DOI: 10.1007/s11430-006-8226-1

# Carbon dioxide exchange and the mechanism of environmental control in a farmland ecosystem in North China Plain

LI Jun[1,2], YU Qiang[1], SUN Xiaomin[1], TONG Xiaojuan[3], REN Chuanyou[1], WANG Jing[1], LIU Enmin[1], ZHU Zhilin[1] & YU Guirui[1]

1. Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China;
2. Graduate University of the Chinese Academy of Sciences, Beijing 100049, China;
3. College of Resources and Environmental studies, Beijing Forestry University, Beijing 100083, China
Correspondence should be addressed to Li Jun (email: lijun@igsnrr.ac.cn)

Received October 27, 2005; accepted March 11, 2006

**Abstract** $CO_2$ flux was measured continuously in a wheat and maize rotation system of North China Plain using the eddy covariance technique to study the characteristic of $CO_2$ exchange and its response to key environmental factors. The results show that nighttime net ecosystem exchange (NEE) varied exponentially with soil temperature. The temperature sensitivities of the ecosystem ($Q_{10}$) were 2.94 and 2.49 in years 2002−2003 and 2003−2004, respectively. The response of gross primary productivity (GPP) to photosynthetically active radiation (PAR) in the crop field can be expressed by a rectangular hyperbolic function. Average $A_{max}$ and $\alpha$ for maize were more than those for wheat. The values of $\alpha$ increased positively with leaf area index (LAI) of wheat. Diurnal variations of NEE were significant from March to May and from July to September, but not remarkable in other months. NEE, GPP and ecosystem respiration ($R_{ec}$) showed significantly seasonal variations in the crop field. The highest mean daily $CO_2$ uptake rate was −10.20 and −12.50 $gC \cdot m^{-2} \cdot d^{-1}$ in 2003 and 2004, for the maize field, respectively, and −8.19 and −9.50 $gC \cdot m^{-2} \cdot d^{-1}$ in 2003 and 2004 for the wheat field, respectively. The maximal $CO_2$ uptake appeared in April or May for wheat and mid-August for maize. During the main growing seasons of winter wheat and summer maize, NEE was controlled by GPP which was chiefly influenced by PAR and LAI. $R_{ec}$ reached its annual maximum in July when $R_{ec}$ and GPP contributed to NEE equally. NEE was dominated by $R_{ec}$ in other months and temperature became a key factor controlling NEE. Total NEE for the wheat field was −77.6 and −152.2 $gC \cdot m^{-2} \cdot a^{-1}$ in years 2002−2003 and 2003−2004, respectively, and −120.1 and −165.6 $gC \cdot m^{-2} \cdot a^{-1}$ in 2003 and 2004 for the maize field, respectively. The cropland of North China Plain was a carbon sink, with annual −197.6 and −317.9 $gC \cdot m^{-2} \cdot a^{-1}$ in years 2002−2003 and 2003−2004, respectively. After considering the carbon in grains, the cropland became a carbon source, which was 340.5 and 107.5 $gC \cdot m^{-2} \cdot a^{-1}$ in years 2002−2003 and 2003−2004, respectively. Affected by climate and filed managements, inter-annual carbon exchange varied largely in the wheat and maize rotation system of North China Plain.

www.scichina.com www.springerlink.com

**Keywords: net ecosystem exchange, gross primary productivity, ecosystem respiration, carbon budget, eddy covariance, winter wheat, summer maize.**

As a core study of global change and regional sustainable development, the research on carbon cycle in terrestrial ecosystems chiefly focuses on net carbon balance in ecosystems. Micrometeorological and chamber-based methods are main approaches to carbon flux measurements in ecosystems. Micrometeorological methods are widely considered as the most reliable and practicable approaches to long-term carbon flux measurement of ecosystems[1,2]. Among various micrometeorological methods, the eddy covariance technique was used by most researchers for its high precision, no need for emendation of diffuse coefficient and stratification stability, and continuous direct measurements of energy and mass flux without disturbing the land surface. The eddy covariance technique has been used to research $CO_2$ exchange between biosphere and atmosphere in many countries and regions one after the other (e.g. AmeriFlux, EUROFlux, AsiaFlux and ChinaFLUX)[3]. Generally, compared with forest ecosystems, farmland ecosystems are regarded as relatively weak sources or sinks. However, recent researches show that farmland can have equal or greater net ecosystem production (NEP) than the natural ecosystems that were converted for crop production[4–6].

Farmland ecosystems, the most active part in global carbon pool, are greatly affected by human activities (e.g. cultivation, irrigation and fertilization), which lead to large variations of net ecosystem exchange (NEE) of $CO_2$. It is evident that farmland ecosystems, especially in mid-latitudes, are strong contributors to regional carbon budget[7]. Agricultural managements and cross-breeding changed remarkably during the past 30 years. The variations (e.g. no-till, residues returned to fields and increased the crop yield) affected the amount of $CO_2$ from atmosphere to plants and $CO_2$ emission from decomposition of residue and soil organic matter[8]. North China Plain is the main area of food production in China. The cultivation areas of wheat and maize in this region account for half and a quarter in the whole country, respectively. Therefore, it is very important to estimate the regional carbon budget and research the mechanism of $CO_2$ exchange in the farmland ecosystem in North China Plain.

There are obvious diurnal, seasonal and annual variations of NEE in ecosystems with vegetations. Based on long-term monitoring $CO_2$ and water vapor flux, people have deeply understood how environmental factors (e.g. temperature, moisture and radiation) force the carbon cycle[9]. However, most of long-term flux measurements of $CO_2$ have been conducted in forest ecosystems and few of them were in grassland and farmland ecosystems[9–12]. A few researches on $CO_2$ flux have been done in farmland but most of them were measured during the growing season, and $CO_2$ loss during the period of fallow was neglected[13–15]. The lack of annual measurements of $CO_2$ exchange in farmland ecosystems decreases the accuracy of assessments on the function of farmland ecosystems in global carbon balance[16]. Based on two years' continuous $CO_2$ eddy-flux measurement, the objects of this study are to research net ecosystem exchange of $CO_2$ in a farmland and its partitioning in the plant and soil, to analyze main controlling factors on diurnal, seasonal and annual variations of $CO_2$ exchange, and to provide theory and data for process modeling research and accurate estimation on regional and global carbon budget.

## 1 Materials and methods

### *1.1 Study site*

The study was carried out at Yucheng Comprehensive Experimental Station (36°57′N, 116°38′E, 23.4 m elev.), Chinese Academy of Sciences. The station is located in North China Plain within the east monsoon region, with a semi-humid and warm temperate climate. Mean annual temperature, precipitation and solar radiation at the area in the past 30 years were 13.1℃, 528 mm and 5225 $MJ \cdot m^{-2}$, respectively. Summer precipitation accounting for nearly 70% of the whole year showed an asymmetric seasonal pattern. Parent materials of the soils are alluviums by the Yellow River. Soil texture of root zone is sandy loam. Soil organic matter and pH value are 1.21% and 7.9−8.0, respectively. Winter wheat and summer maize are planted for rotation in a year. Farmland managements are shown in Table 1. The natural situation and planting systems of the station are typical in North China Plain.

### *1.2 Field measurement*

Eddy covariance system and microclimate gradient measurement system were located in the center of an even crop field with a large area. Wind speed, temperature, humidity and $CO_2$ concentration above canopy were simultaneously measured by an eddy covariance system with a three-dimensional sonic anemometer (model CSAT3, Campbell Sci. Inc., USA), an open-path and fast response infrared gas analyzer (model LI-7500, Li-Cor Inc., USA) at 2.80 m height averagely. All of the above raw data were collected continuously at 10 Hz with a Campbell Scientific data logger (model CR5000, Campbell Sci. Inc., USA), and the 30 min mean data were output.

Microclimate gradient measurement system involved anemometers (model AR-100, Vector Instruments, UK) and psychrometers (model HMP-45C, Vaisala, Finland) at heights of 2.20 and 3.40 m averagely. Photosynthetically active radiation was measured with a quantum sensor (Li-190SB, Li-Cor Inc., USA). Heights of sensors changed with crop growth. During observation periods, wind fetch length was more than 200 m and met well the requirement of micrometeorological gradient measurement. Soil heat flux was determined by two soil-heat-flux plates (Hukseflux, Netherland) buried at 2 cm depth below soil surface. Soil temperature transducers were placed at the depths of soil surface, 10 and 30 cm. Soil moisture sensors were installed at 10 cm and 30 cm depths. Soil moisture was monitored with time domain reflectometry (TDR). Solar radiation, net radiation, air pressure and precipitation were also measured. All apparatuses were controlled with a data logger (model CR23x, Campbell Sci., USA), and the data were stored at intervals of 30 min. All sensors used in the experiment were calibrated strictly. Biomass and leaf area of winter wheat and summer maize were observed weekly during the growing season.

### *1.3 Flux calculations*

Vertical transfer of mass and energy is directly measured by the frequency of turbulence movement in the surface layer. Fluxes of momentum, heat, water vapor and trace gases were determined with the eddy covariance method directly measuring the fluctuation of temperature, humidity, wind velocity and gas concentration. According to Renolds theory, the vertical $CO_2$ flux ($F_c$) can be expressed as follows:

$$\overline{F_c} = \overline{wc_c} = \overline{w}\,\overline{c_c} + \overline{w'c_c'} \tag{1}$$

where $w$ is vertical wind speed and $c_c$ is $CO_2$ concentration. Overbars indicate an averaging operation, and primes denote deviations from the mean. The average vertical wind speeds cannot be directly measured because they are usually less than 1 $mm \cdot s^{-1}$. However, $\overline{w}$ could be calculated if sensible heat flux and water vapor flux ($H$ and $E$) are known. According to Webb-Pearman-Leuning algorithm[17,18], $CO_2$ flux can be computed as follows:

$$\overline{F_c} = \overline{w'c_c'} + \overline{c_c}\left[\frac{\overline{E}}{\overline{c}} + \frac{\overline{H}}{\overline{\rho c_p \theta}}\right], \tag{2}$$

where $c$ is total molar concentration; $\rho$ is the air density; $c_p$ is the specific heat capacity at constant pressure, and $\theta$ is potential temperature.

When atmospheric stratification is stable and turbulence is weak at night, $CO_2$ released from soil and plants hardly arrives to the height of instruments. Pre-

Table 1 Management details in winter wheat and summer maize field

| Crop | Breed | Sowing date | Applied N before sowing ($kgN \cdot ha^{-1}$) | Applied N after sowing ($kgN \cdot ha^{-1}$) | Irrigation (mm) | Harvest date |
|---|---|---|---|---|---|---|
| Winter wheat | Keyu 13 | October 15, 2002 | 84.4 | 172.5 | 225.0 | June 8, 2003 |
| Summer maize | Ludan 981 | June 14, 2003 | | 281.3 | | September 27, 2003 |
| Winter wheat | Keyu 13 | October 23, 2003 | 90.0 | 245.3 | 262.5 | June 13, 2004 |
| Summer maize | Ludan 981 | June 20, 2004 | | 223.5 | | October 2, 2004 |

cision of instruments declined lead to low $CO_2$ fluxes. The threshold of wind friction velocity ($u^*$) can be determined using the relationship between the friction velocity ($u^*$) and $F_c$[11,19]. In our experiment, the threshold of velocity is 0.15 $m \cdot s^{-1}$. Fluxes will be eliminated when $u^*$ was smaller than 0.15 $m \cdot s^{-1}$. When dews appear in the morning and rainy days, the beads on the sensors of $CO_2/H_2O$ infrared gas analyzer can affect the results. Data appearing above and other data over normal range should be discarded during calculation[11]. The data deleted and missed due to the malfunction of instruments or power failure can be filled using the follow methods: (1) the missing data less than 2 h were filled using the linear interpolation; and (2) larger gaps (larger than 2 h) were filled using the Mean Diurnal Variation method.

## 2 Results and discussion

### 2.1 Conditions of climate, soil and vegetation

In order to research carbon dioxide exchange between a farmland and the atmosphere, it is necessary to understand the seasonal variations of key environmental factors. The variations of photosynthetically active radiation (PAR) were remarkably similar in both years 2002—2003 (from November 2002 to October 2003, the same below) and 2003—2004 (from November 2003 to October 2004, the same below) (Fig. 1(a)). Maximal and minimal PAR appeared in June and December, respectively. The annual average temperatures in years 2002—2003 and 2003—2004 were 12.6℃ and 13.4℃, respectively, near the perennial average (13.1℃) (Fig. 1(c)). Owing to continental monsoon climate, seasonal distribution of precipitation was asymmetric. Except for two strong rainfalls in spring and autumn 2003 (Fig. 1), most of the precipitation that fell in summer and spring was generally droughty. Precipitation was 674.5 and 860.8 mm in the years 2002—2003 and 2003—2004, respectively, which was 28% and 63% higher than perennial average (528 mm). Both annual and seasonal variations of soil moisture were large (Fig. 1(d)). Soil volumetric content at the depth of 10 cm ranged from 0.09 to 0.22 $m^3 \cdot m^{-3}$ for the year 2002—2003 and from 0.06 to 0.20 $m^3 \cdot m^{-3}$ for the year 2003—2004. For the wheat field, volumetric soil moisture at the depth of 10cm were 0.14 and 0.10 $m^3 \cdot m^{-3}$ in the 2002—2003 and 2003—2004 seasons, separately. That for the maize field was 0.16 and 0.17 $m^3 \cdot m^{-3}$ in 2003 and 2004, respectively.

The seasonal variations of green leaf area index (LAI) of winter wheat and summer maize during the measurement period are presented in Fig. 1(b). Winter wheat began to elongate in late March and early April 2003, and the peak of LAI (4.22) appeared in late April 2003. As temperature warmed up early in spring 2004, winter wheat returned green and elongated early and LAI increased rapidly. The maximal LAI (6.90) appeared in mid April 2004. Winter wheat grew well in 2004 mainly because of ample fertilization and irrigation (Table 1). Seasonal patterns of summer maize LAI were similar in two years. LAI of summer maize increased rapidly during the elongation stage in mid-late July. It reached peak in early-middle August, then declined slowly. Maximal LAI of summer maize were 5.32 in 2003 and 4.75 in 2004. Less fertilization and more precipitation in summer 2004 than in 2003 led to low LAI of summer maize in 2004 (Table 1).

### 2.2 Ecosystem respiration

Ecosystem respiration ($R_{ec}$) includes shoots respiration ($R_{as}$) and apparent soil respiration ($R_s$). $R_s$ can be divided into heterotrophic soil respiration ($R_h$) and autotrophic root respiration ($R_{ar}$). Temperature is the main factor controlling ecosystem respiration. Many researches showed that ecosystem respiration varied exponentially with temperature[20−23]. Their relationship can be expressed as follows:

$$R_{ec} = R_0 e^{kT_s}, \quad (3)$$

where $R_0$ is ecosystem respiration at a soil temperature of 0℃, and $K$ is an empirical coefficient. The relationship between ecosystem respiration and temperature could be obtained by nighttime NEE and the corresponding temperature. Daily average of nighttime NEE varied exponentially with soil temperature at 0—10 cm depth and were statistically significant at 0.01 level (Fig. 2). The temperature sensitivities of the ecosystem ($Q_{10}$) were 2.94 and 2.49 in years 2002—2003 and 2003—2004, respectively. $Q_{10}$ values in our experiment are higher than the value of 2 used as a

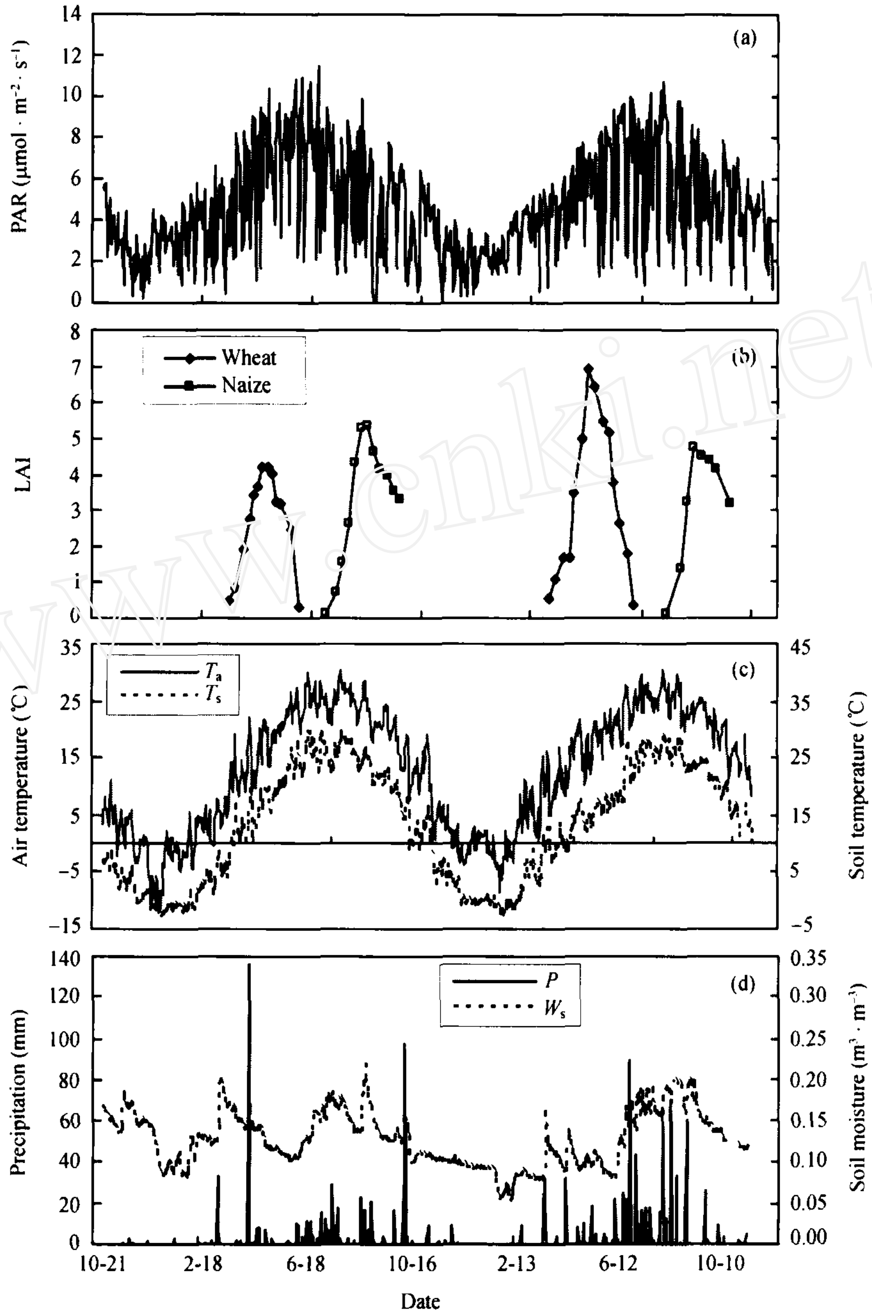


Fig. 1. Seasonal variations of environmental factors and LAI. (c) $T_s$, average soil temperature at 0—10 cm depth; $T_a$, air temperature; (d) $P$, precipitation; $W_s$, soil volumetric water content at 10 cm depth.

default in many respiration models[24]. Fig. 1 shows that nighttime NEE concentrated in the range of low soil temperature, and scattered when soil temperatures were higher than 10℃. The main reasons were that an increase in temperature improved plants to grow rapidly and enhanced the proportion of canopy respiration in ecosystem respiration.

When LAI was very small or close to zero in seedling, over winter or harvest stage), apparent soil respiration played an important role in agricultural ecosystem respiration and led to small $Q_{10}$ values which were 2.71 and 2.20 in the years 2002—2003 and 2003—2004, respectively. It coincided with the results obtained by the chamber method at the same site (average $Q_{10}$ value was 2.70 in winter wheat field in 2003[25]).

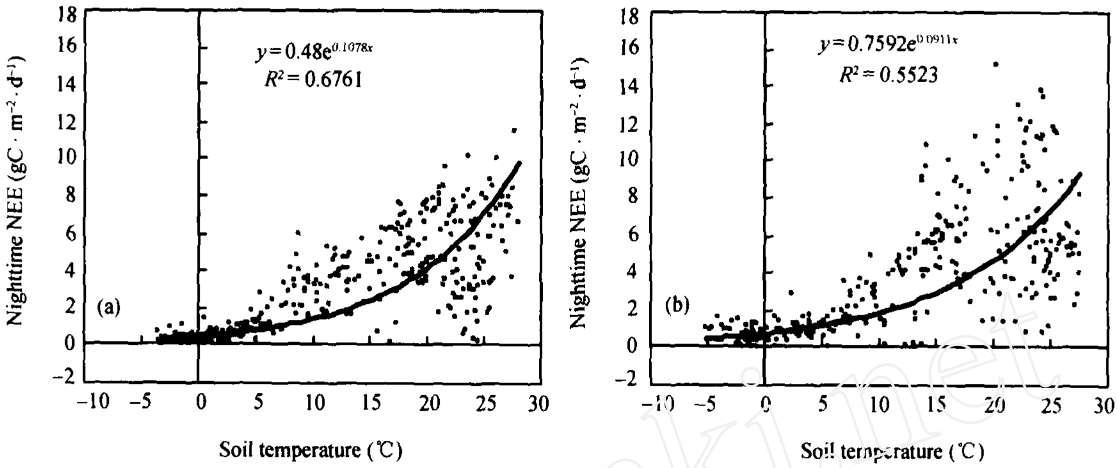


Fig. 2. The response of daily average nighttime NEE to soil temperature in the layer from 0 to 10 cm. (a) November 2002—October 2003; (b) November 2003—October 2004.

### 2.3 Gross primary productivity

Gross primary productivity (GPP) is composed of net ecosystem production (NEP) and ecosystem respiration ($R_{ec}$). GPP can be calculated as follows[26–28]:

$$GPP = NEP + R_{ec} = R_{ec} - NEE \quad (4)$$

where $R_{ec}$ is ecosystem respiration including nighttime and daytime respiration and can be calculated by eq. (3). Since $R_{ec}$ calculated by eq. (3) had high errors in June (after the harvest of winter wheat) with high soil temperature and in October (the period of tillage before wheat sowing), NEE was directly used to replace $R_{ec}$ during these periods when soil was bare. In addition, the extrapolation of $R_{ec}$ based on the relationship between nighttime $R_{ec}$ and temperature would overestimate daytime $R_{ec}$ because leaf respiration exhibited the restrain induced by light. The amount of overestimation is determined by the contribution of leaf respiration to $R_{ec}$ and its restrained degree[26]. However, eq. (3) and eq. (4) are the optimal approaches used in the eddy covariance method at present to estimate $R_{ec}$ and GPP.

For winter wheat and summer maize, GPP enlarged with increasing PAR (Fig. 3). According to Michaelis-Menten kinetics, the response of GPP to PAR can be expressed by a rectangular hyperbolic function[29]:

$$GPP = \frac{A_{max} Q_p}{K_m + Q_p}, \quad (5)$$

where $Q_p$ is incident PAR, $A_{max}$ the maximal assimilation rate when PAR trends to infinite, and $K_m$ Michaelis-Menten constant ($Q_p$ at which assimilation rate is one half of $A_{max}$). The apparent primary light use efficiency ($a$) can be expressed as follows[30]:

$$a = \frac{A_{max}}{K_m}. \quad (6)$$

The monthly and quarterly correlation coefficients of the light response curve were significant in the main growth seasons of winter wheat (from March to May, the same below) and summer maize (from July to September, the same below). Seasonal average $A_{max}$ and $a$ of summer maize were higher than those of winter wheat (Table 2). According to the mechanism of photosynthesis, light quantum efficiency of winter wheat ($C_3$ plant) should be higher than that of summer maize ($C_4$ plant) because $C_4$ plants need two ATP more than $C_3$ plants to assimilate 1 mole $CO_2$. In fact, $A_{max}$ and $a$ of $C_4$ plants are equal to or higher than those of $C_3$ plants because $C_3$ plants have light respiration[31]. Averagely, $A_{max}$ and $a$ of summer maize in our experiments were equal to or higher than the modeling results of $C_4$ plants reported by Ruimy *et al.*[32]. $A_{max}$ of the canopies for winter wheat and summer maize were higher than those observed at the same site by Lu *et al.*[33] and Ma *et al.*[34] using a photosynthetic instrument at leaf level. It may be a system error in different observations using different instruments.

$A_{max}$ could be used to judge whether plant physiological activity is strong or not. During the main growing seasons of winter wheat and summer maize, mean monthly $A_{max}$ increased at first and then declined,

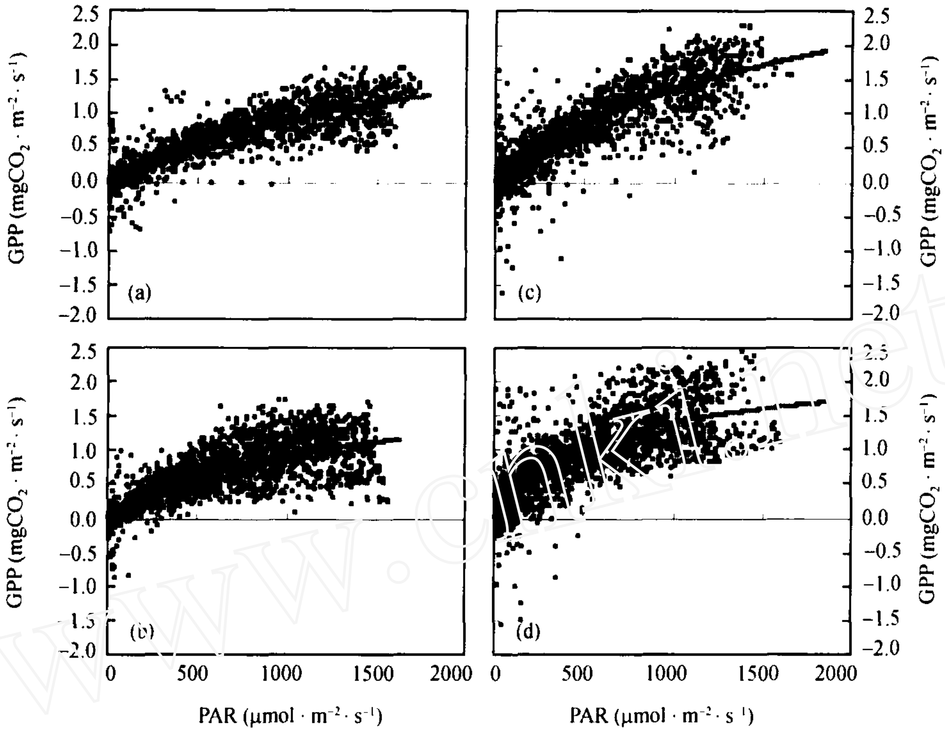


Fig. 3. The response of GPP to PAR for winter wheat and summer maize. (a) and (b) are winter wheat in 2003 and 2004, respectively; (c) and (d) are summer maize in 2003 and 2004, respectively.

Table 2 Seasonal variation of photosynthetic parameters for winter wheat and summer maize[a)]

| Crop | Year | Month | $A_{max}$ | $a$ | $K_m$ | $r^2$ | $n$ |
|---|---|---|---|---|---|---|---|
| Winter wheat | 2003 | Mar | 47.74 | 0.0205 | 2329 | 0.8371 | 96 |
| | | Apr | 56.52 | 0.0319 | 1774 | 0.7514 | 752 |
| | | May | 50.89 | 0.0378 | 1345 | 0.7763 | 754 |
| | | Mar—May | 54.95 | 0.0331 | 1661 | 0.7517 | 1602 |
| | 2004 | Mar | 30.12 | 0.0321 | 938 | 0.7011 | 493 |
| | | Apr | 54.59 | 0.0490 | 1113 | 0.8161 | 762 |
| | | May | 34.52 | 0.0427 | 809 | 0.6142 | 843 |
| | | Mar—May | 42.04 | 0.0416 | 1011 | 0.6548 | 2098 |
| Summer maize | 2003 | Jul | 81.46 | 0.0437 | 1865 | 0.7921 | 489 |
| | | Aug | 101.24 | 0.0535 | 1893 | 0.8069 | 683 |
| | | Sep | 47.37 | 0.0516 | 918 | 0.6333 | 529 |
| | | Jul—Sep | 85.66 | 0.0473 | 1811 | 0.7299 | 1701 |
| | 2004 | Jul | 27.89 | 0.1090 | 256 | 0.5954 | 341 |
| | | Aug | 72.84 | 0.0892 | 816 | 0.7277 | 779 |
| | | Sep | 44.11 | 0.0688 | 641 | 0.5988 | 718 |
| | | Jul—Sep | 51.20 | 0.0821 | 624 | 0.5638 | 1838 |

a) The units of $A_{max}$, $a$, $K_m$ were μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$, μmol $CO_2 \cdot$ μmol$^{-1}$ PAR and μmol PAR $\cdot m^{-2} \cdot s^{-1}$, respectively.

which showed the processes of crop growth, development and senescence (Table 2). Former researches showed that $a$ increased with an increase in LAI[35]. Similar results were found in our experiment in the winter wheat field (Fig. 4). The value of $a$ is an indication of weak light use efficiency of canopy. Usually, weak light reaching the ground is chiefly composed of scatter light. Before winter wheat elongated, short plants and small LAI led to a flat canopy structure that could absorb less scatter light. During and around the anthesis period, canopy height and LAI reached maxima. Favorable canopy structure had advantages to absorb scatter light from every direction. LAI decreased as leaves in the under-layer turned yellow gradually and fell in the late growing season of winter wheat. At this time, the canopy absorbed scatter light weakly. No similar results were found for summer maize mainly because of no effects of plant height and LAI on scatter light uptake by the sparse maize canopy.

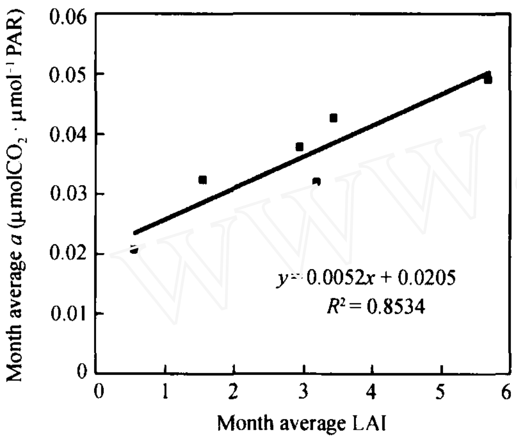


Fig. 4. Relationship between canopy *a* and LAI for winter wheat.

Light saturation point is an important index of plant need for light. It usually decreases under unsuitable environment conditions[31]. In the main growing seasons of winter wheat and summer maize, mean monthly $K_m$ ranged widely from 256 to 2329 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Annual difference of $K_m$ for a breed was more remarkable than its difference between two breeds. On seasonal average, half-saturation points of light in 2004 were only 1/3 or 2/3 of those in 2003. The reason may be that the arid spring and rainy summer in 2004 were not suitable for winter wheat and summer maize growth. Affected by *a*, seasonal variations of $K_m$ were not obvious (Table 2).

### 2.4 Diurnal variation of net carbon exchange

Fig. 5 shows that crop field was a weak source of $CO_2$ in winter and no obvious diurnal NEE could be found from November to February of the next year. During the main growing seasons of winter wheat and summer maize, there were remarkable diurnal variations of NEE. After sunrise, $CO_2$ uptake by the farmland ecosystem increased with enhancing solar radiation. $CO_2$ uptake reached maximum approximately at 12:00. Then, $CO_2$ uptake decreased with the decline of solar radiation and was close to zero at sunset (about 18:00). The crop field became a carbon source at night on account of crop and soil respiration. After harvest (in June and October), the bare soil became a source of $CO_2$ and its diurnal variation was unremarkable.

The maximal peaks of diurnal $CO_2$ uptake in the summer maize field were $-1.14\ mgCO_2 \cdot m^{-2} \cdot s^{-1}$ in 2003 and $-1.42\ mgCO_2 \cdot m^{-2} \cdot s^{-1}$ in 2004. Both appeared in August, which were similar to the seasonal variations of LAI. The maximal peaks of diurnal $CO_2$ uptake by the winter wheat field were $-0.81\ mgCO_2 \cdot m^{-2} \cdot s^{-1}$ in May 2003 and $-1.07\ mgCO_2 \cdot m^{-2} \cdot s^{-1}$ in April 2004 (Fig. 5). In both years, though maximal LAI appeared in April and average PAR in May was higher than that in April, average monthly LAI in May 2003 was slightly smaller than that in April 2003 and its mean monthly PAR was significantly higher than that at the same period in 2004. These led to a higher peak of $CO_2$ uptake by the winter wheat field in May than in April 2003.

Daily difference of NEE in a crop field was determined by the magnitudes of the sources and sinks of $CO_2$. Because soil respiration accounted for a small part of $CO_2$ budget, the daily difference for NEE was chiefly influenced by LAI and its duration time (photosynthetic potential). The daily difference of monthly mean NEE was large in the crop field during the main growing seasons of winter wheat (April—May) and summer maize (August—September). It ranged from 1.0 to 1.9 $mgCO_2 \cdot m^{-2} \cdot s^{-1}$ and average LAI varied between 3 and 5 (Fig. 5). In the maize field, the daily difference of mean monthly NEE varied from 0.7 to 0.8 $mgCO_2 \cdot m^{-2} \cdot s^{-1}$ in July when average LAI was about 1. It became very small (0.1—0.5 $mgCO_2 \cdot m^{-2} \cdot s^{-1}$) when LAI was less than 1. The daily difference of monthly averaged NEE in 2004 was 10% higher than in 2003 for winter wheat and 20% higher than in 2003 for summer maize (Fig. 5). Except for larger LAI of winter wheat in 2004 than in 2003, it was mainly because the annual average temperature and its daily difference were larger in 2004 than in 2003.

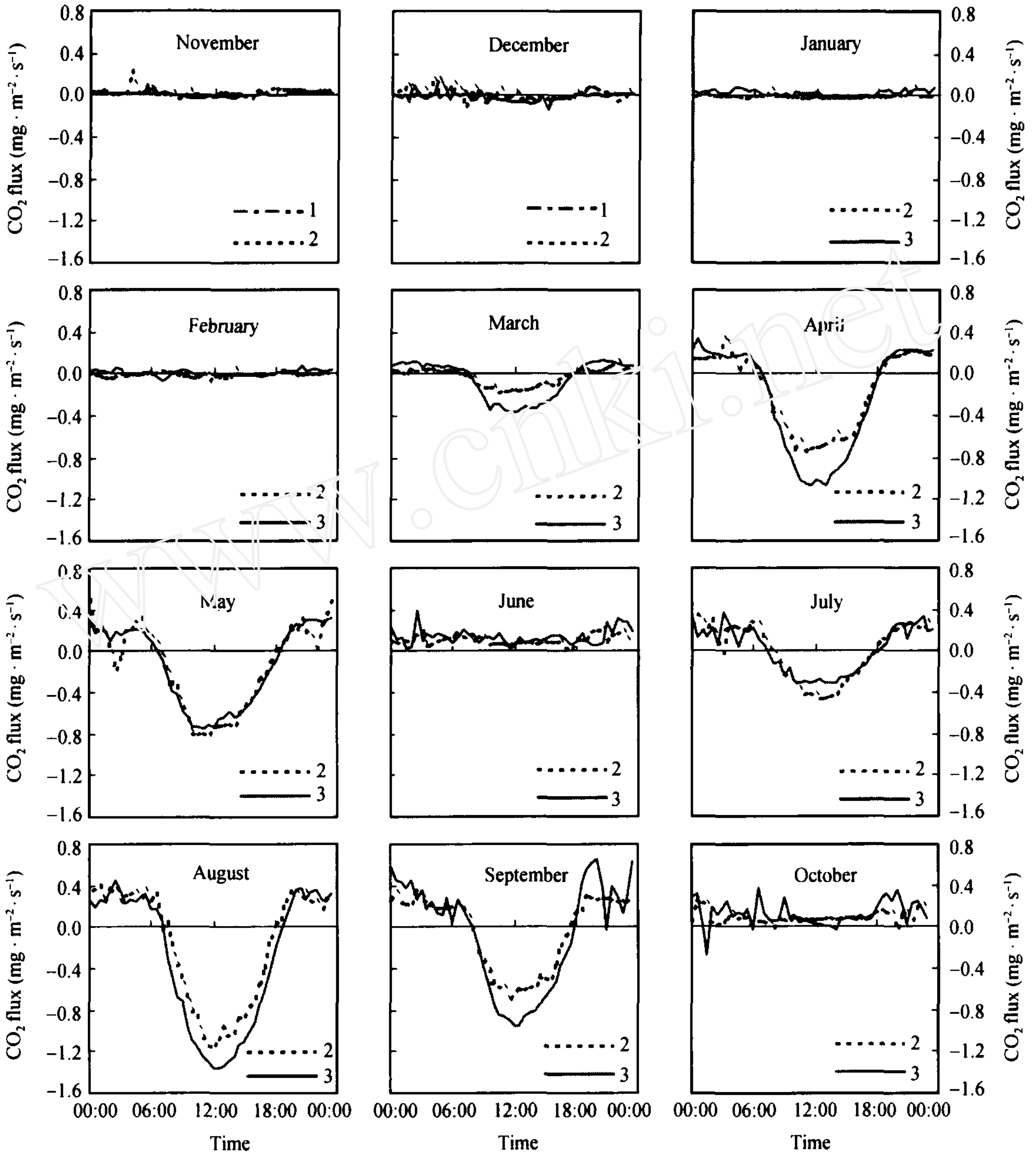


Fig. 5. Diurnal variation of monthly average for NEE in a crop field. 1—3, represent 2002, 2003 and 2004, respectively.

### 2.5 *Seasonal variation of NEE, GPP and $R_{ec}$*

NEE, GPP and $R_{ec}$ show significant seasonal variations in the wheat-maize rotation system (Fig. 6). Based on the positive and negative of NEE, one year could be divided into four stages: two stages of $CO_2$ uptake in the winter wheat and summer maize growing seasons (negative NEE) and two stages of $CO_2$ emission in June and the period from October to February of next year (positive NEE). According to the dates when NEE exchanged between positive and negative, it could be found that the wheat field absorbed $CO_2$ generally from mid and late March to late May, and from mid July to late September or early October for the summer maize field (Table 3). Due to warming up early in spring 2004, winter wheat stood and elongated early and leaf area increased rapidly. Maximal LAI and $CO_2$ uptake rate of winter wheat appeared two weeks earlier in 2004 than in 2003. Annual maximum of daily mean $CO_2$ uptake appeared in mid August in the summer maize field. It was $-10.20$ $gC \cdot m^{-2} \cdot d^{-1}$ in 2003 and $-12.50$ $gC \cdot m^{-2} \cdot d^{-1}$ in 2004.

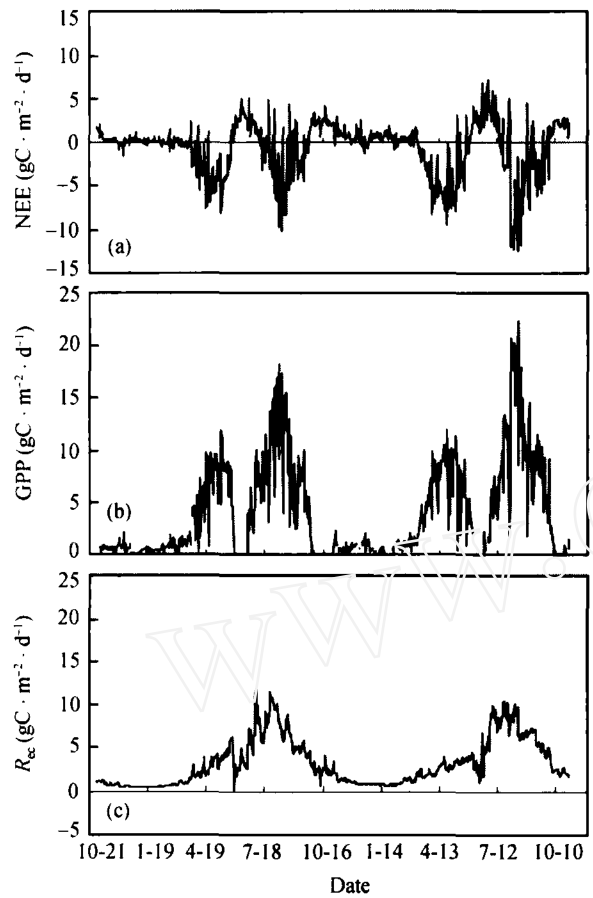


Fig. 6. Seasonal variation of NEE, GPP and $R_{ec}$.

The maximums of daily mean $CO_2$ uptake in the winter wheat field were $-8.19$ gC·m$^{-2}$·d$^{-1}$ in May 2003 and $-9.50$ gC·m$^{-2}$·d$^{-1}$ in April 2004 (Fig. 6 and Table 3) which were lower than those obtained by Baldocchi[13] and Anthoni *et al.*[19] in winter wheat fields and Baker and Griffis[36] in a summer maize field (Table 4). Because seasonal average $A_{max}$ and $a$ of summer maize were higher than those of winter wheat, the maximal $CO_2$ uptake rate of summer maize was larger than that of winter wheat (subsect. 2.3). It was in good agreement with the result from Falge *et al.*[37] who reported that maximal $CO_2$ uptake rate of $C_4$ plants was greater than that of $C_3$ plants. The fluctuation of NEE was large during $CO_2$ uptake stages (Fig. 6). When photosynthesis was weak on cloudy and rainy days, the farmland became a source of $CO_2$ in a short time because NEE was mainly composed of soil and plant respiration. It turned to a $CO_2$ sink quickly when photosynthesis enhanced due to fine weather. Annual maximums of daily mean $CO_2$ emission, with 4.98 and 7.08 gC·m$^{-2}$·d$^{-1}$ in 2003 and 2004, respectively, appeared in late June due to the nearly bare field and the highest soil temperature at this period (Table 3). Total NEE for the winter wheat field was $-77.6$ and $-152.2$ gC·m$^{-2}$·a$^{-1}$ in years 2002—2003 and 2003—2004, respectively, and $-120.1$ and $-165.6$ gC·m$^{-2}$·a$^{-1}$ in 2003 and 2004 for the summer maize field, respectively. In both years, total NEE in the summer maize growing seasons was higher than that in winter wheat growing seasons (Table 5) because the ability of carbon assimilation of maize ($C_4$ plant) is stronger than that of wheat, the $C_3$ plant.

The minimum and maximum of daily mean $R_{ec}$ appeared in January and July (Fig. 6), respectively, similar to the seasonal trend of temperature. The maximal $R_{ec}$ was 11.84 gC·m$^{-2}$·d$^{-1}$ in early July 2003 and 10.29 gC·m$^{-2}$·d$^{-1}$ in late July 2004 (Table 3). The maximal $R_{ec}$ appeared late in 2004 mainly because of the delayed sowing of maize in 2004 and late appearance of the highest topsoil temperature The appearance dates of two GPP peaks were similar to those of maximal carbon uptake (Table 3). Annual maximum of daily mean Gpp appeared in the maize field, with 18.21 and 22.30 gC·m$^{-2}$·d$^{-1}$ in 2003 and 2004, respectively. Maximal daily mean GPP in the winter wheat field was 11.98 and 12.03 gC·m$^{-2}$·d$^{-1}$ in 2003 and 2004, respectively. GPP was close to zero in June and October for the bare crop field (Fig. 6).

Minimal monthly mean GPP and $R_{ec}$ emerged in

Table 3 Dates of NEE exchanged between positive and negative and appearance of the largest $CO_2$ release and uptake

| | Winter wheat field | | Summer maize field | |
|---|---|---|---|---|
| | 2003 | 2004 | 2003 | 2004 |
| Date of NEE changed from positive to negative | late March | early and middle March | middle July | middle July |
| Date of NEE changed from negative to positive | late May | the end of May | late September | early October |
| Emergence of the largest $CO_2$ release | | | 24 June | 27 June |
| Emergence of the largest $CO_2$ uptake | 12 May | 25 April | 13 August | 12 August |
| Emergence of the greatest GPP | 13 May | 25 April | 9 August | 12 August |
| Emergence of the greatest $R_{ec}$ | | | 5 July | 29 July |

Table 4 Comparison of annual maximum of carbon uptake and NEE among different farmland ecosystemS

| Year | Site | Crop | Cultivation measure | Maximal carbon uptake ($gC \cdot m^{-2} \cdot d^{-1}$) | NEE ($gC \cdot m^{-2} \cdot a^{-1}$) | Harvested carbon ($gC \cdot m^{-2} \cdot a^{-1}$) | NEE considered harvested carbon ($gC \cdot m^{-2} \cdot a^{-1}$) | Ref. |
|---|---|---|---|---|---|---|---|---|
| 1991 | Boardman, USA | winter wheat | | −13.4 | | | | [13] |
| 1997 | Ponca, OK, USA | winter wheat | | | −155 | | | [4] |
| 2001 | Thuringia, Germany | winter wheat | tradition tillage | −10.0—−12.0 | −185— −245 | 286 | 41—101 | [19] |
| 1997 | Illinois, USA | maize | no-till more than 14 years | | −532 | 340 | −193 | [38] |
| 1999 | Illinois, USA | maize | no-till more than 14 years | −18.5 | −692 | 437 | −255 | [38] |
| 2001 | Illinois, USA | maize | no-till more than 14 years | | −505 | 399 | −106 | [38] |
| 2001 | Nebraska, USA | maize | no-till more than 10 years | | −517 | 521 | 4 | [39] |
| 2002 | Nebraska, USA | maize | no-till more than 10 years | | −424 | 503 | 79 | [39] |
| 2003 | Nebraska, USA | maize | no-till more than 10 years | | −381 | 470 | 89 | [39] |
| 2002-2003 | Minnesota, USA | corn/soybean rotation | tradition tillage | ≈−14.0 | −376 | 467 | 91 | [36] |
| 2002-2003 | Minnesota, USA | corn/soybean rotation | reduced tillage | ≈−14.0 | −350 | 436 | 86 | [36] |
| 2002-2003 | Yucheng, China | wheat/maize rotation | tradition tillage | −8.2—−10.2 | −198 | 538 | 341 | this study |
| 2003-2004 | Yucheng, China | wheat/maize rotation | tradition tillage | −9.5—−12.5 | −318 | 425 | 107 | this study |

Table 5 Annual average NEE and NEE considered carbon of grain in farmland

| Year | Crop | Grain yield ($gC \cdot m^{-2} \cdot a^{-1}$) | $C_{gr}$ ($gC \cdot m^{-2} \cdot a^{-1}$) | NEE ($gC \cdot m^{-2} \cdot a^{-1}$) | NEE +$C_{gr}$ ($gC \cdot m^{-2} \cdot a^{-1}$) |
|---|---|---|---|---|---|
| 2002—2003 | winter wheat | 526.0 | 203.6 | −77.6 | 126.0 |
| | summer maize | 885.7 | 334.6 | −120.1 | 214.5 |
| 2003—2004 | winter wheat | 543.0 | 210.1 | −152.2 | 57.9 |
| | summer maize | 570.0 | 215.3 | −165.6 | 49.7 |

Table 6 Monthly mean and total annual NEE, GPP, $R_{ec}$, LAI and relative environmental factors in farmland[a)]

| Month | $R_{ec}$ | | GPP | | NEE | | PAR | | Air temperature (℃) | | Precipitation (mm) | | LAI | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 02—03 | 03—04 | 02—03 | 03—04 | 02—03 | 03—04 | 02—03 | 03—04 | 02—03 | 03—04 | 02—03 | 03—04 | 02—03 | 03—04 |
| 11 | 26 | 44 | 10 | 17 | 17 | 27 | 106 | 64 | 4.4 | 5.6 | 1 | 20 | | |
| 12 | 17 | 25 | 19 | 18 | −2 | 7 | 61 | 62 | −2.2 | −0.2 | 8 | 11 | | |
| 1 | 13 | 22 | 8 | 1 | 5 | 22 | 93 | 83 | −3.4 | −1.5 | 3 | 0 | | |
| 2 | 16 | 30 | 18 | 25 | −2 | 5 | 100 | 115 | 1.8 | 4.1 | 2 | 11 | | |
| 3 | 35 | 53 | 43 | 94 | −8 | −41 | 134 | 132 | 6.9 | 8.8 | 43 | 56 | 0.57 | 1.57 |
| 4 | 70 | 78 | 170 | 243 | −100 | −165 | 190 | 177 | 13.7 | 15.2 | 160 | 52 | 3.20 | 5.69 |
| 5 | 134 | 107 | 238 | 204 | −104 | −98 | 241 | 215 | 20.1 | 19.0 | 12 | 47 | 2.95 | 3.44 |
| 6 | 111 | 114 | 32 | 16 | 78 | 98 | 219 | 182 | 24.7 | 23.7 | 57 | 196 | | |
| 7 | 262 | 270 | 268 | 239 | −6 | 32 | 187 | 200 | 25.5 | 26.2 | 108 | 224 | 1.33 | 1.07 |
| 8 | 234 | 230 | 360 | 431 | −126 | −201 | 153 | 171 | 24.7 | 24.4 | 70 | 205 | 4.78 | 4.31 |
| 9 | 134 | 167 | 155 | 229 | −21 | −62 | 133 | 145 | 20.5 | 21.4 | 60 | 27 | 3.74 | 3.41 |
| 10 | 73 | 73 | 0 | 14 | 73 | 58 | 120 | 110 | 13.6 | 14.4 | 152 | 13 | | |
| Entire year | 1173 | 1230 | 1370 | 1563 | −198 | −318 | 1737 | 1655 | | | 675 | 861 | | |

a) The units of monthly and annual accumulated $R_{ec}$, GPP and NEE are $gC \cdot m^{-2} \cdot mon^{-1}$ and $gC \cdot m^{-2} \cdot a^{-1}$; the unit of PAR is $MJ \cdot m^{-2} \cdot d^{-1}$. 2002—2003 and 2003—2004 were simplified to 02—03 and 03—04, respectively.

January/October and January, respectively. Maximumal GPP and $R_{ec}$ occurred in August and July, respectivel The peak of carbon uptake also appeared in August due to the effect of GPP on carbon uptake (Table 6). Monthly average GPP/$R_{ec}$ ratio varied with seasons. It was more than 1 in the main growing seasons. The maximal monthly average GPP/$R_{ec}$ ratio occurred in April and its second peak appeared in August (Fig. 7). It indicates that NEE was controlled by GPP during the main growing seasons of winter wheat and summer maize except for July. GPP was chiefly influenced by PAR and LAI. GPP increased with increasing PAR within a range (Fig. 3), and seasonal trend of GPP corresponded to seasonal pattern of LAI (Figs. 1 and 6). The fine or cloudy weather would lead to a great fluctuation of GPP, which could alter the direction of NEE sometimes in spite of higher LAI (Figs. 1 and 6). There was a distinct influence of temperature on crop growth in early spring. The winter wheat stood and elongated lately in 2003 since winter temperature in 2003 was on average 2℃ lower than in 2004 and temperature increased slowly in spring 2003. Therefore, mean GPP and LAI from March to May 2003 were only 63% and 83% of those in the same period of 2004, respectively (Table 6). Crop growth and development required sufficient accumulated temperature. Without sufficient effective accumulated temperature, crops would grow and develop slowly and LAI and GPP would be small. Suitable irrigation, drainage and fertilization were satisfied with crop growth although the seasonal variation of precipitation was large. The influence of soil moisture and nutrient content on GPP was less than that of light and temperature (Table 6).

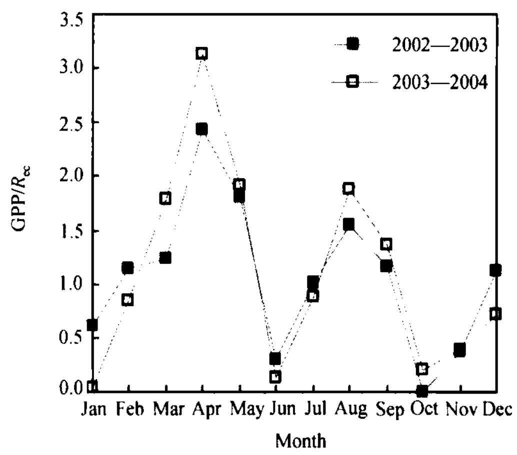


Fig. 7. Monthly mean ratio GPP/$R_{ec}$.

Leaf area and $CO_2$ uptake increased rapidly when maize elongated in mid-late July. Annual maximum of $R_{ec}$ appeared in July, the hottest month of the whole year. In July, The GPP/$R_{ec}$ ratio close to 1 suggested that GPP and $R_{ec}$ contributed to NEE equally at that time (Fig. 7 and Table 6). During the periods from October to February of the next year and June, the GPP/$R_{ec}$ ratio less than 1 implied that NEE was dominated by $R_{ec}$ (Fig. 7) and temperature was a dominant factor controlling NEE. Plant growth slowed down or stopped completely when temperature was low from November to February of the next year. Low respiration of plant and soil resulted in small mean monthly GPP, $R_{ec}$ and NEE (Fig. 7 and Table 6). Although $R_{ec}$ dominated NEE during this period, it had a slight effect on annual NEE. Both relative large contribution of $R_{ec}$ to NEE and the greatest mean monthly $CO_2$ emission occurred in June. Though temperature was not high after maize harvest in October, a great amount of $CO_2$ released from the bare soil disturbed largely by tillage before winter wheat sowing (Table 6).

### 2.6 *Annual carbon budget*

The flux measurement shows that annual NEE in the cropland was −197.6 and −317.9 $gC \cdot m^{-2} \cdot a^{-1}$ in years 2002—2003 and 2003—2004, respectively. The cropland was a carbon sink and its yearly difference was remarkable. Because annual average temperature and precipitation were 7% and 28% higher in the year 2003—2004 than in the year 2002—2003, NEE was 61% more in the year 2003—2004 than in the year 2002—2003. The yearly difference of seasonal patterns on meteorological factors affected NEE strongly (subsect. 2.5). Precipitation concentrates mostly in summer in North China Plain. Precipitation in June and July 2004 was twice or three times of that in the same period of 2003. Though summer maize remained green and grew rapidly which resulted in low yields, the magnitudes of $CO_2$ uptake by summer maize field were high (Table 5). For the winter wheat field, irrigation made the actual amount of input water the same in both years though precipitation in spring 2004 was only 72% of that in the same period of 2003 (Tables 1 and 6). Winter wheat grew well in 2004 because the amount of N fertilizer was 42% higher in 2004 than in 2003 and it warmed early in spring 2004. The prolonged period of carbon sink (20 d more in 2004 than in 2003) led to a higher amount of $CO_2$ uptake in 2004 than in 2003. Sometimes, the effects of field managements (e.g. crop breeds, N fertilization, irrigation and tillage) on NEE were greater than that of climate. When comparing with annual average NEE measured using the eddy covariance method in different regions, we found that the amount of carbon uptake in the traditional cultivated cropland was lower than that without tillage for many years (Table 4). Because agricultural machines enter into the crop field less after using the non-tillage method, the suitable tightness degree of cropland soil reduces the mineralization ratio of soil organic matter, which benefits not only for accumulating organic matter but also for decreasing soil carbon loss. However, some researches showed that there were no differences in NEE between croplands treated with traditional tillage and non-tillage (Table 4)[36]. Generally, the effects of non-tillage on carbon flux in cropland are small in a short time. It should take many years to show the obvious effects.

To improve soil organic matter content, crop straw is returned to the field. $CO_2$ flux measurement using the eddy covariance method includes $CO_2$ releasing from the straw. However, the carbon in grains ($C_{gr}$) is not included in the flux measurement. $C_{gr}$ can be calculated as follows:

$$C_{gr} = (1 - W_{gr}) f_C Y, \tag{7}$$

where $W_{gr}$ is water percentage in the grain (0.14 for wheat[40] and 0.155 for maize[38]); $f_C$ is carbon percentage in the grain (0.45 for wheat[41] and 0.447 for maize[38]); $Y$ is the grain yield. Most of grains harvested from the field were carried to cities or other places and consumed. All of them were transformed to $CO_2$ and then released into the atmosphere. This part of carbon should be involved in the carbon budget of farmland if we scale up the carbon budget from a site to a region. After the carbon in grains was taken into account, most farmland ecosystems turned from carbon sinks to carbon sources. In our experiment, the carbon sources of the cropland were 340.5 and 107.5 $gC \cdot m^{-2} \cdot a^{-1}$ in years 2002—2003 and 2003—2004, respectively. Our results were similar to the observations by Anthoni *et al.*[19], Verma *et al.*[39] and Baker and Griffis[36] ( Table 4).

In North China Plain, two crops (such as winter wheat and summer maize) were generally planted in the farmland for rotation in a year. Farmland was nearly bare from June to early July, the period with the strongest radiation and the highest temperature in the whole year, which led to less $CO_2$ uptake by biannual cropping system than annual cropping system (Table 4). Since there are generally more yields in biannual cropping system than annual cropping system, carbon emission from biannual cropping system was larger than annual cropping system after the carbon in grains was considered.

## 3 Conclusions and prospect

From the discussion above, we derive the following conclusions:

(1) Nighttime NEE varied exponentially with soil temperature. The temperature sensitivities of ecosystem ($Q_{10}$) were 2.94 and 2.49 in years 2002—2003 and 2003—2004, respectively. The response of GPP to PAR in the winter wheat and summer maize field can be expressed by a rectangular hyperbolic function. Average $A_{max}$ and $a$ in the maize season were higher than those in the wheat season. The values of $a$ increased with LAI in the winter wheat field.

(2) There are significant diurnal variations of NEE during the main growing seasons of winter wheat and summer maize, but not obvious in other months. The largest mean monthly diurnal peak of $CO_2$ uptake for the maize field was −1.14 and −1.42 $mgCO_2 \cdot m^{-2} \cdot s^{-1}$ in 2003 and 2004, respectively, and −0.81 and −1.07 $mgCO_2 \cdot m^{-2} \cdot s^{-1}$ in 2003 and 2004, for the wheat field, respectively. The daily differences of NEE were large in April, May, August and September, but small in other months.

(3) Seasonal variations of NEE, GPP and $R_{ec}$ were obvious in the field of winter wheat-summer maize rotation. The highest daily mean $CO_2$ uptake rate for the maize field was −10.20 and −12.50 $gC \cdot m^{-2} \cdot d^{-1}$ in 2003 and 2004, separately, and −8.19 and −9.50 $gC \cdot m^{-2} \cdot d^{-1}$ in 2003 and 2004 for the wheat field, respectively. The maximal daily mean $CO_2$ uptake appeared in April or May for wheat and mid-August for maize which occurred at the same time of the

emergence of GPP peak. In the main growing seasons, NEE was primarily controlled by GPP Which was chiefly determined by PAR and LAI. $R_{ec}$ reached its annual maximum in July, and $R_{ec}$ and GPP contributed to NEE equally at the same period. In other months, NEE was dominated by $R_{ec}$ and temperature became the primary environmental factor controlling NEE.

(4) Total NEE for the wheat field was −77.6 and −152.2 $gC \cdot m^{-2} \cdot a^{-1}$ in years 2002−2003 and 2003−2004, respectively, and −120.1 and −165.6 $gC \cdot m^{-2} \cdot a^{-1}$ in 2003 and 2004 for maize field, respectively. The field of wheat-maize in Norh China Plain was a carbon sink with the average annual NEE of −197.6 and −317.9 $gC \cdot m^{-2} \cdot a^{-1}$ in years 2002−2003 and 2003−2004, respectively. After considering the carbon in the grain, the cropland became a carbon source, with 340.5 and 107.5 $gC \cdot m^{-2} \cdot a^{-1}$ in years 2002−2003 and 2003−2004, respectively. Affected by climate factors and field managements, annual carbon exchange varied greatly in the cropland.

Since crop yields largely affect the carbon budget in farmland, all controlling factors of yields (crop breeds, cultivation systems, fertilizer, irrigation and tillage patterns) will influence the carbon budget of farmland significantly. In North China Plain, the highest yield was found in biannual cropping system that winter wheat was sowed after deep tillage and fertilization, and summer maize was sowed under no-till. One tillage and another non-tillage in biannual cropping system were good for resisting drought, avoiding flood and ensuring stable high yields[42]. However, it is not the best approach to reduce carbon emission from the farmland. In the United States, non-tillage method has been applied since the 1960s that has not only improved economic benefits but also protected the environment. The experiment by Hollinger *et al.*[38] indicated that maize field without tillage for many years not only yielded high but also remained a carbon sink with the carbon in grains considered. Under the background of present light and heat resources in North China Plain, annual cropping has more advantages on enhancing $CO_2$ uptake by crops than biannual cropping although the cost is declining total yields. American experience is worth to use for reference when we go the way of sustaining development and harmonize the relationships among developing economy, improving agricultural production and protecting the environment.

**Acknowledgements** This study was jointly sponsored by the Knowledge Innovation Project of the Chinese Academy of Sciences (Grant No. KZCX1-SW-01-01A), the National Natural Science Fund for Overseas Outstanding Youth (Grant No. 40328001), and the Ministry of Science and Technology of China (Grant No.2002CB412501).

## References

1 Baldocchi D D, Valentini R, Running S, et al. Strategies for measuring and modeling of carbon dioxide and water vapor over terrestrial ecosystems. Global Change Biol, 1996, 2: 159—168
2 Oechel W C, Vourlitis G L, Hastings S J, et al. Acclimation of ecosystem $CO_2$ exchange in the Alaska Arctic in response to decadal warming. Nature, 2000, 406: 978—981
3 Yu G R, Zhang LM, Sun X M, et al. Advances in carbon flux observation and research in Asia. Sci China Ser D-Earth Sci, 2005, 48(Suppl I): 1−16
4 Law B E, Falge E, Gu L, et al. Environment controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agri For Meteorol, 2002, 113: 97—120
5 Baford C C, Wofsy S C, Goulden M L, et al. Factors controlling long- and short-term sequestration of atmospheric $CO_2$ in a mid-latitude forest. Science, 2003, 294: 1688—1691
6 Hollinger D Y, Aber J, Dail B, et al. Spatial and temporal variability in forest-atmosphere $CO_2$ exchange. Global Change Biol, 2004, 10: 1698—1706
7 Soegaard H, Jensen N O, Boegh E, et al. Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modeling. Agri For Meteorol, 2003, 114: 153—173
8 Specht J E, Hume D J, Kumudini S V. Soybean yield potential-a genetic and physiological perspective. Crop Sci, 1999, 39: 1560—1570
9 Baldocchi D D, Falge E, Gu L, et al. FLUXNET: A new tool to study the temporal and spatial and energy flux densities. Bull Am Meteorol Soc, 2001, 82(11): 2415—2434
10 Valentini R, Matteucci G, Dolman A J, et al. Respiration as the main determinant of carbon balance in European forests. Nature, 2000, 404: 861—865
11 Falge E, Baldocchi D D, Olson R. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agri For Meteorol, 2001a, 107: 43—69
12 Falge E, Baldocchi D D, Olson R. Gap filling strategies for long-term energy flux data sets. Agri For Meteorol, 2001b, 107: 71—77
13 Baldocchi D D. A comparative study of mass and energy exchange rates over a closed $C_3$ (wheat) and an open $C_4$ (corn) crop:

II. $CO_2$ exchange and water use efficiency. Agri For Meteorol, 1994, 67(3-4): 291—321

14 Rochette P, desjardins R l, Pattey E, et al. Instantaneous measurements of radiation and water use efficiency of a maize crop. Agron J, 1996, 88: 627—635

15 Buchmann N, Schulze E D. Net $CO_2$ and $H_2O$ fluxes of terrestrial ecosystems. Global Biogeochem Cycles, 1999, 13(3): 751—760

16 Buyanovsky G A, Wager G H. Carbon cycling in cultivated land and its global significance. Global Change Biol, 1998,4: 131—141

17 Webb E K, Pearman G, Leuning R. Correction of flux measurements for density effects due to heat and water vapor transfer. Q J R Meteorol Soc, 1980, 106: 85—100

18 Lee X H, Massman W, Law B. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Netherlands: Kluwer Academic Press, 2004. 130

19 Anthoni P M, Freibauer A, Kolle O, et al. Winter wheat carbon exchange in Thuringia, Germany. Agri For Meteorol, 2004,121: 55—67

20 Wofsy S C, Goulden M L, Munger J W, et al. Net exchange of $CO_2$ in a midlatitude forest. Science, 1993, 260: 1314—1317

21 Baldocchi D D, Vogel C A, Hall B. Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest. Agri For Meteorol, 1997, 83: 147—170

22 Hollinger D Y, Kelliher F M, Schulze E D, et al. Forest-atmosphere carbon dioxide exchange in eastern Siberia. Agri For Meteorol, 1998, 90: 291—306

23 Chen W J, Black T A, Yang P C, et al. Effects of climate variability on the annual carbon sequestration by a boreal aspen forest. Global Change Biol, 1999, 5: 41—53

24 Goulden M L, Daube B C, Fan S M, et al. Gross $CO_2$ uptake by a black spruce forest. J Geophy Res, 1997, 102: 28987—28996

25 Chen S Y, Li J, Lu P L, et al. Soil respiration characteristics in winter wheat field in North China Plain. Chin J Appl Ecol (in Chinese), 2004, 15(9): 1552−1560

26 Janssens I A, Lankreijer H, Matteucci G, et al. Productivity overshadows temperature in determining soil and ecosystem respiration across European forest. Global Change Biol, 2001, 7: 269 — 278

27 Saigusa N, Yamamoto S, Murayama S, et al. Gross primary production and net ecosystem exchange of a cool-temperate deciduous forest estimated by the eddy covariance method. Agri For Meteorol, 2002, 112: 396—404

28 Hirano T, Hirata R, Fujinuma Y, et al. $CO_2$ exchange and water vapor exchange of a larch forest in northern Japan. Tellus, 2003, 55B: 244—257

29 Hollinger D Y, Kelliher F M, Byers J N, et al. Carbon dioxide exchange between an undisturbed old-growth temperate forest and the atmosphere. Ecology, 1994, 75: 134—150

30 Hollinger D Y, Goltz S M, Davidson E A, et al. Seasonal patterns and environmental control of carbon dioxide and water vapor exchange in an ecotonal boreal forest. Global Change Biol, 1999, 5: 891—902

31 Li H S. Contemporary Plant Physiology (in Chinese). Beijing: High Education Press, 2002

32 Ruimy A, Jarvis P G, Baldocchi D D, et al. $CO_2$ fluxes over plant canopies and solar radiation. A review. Adv Ecol Res, 1995, 26: 1−68

33 Lu P L, Yu Q, Liu J D. The response of photosynthesis and transpiration to environment factors in winter wheat. Progr Geogr (in Chinese), 1998, 17(Supp.): 190−197

34 Ma R, Yu Q, Xie X Q, et al. Modelling the response of physiological factors to meteorological elements in summer maize. Progr Geogr (in Chinese), 1998, 17(Supp): 268−275

35 Luo Y Q, Hui D F, Cheng W X, et al. Canopy quantum yield in a mesocosm study. Agri For Meteorol, 2000, 100: 35−48

36 Baker J M, Griffis T J. Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques. Agri For Meteorol, 2005, 128: 163—177

37 Falge E, Tenhunmen J, Baldocchi D, et al. Phase and amplitude of ecosystem carbon release and uptake potentials as derived from FLUXNET measurements. Agri For Meteorol, 2002, 113: 75—95

38 Hollinger S E, Bernacchi C J, Meyers T P. Carbon budget mature no-till ecosystem in North Central Regional of the United States. Agri For Meteorol, 2005, 130: 59—69

39 Verma S B, Dobermann A, Cassman K G, et al. Annual carbon dioxide exchange in irrigated and rained maize-based agroecosystems. Agri For Meteorol, 2005, 131: 77—96

40 Smith P, Smith J U, Powlson D S, et al. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma, 1997, 81: 153—225

41 Hartmann H, Böhm T, Maier L. Umweltrelevante eigenschaften naturbelassener biogener Festbrennstoffe sowie Möglichkeiten zu deren Beeinflussung. Report, Bayerisches Landessansalt für Landtechnic (Freising) und Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen München, 1999

42 Huang C Y. Pedology (in Chinese). Beijing: Chinese Agriculture Press, 2001