



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

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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 CO₂ 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 CO₂ 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"E, 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 CO₂ 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. CO₂ 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 CO₂ 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 methodology¹⁶. A triple-coordinate rotation was performed to align the normal mean vertical velocity measurements to the mean wind streamlines prior to scalar flux calculations¹⁷. The WPL correction was used to eliminate the effect on flux¹⁸. A storage term was added to the calculated CO₂ fluxes to determine NEE; this term was estimated using the single-level measurements of CO₂ concentration with the open-path IRGA¹⁹.

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 μmol 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 form²⁰:

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

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 CO₂ release into the atmosphere and negative values indicate CO₂ 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):

$$\text{GEP} = \text{NEE} - \text{Reco} \quad (3)$$

At the half-hour scale, the units of CO₂ flux were $\mu\text{mol m}^{-2} \text{s}^{-1}$, while at daily, monthly, and annual scales, the units were converted into $\text{g C m}^{-2} \text{day}^{-1}$, $\text{g C m}^{-2} \text{mon}^{-1}$ and $\text{g C m}^{-2} \text{yr}^{-1}$, 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 m² 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 m² m⁻² at the Yueyang site, which was about 25% higher than that observed at Huaining. 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 CO₂ 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 $-37.7 \mu\text{mol m}^{-2} \text{s}^{-1}$; with the onset of senescence in mid October, NEE decreased to $-7 \mu\text{mol m}^{-2} \text{s}^{-1}$. 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 $-20.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ in May and July. Huaining usually had weak carbon exchange rates; the peak NEE value recorded in August in Huaining was about $-22 \mu\text{mol m}^{-2} \text{s}^{-1}$, 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 curve²⁵, 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

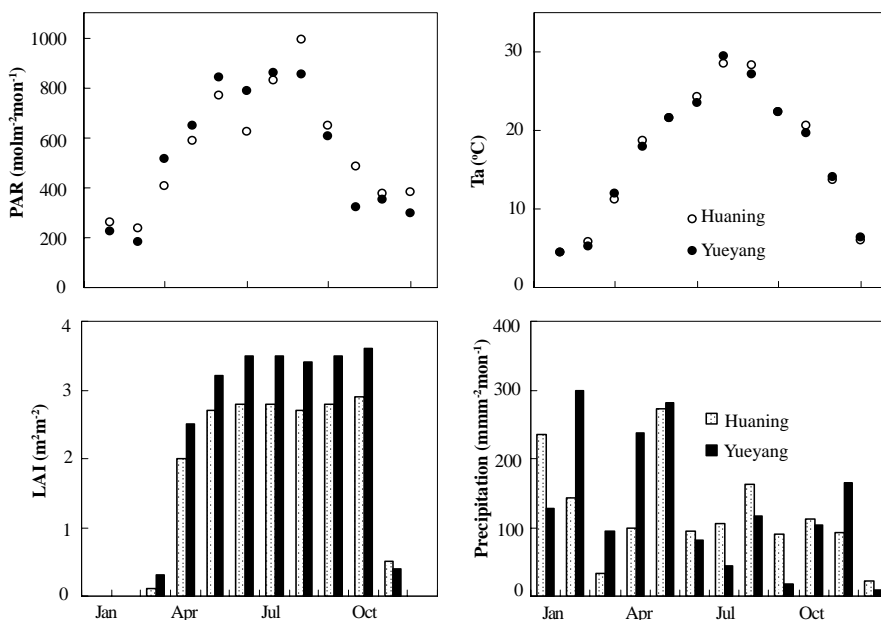


Figure 1. Monthly total photosynthetic active radiation (PAR), monthly average air temperature (Ta), Leaf Area Index (LAI) and monthly precipitation above-canopy.

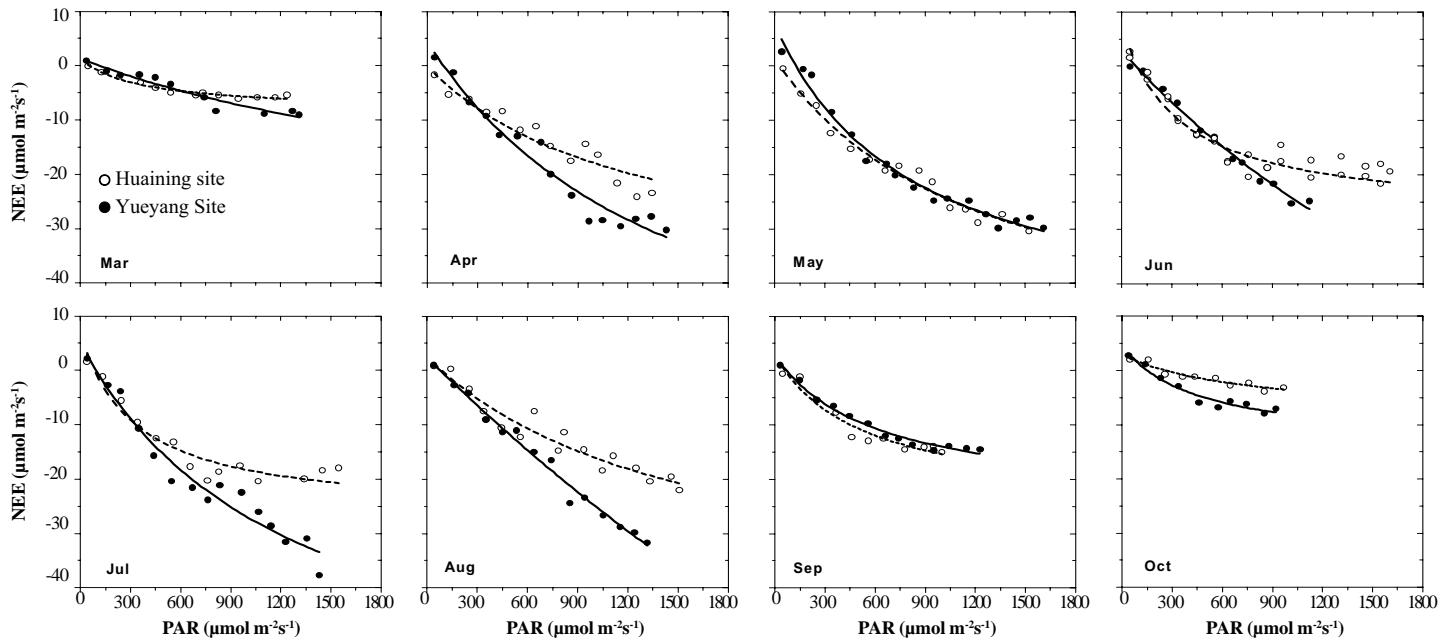


Figure 2. Comparison of NEE-PAR response curves during peak growth conditions.

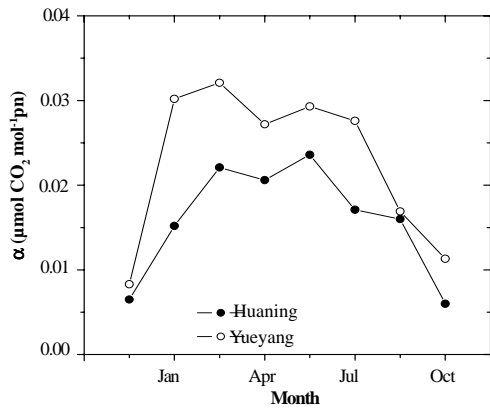


Figure 3. Seasonal pattern of apparent quantum yield (α).

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 $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ photon}$. A sharp increase in α to 0.0302 $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ photon}$ occurred in Yueyang in April, bringing α very close to the peak value (0.0321 $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ photon}$) recorded in Yueyang in May. The greatest and smallest differences in α between the two sites were 0.015 and 0.0009 $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ photon}$, 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 LAI²⁶. 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). CO₂ 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 CO₂ uptake

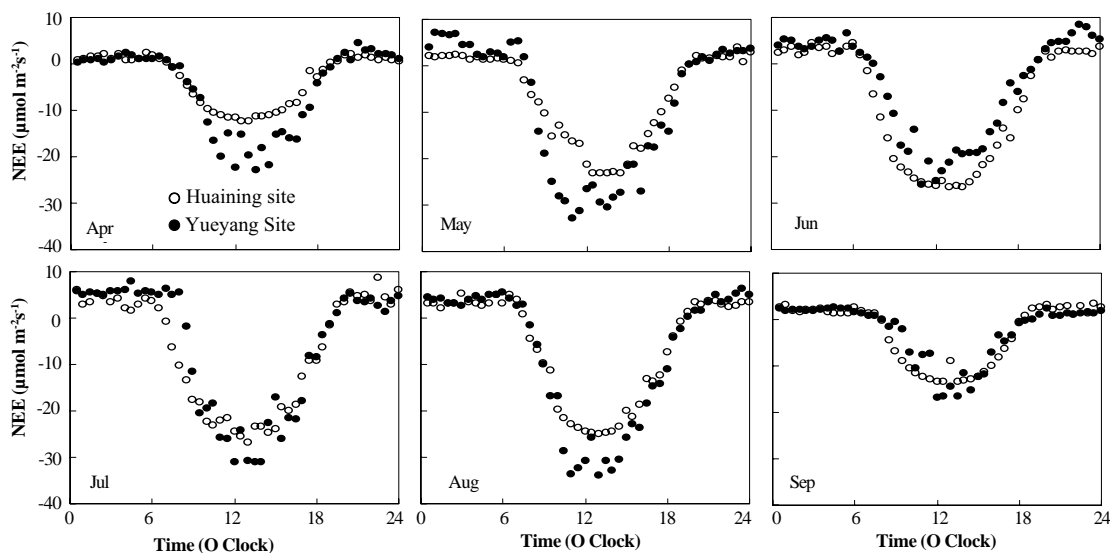


Figure 4. Three-day averaged diurnal course of net carbon exchange (NEE) during growing season.

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 $-12.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ in April to $-23.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ in May, then to about $-26.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ from June to August and $-13.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ 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 $-16.6 \mu\text{mol m}^{-2} \text{s}^{-1}$). 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 $-26.8 \mu\text{mol m}^{-2} \text{s}^{-1}$, which was only 78.9% of the observed value at Yueyang ($34.0 \mu\text{mol m}^{-2} \text{s}^{-1}$). 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 $-28 \mu\text{mol m}^{-2} \text{s}^{-1}$. Yueyang had a higher maximum CO_2 exchange, at $-34.0 \mu\text{mol m}^{-2} \text{s}^{-1}$. This value is close to that measured in a larch forest in Japan²⁷. Overall, poplar plantations had more efficient carbon capture compared to the three typical forest ecosystems along the north-south transect in eastern China²⁸ as a subtropical coniferous plantation in Jiangxi Province²⁹, a temperate broad-leaved Korea pine mixed forest in northeastern China^{30,31} and a subtropical evergreen broadleaf forest in southern China³². A cultivated larch forest in Japan had the same peak CO_2 exchange rate as the Yueyang site²⁷, but maximum CO_2 uptake during day in most nature forest ecosystems in temperate zone is lower than that recorded on the poplar plantations³³⁻³⁷. 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: $-9.8 \text{ g C m}^{-2} \text{ d}^{-1}$ in mid-June at Huaining and $-9.9 \text{ g C m}^{-2} \text{ d}^{-1}$ 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 ($10.95 \text{ g C m}^{-2} \text{ d}^{-1}$).

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

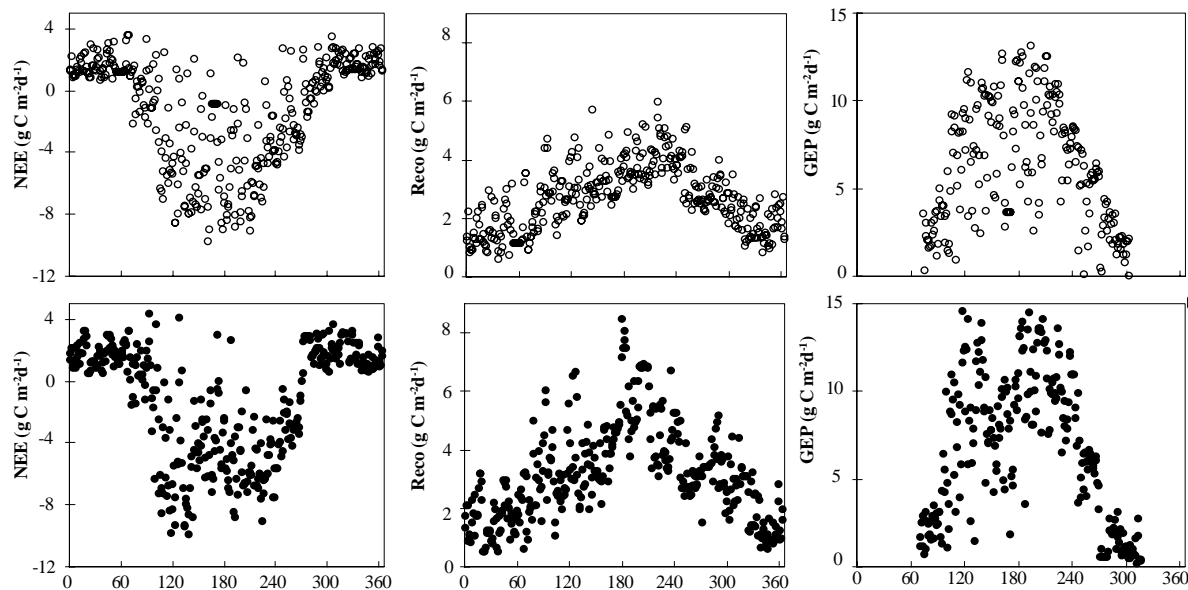


Figure 5. Seasonal patterns of net carbon exchange (NEE), ecosystem respiration (Reco) and gross ecosystem production (GEP) in 2006. ○ Huaining site, ● Yueyang Site.

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 CO₂ 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 CO₂ 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 CO₂ 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 C⁴⁹. 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 sink⁵⁰. 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 years². 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, respectively⁷⁻⁸. 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 processes 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 plantation³¹. A poplar plantation in Beijing had nearly same annual NEE, at 4.62 t C ha⁻¹ yr⁻¹. 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 CO₂ from the atmosphere^{24, 34, 51, 52}.

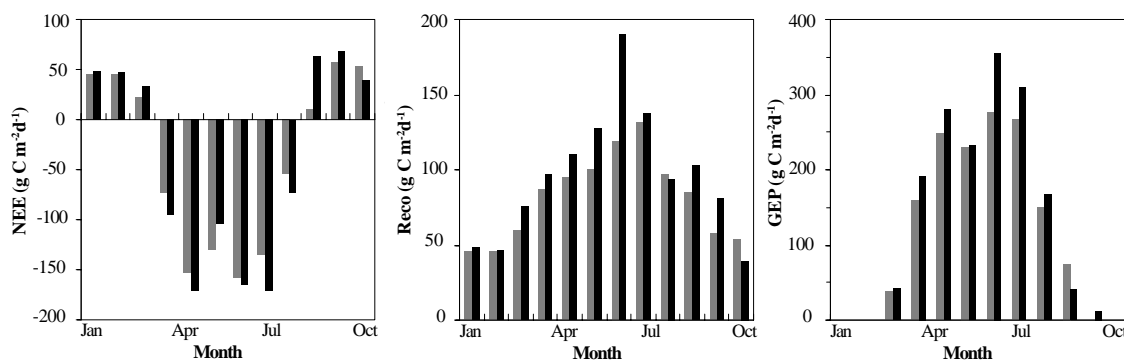


Figure 6. Monthly total net carbon exchange (NEE), ecosystem respiration (Reco) and gross ecosystem production (GEP) in 2006. □ Huaining site, ■ Yueyang Site.

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 $11 \text{ g C m}^{-2} \text{ yr}^{-1}$. (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: $276 \text{ g C m}^{-2} \text{ mon}^{-1}$ at the Huaining and $354.7 \text{ g C m}^{-2} \text{ mon}^{-1}$ 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 $25\text{-}35 \mu\text{mol m}^{-2} \text{ s}^{-1}$). 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 China²⁸.

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