

Seasonal and interannual variations in carbon dioxide exchange over a cropland in the North China Plain

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Abstract

In China, croplands account for a relatively large form of vegetation cover. Quantifying carbon dioxide exchange and understanding the environmental controls on carbon fluxes over croplands are critical in understanding regional carbon budgets and ecosystem behaviors. In this study, the net ecosystem exchange (NEE) at a winter wheat/summer maize rotation cropping site, representative of the main cropping system in the North China Plain, was continuously measured using the eddy covariance technique from 2005 to 2009. In order to interpret the abiotic factors regulating NEE, NEE was partitioned into gross primary production (GPP) and ecosystem respiration (R_{eco}). Daytime R_{eco} was extrapolated from the relationship between nighttime NEE and soil temperature under high turbulent conditions. GPP was then estimated by subtracting daytime NEE from the daytime estimates of R_{eco} . Results show that the seasonal patterns of the temperature responses of R_{eco} and light-response parameters are closely related to the crop phenology. Daily R_{eco} was highly dependent on both daily GPP and air temperature. Interannual variability showed that GPP and R_{eco} were mainly controlled by temperature. Water availability also exerted a limit on R_{eco} . The annual NEE was -585 and -533 g C m^{-2} for two seasons of 2006–2007 and 2007–2008, respectively, and the wheat field absorbed more carbon than the maize field. Thus, we concluded that this cropland was a strong carbon sink. However, when the grain harvest was taken into account, the wheat field was diminished into a weak carbon sink, whereas the maize field was converted into a weak carbon source. The observations showed that severe drought occurring during winter did not reduce wheat yield (or integrated NEE) when sufficient irrigation was carried out during spring.

Keywords: carbon sequestration, ecosystem respiration, eddy covariance, gross primary production, net ecosystem exchange, summer maize, winter wheat

Received 29 September 2009 and accepted 31 October 2009

Introduction

Increasing atmospheric CO_2 concentrations may be one of the most crucial issues related to climate change in the future. Consequently, there is much interest in studying carbon flux dynamics in order to find ways to increase carbon sequestration in terrestrial ecosystems. Since 1990s, a network of eddy covariance sites across a variety of ecosystem biomes has been set up (Baldocchi *et al.*, 2001), which aims at providing estimates of carbon fluxes, understanding the variations in carbon dioxide exchange in terms of environmental controls, and supporting the derivation of model parameters. To date, studies on carbon dioxide exchange have actively focused on forests and grasslands because these certainly play an important role in the global

carbon cycle (Goulden *et al.*, 1996; Owen *et al.*, 2007; Aires *et al.*, 2008). In contrast, agroecosystems have been of relatively less concern (Falge *et al.*, 2002). Croplands are regarded as strong contributors to the regional carbon budget (Buyanovsky & Wagner, 1998; Anthoni *et al.*, 2004b) and they are particularly significant in China where the cropland biome covers the third largest area, following forests and grassland (Liu *et al.*, 2005). The carbon balance in agroecosystems may be readily handled as farm fields are intensively managed (Baker & Griffis, 2005), facilitating the increase in carbon sequestration through changes in crop management.

The North China Plain occupies an agricultural area of about $1.8 \times 10^5 \text{ km}^2$, which accounts for 18.6% of the total agricultural area in China (Wu *et al.*, 2006). Wheat/maize rotation cropping with tillage represents the main cropping system on this plain. More than 50% of the nation's wheat and 33% of its maize are supplied by

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this region (Kendy *et al.*, 2003). To our knowledge, few studies have investigated the carbon dioxide exchange in this region. Li *et al.* (2006) have reported 2-year continuous measurements of NEE in a wheat/maize double cropping system. However, continuous and long-term measurements of NEE are still necessary to explore the seasonal and interannual variations in carbon flux components and how they are controlled by climate variables.

In this study, we reported on three and a half years of carbon fluxes over a typical irrigated wheat/maize rotation cropland, including four full winter wheat seasons and three full summer maize seasons. The main objectives were to (1) quantify the carbon fluxes including gross primary production (GPP), ecosystem respiration (R_{eco}), and net ecosystem exchange (NEE) using the eddy covariance technique; (2) investigate the seasonal variations in the characteristics of CO_2 exchange, and (3) examine the interannual variability in CO_2 exchange in response to environmental drivers.

Materials and methods

Site description

The Weishan flux site is located on a cropland in the North China Plain about 450 km south of Beijing, China (N36°39', E116°03', 30 m asl). The climate is warm temperate and semi-humid. Its mean annual temperature is about 13.3 °C and its mean annual precipitation is about 532 mm. The summer precipitation from June to September accounts for nearly 70% of the annual precipitation. The mean annual irrigation is about 215 mm and is diverted from the Yellow River, primarily concentrated in late February and March when winter wheat is turning green (i.e., leaves are strongly erect).

A flux tower was set up in the middle of a 400 m × 200 m quadrilateral area surrounded by poplar shelterbelts (*Populus tomentosa* Carr.). The site provides a fetch of 400 m in the dominant wind direction with unstable conditions. In the source area of the eddy covariance system, only a small fraction of ground was covered by trees, roads, and channels. Winter wheat is sown in October after deep tillage and is harvested in June of the following year, leaving a partial straw cover on the field. Summer maize is sown in June under no-till and is harvested in October, with corn-stalks ground up onto the field.

The topography in this region is very flat. The soil texture of the root zone is silt loam. Soil organic matter in the winter wheat season of 2008 at the depths of 5, 10, 30, 50, and 100 cm was 1.7%, 1.7%, 0.9%, 0.4%, and 0.3%, respectively.

Measurements and data acquisition

The flux of CO_2 (F_c) was continuously measured using an eddy covariance system at a height of 3.7 m. The system consisted of a 3D sonic anemometer (CSAT3, Campbell Scientific Instruments Inc., Logan, UT, USA) and an open-path infrared gas analyzer (IRGA, model LI-7500, LI-COR Inc., Lincoln, NE, USA) to measure the three components of wind velocity, sonic temperature, and concentrations of water vapor and CO_2 . The data were recorded with a data logger (CR5000, Campbell Scientific Instruments Inc.) at a frequency of 10 Hz. Postprocessing calculations, using the TK2 software package (Mauder & Foken, 2004), included density fluctuation correction (Webb *et al.*, 1980), spectral loss correction (Moore, 1986), planar fit coordinate rotation (Wilczak *et al.*, 2001), sonic virtual temperature conversion, and spike detection (Vickers & Mahrt, 1997). The energy balance was examined for 'closure' by checking the equality of the sum of latent heat (λE) and sensible heat (H) fluxes to the available energy (R_a) ($R_a = R_n - G$). For the half-hourly values, the coefficients a and b in the linear regression model $(\lambda E + H) = aR_a + b$ were 0.74, 0.76, 0.75 and 10.85, 8.04, 3.82 W m^{-2} in 2006, 2007, 2008, respectively. These values were in the range reported by most flux sites (Wilson *et al.*, 2002), and the energy imbalance at our site may have been due to the horizontal advection (Li & Yu, 2007), underestimation of soil heat flux, neglect of energy storage in canopy and top soil, and underestimation of latent and/or sensible heat fluxes. In this study, CO_2 flux was not corrected for energy balance underestimation, as some researchers have suggested (Twine *et al.*, 2000).

Continuous complementary measurements included standard climatological and soil parameters. Rainfall was measured using a tipping bucket rain gauge (TE525MM, Campbell Scientific Instruments Inc.). Wind speed and direction (05103, Young Co., Traverse City, MI, USA) were measured at a height of 10.0 m. Air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland) were measured 1.6 m above the ground. Downward and upward solar and longwave radiation (CNR-1, Kipp & Zonen, Delft, the Netherlands) and photosynthetically active radiation [(photon flux density) PPF] (LI-190SA, LI-COR Inc.) were measured above the canopy at a height of 3.5 m. Soil temperature (Campbell-107, Campbell Scientific Instruments Inc.) and volumetric soil water content (TRIMEZ/IT, IMKO, Ettlingen, Germany) were measured at 0.05, 0.10, 0.20, 0.40, 0.80, and 1.60 m depths in both plots. Two soil heat flux plates (HFP01, Hukseflux, Delft, the Netherlands) were placed at 3.0 cm depth.

Crop yield data before 2009 were collected from a nearby agrometeorological site of the China Meteorolo-

gical Administration, which is about 19 km away from our site and has a similar crop management and fertilization. The dry yield of winter wheat in 2009 was determined gravimetrically after the samples had been dried for 14 h at 80 °C. Replicate samples ($n = 4$) were collected by clipping the crop within a 1 m × 1 m frame.

Soil respiration (R_s) was measured from March 2009 to June 2009 with an automated soil CO₂ flux system (LI-8100, LI-COR Inc.). The inner diameter of the soil collar was 10 cm, and the chamber offset between the soil surface and the lower edge of the chamber base plate was 3 cm. For each measurement, observations were repeated for three counts, and the soil respiration values were estimated by averaging. The surface soil temperature and soil water content at a depth of 10 cm were measured concurrently with the attached temperature probe and soil moisture probe (EC-10, Decagon Devices Inc., Pullman, WA, USA). Four sample points around the flux tower were selected randomly to place the soil collars. The observations were performed during daytime from 13:00 to 15:00 hours every 3 days on sunny days.

Data quality and gap filling

The eddy covariance data were visually screened for anomalous values outside the range normally encountered. Nonstationary and integral turbulence tests (Foken & Wichura, 1996) were employed to detect unfavorable data. The results of both tests were combined to give a quality flag on a scale from 1 to 9 (Table 9 in Mauder & Foken, 2004). The responses of the fluxes to environmental factors were established from half-hourly data with flags 1–3 which were classified as the highest quality data.

The major problem in calculating long-term rates is low-turbulence conditions at night. Commonly, data of F_c with low turbulence were excluded using the threshold of friction velocity (u^*) (Massman & Lee, 2002). We studied the dependence of CO₂ flux on friction velocity in the rapid growth season of crops. As illustrated in Fig. 1, the nighttime fluxes measured below $u^* < 0.1 \text{ m s}^{-1}$ were underestimated. Therefore, all nighttime data with $u^* < 0.1 \text{ m s}^{-1}$ were rejected. Data collected during rainy periods were also excluded. This threshold was similar to those observed over short crops (Anthoni *et al.*, 2004a; Li *et al.*, 2006; Moureaux *et al.*, 2006).

The unfavorable data detected by nonstationary and integral turbulence tests (labeled with flags 7–9) and spike detection were gap-filled using the 'look-up' table method which is based on the empirical relationships among CO₂ fluxes and PPFD, and air temperature when meteorological data are available (Falge *et al.*, 2001). In

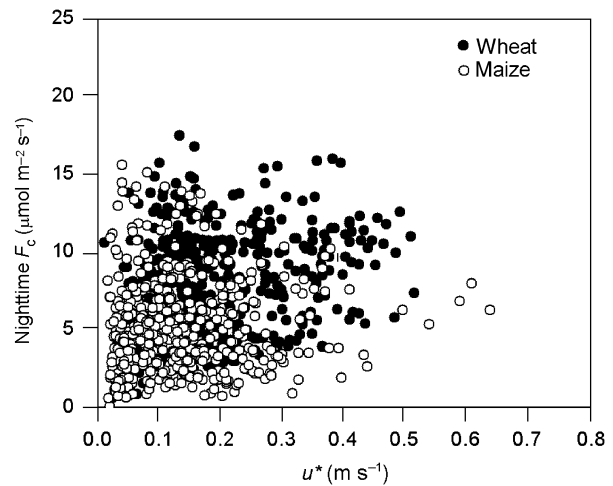


Fig. 1 Relationship between friction velocity (u^*) and nighttime 0.5 h CO₂ flux (F_c). Only data from the rapid growth period (15 April–15 May, 2007 for winter wheat, and 19 July–30 September, 2007 for summer maize) were included in this analysis.

the case of missing meteorological data, the mean diurnal variation method was applied using a 7-day data window (Falge *et al.*, 2001). Nighttime F_c data with $u^* < 0.1 \text{ m s}^{-1}$ were gap-filled with the Vant Hoff equation, which will be introduced later. The missing daily average temperature, daily solar radiation, and daily precipitation data were spatially interpolated from a nearby meteorological station network [see Yang *et al.* (2004), for more details].

Calculation of NEE, GPP, and R_{eco}

The NEE ($\mu\text{mol m}^{-2} \text{ s}^{-1}$) was linked to the eddy covariance flux (F_c , $\mu\text{mol m}^{-2} \text{ s}^{-1}$) by the following equation:

$$\text{NEE} = F_c + F_{st}, \quad (1)$$

where F_{st} is the storage flux, which reflects the accumulation and depletion of CO₂ in the canopy volume. F_{st} was estimated based on the assumption that half-hour changes in CO₂ concentration at the 3.7 m level are representative of the whole layer below the eddy covariance system (Flanagan *et al.*, 2002), as follows:

$$F_{st} = \frac{h\Delta c}{\Delta t}, \quad (2)$$

where h is the height of the flux measurement system and Δc is the change in CO₂ concentration during the time interval, Δt .

NEE is the sum of GPP and R_{eco} . GPP represents CO₂ assimilation by photosynthesis of the vegetation, and R_{eco} consists of respiratory CO₂ release from soil, stems, and foliage. Nighttime NEE values are equal to R_{eco} because GPP equals 0. Thus, the daytime R_{eco} was estimated from a regression model using the relation-

ship between nighttime NEE (defined as downward solar radiation $<20 \text{ W m}^{-2}$) during high turbulence ($u^* > 0.1 \text{ m s}^{-1}$) and soil temperature (T_s) at a depth of 5 cm. GPP is a residual of observed NEE and estimated R_{eco} in daytime. When calculating R_{eco} , the same procedure using a short-term temperature-dependent method, which is based on the Vant Hoff equation [Eqn (3)], was applied using the method described by Reichstein *et al.* (2005). The purpose was to avoid the confounding effects of crop phenology and soil water on the temperature response function, which is as follows:

$$R_{\text{eco}} = R_{\text{ref}} \exp(bT_s), \quad (3)$$

where R_{ref} (the reference respiration when $T_s = 0^\circ\text{C}$) and b are the regression parameters. The temperature sensitivity coefficient (Q_{10}) was calculated using the following equation:

$$Q_{10} = \exp(10b). \quad (4)$$

The short-term temperature sensitivity parameter b for one crop growth season was averaged from all estimates, in 15-day subperiods, with the inverse of the standard error as a weighing factor. The temperature independent level of respiration (i.e., the R_{ref} parameter) for each day was estimated using the least squares spline approximation from all estimates for each 4-day period.

Light response model

There are five basic models used for describing the partial dependence of NEE on PPFD (Gilmanov *et al.*, 2003), in which the Michaelis–Menten rectangular hyperbola model (Suyker *et al.*, 2004; Xu & Baldocchi, 2004) and the nonrectangular hyperbola model (Soegaard & Thorgeirsson, 1998; Hirata *et al.*, 2007) were usually used. We compared these two light-response models. Results showed that the nonrectangular hyperbola equation gave a better fit according to the measures of relative standard error and coefficient of determination, which is expressed as follows:

$$\text{NEE} = \frac{1}{2\theta} (\alpha \text{PPFD} + F_{\text{max}} - \sqrt{(\alpha \text{PPFD} + F_{\text{max}})^2 - 4\alpha F_{\text{max}} \theta \text{PPFD}}) - \gamma, \quad (5)$$

where α is the initial slope of the light response curve, F_{max} is the maximum CO_2 flux at infinite light, γ is the daytime average ecosystem respiration, and θ is the curvature parameter ($0 \leq \theta \leq 1$). The parameters were determined with daytime data for each day via a nonlinear weighted least squares fit. The weighting factors were the reciprocal of the standard deviations of the observations with similar meteorological conditions

within a time window of ± 7 days (Lasslop *et al.*, 2008). At least six half-hourly nongap-filled data points with $u^* > 0.1 \text{ m s}^{-1}$ were required to fit the parameters. Parameters were not included when the relative standard error was $> 60\%$, and the coefficient of determination was < 0.6 , or when parameter values were negative or above 0.17 for α , $20 \mu\text{mol m}^{-2} \text{ s}^{-1}$ for γ , or $150 \mu\text{mol m}^{-2} \text{ s}^{-1}$ for F_{max} . These thresholds were considered to be the upper limits of realistic values.

In the absence of direct measurements of daytime R_{eco} , it was useful to compare γ with the observed R_{eco} during the corresponding dark periods. As a more direct comparison, γ was then corrected for the soil temperature difference between day and night (Gilmanov *et al.*, 2003), which is as follows:

$$R_{\text{eco,pred}} = \gamma \exp(-k_T(T_{s,d} - T_{s,n})), \quad (6)$$

where $R_{\text{eco,pred}}$ is the predicted nighttime-average ecosystem respiration, $T_{s,d}$ is the daytime-average soil temperature, $T_{s,n}$ is the nighttime-average soil temperature, and $k_T = 0.069 (\text{ }^\circ\text{C})^{-1}$.

Results and discussion

Seasonal and interannual variations in environmental variables and crop development

Figure 2 shows the seasonal and interannual variations in weekly average values for air temperature, vapor pressure deficit (VPD), PPFD, soil water content (0–80 cm averaged), and weekly cumulative precipitation. The seasonal sums of PPFD during the winter wheat season (between October 15 and June 8) were 4911, 4379, 4810, and 4109 mol m^{-2} in the years of 2005–2006, 2006–2007, 2007–2008, and 2008–2009, respectively; whereas seasonal sums of PPFD during the summer maize season (between June 15 and October 14) were 3272, 2656, and 2591 mol m^{-2} in the years of 2006, 2007, and 2008, respectively. The seasonal averages of air temperature for the four winter wheat periods specified above were 8.14, 8.88, 8.00, and 8.39 $^\circ\text{C}$, respectively, whereas it was 23.93, 22.62, and 22.69 $^\circ\text{C}$ for the three summer maize seasons specified above, respectively. The VPD curves showed that the seasonal average of VPD during the wheat rapid growth season (March–May) was higher than that during the maize season. Precipitation primarily occurred from June to September. The seasonal cumulative precipitations for the four winter wheat periods were 102.4, 113.9, 120.8, and 236.1 mm, respectively; and it was 215.4, 382.3, and 324.1 mm for the three summer maize seasons, respectively. The climate in the 3 years was drier than in the normal year. The unsynchronized seasonality between precipitation and VPD resulted in more droughts during the winter wheat season

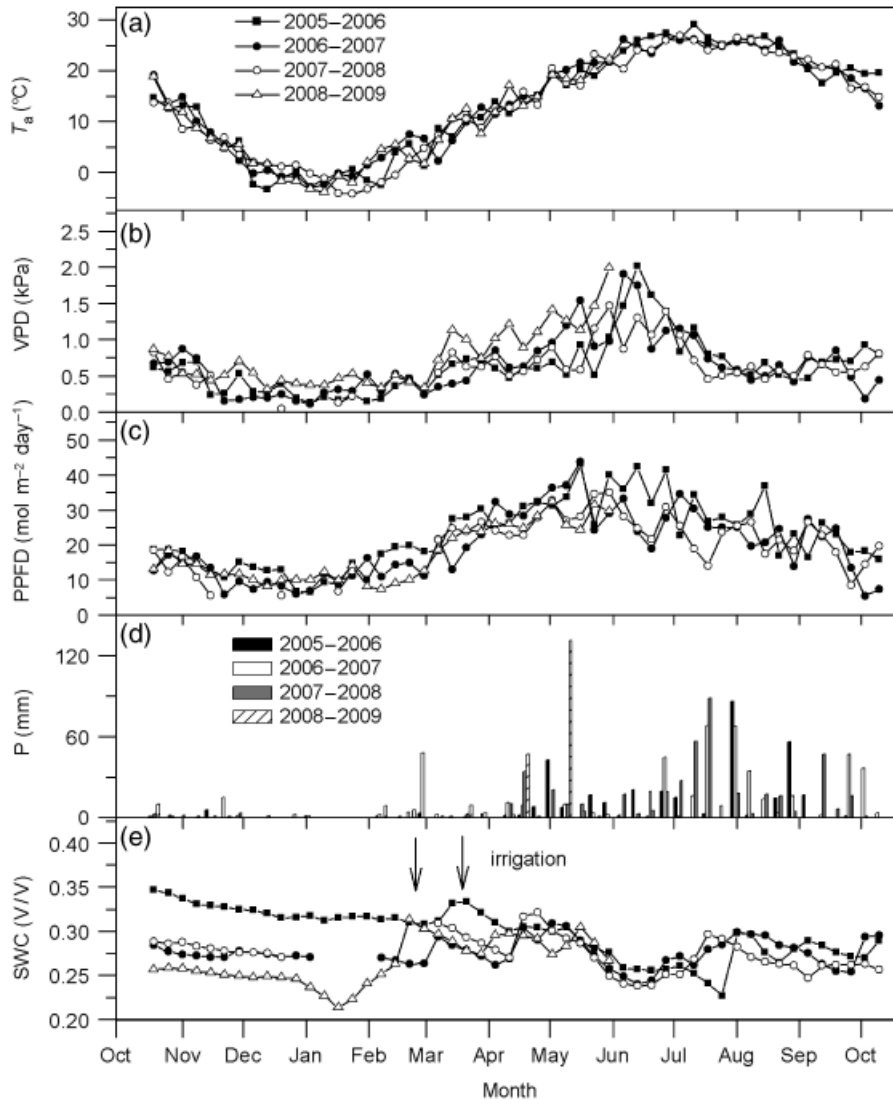


Fig. 2 Seasonal and interannual variations in the weekly averages (or sums) of daily mean air temperature (T_a), daily mean vapor pressure deficit (VPD), daily total photosynthetic photon flux density (PPFD), daily total precipitation (P), and soil water content (SWC, 0–80 cm averaged). Vertical arrows indicate irrigation events.

than during the summer maize season. The soil water content was generally high because of sufficient irrigation during the wheat season and sufficient precipitation during the maize season. In particular, the winter wheat experienced extreme drought stress from fall of 2008 to spring of 2009 (Tao *et al.*, 2009). The soil water content during this period was very low until the first irrigation in late February of 2009. The soil water content during the maize season of July 2006 also demonstrated slight water stress. The PPFD, air temperature, and precipitation showed great interannual variability, providing an opportunity to study the climate variability on carbon dioxide exchange, which will be discussed later in the paper.

Photosynthetically active radiation (PAR) albedo had a good negative correlation with the leaf area index (LAI) (Xu & Baldocchi, 2004; Burba & Verma, 2005). Thus, PAR albedo was used as an alternative indicator of crop development because consecutive measurements of the LAI were unavailable during these study periods. Figure 3 illustrates the seasonal and interannual variations in PAR albedo. It decreased slightly in November with the emergence and tillering of winter wheat, and then increased in winter due to leaf withering during the dormant stage. It remained relatively constant until the leaves became strongly erect in late February. The peak of PAR albedo appeared in late April or early May for the wheat season (the period

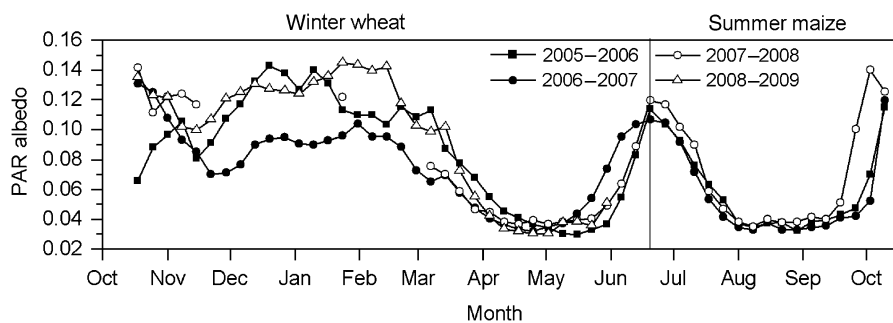


Fig. 3 Seasonal and interannual variations in weekly averages of daily photosynthetically active radiation (PAR) albedo (upward PAR/downward PAR, averaged from 10:00 to 14:00 hours).

from late April to early May is referred to as the 'rapid growth season' for wheat). After the planting of maize in June, the PAR albedo decreased rapidly during the elongation stage in July, reaching a minimum in early August, and then increased rapidly from late September (the period from August to early September is referred to as the 'rapid growth season' for maize). The seasonal variations in PAR albedo showed similar patterns in each year, but with significant interannual variability. The wheat in 2006–2007 had the lowest PAR albedo, but senesced earlier than those in the other years. Severe drought, occurring before March of 2009, was shown to not reduce the LAI of wheat through the inter-comparison of wheat's PAR albedo values in the years of 2005–2006 and 2008–2009.

Comparison of estimated and observed respiration using different approaches

Nighttime respiration can also be estimated from the light-response curve. Comparison of the estimated daytime average respiration (the effect of soil temperature differences between day and night has been accounted for) with the measured nighttime NEE showed a good agreement (Fig. 4). A linear regression over the 3-year period yielded a slope = 0.95 ($R^2 = 0.83$). Therefore, when eddy covariance measurements at night were unavailable, it was concluded that daytime respiration, estimated from the light response curve, could be used to gap-fill the nighttime NEE after necessary temperature corrections. The good agreement between the two estimates also suggested that the uncertainties, primarily in the NEE-PPFD regression model and the non-turbulent processes at night, may be quite limited.

The daytime average ecosystem respiration estimated from the light response curve was also compared with the daytime soil respiration observed with the chamber (Fig. 5). These were in good agreement despite the spatial heterogeneity of the chamber measurements. Theoretically, ecosystem respiration should be greater

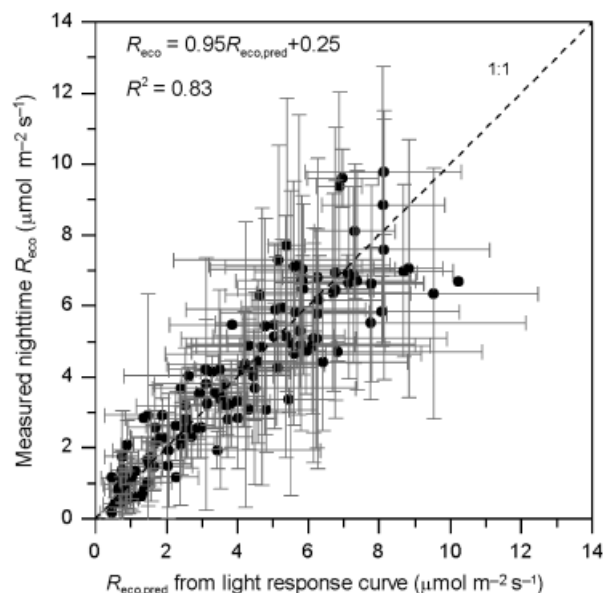


Fig. 4 Comparison of observed nighttime average ($u^* > 0.1 \text{ m s}^{-1}$) with the predicted values of 7-day averages of ecosystem respiration. Predicted values were calculated from daytime estimates using the temperature coefficient $k_T = 0.069 (\text{°C})^{-1}$ ($Q_{10} = 2.0$). Error bars indicate standard deviation of the means.

than soil respiration, as we did not measure the respiration of foliage and stems. However, the measurements from the chamber were slightly greater than the estimates from the light response curve. Our chamber measurements were performed during the period from 13:00 to 15:00 hours, when the soil respiration was slightly higher than the daytime average values because of the slightly higher soil temperature (data not shown). Other studies have also shown there is significant uncertainty when comparing eddy covariance measurements with chamber measurement (Loescher *et al.*, 2006). This uncertainty can even cause to that the chamber estimates to be substantially higher than the eddy covariance estimates (Lavigne *et al.*, 1997; Law *et al.*, 1999). The comparison between the two different

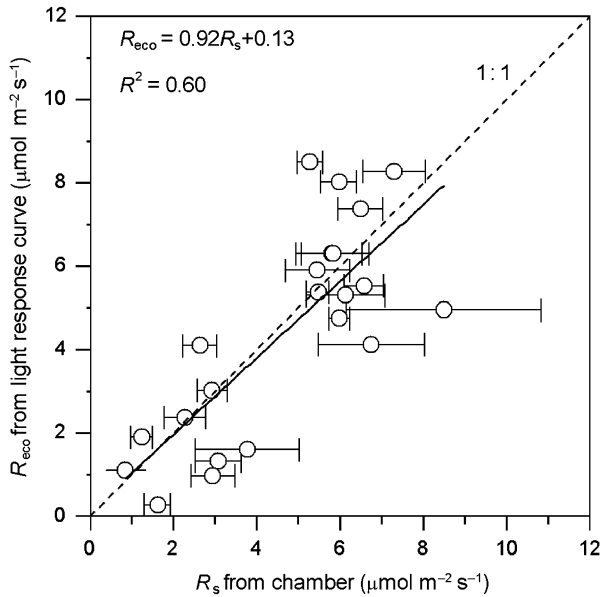


Fig. 5 Comparison of soil respiration observed from chamber and ecosystem respiration estimated from light response curves, March 2009–May 2009. Error bars indicate standard deviation of the means of observations from four points.

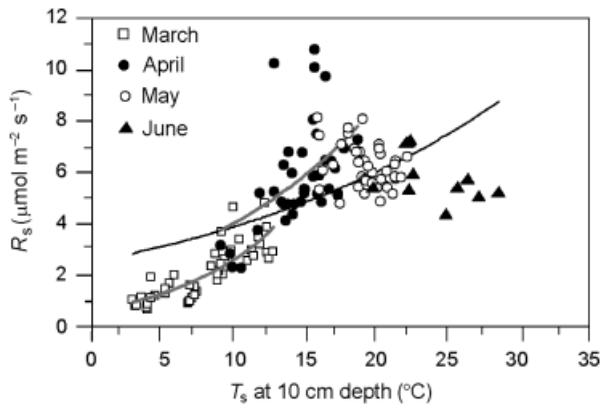


Fig. 6 Responses of soil respiration (R_s) to soil temperature (T_s) at a depth of 10 cm. Data were from the winter wheat season in 2009. The black solid line indicates the nonlinear regression based on all available data for this season (long-term sensitivity approach), whereas grey solid line indicates the nonlinear regression based on the data for each month (short-term sensitivity approach).

observation methods suggested that soil surface respiration was the largest source of ecosystem respiration at our site, and it validated the reliability of the eddy covariance measurement.

Temperature response of respiration

Figure 6 shows the relationship between soil respiration and soil temperature. The Q_{10} value ranged from 4.0 in

Table 1 Q_{10} values for each crop season

Year	Crop	Short-term Q_{10}	Long-term Q_{10}
2005–2006	Winter wheat	2.2	2.3
	Summer maize	1.6	1.3
2006–2007	Winter wheat	2.0	2.7
	Summer maize	1.4	2.3
2007–2008	Winter wheat	2.0	2.3
	Summer maize	3.9	1.6
2008–2009	Winter wheat	2.3	2.7

March to 2.1 in April of 2009, showing an obvious seasonal trend with crop phenology. A declining trend in soil respiration with soil temperature was observed in late May and early June due to the senescence of wheat.

The short-term Q_{10} values of the ecosystem respiration for each crop season are listed in Table 1. They ranged from 2.0 to 2.3 for winter wheat seasons and 1.4 to 3.9 for summer maize seasons. The short-term Q_{10} value of ecosystem respiration was higher than that of soil respiration for 2008–2009, as ecosystem respiration is composed mainly of soil respiration. The R_{ref} parameter showed a clear seasonal trend with crop phenology (Fig. 7), indicating that the temperature function was greatly affected by crop development. The measured values of Q_{10} were within the reported Q_{10} values, which can show wide variations (Raich & Schlesinger, 1992). Other published results in agroecosystems have also indicated wide variations in Q_{10} . For example, the Q_{10} values of 3.6–20.1 for maize were observed in Nebraska, USA (Suyker *et al.*, 2004). In Canada, Pattey *et al.* (2001) observed Q_{10} values ranging from 1.5 to 2.6 for maize growing under a high rate of nitrogen fertilization and from 1.3 to 2.5 under a low rate. Soegaard *et al.* (2003) reported a Q_{10} value of 2.3 at 10 °C during the period from late April to late August for summer wheat in Denmark.

Seasonal patterns of light-response parameters

Figure 8 demonstrates the seasonal course of light response parameters, α , F_{max} and γ . In general, the seasonal patterns of these parameters closely followed crop phenology (Fig. 3). The α values for winter wheat ranged from about 0.01 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in its dormant stage to around 0.055 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at its rapid growth stage. The α values ranged from 0.005 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at the early growth stage to 0.065 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at the rapid growth stage for summer maize. The F_{max} ranged from around 30–65 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for winter wheat, and reached up to 65 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for summer maize.

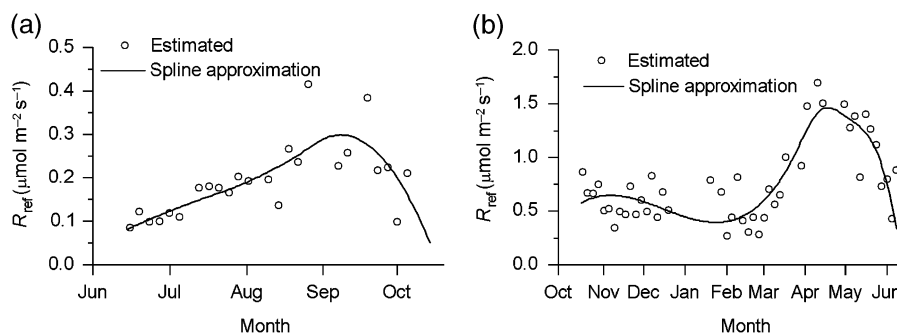


Fig. 7 Examples of seasonal variations in R_{ref} : (a) summer maize season in 2008 ($Q_{10} = 3.9$); (b) winter wheat season from 2008 to 2009 ($Q_{10} = 2.3$). Dots, fitted from nighttime observed NEE; Solid line, spline approximation from the dot values.

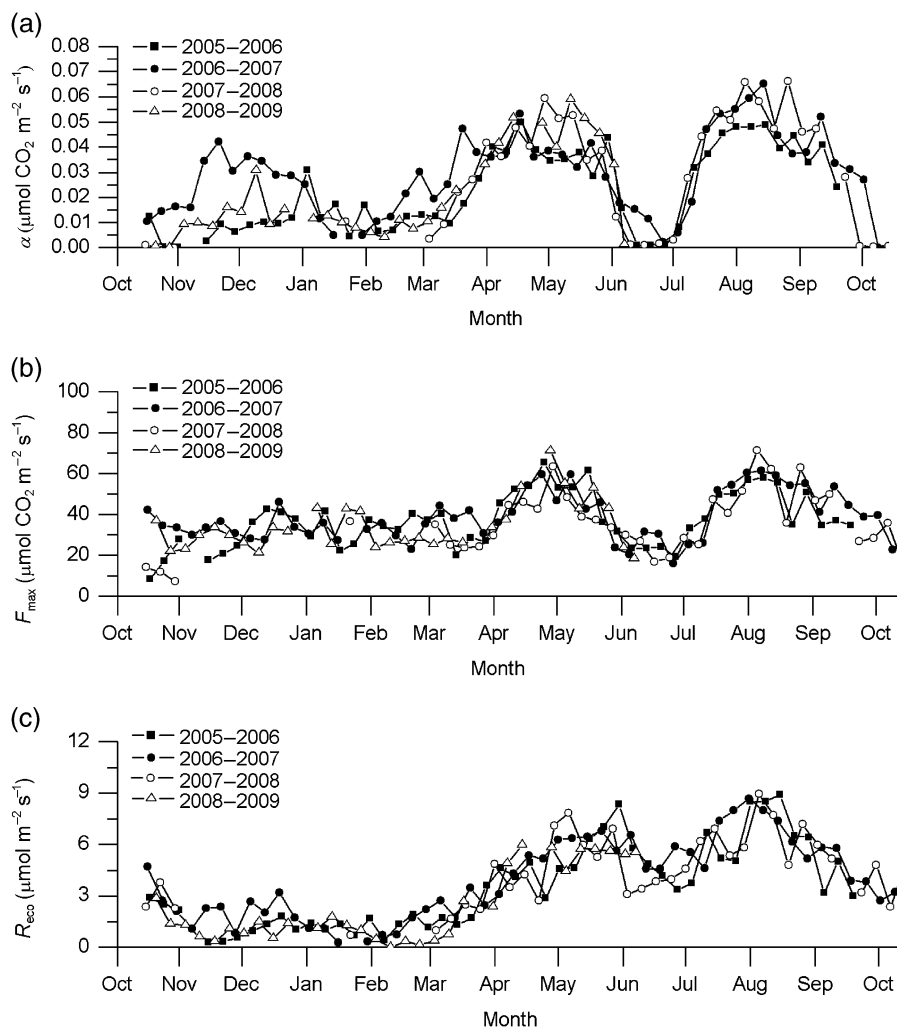


Fig. 8 Seasonal dynamics of light-response parameters: (a) apparent quantum efficiency (α); (b) saturated gross photosynthesis (F_{max}); (c) daytime average ecosystem respiration (γ). Dots, weekly mean values.

Statistically, the peak values of α for the C3 wheat were slightly lower than those for the C4 maize because a C4 plant has higher light use efficiency for photosynthesis than a C3 plant (Hollinger *et al.*, 2005). The quantum

yield reported from our site was comparable with other published data. Anthony *et al.* (2004b) reported an α value of $0.063 \mu\text{mol m}^{-2} \text{s}^{-1}$ during the rapid growth season for winter wheat. Ruimy *et al.* (1995) reported an

α of maize ranging from 0.03 to 0.06 $\mu\text{mol m}^{-2}\text{s}^{-1}$. Suyker *et al.* (2004) reported an α of maize ranging from 0.02 to 0.04 $\mu\text{mol m}^{-2}\text{s}^{-1}$.

The estimated daytime average γ varied closely with temperature, ranging from around 1 $\mu\text{mol m}^{-2}\text{s}^{-1}$ in winter to approximately 9 $\mu\text{mol m}^{-2}\text{s}^{-1}$ in summer. However, it was clearly reduced in June when the two crops were in a rotation period, reflecting the impact of photosynthetic activity on ecosystem respiration.

Seasonal and interannual variations in CO_2 exchange

Figure 9 shows the seasonal variations in daily cumulative GPP, R_{eco} , and NEE over the course of the study. The courses of GPP and NEE showed significant seasonal variations that were closely related to crop development and phenology. Within each year, NEE had two positive periods, when the crops were harvested in early June and early October. The values of NEE in the winter wheat field reached their minimum at -10 to $-11 \text{ g C m}^{-2}\text{ day}^{-1}$ in late April. The minimum daily NEE in the summer maize field appeared in August, ranging from -11 to $15 \text{ g C m}^{-2}\text{ day}^{-1}$. In comparison, Li *et al.* (2006) reported slightly lower minimum values of -10 to $13 \text{ g C m}^{-2}\text{ day}^{-1}$ for NEE in the summer maize field and -8 to $-9 \text{ g C m}^{-2}\text{ day}^{-1}$ in the winter wheat field. Similar values of minimum daily NEE have been also reported in other areas, for instance, -10 to

$-12 \text{ g C m}^{-2}\text{ day}^{-1}$ for wheat in Germany (Anthoni *et al.*, 2004b), and -12 to $-19 \text{ g C m}^{-2}\text{ day}^{-1}$ for maize in the United States (Hollinger *et al.*, 2005). The minimum values of NEE for summer maize were larger than those for winter wheat, which is in line with the results reported by Falge *et al.* (2002), who indicated that the maximum CO_2 uptake of C4 plants was higher than that of C3 plants. The pattern of ecosystem respiration R_{eco} was similar to the daytime averaged ecosystem respiration γ derived from the light-response curve (Fig. 8). The maximum daily values of R_{eco} in wheat seasons did not correspond to the days with the highest GPP values, instead occurring later after the peak GPP with the evolution of temperature. However, the variation in daily R_{eco} in maize seasons was synchronous with the variation in daily temperature. This suggested that R_{eco} was linked to the changes in both temperature and GPP.

Table 2 lists the annual and seasonal sums of GPP, R_{eco} , and NEE. We expected that the missing data from 13 November, 2007 to 16 March, 2008 would not bring excessive underestimation of the annual and seasonal sum values, as the crop field was only a small carbon sink in this period when the winter wheat was dormant. The interannual variation in NEE was large, which was due to both the interannual changes in GPP and R_{eco} . The seasonal sums of NEE for wheat ranged from -303 to -395 g C m^{-2} , whereas they were between -201 and -244 g C m^{-2} for maize. Winter wheat absorbed more

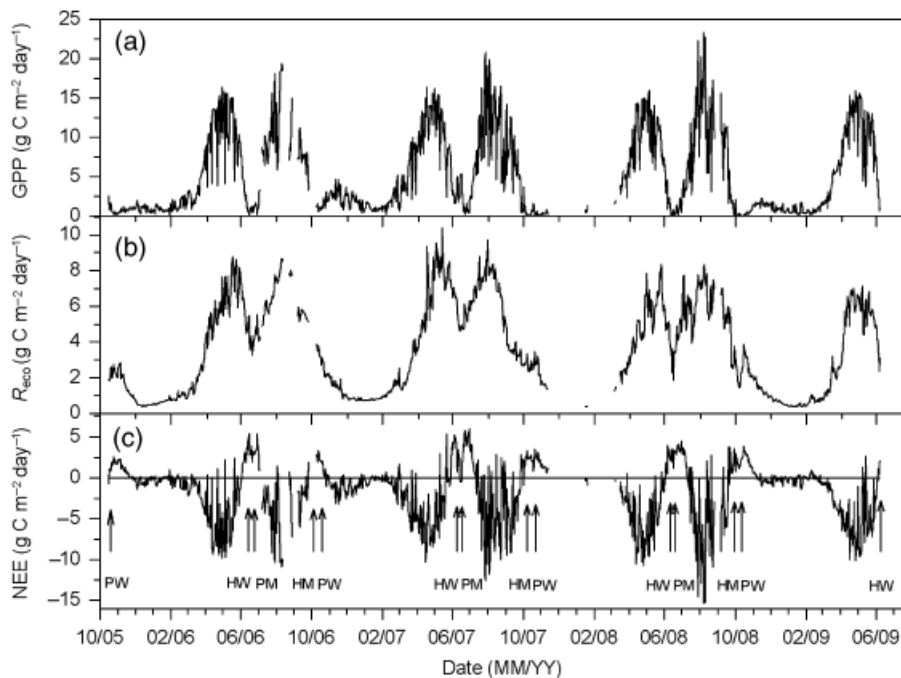


Fig. 9 Seasonal variations in (a) daily gross ecosystem production (GPP), (b) daily ecosystem respiration (R_{eco}) and (c) daily net ecosystem exchange (NEE). PW, plant dates for winter wheat; HW, harvest dates for winter wheat; PM, plant dates for summer maize; HM, harvest dates for summer maize.

Table 2 Annual and seasonal sums of NEE, GPP, and R_{eco}

Season	Year	T_a ($^{\circ}\text{C}$)	PPFD (mol m^{-2})	SWC (v/v)	GPP (g C m^{-2})	R_{eco} (g C m^{-2})	NEE (g C m^{-2})	Yield (g m^{-2})	C_{gr} (g C m^{-2})	NEE + C_{gr} (g C m^{-2})
Annual	2006–2007	13.74	7169	0.28	2008	1423	–585	–	–	–
	2007–2008*	13.16	7545	0.27	1668	1135	–533	–	615	82
Winter wheat (10.15–6.08)	2005–2006	8.14	4911	0.31	961	636	–326	645	250	–76
	2006–2007	8.88	4379	0.28	1114	720	–394	675	261	–133
	2007–2008*	8.00	4810	0.28	782	479	–303	637	247	–56
	2008–2009	8.39	4109	0.27	967	572	–395	656†	295	–100
Summer maize (6.15–10.14)	2006	23.93	3272	0.27	–	–	–	706	267	–
	2007	22.62	2656	0.28	872	672	–201	–	–	–
	2008	22.69	2591	0.26	880	636	–244	975	368	124

*Data from 13 November, 2007 to 16 March, 2008 were missing.

†Dry yield.

Mean air temperature, mean daily cumulative PPFD, mean soil water content, and crop yield are also presented.

T_a , daily mean air temperature; PPFD, photosynthetically active radiation; SWC, soil water content; GPP, gross primary production; R_{eco} , ecosystem respiration; NEE, net ecosystem exchange; C_{gr} , carbon in grains.

CO_2 than did summer maize because more light was absorbed by the wheat. The annual GPP, R_{eco} , and NEE in 2006–2007 and 2007–2008 were 2008, 1423, -585 g C m^{-2} and 1668, 1135, and -533 g C m^{-2} , respectively. The seasonal sums of GPP for both wheat and maize showed that temperature played an important role in controlling GPP. Higher average air temperatures led to a larger GPP. However, no significant correlation was found between PPFD and GPP, or for SWC and GPP. Both the comparisons between wheat seasons in 2005–2006 and 2008–2009 and the comparisons between maize seasons in 2007 and 2008 showed that ecosystem respiration R_{eco} was controlled mainly by temperature and soil water content. A higher R_{eco} could result from a higher temperature and/or higher soil water content.

Uncertainties in estimated CO_2 exchange

There is a potential systematic bias in estimating R_{eco} and NEE as the nighttime measured F_c in low-turbulence conditions. The dependence of NEE on the nighttime friction velocity (u^*) threshold could be site specific, as annual NEE was quite sensitive to u^* at some sites (Anthoni *et al.*, 2004b), and insensitive to u^* when u^* was greater than a certain threshold at other sites (Xu & Baldocchi, 2004). Figure 10 shows the impact of different u^* thresholds on the estimated seasonal sums of NEE. NEE became less negative as u^* increased from 0.0 to about 0.1 m s^{-1} . Increasing u^* after 0.1 m s^{-1} only slightly affected the estimated NEE. The differences in estimated NEE between uncorrected and corrected values at $u^* = 0.1 \text{ m s}^{-1}$ were only 32, 46, and 13 g C m^{-2} for the three seasons. Thus, nighttime low u^*

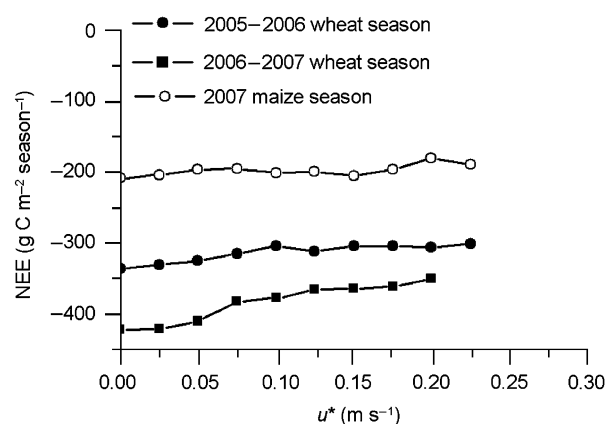


Fig. 10 Dependence of seasonal sums of net ecosystem exchange (NEE) on nighttime friction velocity (u^*). Three full seasons were selected with no large gaps.

was shown to have limited impacts on the estimated seasonal sum of NEE at our site.

As an alternative approach, ecosystem respiration can be estimated using long-term sensitivity (parameters b and R_{ref} are estimated from all available R_{eco} and temperature data during one growth season or a year) (Li *et al.*, 2006; Moureaux *et al.*, 2006). However, Reichstein *et al.* (2005) recommended an algorithm, used in this study, which defines a short-term sensitivity of ecosystem respiration. We compared the results from these two approaches. As shown in Fig. 11, winter wheat shows summer active vegetation and summer maize shows summer passive vegetation. Thus, the GPP of summer maize would be expected to be underestimated using long-term temperature sensitivity, whereas the GPP of winter wheat would be expected to be overestimated (Reichstein *et al.*, 2005). This

consideration was confirmed in our analysis of GPP. Using long-term temperature sensitivity, the GPP of summer maize was underestimated ranging from 0.1% to 5.7% in different seasons, whereas the GPP of winter wheat was overestimated ranging from 0.5% to 8.1% in different seasons. Although the Q_{10} values estimated by the two approaches were somewhat different (Table 1), the seasonal sums of GPP showed nonsignificant bias

between the two approaches. However, the short-term sensitivity method is still recommended, as the seasonal variations in ecosystem respiration would be biased for the dramatic growth dynamics and/or soil moisture effects (R_{eco} would be overestimated in the early and late growth stages and be underestimated in the rapid growth stage) if the long-term temperature sensitivity is used (as shown in Fig. 6).

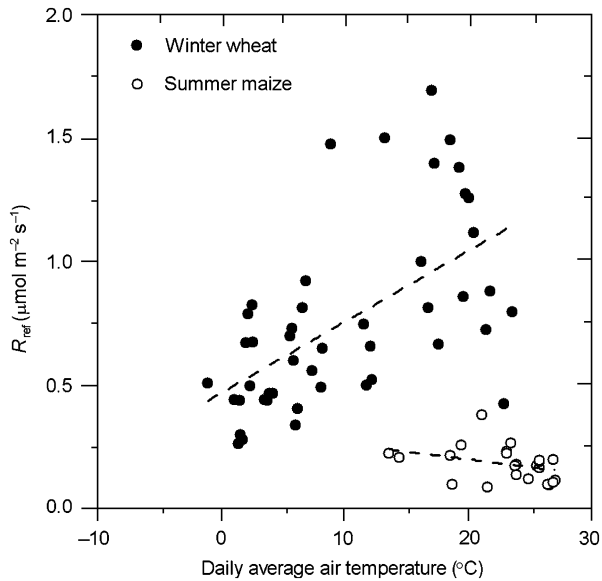


Fig. 11 Examples of the statistical relationship between daily average air temperature and reference respiration (R_{ref}) estimates. Data were from the 2008 maize season and the 2008–2009 wheat season.

Comparison of annual NEE with other ecosystems

The annual NEE was -533 and $-585 \text{ g C m}^{-2} \text{ yr}^{-1}$ in the years of 2006–2007 and 2007–2008, respectively. As compared with other annual cropping agroecosystems, our site with the winter wheat/summer maize rotation cropping system is a relatively strong carbon sink (see Table 3). In contrast, the temperate mixed forest in Northeast China and a steppe in central Mongolia both acted as relatively weak carbon sinks. Our data also showed that the carbon sink of the wheat/maize rotation system, with one tillage per year, was not different from that of the no-till cropland, which is similar to the results reported by Baker & Griffis (2005).

The main difference between agroecosystems and natural ecosystems in terms of carbon budget on a regional scale is that crop grains are harvested and finally transformed to CO_2 , which is again released to the atmosphere. We assumed that all of the crop straws were returned to the field, and the carbon in grains (C_{gr}) was estimated by crop yield (Y), which is as follows:

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

Table 3 Comparison of annual net ecosystem exchange (NEE) among different ecosystems

Site	Latitude	Vegetation	Temperature (°C)	Precipitation (mm)	NEE ($\text{g C m}^{-2} \text{ yr}^{-1}$)	Period	Source
Weishan, China	36°39'N	Wheat/maize rotation, irrigated, tillage	13.3	532	-533 to -585	2006–2008	This study
Nebraska, USA	41°10'N	Maize, irrigated, no-till	11.0	570	-381 to -517	2001–2004	Verma <i>et al.</i> (2005)
Illinois, USA	40°00'N	Maize, rainfed, no-till	-	-	-576	1997–2002	Hollinger <i>et al.</i> (2005)
Gebesee, Germany	51°06'N	Winter wheat, rainfed, tillage	9.7	505	-185 to -245	2001	Anthoni <i>et al.</i> (2004a)
Ponca City, USA	36°46'N	Winter wheat, rainfed, -	14.8	966	-273	1–232 days during 1997	Gilmanov <i>et al.</i> (2003)
Yucheng, China	36°50'N	Wheat/maize rotation, irrigated, tillage	13.1	582	-761 to -1097	2003–2004	Zhang <i>et al.</i> (2008)
Changbaishan, China	42°24'N	Temperate mixed forest	3.6	695	-242 to -279	2003–2005	Yu <i>et al.</i> (2008)
Hentiy, Mongolia	47°13'N	Grazed steppe	1.2	196	-41	2003–2004	Li <i>et al.</i> (2005)

where W_{gr} [0.140 for wheat and 0.155 for maize (Li *et al.*, 2006)] is grain water content, and f_c [0.450 for wheat and 0.447 for maize (Li *et al.*, 2006)] is the fraction of carbon in the grain. Taking into account the carbon released by grains, the carbon sink in the wheat field was greatly diminished, whereas the maize field was turned into a slight carbon source (Table 2). Annually, our site is a weak carbon source if grain carbon loss is considered for the years of 2007–2008. This is similar to other reported results (Anthoni *et al.*, 2004a; Verma *et al.*, 2005).

Possible impacts of climate change on carbon dioxide exchange

As mentioned above, interannual variations in GPP were mainly determined by temperature, whereas interannual variations in R_{eco} were affected by both temperature and soil water content. The variation in NEE depended on the relative contributions from GPP and R_{eco} . From our analysis, although northern China encountered a severe drought during the period from November 2008 to January 2009, neither the seasonal sum of NEE nor the yield of winter wheat in the season of 2008–2009 was reduced comparing with that in the other years. Previous study has shown that winter wheat was most insensitive to water stress in its dormant stage and more sensitive to water stress from stem elongation to heading stages and from heading to milking stages (Zhang *et al.*, 1999). Certain soil water stress in the early vegetative growth period could lead to higher grain yield as a result of small reduction in biomass and an improvement in harvest index (Kang *et al.*, 2002). Thus, the yield (or NEE) of winter wheat would not decrease as a result of the winter drought, as long as sufficient irrigation is carried out in late February when the wheat is turning green. According to the IPCC report (IPCC, 2001) and modeling work (Yu *et al.*, 2008), the air temperature in northern China will increase and northern China will become more xeric as global warming progresses. Our study's results suggested that GPP would increase with increasing temperature, and that R_{eco} would also increase if sufficient irrigation is maintained. Owing to the complexities in crop management and the uncertainties of future climate change, more long-term measurements based on various approaches are needed to investigate the response of carbon sequestration to climate change.

Conclusion

We have presented measured NEE and estimates of GPP and ecosystem respiration from 2005 to 2009 using an eddy covariance technique for winter wheat/sum-

mer maize double cropping fields in the North China Plain. Comparisons of eddy covariance measurements with chamber measurements suggested that ecosystem respiration was primarily composed of soil respiration for this cropland. Seasonal variations in the response of nighttime NEE to temperature and the response of daytime NEE to light showed close association with crop development and phenology (expressed as PAR albedo). Daily R_{eco} was highly dependent on both GPP and temperature. Interannual variations in R_{eco} and GPP were mainly controlled by temperature. Soil water availability also imposed significant limitations on R_{eco} during the drought periods. Nighttime low u^* was shown to have a limited impact on the estimated seasonal sums of NEE. An algorithm, defining a short-term temperature sensitivity of ecosystem respiration, estimated similar integrated GPP as that estimated by an algorithm with long-term temperature sensitivity. Short-term temperature sensitivity algorithm, however, avoids the bias in seasonal variations. The annual NEE was -585 and -533 gC m^{-2} for the 2006–2007 and 2007–2008 seasons, respectively. Seasonal sums of NEE for wheat ranged from -303 to -395 gC m^{-2} , and they were -201 to -244 gC m^{-2} for maize. Integrated NEE showed that both winter wheat and maize fields were strong carbon sinks. However, when the harvest was taken into account, the wheat field was diminished to a small carbon sink, whereas the maize field was converted to a small carbon source. The annual NEE showed that the winter wheat/summer maize cropping field was a small carbon source in 2007–2008, if grain harvest was considered. We observed that severe droughts during fall and winter did not have negative impacts on the seasonal sum of NEE or the yield of wheat.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Project no. 50679029 and no. 50811140089) and the Doctoral Program Foundation of Institutions of Higher Education of China (Project No. 2007000307). The authors would like to express their appreciation to two anonymous reviewers, whose comments and suggestions led to significant improvements in the manuscript.

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