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Carbon budget of a winter-wheat and summer-maize rotation cropland in the North China Plain

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ABSTRACT

Crop management exerts a strong influence on the agroecosystem carbon (C) budget. From October 2007 to October 2008, the net C budget of an intensive winter-wheat and summer-maize double cropping system in the North China Plain (NCP) was investigated in a long-term field experiment with crop residues input, using a combination of eddy covariance, crop growth and soil respiration measurements. The objectives were to qualify the annual C budget and to establish the effects of climatic variables and crop management on C budget.

The net ecosystem exchange of CO_2 (NEE) was partitioned into gross primary production (GPP) and total ecosystem respiration (TER); meanwhile, net primary production (NPP) and soil respiration (SR) were determined to compute autotrophic and heterotrophic respirations. Results showed that the NEE, NPP and SR were 359, 604 and 281 g C m^{-2} in wheat season respectively, and 143, 540 and 413 g C m^{-2} in maize season respectively. Autotrophic respiration dominated TER and was mainly driven by GPP. The net C budget was calculated seasonally based on NPP and considering C input through crop residues and C output through grain harvest. We found the winter-wheat system was a C sink of 90 g C m^{-2}; whereas, the summer-maize system was a C source of 167 g C m^{-2}. Thus, the double cropping system behaved as a C source of 77 g C m^{-2} on an annual basis, corresponding to an annual average loss rate of nearly 1% in topsoil organic carbon stocks during 2003–2008. Though the season length was 52% shorter for maize (113 days) than that for wheat (235 days), over 55% of the CO_2 emissions originated from the warmer and rainy maize season; this implies that the inter seasonal climate variability affected the C flux dynamics mainly and the interaction of soil temperature and moisture is the "single" dominant factor for ecosystem respiration in this area. Our study provides evidence that C was being lost from the intensive wheat-maize double cropping system in the NCP at a rate of 77 g C m^{-2} $year^{-1}$ when harvest removals were considered, even though crop residue C was inputted into the soil since 30 years ago.

1. Introduction

With rising concern about the climatic consequences of greenhouse gas (GHG) emissions, worldwide efforts are being made to augment carbon (C) sequestration and reduce carbon dioxide (CO_2) emissions (Sierra et al., 2013). Agroecosystem has the important potential to both sequester large amounts of C and emit CO_2 (Lal, 2011). Further, cropland canopies change seasonally due to management activities such as planting, tillage, irrigation, fertilizer application and harvesting; and net carbon fluxes are affected by each activity. Thus management practices should be adapted to decrease CO_2 emissions and increase C sequestration (Lal, 2011). Moreover, although the C sequestration potential of cropland is considered as a modest but non-negligible contribution to climate change mitigation (between 3% and 6% of fossil fuel contribution to climate changes), the quantification of the net C sequestration potential is not easy due to the many interactions and the huge spatial variations in cropping systems and management (Hutchinson et al., 2007). Consequently, quantification of crop C sequestration potential remains very uncertain, and variability in stocks and fluxes of C in croplands is a theme of major interest.

During the past two decades, eddy covariance technique has become the most important method for measuring trace gas

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exchange between terrestrial ecosystems and the atmosphere (Taylor et al., 2013). So far most studies on croplands have focused on seasonal patterns of CO_2 flux and annual C balance for different crops. For example, micrometeorological studies of agroecosystem CO_2 fluxes have been conducted over winter wheat (Anthoni et al., 2004), no-till maize (Verma et al., 2005), maize/soybean rotations (Bernacchi et al., 2006), corn/soybean (Baker and Griffis, 2005), winter-wheat/summer-maize (Li et al., 2006), spring-barley/fallow (Davis et al., 2010) and maize/faba/spring-wheat (Glenn et al., 2010). Some of these studies reveal the importance of management practices on plot C budget, e.g., Baker and Griffis (2005) reported that C gain caused by reduced tillage and intercropping compared to conventional management was compensated for by a drop in productivity and an increase in crop residue decomposition. Bernacchi et al. (2006) stated that the conversion of conventional tillage to no-till agriculture in maize/soybean crops in the USA might result in an annual net C sequestration of 20.77 Tg C. More recently, Buysse et al. (2013) conducted a long-term experiment initiated in 1959 in the Hesbaye region of Belgium and focused on residue and farmyard manure contrasted treatments. The authors concluded that residue export and farmyard manure addition caused significant soil organic matter decreases (on average, -7 ± 5 g C m^{-2} year^{-1} over the 50 years) and increases (10 ± 5 g C m^{-2} year^{-1}), respectively; whereas residue restitution had no significant impact on the soil organic matter stocks. In contrast, Ding et al. (2007, 2012),) and Cai and Qin (2006) have demonstrated that long-term straw application and fertilizer application significantly increased soil organic carbon concentrations and soil organic carbon stocks in the 0–20 cm soil in the northern China. Evidently, there remains a considerable degree of uncertainty in the overall C budget of cropland as function of region and management. Therefore, considering management to address whether a cropland is a C source or sink is essential (Béziat et al., 2009).

The North China Plain (NCP) is the largest and most important agricultural region in China. This region produces up to 50% of the cereal consumed in China each year and accounts for 18.6% of the country farmland and supports a population of 203 million (Piao et al., 2010; Godfray et al., 2010). To meet increasing food demands without expanding croplands, annual agricultural practice in much of the NCP has changed from single to double cropping since the late 1970s. Although the NCP produces more than 75% and 32% of the national wheat and maize, respectively (China Statistics Bureau, 2011), the impact of double cropping on the regional C budget, through biophysical feedbacks caused by changes in land surface conditions, remains largely unknown. Meanwhile, limited information is available on C budget of the intensive winter-wheat and summer-maize rotation system as affected by crop managements in the NCP. Furthermore, despite the site has been cropland over thirty years with crop residue mulching, intensive agriculture tends to produce more emissions than the global average due to increased chemical and manure nitrogen inputs. Therefore, the C budget of the intensive double cropping system in the NCP is becoming increasingly crucial.

In the current study, we analyzed the soil organic carbon (SOC) stock (0–20 cm) in the cropland from 1978 until 2008; results showed that after a rapid increase in SOC stock with values ranged between 2.5 and 4.0 kg C m^{-2} from 1978 to 2002, the SOC stock decreased and stabilized at 3.7 kg C m^{-2} from 2003 to 2008 (Fig. 1). Following this conversion, it could have been expected that the soil would be close to equilibrium with respect to C, indicating that C might be lost from the system. To confirm the hypothesis, a field experiment was conducted to evaluate the net C budget, using a combination of eddy covariance, crop growth and soil respiration measurements from October 2007 to October 2008 in the NCP. The specific objectives were: (1) to quantify the annual C budget for

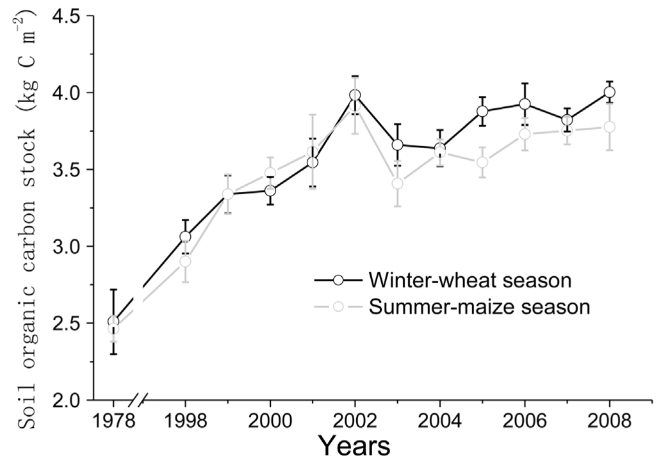

Fig. 1. Evolution over time of the soil organic carbon stock in 0–20 cm soil layer from 1978 to 2008. Bars in figure indicate 1 standard deviation (mean ± SD, $n = 5$).

this system, where crop residues are left on the soil after harvest and where management is intensive with fertilizer applications, irrigations and tillage; (2) to evaluate the effects of seasonal cropping, soil temperature, soil moisture, irrigation and precipitation on C budget in a winter-wheat and summer-maize rotation cropland in the NCP.

2. Materials and methods

2.1. Site description

The studied site is Luancheng Agroecosystem Experimental Station, Chinese Academy of Sciences, which is located in Hebei province (37°53′15″N, 114°41′47″E) at an elevation of 50.1 m. This area represents the typical high production area in the NCP and is at the piedmont of the Taihang Mountains. The climate is semi-arid and semi-humid, with a long cold winter (November–February), and a short spring (March–April). The mean annual temperature is about 12.5 °C and the mean annual precipitation is about 480 mm. The soil is classified as silt loam Haplic Cambisol (FAO-WRB (ISSS-ISRIC-FAO-UNESCO), 1998). Total soil organic matter in the 0–20 cm was 17.0 g kg^{-1} in 2008.

The dominant cropping system in the region is winter-wheat (*Triticum aestivum* L.wheat variety Kenong 199) and summer-maize (*Zea mays* L. maize variety Xianyu 335) double cropping rotation (two crops harvested in a single year) without fallow. Measurements were carried out in a long-term field experiment. Crop rotation has remained unchanged since 1980. Straw was chopped (<5 cm) by automated machine and returned to the field at harvest time. Seeds were directly drilled into the soil. Plowing of the top soil (0–15 cm) occurred once a year after the harvest of the maize crop in October. Details on fertilizer application and crop management activities are presented in Table 1.

2.2. Total soil organic carbon content measurements

The total soil organic carbon content (%TOC) was measured sporadically in 1978 and thereafter twice a year from 1998 until 2008. One soil sample, made up of 10 subsamples taken randomly from the experimental field. The samples for TOC analyses were always taken after wheat and maize harvest and before any fertilizer input. The sampling depth was 0–20 cm. Total organic carbon in soil was determined by wet oxidation method (Snyder and Trofymou, 1984), which uses heat (120 °C) to oxidize organic matter more completely than traditional wet oxidation methods

Table 1
Fertilizer application and timing of crop management activities.

Timing	Fertilization and crop management activities		
	Winter-wheat growing season		Summer-maize growing season
October 17, 2007	Basal fertilizer application ($140.25\,kg\,N\,ha^{-1}$ and $60.26\,kg\,P\,ha^{-1}$)		
October 19, 2007	Tillage and seeding		
April 12, 2008		Supplementary N fertilizer application ($162.75\,kg\,N\,ha^{-1}$)	
April 13, 2008		Irrigation (67.0 mm)	
June 10, 2008		Harvest	
June 11, 2008			Seeding
July 22, 2008			Supplementary N fertilizer application ($276\,kg\,N\,ha^{-1}$); irrigation (60.0 mm)
October 2, 2008			Harvest

do. An average bulk density of $1470\,kg\,m^{-3}$ (Wang et al., 2013) was used to convert the %C values into soil organic carbon stocks (SOC, $kg\,C\,m^{-2}$), using (Tivet et al., 2012):

$$SOC = TOC \times \rho_b \times e \quad (1)$$

where TOC is the content of total organic carbon ($g\,C\,(kg\,soil)^{-1}$), ρ_b the soil bulk density ($kg\,m^{-3}$), e is the measurement depth (0–20 cm in this case).

2.3. Continuous measurement of climate and driving factors

Air temperature (AT), soil temperature (ST) at the depths of 5, 10, 20, 40 and 80 cm (109-L Temperature Probe, Campbell Scientific Instruments Inc., Logan, UT, USA) and soil water content (CS616 Water Content Reflectometers, Campbell Scientific Instruments Inc., Logan, UT, USA) at the depths of 10, 40 and 80 cm were measured every 30 min at soil profile near the flux tower; rainfall was measured with a tipping bucket gauge (TE525MM, Campbell Scientific Instruments Inc., Logan, UT, USA); the irrigation amount was measured with an ultrasonic flowmeter (TDS-100P, Haozhixinyuan Science and Technology Development Co., Ltd., Beijing, China). All apparatuses were controlled by a data logger (Model CR23X, Campbell Scientific Instruments Inc., Logan, UT, USA), and all sensors used in the experiment were calibrated frequently.

2.4. Eddy covariance flux measurements

The net ecosystem exchange of CO_2 (NEE, note the definitions of the sign conventions in Table 2) between the biosphere and atmosphere was measured with an open-path eddy covariance system. The eddy covariance (EC) station was set up in 5 November 2007 in the middle of the agricultural field, which has a rectangular size of 200 m × 300 m. Instrument heights were 3.0 m (at least 1 m higher than crops at their maximum development). The EC station consists of a three-dimensional sonic anemometer (CSAT-3, Campbell Scientific Instruments Inc., Logan, UT, USA) and an open-path infrared gas analyzer (LI-COR 7500, LI-COR Inc., Lincoln, NE, USA). Data were recorded at 20 Hz on a data logger (Model CR5000, Campbell Scientific Inc., Logan, UT, USA), then block-averaged over 30 min for analysis and archiving, and stored on a 1 GB compact flash card. Zero and span calibrations were performed for CO_2 and H_2O every six month. This was the standard system used in the Chinese Terrestrial Ecosystem Flux Research Network (ChinaFLUX) (Yu et al., 2013).

2.5. Crop measurements

To trace crop development, changes in NPP were estimated at every crop growth stage. Dry matter (DM) and green leaf area indexes (GLAI) were measured at every crop growth stage from October 2007 to October 2008. DM was measured by plant sampling method. Five measurement points were uniformly distributed around the southern half of the flux tower, reserving the northern half for soil respiration measurement. From each measurement point, all of the plants in two 1.0 m sections of row were cut at ground level and combined. Fresh and dry phytomass and GLAI were obtained from these samples. A subsample (25–30 tillers for wheat; 5–10 plants for maize) was randomly selected from each sample, the leaf blades removed, and the area of green leaf blades measured with an area meter (LAI-2000, LI-COR Inc., Lincoln, NE, USA).

Roots were sampled at the five measurement points by removing soil cores. Cores were obtained by driving steel tubes (7 cm diameter) into the ground with a portable, motorized hammer. The tubes were withdrawn with a hand-operated winch

Table 2
List of abbreviations and symbols and their definitions, units and sign conventions.

Abbreviation/ symbol	Full name	Unit	Sign conventions and comments
NEE	Net ecosystem exchange of CO_2	$g\,C\,m^{-2}\,day^{-1}$	Positive corresponds to a carbon sink
GPP	Gross primary production	$g\,C\,m^{-2}\,day^{-1}$	Positive corresponds to a carbon sink
TER, R_E	Total ecosystem respiration	$g\,C\,m^{-2}\,day^{-1}$	Positive corresponds to a carbon release
DM	Dry matter	$g\,m^{-2}$	
GLAI	Green leaf area index		
SR	Soil respiration	$g\,C\,m^{-2}\,day^{-1}$	
f_c	Soil CO_2 efflux rate	$mmol\,m^{-2}\,s^{-1}$	
Q_{10}	Temperature sensitivity of soil respiration		
AB	Aboveground biomass	$g\,m^{-2}$	
NPP	Net primary production	$g\,C\,m^{-2}$	
R_a	Ecosystem autotrophic respiration	$g\,C\,m^{-2}\,day^{-1}$	
R_h	Ecosystem heterotrophic respiration	$g\,C\,m^{-2}\,day^{-1}$	
R_{aa}	Aboveground autotrophic respiration	$g\,C\,m^{-2}\,day^{-1}$	
R_{ab}	Belowground autotrophic respiration	$g\,C\,m^{-2}\,day^{-1}$	
AT	Air temperature	°C	
ST	Soil temperature	°C	
M	Soil moisture (volumetric water content)	%	
u^*	Friction velocity	$m\,s^{-1}$	

and tripod. Six cores were taken on each point, 3 to a depth of 1 m and 3 to 1.8 m. Cores were cut into 20 cm lengths after allowing for compaction and the roots washed out in special cans equipped with high pressure water jets. Roots and plant debris were collected on 0.5 mm sieves. The components of the subsample (root, leaf blades, stems including leaf sheaths, and heads) and the remainder of the large sample were put in separate bags, dried at 70 °C to constant weight, and weighed. Grain and straw yields were measured and the harvest index (HI, grain yield/biomass yield) was calculated at harvest time.

2.6. Soil respiration measurements

Soil respiration (SR) was measured using an automated soil CO_2 flux system (LI-COR 8100, LI-COR Inc., Lincoln, NE, USA) equipped with a portable chamber (Model 8100-103). Soil respiration was determined directly between the rows of crops between 9:00 and 11:00 AM local time from October 2007 to October 2008, once a week. A polyvinyl chloride (PVC) collars (20.3 cm in diameter and 10 cm in height) was inserted into the soil base to a depth of 2.5 cm at each sampling point, about 4 weeks before the first measurement. All five collars were left at the site for the entire study period. Soil temperature (ST) at 5 cm depth and volumetric soil water content at 10, 20 and 30 cm depths were monitored simultaneously near PVC collars using the temperature and moisture sensors attached to LI-8100 automated soil CO_2 flux system.

2.7. Data processing and calculations

2.7.1. Calculations of CO_2 fluxes

To ensure the reliable processing of flux data, ChinaFLUX developed a series of proven methodologies for assessing the flux data quality control including coordinate rotation, WPL correction, canopy storage calculation, nighttime flux correction, and gap filling and flux partitioning (Yu et al., 2013).

Firstly, we applied the analytical footprint model (Kormann and Meixner, 2001) to estimate how well the measured fluxes captured the sources and sinks of the cropland. If more than 70% of the 30 min flux footprint overlapped with the area of interest, the data were used for further analysis; otherwise the data were rejected. In our study, 19% of the flux measurements did not originate from the area of interest. Secondly, prior to conducting the scalar flux computation, three dimensional rotation of the coordinate was applied to wind components to remove the effect of instrument tilt or irregularity on airflow (Zhu et al., 2005). The WPL correction was then applied to adjust the effect of air density caused by the transfer of heat and water vapor with the method described by Webb et al. (1980). Thirdly, storage flux was calculated and the abnormal values were eliminated. An important source of error in the calculation of NEE is the underestimation of nighttime fluxes, due to low turbulence conditions. The nighttime CO_2 flux data under low atmospheric turbulence conditions were screened using site-specific thresholds of friction velocity (u^*), which was identified with the method described by Reichstein et al. (2005). In our experiment, the threshold velocity is 0.15 m s^{-1}. Fluxes will be eliminated when u^* is smaller than 0.15 m s^{-1}. Based on this criterion 25% of all data had to be rejected at the site, particularly at night.

2.7.2. Flux gap filling and NEE partitioning

The data gaps were filled with the nonlinear regression method suggested by Falge et al. (2001) and the NEE was partitioned into GPP and TER with the method described by Reichstein et al. (2005). NEE gaps were filled in to compute daily to annual fluxes and data gaps were filled using parameterization or mean diurnal variation approaches. Where there were missing meteorological data, the mean diurnal variation was applied using an 11-day data window (Falge et al., 2001). Elsewhere, gaps were filled using the empirical NEE–climate relationship. Daytime gaps were estimated using an NEE–photosynthetically photon flux density (Q) relationship based on 10-day periods. The relationship used was the Misterlich equation (Eq.) (Aubinet et al., 2001):

$$\mathrm{NEE} = -(N_s + R_d)\left(1 - \exp\left(\frac{-\alpha Q}{N_s + R_d}\right)\right) + R_d \quad (2)$$

where N_s is the NEE at light saturation, α is the apparent quantum efficiency (the initial slope of the curve) and R_d the dark respiration.

Night-time gaps were estimated using a respiration–soil temperature relationship (Lloyd and Taylor, 1994). The method described in Reichstein et al. (2005), based on the Lloyd and Taylor (1994) model parameters optimization, and was followed:

$$R_E = R_{\mathrm{ref}} \times \exp\left(E_0\left(\frac{1}{T_{\mathrm{ref}} - T_0} - \frac{1}{T_a - T_0}\right)\right) \quad (3)$$

where R_E is total ecosystem respiration; R_{ref} is the respiration at the reference temperature T_{ref} (here 10 °C); E_0 is a parameter characterizing the respiration sensitivity to temperature; and T_0 is a temperature scale parameter kept constant at −46.02 °C as in Lloyd and Taylor (1994) to avoid any over-parameterization of the model as explained by Reichstein et al. (2005). T_a is the soil temperature expressed in Kelvin and measured at a depth of 5.0 cm. The parameterization was fitted on data for the whole period corresponding to mixed conditions.

After gap filling was achieved, NEE was partitioned into GPP and TER (R_E) components, as follows:

$$\mathrm{GPP} = \mathrm{NEE} - \mathrm{TER} \quad (4)$$

2.7.3. Biomass partitioning

Wheat and maize biomass was measured at every crop growth stage (see Section 2.5 for details), and the C content of net primary production (NPP) was calculated as follows:

$$C_{\mathrm{NPP}} = \mathrm{NPP} \times 0.44 \quad (5)$$

where NPP is the net primary production (g m^{-2}); C_{NPP} (g C m^{-2}) is the total amount of C in NPP; the coefficient 0.44 was derived from three assumed factors: 0.27, the C content of CO_2; 0.68, the conversion of CO_2 to carbohydrate (CH_2O/CO_2); and 0.90, the conversion of carbohydrate to plant biomass (photosynthesis equation, biomass/CH_2O). Further,

$$C_{\mathrm{grain}} = (1 - W_{\mathrm{grain}}) \times f_c \times Y \quad (6)$$

where C_{grain} is the C content of grain; W_{grain} is the water percentage in dry grain (0.14 for wheat; 0.155 for maize) (Li et al., 2006); f_c is the carbon percentage in grain (0.45 for wheat; 0.447 for maize) which was determined after harvest; Y is grain yield.

2.7.4. Calculation of soil respiration

The soil CO_2 efflux rate was computed using the following equation:

$$F_c = \frac{10VP_0\left(1 - \frac{W}{1000}\right)}{RS(t_0 + 273.15)}\frac{\partial C'}{\partial t} \quad (7)$$

where F_c is the soil CO_2 efflux rate (mmol m^{-2} s^{-1}), V is the volume (cm^3), P_0 is the initial pressure (kPa), W is the initial water vapor mole fraction (mmol mol^{-1}), S is soil surface area (cm^2), T_0 is initial air temperature (°C) and $\partial C'/\partial t$ is the initial rate of change in water-corrected CO_2 mole fraction (mmol^{-1} s^{-1}).

On the basis of the whole year data, we established exponential and inverse functions given in Eqs. (8) and (9) to describe the relationship between soil respiration and soil temperature at 5 cm depth and between soil respiration and soil moisture at 10 cm depth:

$$SR = \alpha \times e^{\beta t} \quad (8)$$

$$SR = \frac{\gamma}{M} + \delta \quad (9)$$

where SR, t, and M are soil respiration rate, soil temperature, and soil water content, respectively; and α,β, γ and δ are constant coefficients. The temperature sensitivity (Q_{10}) of soil respiration based on Eq. (8) was calculated as:

$$Q_{10} = \exp(10 \times \beta) \quad (10)$$

A new equation was established by combining Eqs. (8) and (9) to describe the interactive effects of soil temperature and water content on soil respiration (Wan and Luo, 2003).

$$SR = \alpha \times T^{\beta} \times M^{\gamma} \quad (11)$$

where α, β and γ are constant coefficients.

2.7.5. Scaling for cumulative soil CO_2 efflux

Soil CO_2 emissions over the two crop growing seasons were calculated by integrating the CO_2 efflux for the period from October 2007 to October 2008 using the observed ecosystem-specific response equation between soil respiration and soil temperature (Eq. (8)).

Further estimates of annual and season soil CO_2 emissions for the ecosystems were obtained by interpolating the average CO_2 flux rate between sampling dates, and computing the sum of the products of the average flux rate and the time between respective sampling dates for each measurement period (Frank and Dugas, 2001) as follows:

$$SR_{cumulative} = \sum_{i=1}^{n} (\alpha \times e^{\beta t})_i \times 24 \quad (12)$$

where $SR_{cumulative}$ is total CO_2 emitted in the measurement season ($g\,C\,m^{-2}$); n is the total number of measurements performed.

2.7.6. Calculation of carbon budgets

Total ecosystem respiration (TER) can be partitioned into autotrophic (R_a) and heterotrophic (R_h) contributions, and autotrophic respiration can be further divided into its aboveground (R_{aa}) and belowground (R_{ab}) components. These terms were assessed from eddy covariance measurements, SR and crop growth measurements as follows:

$$R_a = GPP - NPP \quad (13)$$

$$R_{aa} = TER - SR \quad (14)$$

$$R_{ab} = R_a - R_{aa} \quad (15)$$

$$R_h = TER - R_a = NPP - NEE \quad (16)$$

2.8. Statistical analyses

All the statistical analyses were performed using SPSS for Windows Software (Version 18.0, SPSS Inc., Chicago, IL, USA). Simple linear regression was used to evaluate the relationships between environmental variables and NEE, GPP and TER separately. Stepwise regression was used to test the influence of environmental variables on NEE, GPP and TER. Pearson's correlation coefficient was used to analyze the relations between soil environment variables and soil respiration. The effect of soil temperature and moisture on soil respiration was evaluated by exponential, inverse and multiple regressions. Unless indicated otherwise, the differences were only considered significant when $P < 0.05$.

3. Results

3.1. Environmental variables and eddy covariance measurements

Daily environmental variables and the NEE, TER and GPP are shown in Fig. 2. Both air and soil temperature showed clearly seasonal variations; mean annual air temperature was 12.44 °C, with daily average temperature values ranging from 6.71 °C (winter-wheat season) to 23.39 °C (summer-maize season); mean annual soil temperature at 5, 10, 20, 40 and 80 cm depths were 13.33, 13.24, 13.07, 12.99 and 12.57, respectively (Fig. 2a). Precipitation over the whole year was 535 mm, which was similar to the long-term average annual rainfall (480 mm). Precipitation showed very strong seasonality, with 71% occurring during the summer-maize growing season (from June to September); similarly, volumetric soil water content also varied seasonally, with lows across the winter-wheat growing season (November–April) ranging between 12.8 and 26.5% and highs

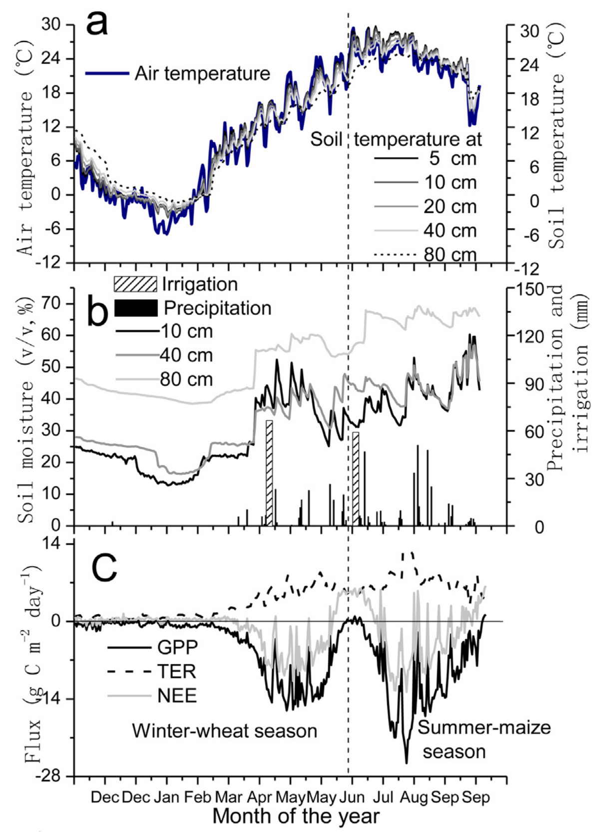

Fig. 2. Seasonal patterns in daily air temperature and soil temperature at 5, 10, 20, 40 and 80 cm depths (daily mean) (a); precipitation (daily mean), irrigation and soil moisture at 10, 40 and 80 cm depths (daily mean, volumetric soil water content, %) (b); evolution over time of the daily net ecosystem exchange (NEE), total ecosystem respiration (TER), and gross primary productivity (GPP) in the winter-wheat and summer-maize double cropping system (c).

Table 3
Linear regressions for the relationship between environmental variables and NEE, GPP and TER.

Crop	Environmental variable	NEE ($g C m^{-2} day^{-1}$)	GPP ($g C m^{-2} day^{-1}$)	TER ($g C m^{-2} day^{-1}$)
Winter-wheat	Air temperature (AT)	−0.556[a]	−0.793[a]	0.927[a]
	Soil temperature at 5 cm (ST_5)	−0.576[a]	−0.808[a]	0.934[a]
	Soil temperature at 10 cm (ST_{10})	−0.574[a]	−0.805[a]	0.929[a]
	Soil temperature at 20 cm (ST_{20})	−0.573[a]	−0.800[a]	0.922[a]
	Soil temperature at 40 cm (ST_{40})	−0.573[a]	−0.797[a]	0.914[a]
	Soil temperature at 80 cm (ST_{80})	−0.565[a]	−0.771[a]	0.871[a]
	Volumetric soil water content at 10 cm (SM_{10})	−0.743[a]	−0.835[a]	0.776[a]
	Volumetric soil water content at 40 cm (SM_{40})	−0.639[a]	−0.797[a]	0.831[a]
	Volumetric soil water content at 80 cm (SM_{80})	−0.737[a]	−0.893[a]	0.904[a]
	Precipitation	0.003	0.076	0.161[b]
Summer-maize	Air temperature (AT)	−0.241[b]	−0.303[a]	0.384[a]
	Soil temperature at 5 cm (ST_5)	−0.341[a]	−0.384[a]	0.395[a]
	Soil temperature at 10 cm (ST_{10})	−0.343[a]	−0.388[a]	0.403[a]
	Soil temperature at 20 cm (ST_{20})	−0.344[a]	−0.392[a]	0.413[a]
	Soil temperature at 40 cm (ST_{40})	−0.365[a]	−0.413[a]	0.430[a]
	Soil temperature at 80 cm (ST_{80})	−0.517[a]	−0.560[a]	0.525[a]
	Volumetric soil water content at 10 cm (SM_{10})	0.045	−0.032	−0.011
	Volumetric soil water content at 40 cm (SM_{40})	−0.336[a]	0.343[a]	−0.268[a]
	Volumetric soil water content at 80 cm (SM_{80})	−0.409[a]	−0.380[a]	0.202[b]
	Precipitation	0.274[a]	0.240[b]	−0.088

Pearson's correlation coefficient, 2-tailed tests of significance.
[a] Significant correlation at a <0.01.
[b] Significant correlation at a <0.05.

across the summer-maize growing season (June–September) ranging from 27.2 to 60.3% (Fig. 2b). Soil moisture contents in soil profile were consistent with rainfall and irrigation events, and much higher during the rainy summer-maize growing season.

The daily NEE, TER and GPP are shown in Fig. 2c. The evolution of NEE, TER and GPP clearly depicts the double cropping system, which is characteristic for the NCP. Values were small during the autumn and winter seasons from early November to early March. From mid-March to May the NEE, TER and GPP increased in absolute values, which related to the wheat development. During this period air and soil temperature and precipitation rose, fertilizer N and irrigation were applied (Table 1; Fig. 2a and b), which all boosted primary production. Thereafter, the GPP and NEE decreased because the wheat crop reached maturity prior to senescence, but the TER remained more or less stable at high level. From mid-July to early September, the GPP and NEE increased again due to the development of maize, the high temperature and rainfall and also because of fertilizer N additions; meanwhile, the maximal TER values, exceeding 11 $g C m^{-2} day^{-1}$, were observed during the hot summer months July and August, and these coincided also with the peaks in GPP and NEE (Table 1 and Fig. 2).

3.2. Relationships between environmental variables and NEE, TER and GPP

Both the NEE and GPP in the winter-wheat growing season all showed significant negative correlations with air temperature (AT), soil temperature (ST) at 5, 10, 20, 40 and 80 cm depths, and volumetric soil water content (SM) at 10, 40 and 80 cm depths ($P < 0.01$); the TER in the winter-wheat growing season showed a

Table 4
Stepwise regressions for the relationship between environmental variables and NEE, GPP and TER.

Crop	Environmental variable	NEE		GPP		TER	
		r[a]	*p*[b]	*r*	*p*	*r*	*p*
Winter-wheat	Air temperature (AT)	–	–	–	–	0.347	0.000
	Soil temperature at 5 cm (ST_5)	–	–	1.312	0.000	0.784	0.000
	Soil temperature at 40 cm (ST_{40})	–	–	1.313	0.000	–	–
	Soil temperature at 80 cm (ST_{80})	0.362	0.000	–	–	−0.637	0.000
	Volumetric soil water content at 10 cm (SM_{10})	−0.824	0.000	−0.359	0.000	−0.286	0.000
	Volumetric soil water content at 40 cm (SM_{40})	0.795	0.000	0.607	0.000	−0.250	0.000
	Volumetric soil water content at 80 cm (SM_{80})	−1.111	0.000	1.192	0.000	0.985	0.000
	Precipitation	0.219	0.000	0.114	0.000	–	–
	Overall model[c]		0.000		0.000		0.000
Summer-maize	Air temperature (AT)	0.533	0.015	–	–	0.818	0.002
	Soil temperature at 5 cm (ST_5)	–	–	–	–	−5.961	0.002
	Soil temperature at 10 cm (ST_{10})	−3.510	0.000	–	–	–	–
	Soil temperature at 20 cm (ST_{20})	–	–	7.458	0.000	22.022	0.000
	Soil temperature at 40 cm (ST_{40})	5.397	0.000	10.891	0.000	−20.914	0.000
	Soil temperature at 80 cm (ST_{80})	−2.869	0.000	4.147	0.000	5.012	0.000
	Volumetric soil water content at 10 cm (SM_{10})	–	–	–	–	0.468	0.001
	Volumetric soil water content at 40 cm (SM_{40})	0.211	0.004	–	–	–	–
	Volumetric soil water content at 80 cm (SM_{80})	–	–	0.217	0.007	−0.591	0.000
	Precipitation	0.140	0.026	0.134	0.028	–	–
	Overall model[c]		0.000		0.000		0.000

[a] The partial regression coefficient (*r*) value in the stepwise regression.
[b] The partial *P* value for the specific factor.
[c] The statistics for the regression model combining all factors that were significant at $P < 0.01$.

significant positive correlation with AT ($P < 0.01$), ST at all five depths ($P < 0.01$), SM at all three depths ($P < 0.01$), and precipitation ($P < 0.05$) (Table 3). Both the NEE and GPP in the summer-maize growing season showed significant negative correlations with AT, ST at all five depths, and SM at 40 and 80 cm depths ($P < 0.01$); whereas, they all showed significant positive correlations with precipitation ($P < 0.01$ for NEE, $P < 0.05$ for GPP). The TER in the summer-maize season showed a significant positive correlation with AT ($P < 0.01$), ST at all five depths ($P < 0.01$), and SM at 80 cm depth ($P < 0.05$) (Table 3).

The stepwise regression analysis showed in the winter-wheat growing season, a combination of ST_{80}, SM_{10}, SM_{40}, SM_{80} and precipitation could best predict the NEE variation; ST_5, ST_{40}, SM_{10}, SM_{40}, SM_{80} and precipitation could explain the variation in the GPP observed at a significant level; and AT, ST_5, ST_{80}, SM_{10}, SM_{40} and SM_{80} could best predict the TER variation (Table 4). The stepwise regression analysis showed in the summer-maize season, a combination of AT, ST_{10}, ST_{40}, ST_{80}, SM_{40} and precipitation could best predict the NEE variation; ST_{20}, ST_{40}, ST_{80}, SM_{80} and precipitation could explain the variation in the GPP observed at a significant level; and AT, ST_5, ST_{20}, ST_{40}, ST_{80}, SM_{10} and SM_{80} could best predict the TER variation (Table 4).

3.3. Biomass measurements

The evolution over time of the GLAI, DM, and the components of NPP are given in Fig. 3. From mid-October 2007 to mid-March 2008, the GLAI, aboveground biomass (AB) and NPP showed small change ranges because of the weak crop development, increasing from 0.51 to 0.82, 70 to 81 g DM m^{-2} and 30 to 36 g C m^{-2}, respectively (Fig. 3). From mid-March to mid-April, the GLAI, AB and NPP showed great change ranges resulted from the crop development that occurred when temperature rose (Figs. 2a and 3), increasing further to 6.14, 637 g DM m^{-2} and 300 g C m^{-2}, respectively. From mid-April to early May the AB increased further to 839 g m^{-2}, but the GLAI decreased because of the senescence of older leaves. From early May to early June grain increased from 162 to 694 g DM m^{-2} (Fig. 3b). The maize growing season was short. From mid-June to mid-July, the GLAI, AB and NPP increased from 0.26 to 1.25, 21 to 99 g DM m^{-2} and 10 to 51 g C m^{-2}, respectively (Fig. 3). From mid-July to mid-August the AB increased further to 613 g DM m^{-2}. From early August to early October grain increased from 58 to 819 g DM m^{-2} (Fig. 3b).

Summer maize and winter wheat reached similar maximum aboveground dry matter yields of 1482–1493 g m^{-2} at the harvest time; and final grain yields of wheat and maize were between 700 and 800 g m^{-2} (Fig. 3b). And the harvest index was 0.40 for wheat and 0.49 for maize (Fig. 3a and b); this means most of the accumulated C was present in the grain. In addition, the relative mass of roots changed over the growing season; in proportion the mass is higher during later growth stage than during the early growth stages (Fig. 3b).

3.4. Respiration measurements

The evolution of SR, soil air temperature at 5 cm depth and volumetric soil water content at 10, 20 and 30 cm depths over time is presented in Fig. 4. Soil temperature showed clearly seasonal variation (Fig. 4a); volumetric soil water contents were higher during the rainy season and consistent with rainfall and irrigation events (Figs. 4b, 2b and Table 1). From November to early March, the SR was close to the TER, between 0 and 2 g C m^{-2} day^{-1}; in

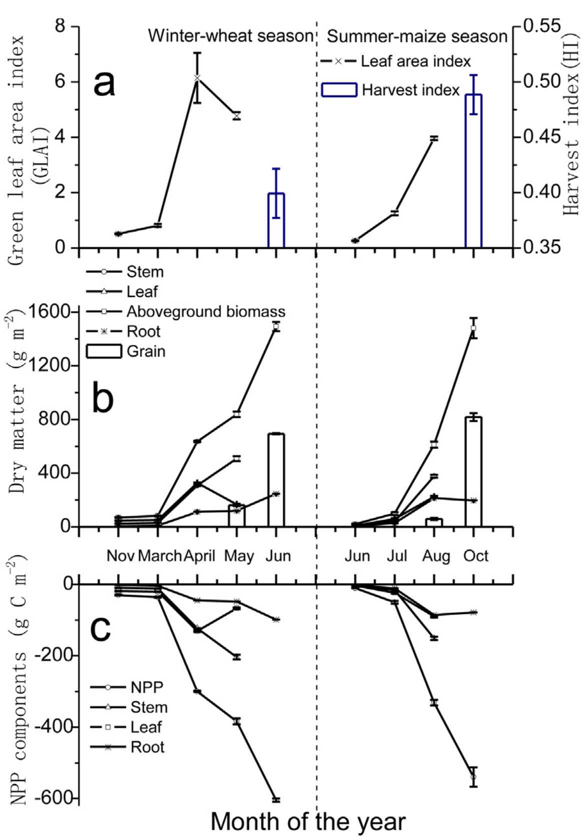

Fig. 3. Evolution over time of the green leaf area index (GLAI) and the harvest index (HI, ratio between grain yield and biomass yield) (a); also shown is the root, stem, leaf, grain and aboveground dry matter (b); and the NPP components (c). Bars in figures indicate 1 standard deviation (mean ± SD, $n = 5$).

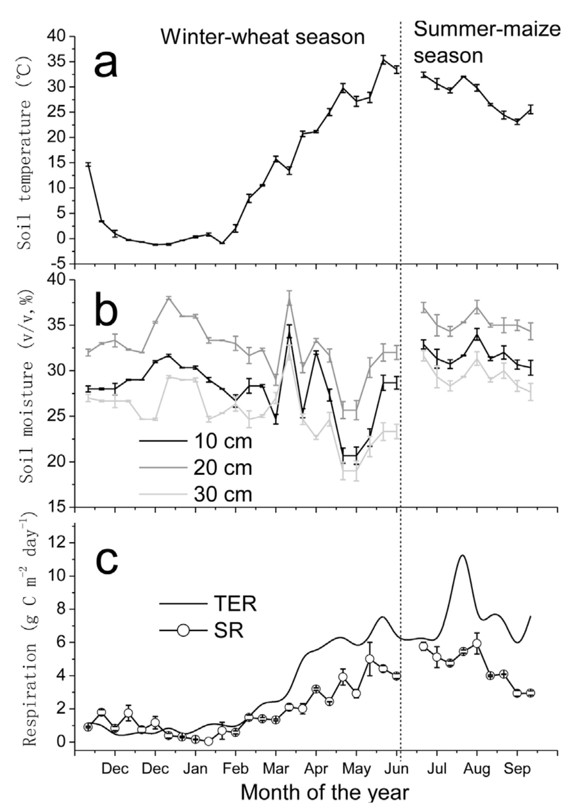

Fig. 4. Seasonal pattern of soil temperature at 5 cm depth (a); also shown is the soil moisture at 10, 20 and 30 cm depths (volumetric soil water content, %) (b); and the soil respiration (SR) and the daily total ecosystem respiration (TER) (c). Bars in figures indicate 1 standard deviation (mean ± SD, $n = 5$).

some occasions, the SR exceeded the TER, which we attribute to the variations or bias at low temperature in the measurement of SR or TER (Figs. 4c and 2a). From early March to early May both the SR and TER increased. But the SR increased more slowly than the TER, then remaining quite stable between 2 and 4 g C m^{-2} day^{-1} until May (Fig. 4c). This suggests that the main cause of the TER increase at this period resulted from the aboveground autotrophic component and is related to crop development. From May to September, the SR reached values of 4–6 g C m^{-2} day^{-1}, while the TER reached values of 6–8 g C m^{-2} day^{-1} and in moist and hot August maxima of more than 11 g C m^{-2} day^{-1} (Fig. 4c). Evidently, the SR and R_{aa} were large from March to May and July to September, during the vigorous growth stages of winter-wheat and summer-maize, respectively (Fig. 4c).

The evolution of R_a, R_h, R_{aa} and R_{ab} is presented in Fig. 5. These variables were inferred from Eqs. (13)–(16). From mid-November to mid-March, R_a and R_h remained at a relatively low level; during this time R_a resulted mainly from R_{ab} (Fig. 5). From mid-March to mid-May R_a and R_h increased sharply and with the values reached 425 and 116 g C m^{-2}, respectively; the high values suggest that the soil respiration increased as soon as the wheat was developed and inflorescence emerged. From mid-May to early-June, R_{ab} decreased, whereas R_h increased sharply; the low R_{ab} values suggest that the belowground autotrophic respiration decreased as soon as the wheat was mature. From mid-June to mid-August R_a, R_h, R_{aa} and R_{ab} increased sharply and reached 393, 192, 312 and 82 g C m^{-2}, respectively (Fig. 5); the high values suggest that the soil respiration increased as soon as the maize was developed and inflorescence emerged. From mid-August to early-October, R_{ab} decreased sharply to 16 g C m^{-2} because of the maturity of maize.

3.5. Combined relationships among soil respiration, soil temperature and soil water content

SR in the winter-wheat season, the summer-maize season and the whole year showed significant positive correlations with soil temperature at 5 cm depth ($P < 0.01$) (Table 5). SR in the winter-wheat season showed a significant negative correlation with soil moisture at 10, 20 ($P < 0.05$), and 30 cm ($P < 0.01$) depths; whereas, SR in the summer-maize season showed a significant positive correlation with soil moisture at all three depths ($P < 0.05$) (Table 5).

Soil respiration rates increased exponentially with soil temperature at 5 cm depth in the winter-wheat, summer-maize seasons and the whole year (Table 5). The exponential function showed a good fit for representing the dependence of soil CO_2 efflux on soil temperature; and soil temperature explained 55–79% of the seasonal changes in soil respiration using the exponential function (Table 5). SR was significantly inversely associated with soil moisture at all three depths both in the winter-wheat and summer-maize seasons ($P < 0.05$); soil moisture alone explained 21–44% and 51–62% of the variations in SR using the inverse function in the winter-wheat and summer-maize seasons, respectively (Table 5).

Application of a four-variable interactive function (Eq. (11)) explained 77–97% of the variation in soil respiration, suggesting a better representation of the relationship than single factor functions using either soil temperature or soil moisture (Table 5). This suggested that soil respiration was dominated by the interaction of soil temperature and soil moisture rather than by a single factor.

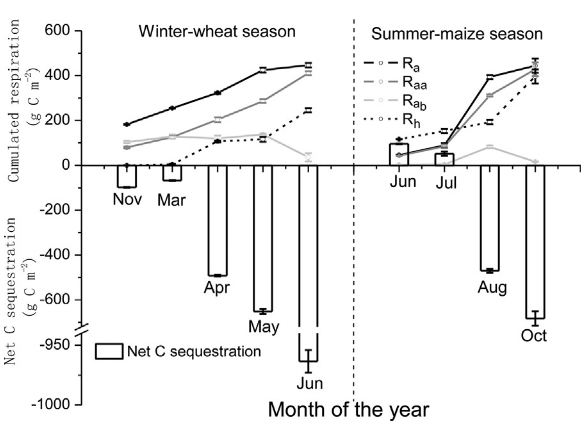

Fig. 5. Evolution over time of the ecosystem respiration components (autotrophic respiration, R_a; heterotrophic respiration, R_h; aboveground autotrophic respiration, R_{aa}; and belowground autotrophic respiration, R_{ab}); also shown is the net carbon sequestration (combines by NEE and NPP). Bars in figures indicate 1 standard deviation (mean ± SD, $n = 5$).

3.6. Carbon budget

We estimated the net carbon budget as the sum of net ecosystem production, harvest removals (negative) and crop residue carbon additions (positive). Fig. 6 shows two synthesis overviews of the C budgets in the winter-wheat and summer-maize seasons in the NCP. In the winter-wheat growing season, the crop assimilated 1051 g C m^{-2} and the ecosystem emitted 692 g C m^{-2}; the NEE and NPP was 359 and 604 g C m^{-2}, respectively; because the net ecosystem C sequestration was 90 g C m^{-2} greater compared to the exported after grain harvest, the ecosystem was a C sink (Fig. 6a). In the summer-maize growing season, the crop assimilated 984 g C m^{-2} and the ecosystem emitted 841 g C m^{-2}; the NEE and NPP was 143 and 540 g C m^{-2}, respectively; because the net ecosystem C sequestration was 167 g C m^{-2} lesser compared to the exported after grain harvest, the ecosystem was a C source (Fig. 6b). Therefore, on an annual basis the winter-wheat and summer-maize rotation system in the NCP was losing carbon at a rate of 77 g C m^{-2} $year^{-1}$.

TER can be divided into the aboveground and belowground components. In the winter-wheat growing season, R_{aa} and SR were 411 and 281 g C m^{-2} respectively, equivalent to 59.4% and 40.6% of the TER, respectively (Fig. 6a). In the summer-maize growing season, R_{aa} and SR were 428 and 413 g C m^{-2} respectively, equivalent to 50.9% and 49.1% of the TER, respectively (Fig. 6b). The R_a to TER ratios were 0.65:1 and 0.53:1 in the winter-wheat and summer-maize seasons, respectively; indicating that autotrophic respiration dominated ecosystem respiration. The TER to GPP ratio was significantly higher for the maize crop (0.85:1) than for the wheat crop (0.66:1); the higher ratio for summer-maize than for winter-wheat reflects that the latter was grown under more cold and dry conditions than the former.

4. Discussions

4.1. SOC stocks of winter-wheat and summer-maize seasons

The present study showed that the SOC evolution (2.51–3.98 kg C m^{-2} for wheat; 2.46–3.91 kg C m^{-2} for maize) observed in the wheat-maize double cropping system took place mainly during the first 24 years (1978–2002), with the SOC remaining fairly stable (3.82 kg C m^{-2} for wheat; 3.64 kg C m^{-2} for maize) during the subsequent 6 years (2003–2008) (Fig. 1). This could suggest that the soils reached a new equilibrium within about 24 years after applications of crop residues, as also shown by Powlson et al. (2012) and Buysse et al. (2013). The increase in topsoil SOC stock (0–20 cm) during the first 24 years was expected because of the additional straw carbon input into soil. Furthermore, the intensive cropping system in the NCP is characterized by high inputs of chemical and manure fertilizer. Manure is generally

Table 5
Comparison of coefficients of determination (R^2) of different regression equations on soil respiration (SR) against soil temperature (T) and soil moisture (volumetric soil water content, M).

	Correlation analysis (Pearson)			Model function	Coefficient of determination (R^2)		
	SR in winter-wheat season	SR in summer-maize season	SR in the whole year		Winter-wheat	Summer-maize	Whole year
Soil temperature at 5 cm (T_5)	0.891[**]	0.896[**]	0.900[**]	$SR = \alpha \times e^{\beta T}$	0.549[a]	0.786[a]	0.669[a]
Soil moisture at 10 cm (M_{10})	−0.421[*]	0.768[*]	0.153	$SR = \gamma / M + \delta$	0.212[b]	0.602[b]	0.005
Soil moisture at 20 cm (M_{20})	−0.511[*]	0.710[*]	0.038		0.259[b]	0.505[b]	0.001
Soil moisture at 30 cm (M_{30})	−0.641[**]	0.780[*]	0.109		0.438[a]	0.617[b]	0.001
Overall model	$SR = \alpha \times T^{\beta} \times M^{\gamma}$						
Wheat	$SR = 0.064 \times T_5^{0.73} \times M_{10}^{-2.25} \times M_{20}^{3.35} \times M_{30}^{-0.82}$				0.849[a]		
Maize	$SR = 0.542 \times T_5^{1.57} \times M_{10}^{4.27} \times M_{20}^{-8.30} \times M_{30}^{3.47}$					0.967[a]	
Whole year	$SR = 0.136 \times T_5^{0.79} \times M_{10}^{-0.78} \times M_{20}^{0.27} \times M_{30}^{0.72}$						0.770[a]

[*] Significant correlation at a <0.05.
[**] Significant correlation at a <0.01.
[a] Regressions were significant at $P < 0.01$.
[b] Regressions were significant at $P < 0.05$.

acknowledged to improve soil structure and favor aggregation and physical protection of organic matter against decomposition (Smith et al., 1997; Kong et al., 2005), which leads to SOC content increase. The average SOC stock in the NCP (59% more SOC after 24 years) was much higher than that observed by Buysse et al. (2013) (14% more SOC after 50 years) and much lower than that observed by Powlson et al. (2012) (about 100% SOC increase in 50 years), probably due to the much lower C application (500 g C m^{-2} every 3–4 years) in Buysse et al. (2013) and much higher C application rates (1050 g C m^{-2} $year^{-1}$) in Powlson et al. (2012), as opposed to about 570 g C m^{-2} $year^{-1}$ in our study (Fig. 6). Besides, in addition to being influenced by the amount of carbon residues added to the soils, the progressive reaching of the equilibrium at the crop field in the NCP could be affected by potentially small agricultural changes during this long experimental period (e.g., yield improvement, pesticide and fungicide applications, and nitrogen fertilization).

The most surprising result was the decrease in topsoil SOC stock (0–20 cm) (4% for wheat and 7% for maize) during 2003–2008 as compared to these in 2002. Therefore, the general hypothesis of the study reported here is that after crop residue mulching over two decades, the soil organic carbon stock might have reached the saturation point (Fig. 1). Considering intensive agriculture tends to produce more emissions than the global average due to increased chemical and manure N inputs, the system might begin to lose carbon.

4.2. C fluxes of winter-wheat and summer-maize seasons

The GPP, TER (R_a and R_h) and SR values in the winter-wheat and summer-maize double cropping system clearly depict the crop development (Figs. 2, 4 and 5). During the booming period (from mid-April to mid-May for wheat; from mid-July to mid-August for maize), R_a constituted about 79% and 67% of the TER for wheat and maize, respectively (Fig. 5). Meanwhile, the TER was 46% and 56% of GPP for wheat and maize, respectively (Fig. 2c); similar ratios (41–50% for wheat; 53–65% for maize) had been observed by Li et al. (2006) during the period of intensive crop development in northern China. Furthermore, the general predictions of Ra/GPP ratio are between 0.3 and 0.6 (Amthor, 1989; Amthor and Baldocchi, 2001; Albrizio and Steduto, 2003), in agreement with our results (0.43 for wheat; 0.45 for maize) (Fig. 6). These results suggest that, at the seasonal scale, the TER results mainly from R_a, and crop development is a more important driving variable for ecosystem respiration than other variables during vegetation periods. Meanwhile, the dependence of R_a on GPP appears quite logical as autotrophic respiration results in particular from the plant growth process that is fed by plant assimilation.

Another interesting result is that the GPP begun to decrease after blooming period (late-May for wheat; late-August for maize), but the TER remained still fairly constant until early-June for wheat and early-October for maize (Fig. 2c); for example, the ratios of the

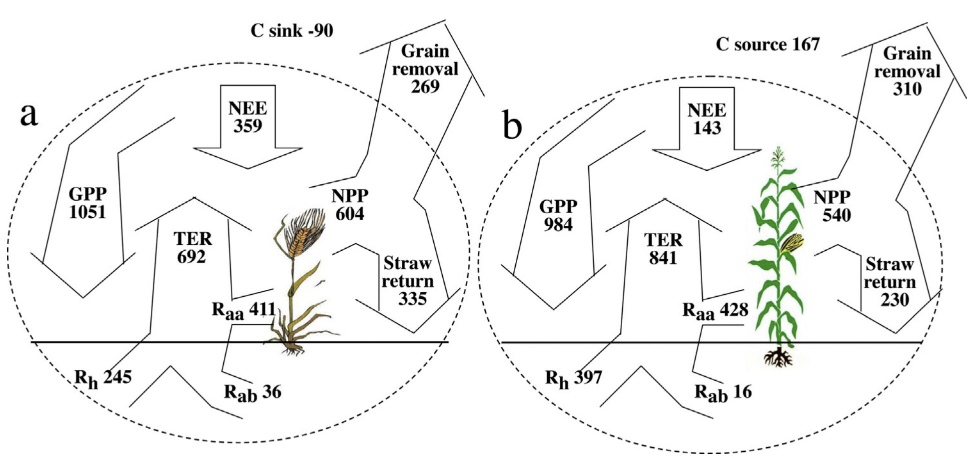

Fig. 6. Carbon budget of the winter-wheat (a) and summer-maize (b) double cropping system during the cultivation period in the North China Plain. Cumulated fluxes are given in g C m^{-2}.

TER to GPP increased to 66% and 85% for wheat and maize respectively at the harvest time (Fig. 6). This stability of the TER was attributed mainly to the sharply increase of R_h during the crop maturity period, which was higher compared to the decrease of R_{ab} (Fig. 5); for example, R_h was about 35% to 47% of the TER at the harvest time; meanwhile, the R_{ab} was about 2–5% of the TER (Fig. 6). The sharply decline of R_{ab} may be explained by the translocation of photosynthesis products from the roots to the grain that takes place after flowering in cereals (Johnson et al., 1981; Anthoni et al., 2004). We suspect that the amount of assimilated C after flowering was still significant; presumably, it may also be due to the ear C resulted both from assimilation and from C translocation from stems, leaves and roots.

4.3. C budgets of winter-wheat and summer-maize seasons

The main result of C budget is that the winter-wheat system acted as a carbon sink, with seasonal sequestration of 90 g C m^{-2}; the summer-maize system acted as a carbon source, with seasonal emission of 167 g C m^{-2} (Fig. 6). This provides strong evidence that the winter-wheat and summer-maize double cropping system in the NCP was a small carbon source of 77 g C m^{-2} year^{-1}. This means that 77 g C m^{-2} year^{-1} was decomposed in phytomass and/or soil of this agro-ecosystem.

The great difference in C accumulation between the winter-wheat and the summer-maize growing seasons is most probably affected by the high variability of TER and NPP due to changes in environmental conditions and crop types. For example, Fig. 2 shows that the summer-maize growing season was characterized by the warmer temperature, higher relative humidity and precipitation amount; consequently, the C emissions were higher in the summer-maize growing season (841 g C m^{-2}) than these in the winter-wheat growing season (692 g C m^{-2}) (Fig. 6). Hence, we suspect that the mineralization of the previous season's wheat straw occurs during the hot-rainy summer-maize growing period (Fig. 2a and b), when CO_2 fluxes from decomposing straw and other sources are newly available for plant photosynthesis. These could also help to partially explain why the SOC stock was much lower in the summer-maize season compared to that in the winter-wheat season during 2003–2008 (Fig. 1). Moreover, Wang et al. (2010) argues that ecosystem respiration is mainly controlled by soil temperature, while Shi et al. (2012) believes that soil moisture is also a dominant factor, especially in arid and semiarid areas. In our study, the TER and SR were governed by both the soil temperature and moisture (Tables 3–5). This implies that the interaction of soil temperature and moisture is the "single" dominant factor for ecosystem respiration in this area. Rather, interaction of soil temperature and moisture better explained the variations of the TER and SR from the relatively colder and drier wheat growing season to the warmer and wetter maize growing season (Figs. 2a,b, 6 and Tables 3–5). Consequently, the characteristics of maize vegetation period (e.g., shorter, warmer and wetter) are the most likely reasons for what could have led to the lower maize NPP and higher C emissions during the growing season (Figs. 2, 6 and Table 1).

Furthermore, the harvest index of the summer-maize was higher (0.49) than that of the winter-wheat (0.40) (Fig. 3a and b); thus the grain yield of maize (310 g C m^{-2}) was higher than that of wheat (269 g C m^{-2}); whereas, the straw yield of maize (230 g C m^{-2}) was lower than that of the wheat (335 g C m^{-2}) (Fig. 6). This means that the carbon gained by the maize field was less than that gained by the wheat field; in contrast, the carbon exported by the maize field was higher than that exported by the wheat field. As a result, this leads directly to a smaller amount of crop residue for C input and a larger amount of grain for C output in the maize growing season. These results would imply that, given the TER, SR and NPP observed in the NCP: (1) TER and NPP govern the sizes of C sink or C source in the winter-wheat and summer-maize rotation system; (2) TER and SR trend to increase with soil temperature and soil moisture before reaching respective threshold; (3) For different ecosystems at the same site with different climatic conditions, soil chemical, biological properties, crop types and managements should be responsible for the C sink or source responses.

4.4. Management impacts on C budget

Marked differences in crop management activities are shown between the two crop seasons in Table 1. First, nitrogen (N) fertilizer was applied twice with the total amount of 303 kg N ha^{-1} during the longer winter-wheat growing season (235 days), whereas, it was only applied once (276 kg N ha^{-1}) during the shorter summer-maize growing season (113 days). In general, N is usually the most growth-limiting plant nutrient in ecosystems that limits total biomass production (Cai and Qin, 2006). In our study, the net carbon sequestration (combined by NEE and NPP) increased sharply after N fertilizer applications in mid-April for wheat and in late July for maize (Fig. 5). Therefore, we suspect that the maize NPP was smaller than that of the wheat probably partly due to the lower N fertilizer application rate in the growing season.

Second, over the whole experimental period there was only one tillage pass in the autumn for winter-wheat seedling (Table 1). The current scientific literature does not support favoring no-till over plowing for carbon sequestration. Recent reviews suggest that under a variety of environmental conditions no-till sequesters no more carbon than plowing (Baker and Griffis, 2005; Baker et al., 2007; Blanco-Canqui and Lal, 2008). For example, Baker and Griffis (2005) compared two adjacent fields, both in maize/soybean rotation, with one under conventional tillage and the other under strip tillage, a conservation tillage practice in which most of the surface is undisturbed. They found no C sequestration benefit from the conservation tillage, and both systems were apparently small net sources of C over the 2-year period. Moreover, Baker et al. (2007) reported that on average, no-till systems tend to show increased carbon at shallow depths where crop residues are found, but at greater depths plowed soils typically sequester more carbon. In our study, one-time autumn tillage for winter-wheat seedling seemed to have no effect on carbon sequestration, which is in good agreement with above literatures.

Third, both the winter-wheat and summer-maize were irrigated once during the growing seasons (67 mm for wheat; 60 mm for maize) and the annual amount of precipitation was 535 mm, with 71% occurring in the summer-maize growing season (Table 1 and Fig. 2b). In general application of water to drylands influences biomass productivity, increases the amount of residue returned, changes mineralization rates, and alters the carbonate balance. Lal (2011) believes that there is a large potential for carbon sequestration by the use of irrigation. In contrast, a few studies do not support favoring irrigation over no-irrigation for carbon sequestration (Verma et al., 2005; Béziat et al., 2009). For example, Verma et al. (2005) compared three adjacent fields in Nebraska, one was in irrigated continuous maize, one in irrigated maize/soybean rotation, and the other in dryland maize (no irrigation). The authors found that though there were differences among systems in gross primary productivity and yield, the net carbon balance computed from NEE and yield was essentially zero for all treatments. Therefore, it seems like that the effect of irrigation on carbon sequestration appears to be highly site/condition dependent. In our study, the irrigation amount was $<$30% of the seasonal water inflow (precipitation plus irrigation) (29% for wheat; 14% for maize); it seems like that precipitation is the main factor affecting carbon sequestration compared to irrigation in the winter-wheat and summer-maize double cropping rotation in the NCP.

4.5. Comparison to other cropping systems

We compared the annual carbon budget obtained in our study with those in previous studies of other sites. The SR to TER ratio was 0.41 in the wheat growing season, which was similar to that reported for wheat crops (0.39) by Suleau et al. (2011) and lower than that reported for wheat crops (0.55) by Moureaux et al. (2008) in Lonzée, about 45 km at the south-east of Brussels in Belgium. The SR to TER ratio was 0.49 in the maize growing season, which was higher than that reported for maize crops (0.41) by Jans et al. (2010) in the Northwest of Wageningen in the Netherlands; unlike N fertilizer applications and straw returning in our study, they applied organic fertilizer by coulter injection of manure (25% cow; 75% pig). Furthermore, the TER to GPP ratio (0.66 for wheat and 0.85 for maize, Fig. 6) was in good agreement with ratios at harvest time reported by Li et al. (2006) in the northern China (0.60–0.61 for wheat; 0.85–0.91 for maize). These could imply that the ratios of the same crop in different regions can be influenced by climate and/or cropland management practice.

The maize ecosystem was a carbon source of 167 g C m^{-2} and wheat ecosystem was a carbon sink of 90 g C m^{-2}; hence, the winter-wheat and summer-maize double cropping system in the NCP acted as a net C source of 77 g C m^{-2} in 2007–2008. This result is consistent with the finding from similar agrosystems, which have shown small to moderate C source between 107 and 341 g C m^{-2} $year^{-1}$ over 2 one-year winter wheat/summer maize rotations in northern China (Li et al., 2006). Similar observations have been made in other agrosystem; e.g., for a four years rotation of sugar beat/winter wheat/potato/winter wheat, Aubinet et al. (2009) observed a lower C source of 42 g C m^{-2} $year^{-1}$. Béziat et al. (2009) argued that wheat/maize rotation had C sink/source close to neutrality in the USA; and it has also been reported that a maize/soybean rotation is close to neutrality with a carbon balance in the USA, some studies found non-significant low carbon sinks (Baker and Griffis, 2005; Dobermann et al., 2006), and others non-significant low carbon sources (Grant et al., 2007). Therefore, we suspect that these differences were mostly due to climatic conditions and management practices (crop rotation, fertilizer application, irrigation, tillage, residue removal, etc.).

Furthermore, through a modeling approach and simulation over 100 years Grant et al. (2007) believes that carbon storage potential in agroecosystem is limited; however, after long-term field experiments Ding et al. (2012) demonstrated that long-term straw application and fertilization significantly increased soil organic carbon concentrations and SOC stocks in 0–20 cm soil in the northern China. In contrast, Fan et al. (2014) recently found that while carrying out a long-term field experiment established in 1989 under an intensive wheat–maize cropping system in the northern China that the average organic C sequestration rate in the 0–60 cm depth decreased from about 0.66–0.29 Mg C ha^{-1} $year^{-1}$ with fertilization and crop residue input from 1989 to 2009, indicating that the SOC stock was reaching saturation. Similarly, we found while carrying out a 30-years field experiment of crop residues input that the SOC stock in 0–20 cm soil increased rapidly during 1978–2002, then decreased and stabilized during 2003–2008 (Fig. 1), which is in good agreement with the findings reported by Fan et al. (2014). This could suggest that the intensive cropland in the NCP had reached a new C equilibrium after 30-years of crop residues return; and C is lost through ecosystem respiration and grain harvest removal in the summer-maize growing season (Fig. 6). Therefore, based on the present study, the carbon storage potential in the winter-wheat and summer-maize rotation system in the NCP seems to be very poor.

4.6. The uncertainties of the measured ecosystem carbon budget components

Although the double cropping system C budget was successfully evaluated for the first time in the NCP, there were some uncertainties of these estimates differ substantially due to the different methods applied and different scales of observation. Average values or sums without reference to their uncertainty are thus incomplete. Therefore, in the following the uncertainties of the individual ecosystem carbon budget component estimates are discussed.

Firstly, carbon fluxes used in our study were derived from the observed NEE by the eddy covariance technique, which contained some uncertainties (Richardson et al., 2012), and NEE-based net ecosystem productivity would be overestimated in the double cropping system (Chapin et al., 2006); whereas, according to Eq. (16) the heterotrophic respiration (R_h) would be underestimated. Secondly, our estimates of ecosystem respiration were climate-based potential carbon fluxes, while many factors, including human activities (Chapin et al., 2012), were not considered, e.g., insecticide spraying, herbicide spraying etc. We also made no more comprehensive analyses about how management activities affected the variability of carbon fluxes, which may lead to some uncertainties in our estimates. Therefore, further studies should develop new assessment schemes integrating geographical statistics with ecological processes. Finally, some inconsistencies were observed between the SR and TER estimations, the former being slightly greater than the latter during November–December (see Fig. 4c). This probably resulted from the uncertainties for both variables at low air temperature (about −3 to −7 °C, Fig. 2a) and the spatial variations in SR; but the impact of this uncertainty on the cumulated flux was very small.

5. Conclusions

The winter-wheat and summer-maize double cropping system in the NCP acted as a C source of 77 g C m^{-2} on an annual basis, with seasonal C sequestration of 90 and C loss of 167 g C m^{-2} in the wheat and maize seasons, respectively. The great difference in C budgets of the two seasons is most probably affected by the high variability of TER and NPP due to changes in environmental conditions and crop management activities; i.e., the TER increased nearly 1/4 and NPP decreased over 1/10 during the warmer and rainy maize season compared to these in the colder and dryer wheat season. Furthermore, although the season length was 52% shorter for summer maize (113 days) than that for winter wheat (235 days), over 55% of the CO_2 emissions originated from maize season and the heterotrophic respiration increased nearly 2/3 in the summer maize season compared to that in the winter wheat season. This implies that although the carbon flux dynamics were strongly correlated to crop development, inter seasonal climate variability affected these dynamics mainly. Further, we found the interaction of soil temperature and moisture is the “single” dominant factor for ecosystem respiration in this area.

The expected trends (SOC stocks increase in 0–20 cm soil) leveled off 24 years after the start of the experiment, while a new equilibrium seemed to be reached. The unexpected trends (SOC stocks decrease in 0–20 cm soil) were found during the subsequent 6 years. This particularly shows that the intensive winter-wheat and summer-maize double cropping system in the NCP tends to produce more C emissions due to increased chemical N inputs. Carbon was being lost at a rate of 77 g C m^{-2} from the annual cropping system in the NCP when harvest removals were considered, even though C was added through straw residues. In order to reduce C release and improve C sequestration, crop species and management regimes deserve more attention and should be evaluated as accurately as possible in this area.

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