and denser plantation at the Yueyang site. We believe that the lower growing season GEP at the Huaining site was mainly the result of a lower canopy apparent quantum yield and due to a lower LAI. The reduced LAI was the result of thinner stems and shorter growing days at the Huaining site. Because the effects of temperature on Reco and GEP partially offset each other, seasonal variability in canopy duration was the dominant influence on NEE. (c) The younger plantation had a slightly higher carbon uptake capacity than the mature plantation, and other poplar plantations show a similar instantaneous carbon exchange rate (about 25-35 μmol m^{-2} s^{-1}). The principal influence on the daytime NEE at both sites was radiation. The ecosystem α values recorded in the middle of the 2006 growing season at both sites were much higher than the values in three typical forest ecosystems along the north-south transect in eastern China [28].

Acknowledgements

This paper is based on the project supported by the USCCC (US-China Carbon Consortium) and The National Natural Science Foundation of China (No. 41071334), the authors would like to thank Yan Wang and Zhaoyan Wang for the field work and data analysis.

References

[1]FAO 2007. Country Profile China. Forestry Department, FAO, Rome.

[2]Fang, S., Xue, J. and Tang, L. 2007. Biomass production and carbon sequestration potential in poplar plantations with different management patterns. J. Environ. Manage. **85**:672-679.

[3]Cannell, M. G. R. 2003. Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass Bioenerg. **24**:97-116.

[4]Righelato, R. and Spracklen, D. V. 2007. Carbon mitigation by biofuels or by saving and restoring forests? Sci. Total Environ. **17**(317):902.

[5]Christersson, L. 2008. Poplar plantations for paper and energy in the south of Sweden. Biomass Bioenerg. **32**(11):997-1000.

[6]Yemshanov, D. and McKenney, D. 2008. Fast-growing poplar plantations as a bioenergy supply source for Canada. Biomass Bioenerg. **32**(3):185-197.

[7]Zha, T. 2007. Carbon Balance of a Poplar Plantation Ecosystem in Daxing, Beijing. Doctoral thesis, Beijing Forestry University, Beijing .

[8]Migliavacca, M., Meroni, M., Manca, G., Matteucci, G., Montagnani L., Grassi, G., Zenone, T., Teobaldelli, M., Goded, I., Colombo, R. and Seufert, G. 2009. Seasonal and interannual patterns of carbon and water fluxes of a poplar plantation under peculiar eco-climatic conditions. Agr. Forest Meteorol. **149**(9):1460-1476.

[9]Wilske, B., Lu, N., Wei, L., Chen, S., Zha, T., Liu, C., Xu, W., Noormets, A., Huang, J., Wei, Y., Chen, J., Zhang, Z., Ni, J., Sun, G., Guo, K. McNulty, S., John, R., Han, X., Lin, G. and Chen, J. 2009. Poplar plantation has the potential to alter the water balance in semiarid Inner Mongolia. J. Environ. Manage. **90**:2762-2770.

[10]Feng, Y., Ju, G. and Zhu, C. 2003. Responses of photosynthesis and PV2 parameters to water stress in poplar clone seedlings. Scientia Silvae Sinicae **39**(3):30-36.

[11]Jiang, G. 2004. Plant Ecophysiology. Higher Education Press, Beijing.

[12]Zhang, J., Zhang, Z., Zha, T., Chen, J., Sun, G., Liu, C., Cui, L., Chen, J. and Shen, L. 2006. Physiological regulations of photosynthesis in a poplar plantation on a sandy soil. Acta Ecologica Sinica **26**(5):1523-1532.

[13]Calfapietra, C., Tulva, I., Eensalu, E., Perez, M., De Angelis, P., Scarascia-Mugnozza, G. and Kull, O. 2005. Canopy profiles of photosynthetic parameters under elevated CO_2 and N fertilization in a poplar plantation. Environ. Pollut. **137**(3):525-535.

[14]Fang, S., Xu, X., Lu, S. and Tang, L. 1999. Growth dynamics and biomass production in short-rotation poplar plantations: 6-year results for three clones at four spacings. Biomass Bioenerg. **17**(5):415-425.

[15]Jiang, G. M., Han, X. G. and Wu, J. 2006. Restoration and management of the Inner Mongolia grassland require a sustainable strategy. Ambio **35**:269-270.

[16]Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, Ch., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. and Vesala, T. 2000. Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Adv. Ecol. Res. **30**:113-175.

[17]Wilczak, J. M., Oncley, S. P. and Stage, S. A. 2001. Sonic anemometer tilt correction algorithms. Bound-Lay. Meteorol. **99**:127-150.

[18]Webb, E. K., Pearman, G. I. and Leuning, R. 1980. Corrections of flux measurements for density effects due to heat and water vapor transfer. Quart. J. R. Meteorol. Soc. **106**:85-100.

[19]Glenn, A. J., Flanagan, L. B., Syed, K. H. and Carlson, P. J. 2006. Comparison of net ecosystem CO_2 exchange in two peatlands in western Canada with contrasting dominant vegetation, *Sphagnum* and *Carex*. Agr. Forest Meteorol. **140**:115-135.

[20]Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B. E., Meyers, T., Moncrieff, J., Moors, E., Munger, J. W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K. and Wofsy, S. 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agr. Forest Meteorol. **107**:43-69.

[21]Goulden, M. L., Munger, J. W., Fan, S. M., Daube, B. C. and Wofsy, S. C. 1996. Measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy. Global Change Biol. **2**:169-182.

[22]Lee, X., Massman, W. and Law, B. (eds) 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publishers, Dordrecht, 250 p.

[23]Flanagan, L. B., Wever, L. A. and Carlson, P. J. 2002. Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland. Global Change Biol. **8**:599-615.

[24] Law, B. E., Falge, E., Gu, L., Baldocchi, D. D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A. J., Falk, M., Fuentes, J. D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I. A., Jarvis, P., Jensen, N.O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw U, K. T., Thorgeirsson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K. and Wofsy, S. 2002. Environmental controls over carbon dioxide and water

vapor exchange of terrestrial vegetation. Agr. Forest Meteorol. **113**:97-120.

[25]Suyker, A. E. and Verma, S. B. 2001. Year-round observations of the net ecosystem exchange of carbon dioxide in a native tallgrass prairie. Global Change Biol. **7**:279-289.

[26]Griffis, T. J., Black, T. A., Morgenstern, K., Barr, A. G., Nesic, Z., Drewitt, G. B., Gaumont-Guay, D. and McCaughey, J. H. 2003. Ecophysiological controls on the carbon balances of three southern boreal forests. Agr. Forest Meteorol. **117**:53-71.

[27]Hirata, R., Hirano, T., Saigusa, N., Fujinuma, Y., Inukai, K., Kitamori, Y., Takahashi, Y. and Yamamoto, S. 2007. Seasonal and interannual variations in carbon dioxide exchange of a temperate larch forest. Agr. Forest Meteorol. **147**:110-124.

[28]Zhang, L., Yu, G., Sun, X., Wen, X., Ren, C., Song, X., Liu, Y., Guan, D., Yan, J. and Zhang, Y. 2006. Seasonal variation of carbon exchange of typical forest ecosystems along the eastern forest transect in China. Sci. China Ser. D **49**:47-62.

[29]Liu, Y., Yu, G., Wen, X.,Wang, Y., Song, X., Li, J., Sun, X., Yang, F., Chen, Y. and Liu, Q. 2006. Seasonal dynamics of CO_2 fluxes from subtropical plantation coniferous ecosystem. Sci. China Ser. D **49**:99-109.

[30]Wu, J., Guan, D., Sun, X., Yu, G., Zhao, X., Han, S. and Jin, C. 2005. Eddy flux corrections for CO_2 exchange in broad-leaved Korean pine mixed forest of Changbai Mountains. Sci. China Ser. D **48**:106-115.

[31]Zhang, J. H., Han, S. J. and Yu, G. R. 2006. Seasonal variation in carbon dioxide exchange over a 200-year-old Chinese broad-leaved Korean pine mixed forest. Agr. Forest Meteorol. **137**(3-4):150-165.

[32]Zhang, L. M, Yu, G. R., Sun, X. M., Wen, X. F., Ren, C. Y., Fu, Y. L., Li, Q. K., Li, Z. Q., Liu, Y. F., Guan, D. X. and Yan, J. H. 2006. Seasonal variations of ecosystem apparent quantum yield (alpha) and maximum photosynthesis rate (P-max) of different forest ecosystems in China. Agr. Forest Meteorol. **137**:176-187.

[33]Kellomaki, S. and Wang, K. Y. 2000. Short-term environmental controls on carbon dioxide flux in a boreal coniferous forest: Model computation compared with measurements by eddy covariance. Ecol. Model. **128**:63-88.

[34]Falge, E., Tenhunen, J., Baldocchi, D., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Bonnefond, J. M., Burba, G., Clement, R., Davis, K. J., Elbers, J. A., Falk, M., Goldstein, A. H., Grelle, A., Granier, A., Grünwald, T., Gumundsson, J., Hollinger, D., Janssens, I. A., Keronen, P., Kowalski, A. S., Katul, G., Law, B. E., Malhi, Y., Meyers, T., Monson, R. K., Moors, E., Munger, J. W., Oechel,W., Paw U, K. T., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Thorgeirsson, H., Tirone, G., Turnipseed, A., Wilson, K. and Wofsy, S. 2002. Phase and amplitude of ecosystem carbon release and uptake potentials as derived from FLUXNET measurements. Agr. Forest Meteorol. **113**:75-95.

[35]Liu, Y., Song, X., Yu, G., Sun, X., Wen, X. and Chen, Y. 2005. Seasonal variation of CO_2 flux and its environmental factors in evergreen coniferous plantation. Sci. China Ser. D **48**:123-132.

[36]Gu, F., Cao, M., Wen, X., Liu Y. and Tao, B. 2006. A comparison between simulated and measured CO_2 and water flux in a subtropical coniferous forest. Sci. China Ser. D **49**:241-251.

[37]Ibrom, A., Jarvis, P. G.,Clement, R., Morgenstern, K., Oltchev, A., Medlyn, B.E., Wang, Y. P., Wingate,L., Moncrieff, J. B. and Gravenhorst, G. 2006. A comparative analysis of simulated and observed photosynthetic CO_2 uptake in two coniferous forest canopies.Tree Physiol. **26**:845-864.

[38]Zerbe, S. 2003. Vegetation and future natural development of plantations with the black poplar hybrid *Populus x euramericana* Guinier introduced to Central Europe. Forest Ecol. Manage. **179**:293-309.

[39]Barrio-Anta, M., Sixto-Blanco, H., De Viñas, I. C. R. and Castedo-Dorado, F. 2008. Dynamic growth model for I-214 poplar plantations in the northern and central plateaux in Spain. Forest Ecol. Manage. **255**:1167-1178.

[40]Dennis, B. 2008. Breathing of the terrestrial biosphere: Lessons learned from a global network of carbon dioxide flux measurement systems. Aust. J. Bot. **56**:1-26.

[41]Tian, H., Melillo, J. M., Kicklighter, D. W., McGuire, A. D., Helfrich Iii, J., Moore Iii, B. and Vörösmarty, C. J. 2000. Climatic and biotic controls on annual carbon storage in Amazonian ecosystems. Global Ecol. Biogeogr. **9**:315-335.

[42]Rambal, S., Ourcival, J. M., Joffre, R., Mouillot, F., Nouvellon, Y., Reichstein, M. and Rocheteau, A. 2003. Drought controls over conductance and assimilation of a Mediterranean evergreen ecosystem: Scaling from leaf to canopy. Global Change Biol. **9**:1813-1824.

[43]Ciais, P. H., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, Chr., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M. J., Schulze, E. D., Vesala, T. and Valentini, R. 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature **437**:529-533.

[44]Kljun, N., Black, T., Griffis, J., Barr, A. G., Gaumont-Guay, D., Morgenstern, K., McCaughey, J. H. and Nesic, Z. 2006. Response of net ecosystem productivity of three boreal forest stands to drought. Ecosystems **9**:1128-1144.

[45]Reichstein, M., Ciais, P., Papale, D., Valentini, R., Running, S., Viovy, N., Cramer, W., Granier, A., Ogee, J., Allard, V., Aubinet, M., Bernhofer Chr., Buchmann, N., Carrara, A., Grünwald, T., Heimann, M., Heinesch, B., Knohl, A., Kutsch, W., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Pilegaard, K., Pumpanen, J., Rambal, S., Schaphoff, S., Seufert, G., Soussana, J. F., Sanz, M. J., Vesala, T. and Zhao, M. 2007. Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: A joint flux tower, remote sensing and modelling analysis. Global Change Biol. **13**:634-651.

[46]Urban, O., Janouš, D., Acosta, M., Czerni, R., Marková, I., Navrátil, M., Pavelka, M., Pokorni, R., Šprtová, M., Zhang, R., Špunda, V., Grace, J. and Marek,M.V. 2007. Ecophysiological controls over the net ecosystem exchange of mountain spruce stand. Comparison of the response in direct vs. diffuse solar radiation. Global Change Biol. **13**:157-168.

[47]Irvine, J., Law, B. E., Kurpius, M. R., Anthon, P. M., Moore, D. and Schwarz, P. A. 2004. Age-related changes in ecosystem structure and function and effects on water and carbon exchange in ponderosa pine. Tree Physiol. **24**:753-763.

[48]Humphreys, E. R., Black, T. A., Morgenstern, K., Cai, T., Drewitt, G. B., Nesic, Z. and Trofymow, J. A. 2006. Carbon dioxide fluxes in coastal Douglas-fir stands at different stages of development after clearcut harvesting. Agr. Forest Meteorol. **140**:6-22.

[49]Schwalm, C. R., Black, T. A., Morgenstern, K.and Humphreys, E. R. 2007. A method for deriving net primary productivity and component respiratory fluxes from tower-based eddy covariance data: A case study using a 17-year data record from a Douglas-fir chronosequence. Global Change Biol. **13**:370-385.

[50]Kolari, P., Pumpanen, J., Rannik, Ü., Ilvesniemi, H., Hari, P. and Berninger, F. 2004. Carbon balance of different aged Scots pine forests in Southern Finland. Global Change Biol. **10**:1106-1119.

[51]Van Dijk, A. and Dolman, A. J. 2004. Estimates of CO_2 uptake and release among European forests based on eddy covariance data. Global Change Biol. **10**:1445-1459.

[52]Hirata, R., Saigusa, N., Yamamoto, S., Ohtani, Y., Ide, R., Asanuma, J., Gamo, M., Hirano, T., Kondo, H., Kosugi, Y., Li, S., Nakai, Y., Takagi, K., Tani, M. and Wang, H. 2008. Spatial distribution of carbon balance in forest ecosystems across East Asia. Agr. Forest Meteorol. **148**:761-775.