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Seasonal and Interannual Variations of Carbon Exchange over a Rice–Wheat Rotation System on the North China Plain

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ABSTRACT

Rice–wheat (R–W) rotation systems are ubiquitous in South and East Asia, and play an important role in modulating the carbon cycle and climate. Long-term, continuous flux measurements help in better understanding the seasonal and interannual variation of the carbon budget over R–W rotation systems. In this study, measurements of CO_2 fluxes and meteorological variables over an R–W rotation system on the North China Plain from 2007 to 2010 were analyzed. To analyze the abiotic factors regulating Net Ecosystem Exchange (NEE), NEE was partitioned into gross primary production (GPP) and ecosystem respiration. Nighttime NEE or ecosystem respiration was controlled primarily by soil temperature, while daytime NEE was mainly determined by photosythetically active radiation (PAR). The responses of nighttime NEE to soil temperature and daytime NEE to light were closely associated with crop development and photosynthetic activity, respectively. Moreover, the interannual variation in GPP and NEE mainly depended on precipitation and PAR. Overall, NEE was negative on the annual scale and the rotation system behaved as a carbon sink of 982 g C m^{-2} per year over the three years. The winter wheat field took up more CO_2 than the rice paddy during the longer growing season, while the daily NEE for wheat and rice were -2.35 and -3.96 g C m^{-2}, respectively. After the grain harvest was subtracted from the NEE, the winter wheat field became a moderately strong carbon sink of 251–334 g C m^{-2} per season, whereas the rice paddy switched to a weak carbon sink of 107–132 per season.

Key words: net ecosystem exchange, gross primary production, rice–wheat rotation system

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1. Introduction

Land–atmosphere exchanges of carbon dioxide (CO_2) strongly affect the carbon cycle and climate variability (Dickinson, 1995; Entekhabi, 1995; Betts et al., 1996; Pielke et al., 1998; Dadson et al., 2013). Understanding the seasonal and interannual variation of carbon exchanges has drawn much attention across many disciplines, such as the atmospheric/climate sciences (Ma et al., 2003; Baldocchi, 2008; Hossen et al., 2012) and ecology (Kueppers and Snyder, 2012; Yu et al., 2013; Baldocchi, 2014). For example, micrometeorological observations of the carbon exchanges between terrestrial ecosystems and the atmosphere have been made routinely over different land covers worldwide (e.g., the AmeriFlux, EuroFlux and AsiaFlux networks) to evaluate the interactions and feedbacks at the surface–atmosphere interface (Baldocchi et al., 2001; Liu et al., 2008; Beringer et al., 2011; Chen et al., 2013; Richardson et al., 2013). These measurements not only help in understanding the variation in carbon exchange in terms of environmental controls, but also in quantifying the uncertainty in land surface, global climate and earth system models (Xia et al., 2012; Xu et al., 2012; Barman et al., 2014; Kasurinen et al., 2014). Together, the above studies offer an evaluation of the interactions and feedbacks between the land surface and atmosphere.

Owing to the strong link between the increasing atmospheric CO_2 concentration and climate change (IPCC, 2013), the carbon exchange between various ecosystems and the atmosphere is of crucial importance. Cultivated land occupies about 40% of Earth's terrestrial surface (5.0×10^9 hectares), of which 30% is used for agriculture (Dufranne et al., 2011). Agricultural fields usually behave as net carbon sinks during the growing season and thus have the potential to mitigate the

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effects of increasing greenhouse gas emissions (Schmidt et al., 2012). However, there is still considerable uncertainty in estimates of carbon sequestration potential over agricultural fields in the literature (Mauder et al., 2013). Accurate estimates of the carbon exchange between agricultural fields and the atmosphere remain a challenge, particularly on long-term scales (Béziat et al., 2009).

Rice–wheat (R–W) rotation systems are ubiquitous in South and East Asia, occupying 24 million hectares in total. China currently has a total of 13 million hectares of R–W fields, primarily in Anhui, Jiangsu, Hubei and Sichuan provinces. The present study was conducted to better understand the seasonal and interannual variation of the carbon exchange over an R–W rotation field in the Huaihe River basin on the North China Plain, which is one of the most important agricultural production areas in China (Timsina and Connor, 2001; Tanaka et al., 2007). Previous investigations on carbon exchanges between agricultural fields and the atmosphere have often focused on winter wheat (Falge et al., 2001b; Gilmanov et al., 2003; Anthoni et al., 2004; Li et al., 2006; Moureaux et al., 2006; Aubinet et al., 2009; Béziat et al., 2009; Lei and Yang, 2010; Schmidt et al., 2012; Bao et al., 2014), sugar beet (Moureaux et al., 2006; Aubinet et al., 2009), maize (Suyker et al., 2005; Verma et al., 2005; Bavin et al., 2009; Béziat et al., 2009), potato (Anthoni et al., 2004; Aubinet et al., 2009), and rice (Martano, 2000; Gao et al., 2003; Saito et al., 2005; Alberto et al., 2009; 2011; Bhattacharyya et al., 2013), but less effort has been made to study the carbon fluxes over R–W rotation systems. This is partly due to the fact that many previous studies were limited to short periods of time. Only recently have measurements over extended periods become available, enabling the study of carbon exchanges between rotation fields and the atmosphere (Aubinet et al., 2009; Béziat et al., 2009; Lei and Yang, 2010; Schmidt et al., 2012). However, the current status of research still features considerable uncertainty in the North China Plain region, which we were motivated to address in the current work. Li et al. (2006) estimated that the annual net ecosystem exchange (NEE) of winter wheat was about -78 to -152 g C m^{-2}, while Bao et al. (2014) reported that the NEE of winter wheat ranged from -137 to -394 g C m^{-2} for the same experimental station. In addition, Lei and Yang (2010) reported that the NEE of winter wheat over the North China Plain was approximately -303 to -395 g C m^{-2} (see Table 1). To better understand the uncertainty in the carbon budget over this area, long-term eddy-covariance measurements of CO_2 flux, together with meteorological measurements, were used in the present study to investigate the carbon exchanges between the R–W rotation field and the atmosphere over the North China Plain.

The specific objectives of this study were to: (1) derive a consistent three-year dataset of carbon fluxes from eddy-covariance measurements; (2) characterize the seasonal and interannual variation in CO_2 fluxes over this R–W rotation field and quantify the differences between rice and wheat; and (3) investigate the responses of NEE, gross primary production (GPP) and ecosystem respiration (R_{eco}) to meteorological conditions and crop management.

2. Data and methodology

2.1. *Site description and crop history*

The long-term field experiment was conducted from 1 July 2007 to 31 July 2010 at Shouxian Agro-Ecosystem Station located in the Huaihe River basin, China (32°33′N,

Table 1. Comparison of NEE of winter wheat and summer rice across different sites.

Site	Latitude	Season	NEE (g C m^{-2} yr^{-1})	min NEE (g C m^{-2} d^{-1})	Reference
Growing season (winter wheat)					
Yucheng (CN)	30°56′N	October–June (2002–03)	−78	−8.0	Li et al. (2006)
Yucheng (CN)	30°56′N	October–June (2003–04)	−152	−9.0	Li et al. (2006)
Weishan (CN)	36°39′N	October–August(2005–09)	−303 to −395	−10.0 to −13.0	Lei and Yang (2010)
Ponca City (US)	36°46′N	January 1996–August 1997	−273		Gilmanov et al. (2003)
Lamsquerè	43°54′N	October–August (2005–06)	−369 (±30)	−9.8	Béziat et al. (2009)
Lonzée (BE)	50°33′N	November 2004–August 2005	−630 (±30)		Aubinet et al. (2009)
Lonzée (BE)	50°33′N	November 2006–August 2007	−730 (±40)		Aubinet et al. (2009)
Selhausen (DE)	50°52′N	November 2007–August 2008	−445		Schmidt et al. (2012)
Selhausen (DE)	50°52′N	October 2008–July 2009	−502		Schmidt et al. (2012)
Gebesee (DE)	51°06′N	October 2000–August 2001	−185 to 245	−8.0	Anthoni et al.(2004)
Shouxian (CN)	32°33′N	October–May (2007–08)	−583	−14.3	This study
Shouxian (CN)	32°33′N	October–May (2008–2009)	−512	−11.0	This study
Shouxian (CN)	32°33′N	October–May (2009–2010)	−451	−10.9	This study
Growing season (summer rice)					
Los Baños (PH)	14°09′N	January–April 2008 (flooded)	−258	−10.0	Alberto et al. (2009)
Los Banos (PH)	14°09′N	January–April 2008 (aerobic)	−85	−6.0	Alberto et al.(2009)
Cuttack (IND)	20°27′N	July–October 2010	−448		Bhmttachmryya et al. (2013)
Tukuba (JPN)	36°03′N	May–September 2002	−400	−13.1	Saito et al. (2005)
Shouxian (CN)	32°33′N	June–September 2008	−438	−15.3	This study
Shouxian (CN)	32°33′N	June–September 2009	−431	−12.4	This study

116°47′E; 26.8 m above sea level), which is one of the five national climate observatories operated by the China Meteorological Administration. A flux tower that takes eddy-covariance measurements is located in the southwest corner of a 120 m × 100 m R–W field (see Fig. 1). The local climate is characterized as northern subtropical semi-humid monsoon climate. The annual mean temperature is about 15°C and annual precipitation is about 900 mm. Summer (from June to September) precipitation accounts for nearly 60% of the annual precipitation amount, which meets the high water demand of rice. Drought sometimes occurs due to lack of precipitation in the growing season of wheat. During the study period, the dominant wind direction ranged from northeast to east, and the mean wind speed was 3.1 m s^{-1} near the surface. The terrain of the site is flat and covered with yellow cinnamon soil according to the classification system of the Food and Agriculture Organization (FAO) (FAO, 2007). The soil texture is silty clay loam and the average soil organic carbon concentration was 11.14 g kg^{-1} during the study period. The distance from the nearest village is more than 500 m.

Over this R–W field, winter wheat grows from October to June and summer rice grows from June to September every year. Uniform crops at similar growth stages surrounds the test site. All crops are traditionally cultivated and the crop management activities are detailed in Table 2. The different growth stages for winter wheat and summer rice are also listed in Table 2.

2.2. *Observational data*

Fluxes of CO_2 (F_c), sensible heat and latent heat were calculated with measurements from an eddy covariance system mounted at 4 m above the ground surface. The eddy covariance system consisted of a 3D sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT, USA) and an open-path infrared gas analyzer (IRGA, model LI7500, LI-COR Inc., Lincoln, NE, USA). Turbulence data were recorded at a sampling rate of 10 Hz using a high performance data logger (CR5000, Campbell Scientific Instruments Inc., Logan, UT, USA).

In this study, PAR—indicated by the photosynthetic photon flux density (PPFD)—was measured using a CNR-1 net radiometer LI-190SB quantum sensor (Li-COR, Inc., USA). Air temperature and relative humidity were measured with probes (HMP45C, Campbell Scientific, Inc., USA) mounted at a height of 4 m. Soil heat flux was measured by heat flux plates (HFP01, Hukseflux Thermal Sensors, Delft, Netherlands) at depths of 0.05, 0.10, 0.15, 0.20, and 0.40 m. Soil temperature and soil water content (SWC) were measured at depths of 0.05, 0.10, 0.20, 0.40, 0.80, and 1.60 m. Precipitation data were obtained from a meteorological station situated 5 km from the experimental site, using a tipping bucket at a height of 1.0 m (TE525MM, Campbell Scientific, Inc., USA).

2.3. *Data quality and gap filling*

In this study, 30 min was chosen as the interval for the calculation of the average turbulent fluxes. The time series of wind speed, air temperature, water vapor concentration and CO_2 concentration were first linearly-detrended and angle-controlled, i.e., data with wind coming from the back of the tower were excluded (see Li and Bou-Zeid, 2011; Li et al., 2012). The time series were then rotated according to the double-angle coordinate rotations to make the half-hourly wind vector align with the local streamline (Anthoni et al., 2004). Following Moore (1986) for co-spectral corrections, the computed fluxes were adjusted to account for the effect of sensor separation between the sonic anemometer and gas analyzer. We then eliminated data noise and other interference using the criterion of $X(h) < (X - 4\sigma)$ or $X(h) > (X + 4\sigma)$,

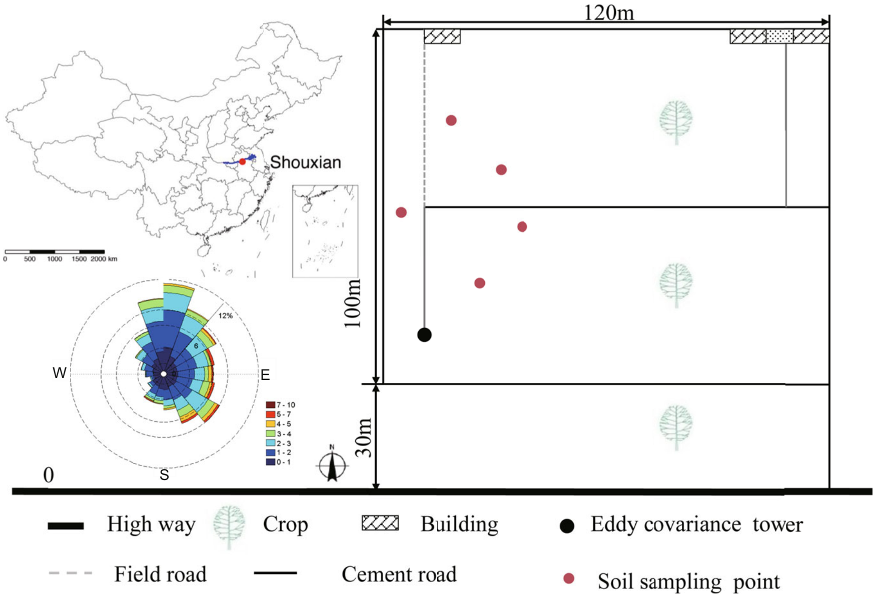

Fig. 1. The location of Shouxian experimental site and a map of the surrounding agricultural field. The wind rose is also shown.

Table 2. Major crop activities and main growing stages during the observation period.

Date	Crop activities and main growing stages
5 October 2007	Plowing
24 October 2007	Sowing of winter wheat Fertilization: 14.3 kg N $\mathrm{hm^{-2}}$, 3.8 kg P $\mathrm{hm^{-2}}$, 3.8 kg K $\mathrm{hm^{-2}}$
22 February 2008	Tillering stage weed control: 0.006 L $\mathrm{hm^{-2}}$
8 March 2008	Jointing stage
1 April 2008	Booting stage
11 April 2008	Milk-filling stage
26 April 2008	Ripening stage
28 May 2008	Harvesting of winter wheat crop yield: 6400 kg $\mathrm{hm^{-2}}$
1 June 2008	Burning straw
11 June 2008	Fertilization: 15.5 kg N $\mathrm{hm^{-2}}$, 11.3 kg P $\mathrm{hm^{-2}}$, 11.3 kg K $\mathrm{hm^{-2}}$
13 June 2008	Rice transplanting
20 June 2008	Tillering stage
1 July 2008	Jointing stage
16 July 2008	Booting stage insecticide treatment: 0.033 L $\mathrm{hm^{-2}}$
8 August 2008	Milk-filling stage weed control: 0.038 L $\mathrm{hm^{-2}}$
16 September 2008	Ripening stage spraying of leaf fertilizer: 0.0075 L $\mathrm{hm^{-2}}$
18 September 2008	Harvesting of rice crop yield: 8200 kg $\mathrm{hm^{-2}}$
3 October 2008	Plowing
22 October 2008	Sowing of winter wheat Fertilization: 15.5 kg N $\mathrm{hm^{-2}}$, 11.3 kg P $\mathrm{hm^{-2}}$, 11.3 kg K $\mathrm{hm^{-2}}$
23 February 2009	Tilling stage weed control: 0.006 L $\mathrm{hm^{-2}}$
12 March 2009	Jointing stage weed control: 0.006 L $\mathrm{hm^{-2}}$
5 April 2009	Booting stage
17 April 2009	Milk-filling stage
4 May 2009	Ripening stage
29 May 2009	Harvesting of winter wheat crop yield: 8200 kg $\mathrm{hm^{-2}}$
1 June 2009	Burning straw
10 June 2009	Fertilization: 14.3 kg N $\mathrm{hm^{-2}}$, 3.8 kg P $\mathrm{hm^{-2}}$, 3.8 kg K $\mathrm{hm^{-2}}$
12 June 2009	Rice transplanting
20 June 2009	Tillering stage
1 July 2009	Jointing stage
18 July 2009	Booting stage insecticide treatment: 0.033 L $\mathrm{hm^{-2}}$
12 August 2009	Milk-filling stage weed control 0.038 L $\mathrm{hm^{-2}}$
16 September 2009	Ripening stage spraying of leaf fertilizer: 0.0075 L $\mathrm{hm^{-2}}$
28 September 2009	Harvesting of rice crop yield: 7700 kg $\mathrm{hm^{-2}}$
5 October 2009	Plowing
18 October 2009	Sowing of winter wheat Fertilization: 18.3 kg N $\mathrm{hm^{-2}}$, 4.9 kg P $\mathrm{hm^{-2}}$, 4.9 kg K $\mathrm{hm^{-2}}$
25 February 2010	Tilling stage weed control: 0.006 L $\mathrm{hm^{-2}}$
20 March 2010	Jointing stage weed control: 0.006 L $\mathrm{hm^{-2}}$
10 April 2010	Booting stage
23 April 2010	Milk-filling stage
14 May 2010	Ripening stage fungicide treatment: 0.033 L $\mathrm{hm^{-2}}$
13 June 2010	Harvesting of winter wheat crop yield: 4400 kg $\mathrm{hm^{-2}}$

where $X(h)$ denotes the time series of the turbulence component, X is the mean over the averaging interval, and σ is the standard deviation (Gao et al., 2003). To account for the density effect on turbulent fluxes of CO_2, Webb–Pearman–Leuning correction (Webb et al., 1980) was applied. Data in the one hour after a rain event were removed (Munger and Loescher, 2004). When turbulence is weak, the nighttime friction velocity (u_*) threshold can be used to screen the original data associated with eddy covariance measurements (Massman and Lee, 2002). In our study site, the u_* threshold was found to be 0.1 m $\mathrm{s^{-1}}$ and the differences in estimated NEE between uncorrected and corrected values were only −5, −20, −59, 29 and 16 g C $\mathrm{m^{-2}}$ for the 2007–08, 2008–09 and 2009–10 winter wheat growing seasons and 2008 and 2009 rice growing seasons, respectively (Fig. 2). This suggested that the impact of nighttime u_* on the estimated seasonal NEE was limited at the site, so we chose not to use the u_* threshold to screen the original data. Overall, 37% of the data were missing due to rain and non-representative wind directions during the winter wheat periods, while 32% were missing during the summer rice periods. Data gaps in the time series of F_c were filled using the following methodology: a linear interpolation method was used to fill the gaps when the missing time was within 2 h; the mean diurnal variation method (Falge et al., 2001b) was used to fill the gaps when the missing time was between 2 h and 1 d; longer gaps were filled using the nonlinear regression method, which was based on the response of half-hourly F_c to soil temperature and radiation at nighttime and during the daytime, respectively (Falge et al., 2001a; Moureaux et al., 2006; Moffat et al., 2007), as discussed later. According to previous studies, the short-term sensitivity method is still recommended in estimating R_{eco} (Lei and Yang, 2010). So, in this study, we used the short-term method to estimate R_{eco} and compared the results to those estimated from the long-term method. The R_{eco} of winter wheat was underestimated by 6%–17% in the three years using the long-term method, while the R_{eco} of summer rice was overestimated by 3% in 2008 and underestimated by 3% in 2009 using the long-term method. Thus,

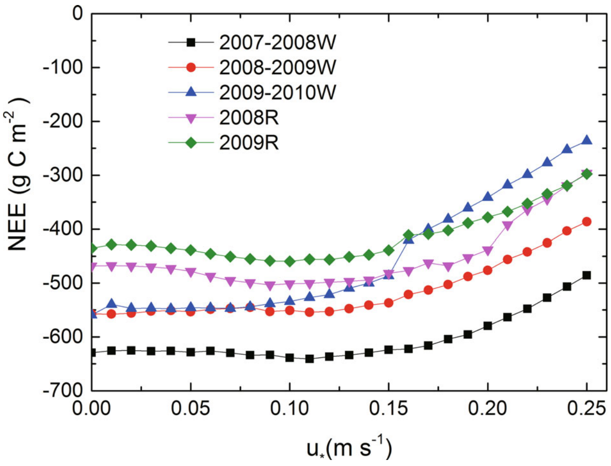

Fig. 2. Dependence of seasonal sums of net ecosystem exchange (NEE) on the nighttime friction velocity (u_*) threshold.

the GPP of winter wheat was underestimated by 7%–9% in the three years using the long-term method, whereas the GPP of summer rice was overestimated by 2% in 2008 and underestimated by 1% in 2009 using the long-term method.

2.4. *Calculation of NEE, R_{eco} and GPP*

NEE (units: μmol m^{-2} s^{-1}) is linked to the measured $\mathrm{CO_2}$ flux at the top of the canopy (F_{c}; units: μmol m^{-2} s^{-1}) via the following equation:

$$\mathrm{NEE} = F_{\mathrm{c}} + F_{\mathrm{st}} \,, \tag{1}$$

where F_{st} is the $\mathrm{CO_2}$ storage associated with the accumulation and depletion of $\mathrm{CO_2}$ within the canopy, which can be estimated following $F_{\mathrm{st}} = h\Delta c/\Delta t$ (Flanagan et al., 2002), where h is the height of the eddy covariance flux measurement system, and Δc is the change in $\mathrm{CO_2}$ concentration during the time interval, Δt. Over long-term time scales (several days or more), F_{st} can be neglected because the cumulative storage $\mathrm{CO_2}$ flux is close to zero (Flanagan et al., 2002; Tong et al., 2012).

NEE is the imbalance between GPP and R_{eco} (Falge et al., 2002). During nighttime when GPP is zero, NEE equals R_{eco}. To estimate R_{eco}, a regression model based on the exponential relationship between the nighttime NEE and soil temperature (nighttime period defined as the time of day when downwelling shortwave radiation is $<$20 W m^{-2}), or the Vant Hoff equation (Xu et al., 2004), can be fitted:

$$R_{\mathrm{eco}} = R_{\mathrm{ref}} \exp(BT_{\mathrm{soil}}) \,, \tag{2}$$

where R_{ref} denotes the value of R_{eco} at $T_{\mathrm{soil}} = 0°\mathrm{C}$, B is an empirical coefficient, and T_{soil} is the soil temperature measured at a depth of 0.05 m. In our study, we applied both the short-term temperature dependent method and the long-term temperature dependent method, following Reichstein et al. (2005), to estimate B and R_{ref}, respectively. Based on the fitted R_{ref} and B, Eq. (2) could be applied to estimate both the daytime and nighttime R_{eco}. The response of NEE to soil temperature is often characterized by $Q_{10}(e^{10B})$, which denotes the increased ratio of soil respiration with a 10°C increase in soil temperature. Note that in our study, both the short-term and the long-term temperature dependent method were used to estimate B. The daytime GPP is then calculated as $\mathrm{GPP} = -\mathrm{NEE} + R_{\mathrm{eco}}$ (Schmidt et al., 2012).

The grain harvest should be taken into consideration when carbon remains in the agroecosystem, so that the net ecosystem carbon balance (NECB) can be estimated (Chapin III et al., 2006). To do so, the crop yield (γ) is used to estimate the carbon in grains (C_{gr}) (Hollinger et al., 2005):

$$C_{\mathrm{gr}} = (1 - W_{\mathrm{gr}}) f_{\mathrm{c}} \gamma \,, \tag{3}$$

where the grain water content W_{gr} is 0.14 for wheat and 0.13 for rice and the fraction of carbon in the grain f_{c} is 0.45 for wheat and 0.43 for rice (Li et al., 2006). The NECB is then calculated as $-\mathrm{NEE} - C_{\mathrm{gr}}$ (Chapin III et al., 2006; Lei and Yang, 2010).

2.5. *Light response models*

During daytime, the relationship between NEE and PAR (indicated by PPFD; units: μmol m^{-2} s^{-1}) can be described by five different models (Gilmanov et al., 2003). Following scrutiny of the coefficients of determination (r^2) and relative error, we found that the Michaelis–Menten Kintics model (Marquardt, 1963) was the best fit for our data:

$$\mathrm{NEE} = -\frac{\alpha A_{\max}\mathrm{PPFD}}{\alpha \mathrm{PPFD} + A_{\max}} + R_{\mathrm{d}}, \tag{4}$$

where α is the initial light use efficiency, $A_{\max}$ is the maximum photosynthetic capacity at light saturation, PPFD is measured photo synthetic photon flux density (μmol m^{-2} s^{-1}) and R_{d} is dark respiration during the daytime.

The NEE calculated by Eq. (4) usually differed from the measured NEE, and a residual NEE was produced. According to the method used by Curiel yuste et al. (2004) and Tong et al. (2014), the residual NEE is the observed NEE minus the modeled NEE from Eq. (4): $\mathrm{NEE}_{\mathrm{residual}} = \mathrm{NEE} - \mathrm{NEE}_{\mathrm{model}}$.

3. Results

3.1. *Meteorological conditions*

Figure 3 shows the seasonal and interannual variation in daily-averaged values for wind speed, air, soil temperature, vapor pressure deficit (VPD), SWC and daily-accumulative PAR and precipitation. During the study period, the site was characterized by cool, dry winters, and warm, wet summers. Wind speed in the winter wheat growing season (1.9 m s^{-1}) was relatively higher than that during the summer rice growing season (1.2 m s^{-1}) (Fig. 3a). Seasonal patterns of daily-averaged air and soil temperature and daily-accumulative PAR were similar (Figs. 3b and 3d), whilst PAR showed more variability at daily scales. The annual maximum PAR appeared in May/June and the annual minimum appeared in January/December. The amount of annual PAR varied from 8449 to 8756 mol m^{-2} yr^{-1}, with an average of 8603 mol m^{-2} yr^{-1}. The average PAR of summer rice was larger than that of winter wheat (611 versus 514 μmol m^{-2} s^{-1}). VPD remained below 4 kPa and was higher in the summer and lower in the winter. The daily-averaged VPD in the summer rice growing season was higher than that during the winter wheat growing season due to the higher air temperature (Fig. 3c). The winter wheat experienced moderate drought stress from December 2009 to January 2010 (Fig. 3f). Intensive rainfall occurred during the summer monsoon period and concomitantly the SWC peaked in summer (Fig. 3f). All variables showed significant seasonal variability, resulting in significant seasonal variation in carbon exchange, which is discussed in the next section.

3.2. *NEE, R_{eco} and GPP*

In this section, the seasonal and interannual variation in NEE, GPP and R_{eco} are examined. Daily accumulative values of NEE, GPP and R_{eco} are shown in Fig. 4. As expected, NEE showed significant seasonal variation that was closely related

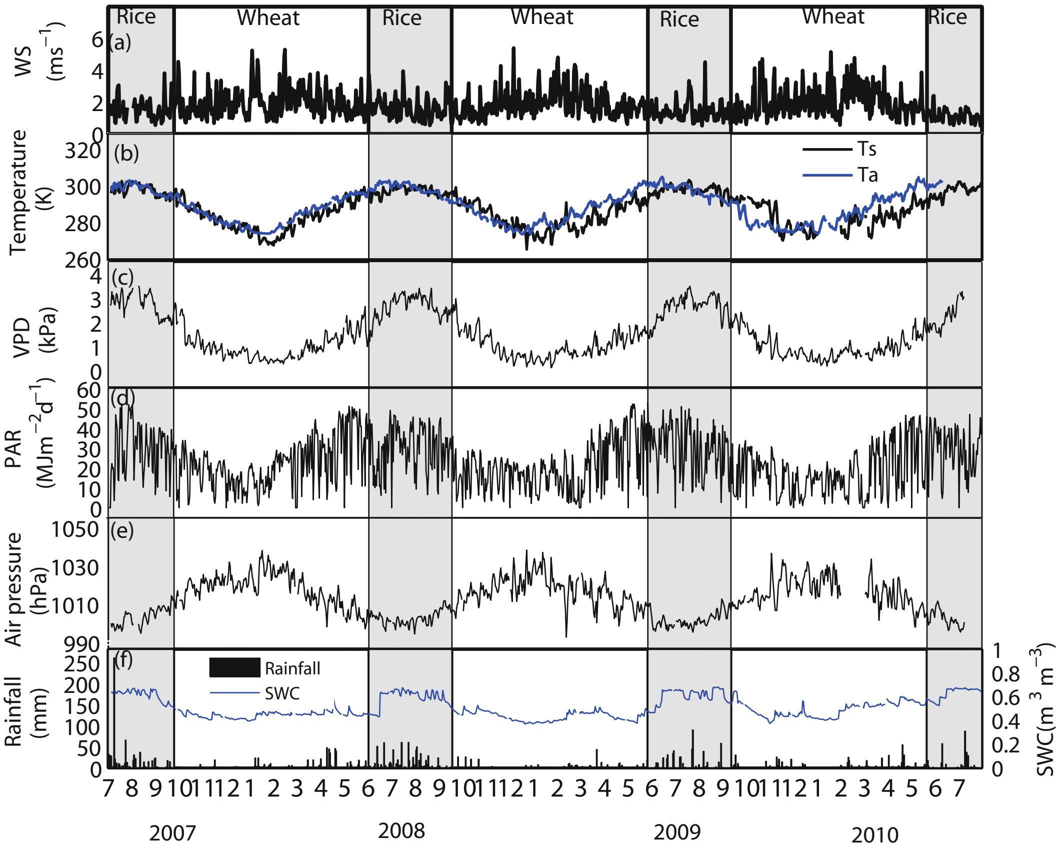

Fig. 3. Daily-averaged (a) wind speed (WS), (b) air and soil temperatures, (c) VPD, (d) PAR, (e) air pressure, (f) rainfall and SWC.

to crop development and phenology (Schmidt et al., 2012). NEE was negative during cropping periods but positive during intercropping periods. The annual maximum values of daily NEE over the three-year study period ranged from 2.77 to 3.23 g C m^{-2} d^{-1}. The annual minimum values of daily NEE ranged from -10.93 to -14.26 g C m^{-2} d^{-1} for winter wheat but from -12.41 to -15.27 g C m^{-2} d^{-1} for summer rice, suggesting important impacts of climate conditions and crop management activities on carbon exchange. The daily accumulative $R_{\rm eco}$ ranged from 5.00 to 6.60 g C m^{-2} d^{-1} during the winter wheat growing season and from 6.34 to 9.88 g C m^{-2} d^{-1} during the summer rice growing season (Fig. 4b), again suggesting that significant seasonal and interannual variation existed in $R_{\rm eco}$, as a result of variation in climatic conditions and crop management activities. As can be seen, $R_{\rm eco}$ decreased rapidly during the maturing stage, despite soil temperature still being high, which is the main driving variable for respiration. This is due to soil respiration ($R_{\rm S}$) being composed of heterotrophic respiration ($R_{\rm H}$) and autotrophic respiration ($R_{\rm A}$), with the latter suppressed during the maturing stage because roots stop growing and some old roots are senesced (Zhang et al., 2013). After the harvest, $R_{\rm eco}$ remained high (about 4.00 g C m^{-2} d^{-1}) because root residue would have been left in the soil and the high temperature of the soil would have led to an increase in $R_{\rm H}$.

There was a phase difference between the maximum values of GPP and $R_{\rm eco}$. The maximum values of GPP were often ahead of the maximum values of $R_{\rm eco}$ and concurred with the minimum values of NEE. After the long, slow growing stage of the winter wheat, GPP showed a rapid increase from late March, reached its maximum around late May, and then underwent a steep decrease during the maturing stage. The maximum values of GPP over the winter wheat field ranged from 13.95 to 19.89 g C m^{-2} d^{-1} over the three-year study period. During the summer rice growing period, GPP also showed a rapid increase from late June and reached its maximum in July, with values ranging from 18.04 to 20.56 g C m^{-2} d^{-1}. The high level of GPP continued until mid-August, and underwent a steep decrease as it entered the maturing stage.

3.3. *Response of NEE, $R_{\rm eco}$ and GPP to major environmental factors*

3.3.1. *Response of daytime NEE to light*

It is well acknowledged that PAR is an important environmental driver for variation in NEE during the daytime (Baldocchi et al., 2001; Wagle and Kakani, 2014). The relationship between NEE and PAR can be described by a rectangular hyperbolic function, Eq. (4), during the main growing stages (tillering stage, jointing stage, booting stage, grain-filling stage and ripening stage; see Table 2), as shown in Fig. 4. Also shown are the fitted parameters in Eq. (4). It is clear that seasonal changes in PAR explained between about 56% and 87% of the variability in daytime NEE of the two duirng the main growing seasons. and the response of daytime NEE to PAR changed with crop phenology. During the different growing stages, the parameters derived from hyperbolic regession were slightly different with crop development, especially during the tillering and ripening stage. Moreover, the two crops also showed dissimilarities in their NEE responses to light. The mean value of $A_{\max}$ ranged from -0.91 to 15.2 μmol m^{-2} s^{-1} in the winter wheat growing periods (Fig. 5a), and from 0.41 to 39.3 μmol m^{-2} s^{-1} during those of the summer rice (Fig. 5b). The values of α (4×10^{-4} to 2.4×10^{-3} μmol m^{-2} s^{-1}) for winter wheat in this study are relatively higher than the values (-2.3×10^{-2} to -4.1×10^{-2} μmol m^{-2} s^{-1}) reported by Béziat et al. (2009) for the same type of plant, but lower than those reported by Anthoni et al. (2004). The values of α (9×10^{-5} to 9×10^{-4} μmol m^{-2} s^{-1}) for summer rice in this study were lower than those of winter wheat. During the rapid growth periods of the two crops, a stronger impact of PAR on NEE was observed. The R^2 values in the booting stage were higher than those in the jointing and grain-filling stages for both winter wheat and summer rice. When crops had matured, NEE showed a weak dependence on PAR for winter wheat. However, NEE still showed a strong correlation with PAR in the summer rice ripening stage.

For a subset of sites, we separated the PAR data into clear- and cloudy-sky conditions, according to the light quality. The first category corresponded to a ratio of diffuse PAR to total PAR (d/t) of lower than 0.5 (clear-sky conditions) and the other category to a ration of higher than 0.5 (cloudy-sky conditions) (Fig. 5). It is evident that the R^2 values for cloudy-sky conditions were higher than those for clear-sky conditions, suggesting that PAR was probably not the most important control factor influencing NEE under clear-sky conditions. Rather, it might be modulated by other climatic variables such as VPD or soil temperature. In the fitted relationships between NEE and PAR, the mean α under cloudy conditions was also higher than that under clear-sky conditions; however, the mean $A_{\max}$ under cloudy conditions was lower than that under clear-sky conditions. Such observations are consistent with previous studies over a variety of ecosystems (Gu et al., 2002; Law et al., 2002; Suyker et al., 2005; Béziat et al., 2009). Higher values of α when $d/t > 0.5$ (more diffuse light) are probably caused by a relatively homogeneous distribution of radiation among all leaves in plant canopies (Gu et al., 2002), which results in better light use efficiency and promotes NEE. In particular, we found that NEE was more positive (i.e., less net carbon uptake) under clear-sky conditions than under clear-sky conditions when the total PAR was of similar magnitude. In addition, a higher carbon uptake under cloudy conditions might be related to other climatic variables such as VPD or soil temperature. For example, under cloudy conditions, the soil temperature is lower and soil moisture is higher, which may reduce respiration and therefore increase NEE, as suggested by Baldocchi et al. (1997) and Freedman et al. (2001).

3.3.2. *Response of NEE and $\boldsymbol{R}_{\text{eco}}$ to soil temperature and SWC*

Temperature is one of the main controlling factors for R_{eco} (Saito et al., 2005; Aubinet et al., 2009; Lei and Yang, 2010; Tong et al., 2012). Our study used Eq. (2) to determine which temperature was more relevant and appropriate for use as a reference temperature to calculate R_{eco}. When R_{eco} calculated from Eq. (3) was plotted against soil temperature at a depth of 5 cm, the correlation coefficient (r^2) values were 0.74 for the winter wheat growing season and 0.61 in the summer rice growing season–higher than the R^2 values when plotted against air temperature or soil temperature

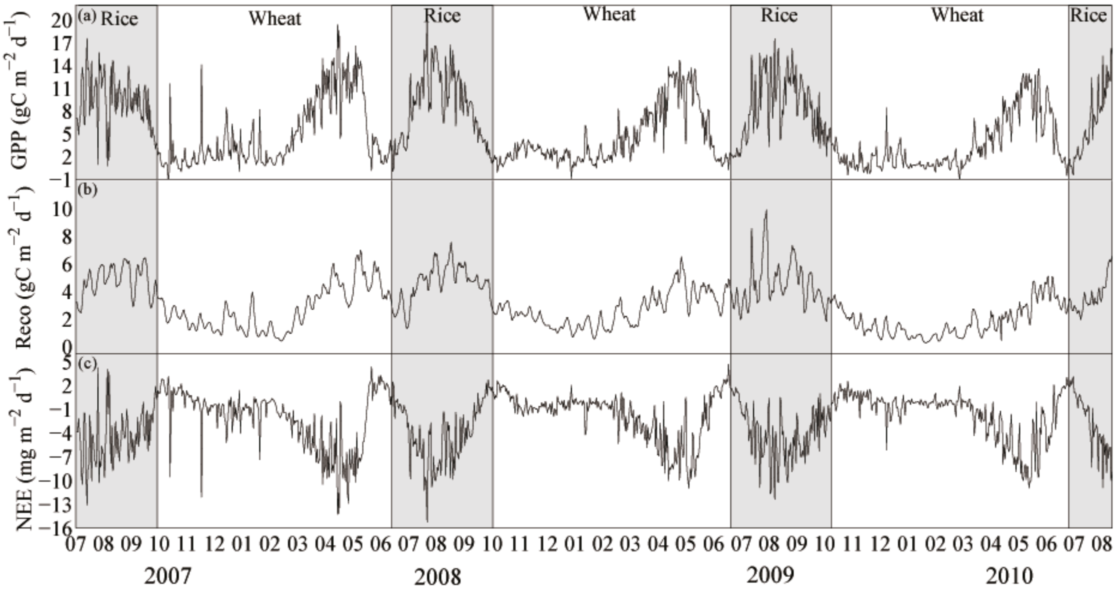

Fig. 4. Daily-averaged GPP, R_{eco} and NEE.

at depths of 0 cm and 10 cm. Given that NEE is equal to R_{eco} at nighttime, we can now examine the responses of nighttime NEE to soil temperature in the main growing periods of wheat and rice. We separated the nighttime NEE according to soil temperature bins, and then examined the bin-averaged results during the growing seasons of the two crops. As shown in Fig. 5a, there was strong similarity between the responses of nighttime NEE to soil temperature between winter wheat and summer rice. Overall, soil temperature explained 53%–93% of the variability of the ecosystem respiration (Fig. 6a). During the three-year study period, the long-term Q_{10} ranged from 3.21 to 3.64 for winter wheat and 1.81 to 3.31 for summer rice; the short-term Q_{10} ranged from 2.41 to 3.32 for winter wheat and 1.82 to 2.12 for summer rice (Table 3).

To analyze the possible impacts of environmental factors on daytime NEE besides PAR, the dependence of the residual

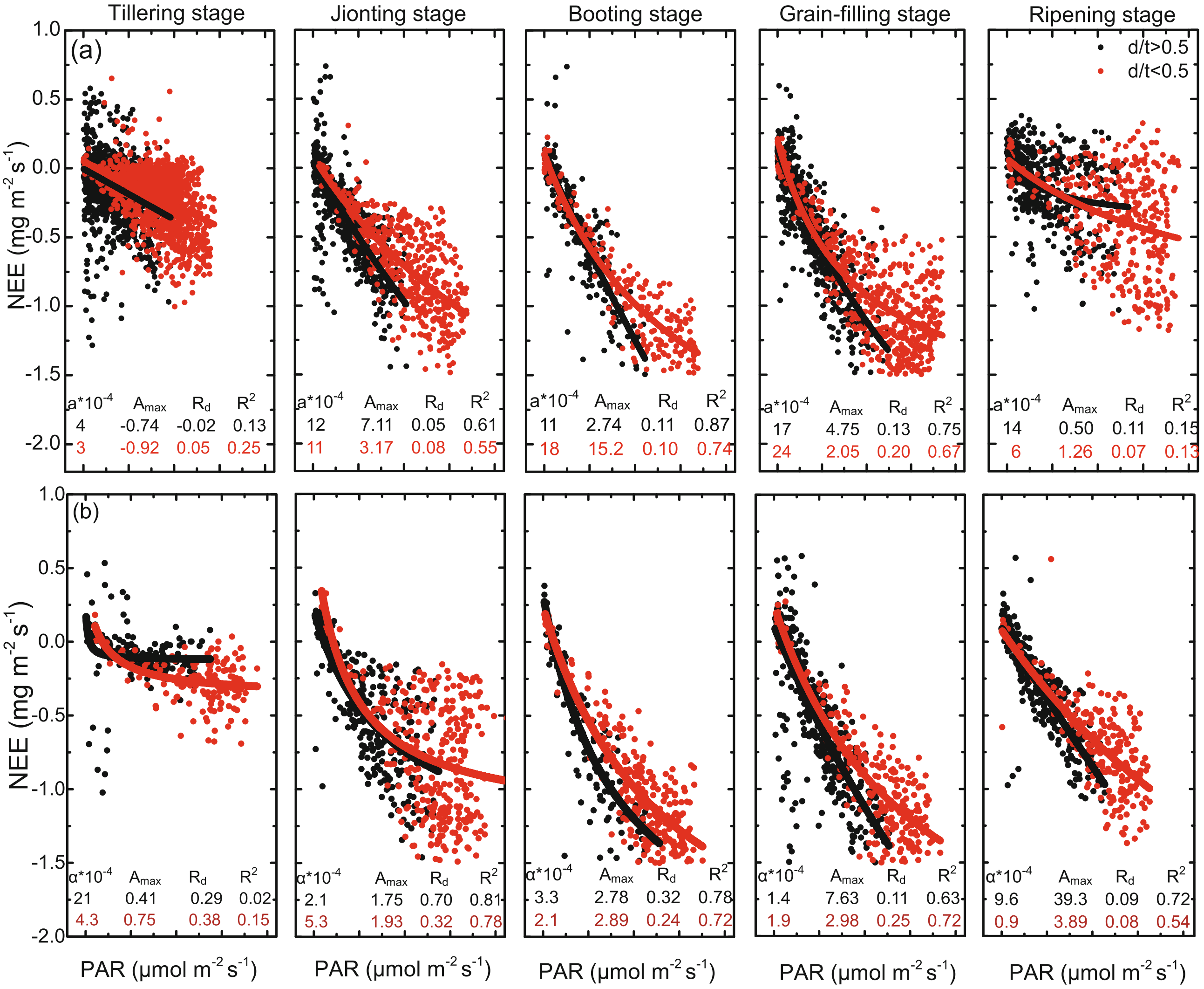

Fig. 5. Response of NEE to diffuse and direct PAR during the five main growing stages of winter wheat (top panels) and summer rice (bottom panels) in 2007–10. Fitted curves were calculated using the non-rectangular hyperbola equation, as in Eq. (4), under clear-sky conditions (the ratio of diffuse PPFD to total PPFD lower than 0.5, $d/t < 0.5$) and cloudy-sky conditions ($d/t > 0.5$).

Table 3. Parameters that control the response of nighttime NEE to soil temperature [see Eq. (2)]. half-hourly flux data were separated into temperature bins of 1 K widths and then averaged over each bin; n is the number of bins.

Year	Crop	R_{ref} (long-term) (mg CO$_2$ m^{-2} s^{-1})	Long-term B	Short-term B	Long-term Q_{10}	Short-term Q_{10}	r^2	n
2007–08	Wheat	0.061	0.117	0.076	3.22	2.14	0.73	24
2008	Rice	0.029	0.120	0.075	3.31	2.12	0.53	26
2008–09	Wheat	0.064	0.116	0.083	3.20	2.41	0.56	24
2009	Rice	0.102	0.070	0.073	2.01	2.07	0.71	22
2009–10	Wheat	0.020	0.129	0.120	3.64	3.32	0.64	24

NEE on SWC is shown in Fig. 6b. It is clear that the residual NEE decreased with increasing SWC in our R–W rotation system. This indicates that the ability of carbon uptake by summer rice and winter wheat increased under wet conditions. This decreasing trend clearly levelled off for summer rice as SWC exceeded approximately 0.6 $m^3\ m^{-3}$ (Fig. 6b). This could be explained by a decrease in respiration, a lack of oxygen and CO_2 accumulation in the soil under high humidity, i.e., because when SWC increases, the soil pores become filled with water in a drained field (Davidson et al., 2000; Dadson et al., 2013). Moureaux et al. (2006) also observed 21% of the assimilation under high SWC. This levelling-off behavior was not observed for wheat due to the fact that the SWC values were lower.

3.4. *Annual carbon budget*

The daily accumulative values of NEE, GPP and R_{eco} are shown in Fig. 7 for the three years. The annual NEE, GPP and R_{eco} results were −1021, 2207 and 1189 g C m^{-2}, respectively, for 2007–08, and −943, 2204 and 1061 g C m^{-2}, respectively, for 2008–09. When wheat and rice were analyzed separately, on average, winter wheat contributed 56%, 54% and 56% to the annual totals of NEE, R_{eco} and GPP, respectively, while summer rice contributed 45%, 46% and 44%.

A positive slope of cumulative NEE indicates that the ecosystem is behaving as a carbon source, while a negative slope indicates a carbon sink. Differences in crop characteristics resulted in quite different values of cumulative NEE for winter wheat and summer rice. For winter wheat, NEE values were close to zero from the end of October until February in the following year, especially for 2009–10. The values of NEE then became negative, implying that the ecosystem began to store CO_2. The cumulative NEE values were −583, −512 and −451 g C m^{-2} in the 2007–08, 2008–09 and 2009–10 winter wheat growing seasons, respectively. From May to June, winter wheat enters its ripening stage and the leaf area index decreases significantly. As a result, photo-

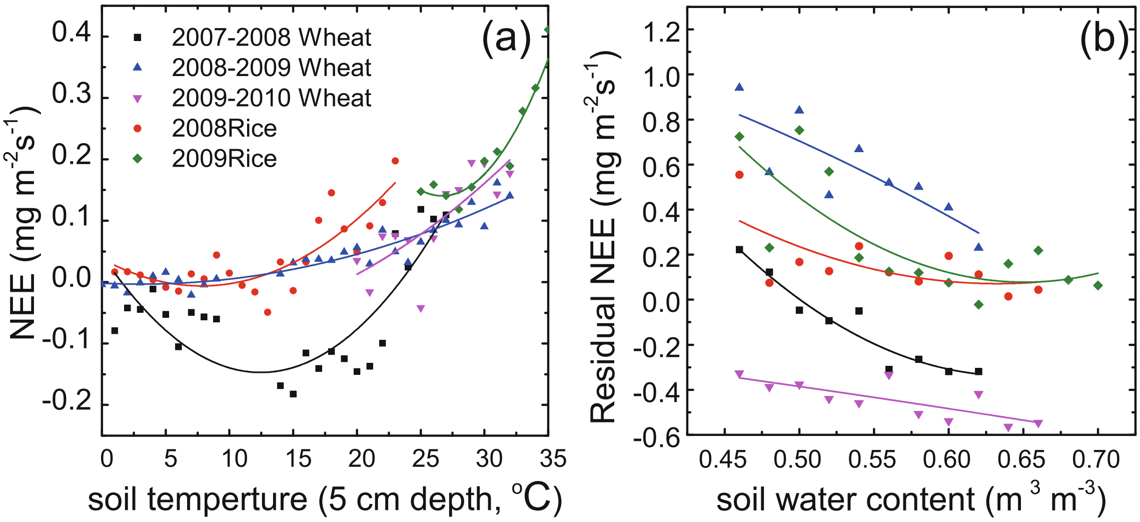

Fig. 6. Response of nighttime NEE to soil temperature at a depth of 5 cm (a), and the response of residual daytime NEE to SWC during the main growing stages of winter wheat in 2007–10 (b).

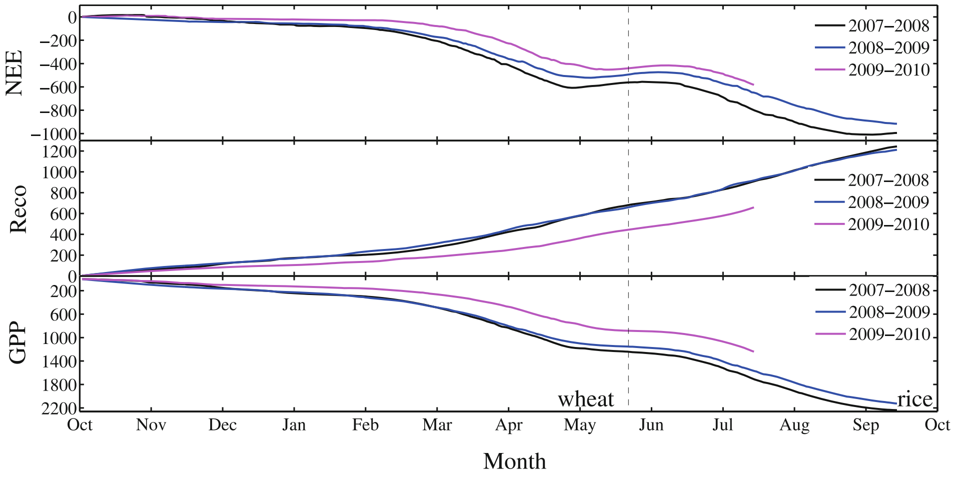

Fig. 7. Comparison of cumulative NEE, R_{eco} and GPP for the three years (all fluxes are in units of g C m^{-2}).

synthetic activity is hindered. On the other hand, the $R_{\rm eco}$ remained high during this period and hence the ecosystem changed from a carbon sink to a carbon source. After the rice was planted, the field started to assimilate carbon again and the slope of cumulative NEE changed to negative. During the rice growing season—from mid-June to the end of September—the ecosystem stored carbon and the cumulative NEE results were -438 and -431 g C m^{-2} in 2008 and 2009, respectively. Overall, the winter wheat field took up more CO_2 during its growing season length of 219 days, as compared with the rice paddy during its growing season length of 109 days. However, the average daily NEE of rice was much higher (-3.96 g C m^{-2} d^{-1}) than that of wheat (-2.35 g C m^{-2} d^{-1}) due to the much longer growing season length of wheat (Table 4). During the study period, the annual NEE ranged from -943 to -1018 g C m^{-2} yr^{-1} and the R–W rotation field acted as a carbon sink of 981 g C m^{-2} yr^{-1} on average over the three-year period.

Not all negative NEE is accumulated in ecosystems, since carbon can be removed during harvest, which is also an important component of the carbon cycle (Eugster et al., 2010). The carbon grains of the winter wheat calculated from Eq. (3) were 334, 251 and 280 g C m^{-2} in 2007–08, 2008–09 and 2009–10, respectively. When these carbon grains were considered, the wheat field turned into a moderately strong carbon sink of 251–334 g C m^{-2}. This is in agreement with previous results (Anthoni et al., 2004; Verma et al., 2005; Lei and Yang, 2010). Similarly, the carbon grains of summer rice were 132 and 107 g C m^{-2} in 2008 and 2009, respectively. Likewise, when these carbon grains were considered, the summer rice paddy became a weak carbon sink of 107–132 g C m^{-2}.

4. Discussion

4.1. *Possible impact of meteorological variability on interannual carbon exchange*

Due to the lack of data from August 2010 to October 2010, we could not quantify the annual accumulative NEE, GPP and $R_{\rm eco}$ for 2009–10, but we did notice any significant differences in the period 2009–10 compared to the previous two years (see Fig. 7). During the whole study period, there was no significant change in terms of soil texture and farm management (except for taking wheat residue away from the field instead of burning it in the 2010 wheat harvest). Crops were also cultivated by the same farm manager following the same traditional farming pattern. Meteorological conditions, on the other hand, changed from year to year, and were probably responsible for the differences in NEE, GPP and $R_{\rm eco}$ among the different years. In particular, the low GPP during the 2009–10 winter wheat growing season might have resulted from an early spring drought. Later on, continuous precipitation further caused wheat scab disease, which hindered carbon assimilation during the grain filling stage and the yield of the 2009–10 winter wheat was reduced by 34% compared to that in 2008–09 (Tables 3 and 4). In addition, in summer 2009, El Niño occurred, weakening the monsoon and leading to a significant reduction in rainfall during the rice growing season. Only 423 mm of rainfall fell in the summer rice season of 2009, which was much less than that during the summer rice season of 2008 (534 mm). This might have caused the lower NEE and GPP during the 2009 rice growing season compared to those during the 2008 rice growing season (Fig. 7 and Table 4). In addition to precipitation, PAR also played an important role in controlling the interannual GPP; higher accumulated PAR corresponded to higher accumulated GPP (see Table 4). Comparisons between the three winter wheat seasons and two summer rice seasons showed that the interannual variation in GPP and NEE was controlled mainly by precipitation and PAR, while the seasonal variation in NEE was controlled primarily by PAR, soil temperature and SWC (see section 3.3). Meanwhile, the interannual variability in NEE and GPP was mainly determined by temperature at a site in Weishan over the North Plain China (Lei and Yang, 2010).

4.2. *Impact of crop management on carbon exchange*

Field management during the three years followed a conventional system for winter wheat and summer rice. Farm cultivation was applied in five steps: plowing, fertilization, weed control, insecticide and harvesting. First, stubble plowing (25 cm) was carried out before sowing (Table 2), possibly impacting on the assimilation and soil respiration of root residues and soil microorganisms; the magnitude of $R_{\rm eco}$ decreased by 1 g C m^{-2} d^{-1} over 3 days. Aubinet et al. (2009) observed that the influence of plowing alone was also limited, not exceeding 2–3 g C m^{-2} d^{-1} over 1 or 2 d after the intervention. In contrast, for a winter wheat crop in Belgium, Schmidt et al. (2012) found an increase of 1 g C m^{-2} d^{-1} for a period of 5–6 days after plowing.

Basic fertilizer was applied during the sowing period, during which the most remarkable effect was an increase of GPP and $R_{\rm eco}$ up to 2–3 g C m^{-2} d^{-1} over 8 days. Spraying leaf fertilization had a minor effect on carbon flux, an increase in GPP of approximately 1–2 g C m^{-2} d^{-1} but did not change $R_{\rm eco}$ obviously for a period of a week after fertilization. Weed control applied on 22 February and 12 August induced a progressive decrease in GPP but did not change $R_{\rm eco}$ obviously; as a result, the exchange of CO_2 (NEE) was also suppressed (close to zero). Insecticide treatments were sprayed on the summer rice generally during 16–18 July, which decreased GPP and $R_{\rm eco}$, but this decrease did not last longer than a week.

Some impacts of crop management on the carbon budget are also apparent in the results presented in Fig. 3: After harvest, $R_{\rm eco}$ remained high (about 4.00 g C m^{-2} d^{-1}) because root residues would have been left in the soil and the high temperature of the soil would have led to an increase in $R_{\rm H}$. Such an additional emission was clearly visible for about two weeks. Moureaux et al. (2006) reported that the residual part, with a value of 0.02 kg C m^{-2}, contributed 5% of the seasonal carbon budget.

In the 2008 and 2009 winter wheat harvest, we followed

Table 4. Summary of the meteorological conditions, carbon-related fluxes, and other important variables over the three-year study period.

Season	Year	T (°)	PAR (mol m^{-2})	SWC (m^3 m^{-3})	Precipitation mm	NEE (g C m^{-2})	NEE/yield (g C g^{-1})	NEE/day g C m^{-2} d^{-1}	GPP (g C m^{-2})	R_{eco} (g C m^{-2})	Z (GPP/R_{eco})	Yield (g m^{-2})	C_{gr} (g C m^{-2})	NECB (g C m^{-2})
Wheat	2007–08	9.32	5.00	0.45	322	−583	−0.906	−2.66	1220	637	1.92	643	249	334
Wheat	2008–09	9.77	4.22	0.43	270	−512	−0.759	−2.33	1135	623	1.83	675	261	251
wheat	2009–10	9.95	3.93	0.49	462	−451	−1.018	−2.06	859	459	1.87	443	171	280
Rice	2008	25.44	3.45	0.59	534	−438	−0.533	−3.98	987	552	1.79	821	306	132
Rice	2009	25.03	3.70	0.62	432	−431	−0.560	−3.94	966	538	1.80	769	324	107
Wheat	(average)	9.68	4.38	0.47	351	−515	−0.642	−2.35	1071	573	1.87	587	227	288
Rice	(average)	25.36	3.58	0.61	966	−435	−0.547	−3.96	976	545	1.79	795	315	120

the traditional harvest management method in which crop stubble was left on the field while the straw was burned *in situ*. As a result, we found a transient effect on NEE (maximum NEE) after burning the wheat straw, reaching a peak of 3.23 and 4.66 g C m^{-2} d^{-1} in 2008 and 2009. However, following a ban on residual burning, there was a change in tillage practice in the 2010 wheat harvest, but the NEE did not change obviously when removing straw away from the field without burning (Fig. 4). In a 31-year study of the impact of stubble burning, little impact was found on carbon sequestration due to a small but quantitatively significant input of stable carbon into the soil (Osborne et al., 2010). Although some remarkable effects were observed in our study in terms of the short-term management impact on the carbon budget, a clear relationship could not be established due to the influence of other environmental factors. Future studies using more detailed long-term measurements are needed to better understand the response of the carbon budget to crop management.

4.3. *Comparison of carbon fluxes between summer rice and winter wheat*

The differences between winter wheat and summer rice in NEE and other carbon-related fluxes/variables are summarized in Table 4. Based on our results, the NEE, as well as the relationship NEE/yield, for the growing season of winter wheat (-515 g C m^{-2}; -0.642 g C g^{-1}) was larger compared to rice (-435 C m^{-2}; -0.547 g C g^{-1}), indicating that winter wheat was a stronger CO_2 sink, probably because of the longer growing season. Nonetheless, as mentioned earlier, the average daily NEE of winter wheat was smaller than that of summer rice (-2.35 vs. -3.96 g C m^{-2}).

In general, the Q_{10} for winter wheat was higher than that for summer rice, and the short-term Q_{10} was lower than the long-term Q_{10}, which is in agreement with previous studies (Reichstein et al., 2005). Other studies have reported similar values of Q_{10}. For instance, the short-term and long-term Q_{10} values for winter wheat were 2.1 and 2.5 at Weishan, China, which are lower than values at our site, despite the two sites being on the same line of longitude (Lei and Yang, 2010). The values of long-term Q_{10} for winter wheat at our site are closer to the results of Li et al. (2006) (2.49–2.94). The different values of Q_{10} among studies might be attributable to soil temperature, SWC, root biomass, litter inputs, microbial populations, fertilizer usage and other ecohydrological processes (Curiel yuste et al., 2004; Tong et al., 2012).

4.4. *Comparison of GPP under clear- and cloudy-sky conditions during the growing season*

GPP under cloudy-sky conditions was greater than under clear-sky conditions during the winter wheat growing season (on average, 301 vs. 368 g C m^{-2}); whereas, GPP under cloudy-sky conditions was lower than under clear-sky conditions in the summer rice growing season (on average, 360 vs. 225 g C m^{-2}). These findings are consistent with the study of Tong et al. (2014), which reported that the net carbon uptake was higher under cloudy-sky conditions than under

Table 5. Precipitation in the four seasons during 2007–10 (units: mm).

	Spring	Summer	Autumn	Winter
2007	188	776	84	83
2008	221	534	65	75
2009	183	499	155	108
2010	261	346	221	-

clear-sky conditions over winter wheat fields on the North Plain China. Our study is also consistent with studies over different ecosystems, in which it has been shown that carbon uptake is higher under clear-sky conditions (Hollinger et al., 1998; Alton, 2008; Zhang et al., 2013). We separated the PAR data into two parts according to light intensity to identify the differences in GPP in different zones of PAR: PAR less than 1000 μmol m^{-2} s^{-1} and PAR higher than 1000 μmol m^{-2} s^{-1} (Table 6). A dramatic drop was found in accumulated GPP during the winter wheat growing season when PAR was higher than 1000 μmol m^{-2} s^{-1} under clear-sky conditions (on average, 10 g C m^{-2}), indicating lower light-use efficiency and less positive GPP (i.e., less net carbon uptake) under clear-sky conditions than under cloudy-sky conditions when PAR is higher than 1000 μmol m^{-2} s^{-1} (see Fig. 5). A possible explanation for this is that canopy leaves are often light-saturated when suffering from direct sunlight conditions and, therefore, they possess low light-use efficiency; whereas, leaves in the shade are more light-use efficient when exposed to diffuse sunlight conditions (Knohl and Baldocchi, 2008). Leaves in the shade were more light-use efficient, with an average GPP value of 218 g C m^{-2} when exposed to diffuse sunlight conditions during the winter wheat season.

Secondly, the higher carbon uptake under cloudy-sky conditions might be related to other climatic variables such as VPD or soil temperature. For example, under cloudy-sky conditions, the soil temperature would be lower and soil moisture higher, which may reduce respiration and therefore increase NEE. A reduction in VPD and blue light induces increasing canopy stomatal conductance during cloudy-sky conditions, which can enhance the rate of photosynthesis (Baldocchi et al., 1997; Freedman et al., 2001).

The two crops led us to different conclusions in terms of the impact of cloud on carbon sequestration during PAR less than 1000 μmol m^{-2} s^{-1}. There was a decline in accumulated GPP during summer rice growing season when PAR was less than 1000 μmol m^{-2} s^{-1} under cloudy-sky conditions (41 g C m^{-2} during summer rice growing season versus 179 g C m^{-2} during winter wheat growing season), owing to the fact that the ratio of PAR under cloudy-sky conditions to under clear-sky conditions for winter wheat was much larger than that for summer rice (200 vs. 6 μmol m^{-2} s^{-1}). This may be the cause of why the GPP under cloudy-sky conditions was lower than under clear-sky conditions in the summer rice growing season.

4.5. *Comparison of NEE with other ecosystems*

To compare our results with previous studies, Table 1 documents the carbon fluxes reported in the literature over wheat fields from 30°N to 50°N and summer rice from 14°N to 36°N. The largest difference exists in the NEE of winter wheat between our results and those of Li et al. (2006) from the site at Yucheng, with similar growing season length. Their values are, on average, 79% smaller, which is most likely due to differences in soil type; Yucheng features saline, cultivated damp soil containing a lot of lime, which can neutralize carbon absorption due to lime emitting CO_2. Furthermore, compared with the previous crop type at Yucheng, summer maize, rice planting at our site in the previous season accelerated the soil nitrification–denitrification rate in the following winter wheat season (Timsina et al., 2001); this may be an important reason for the large difference.

Our results are smaller than the results of the site at Lonzée by 24%, which may be due to the longer growing season there (Alberto et al., 2009). The NEE of the rice paddy in our study (-438 and -431 g C m^{-2} in 2008 and 2009, respectively) was similar to observations reported by Saito et al. (2005) and Bhattacharyya et al. (2013) (without consideration of carbon grains), while large differences exist compared to the NEE at Los Banos (-258 g C m^{-2} from a flooded rice field and -85 g C m^{-2} from an aerobic rice field, without consideration of carbon grains) reported by Alberto et al. (2009). Their lower values of NEE were probably a result of the tropical monsoon climate dictating a shorter growing season, and the flooded crop management.

The seasonal minimum values of NEE (-12.4 to -15.3 g C m^{-2} d^{-1}) of summer rice at our study site are similar to the value of -13.1 g C m^{-2} d^{-1} from Japan (Saito et al., 2005), but lower than the value of -6 g C m^{-2} d^{-1} from the Philippines (Alberto et al., 2009). These differences can be attributed to the different soil characteristics. For example, aerobic soil conditions are found in the Philippines, while flooded soil conditions are prevalent at our study site. The seasonal minimum values of NEE (-10.9 to -11.0 g C m^{-2} d^{-1}) of winter wheat are similar to the results of Lei and Yang (2010) (-10.0 to -13.0 g C m^{-2} d^{-1}). In comparison, Li et al. (2006) reported slightly higher minimum NEE of -8.0 to -9.0 g C m^{-2} d^{-1} over their winter wheat field. In other continents, the minimum NEE ranges from -10.0 to -12.0 g C m^{-2} d^{-1} (Anthoni et al., 2004) in Germany and -8.6 to -10.5 g C m^{-2} d^{-1} in France (Béziat et al., 2009). The differences are most likely due to differences in crop management, climatic conditions, soil conditions, length of the growing season, and crop type. These comparisons highlight the large level of uncertainty in estimated NEE across different studies. More long-term measurements are clearly needed to investigate the estimation of NEE.

4.6. *Uncertainty in estimated carbon exchange*

A source of uncertainty in calculating the carbon budget at our site may result from neglecting C_{ag}, which includes secondary sources of carbon emissions from applying agro-

Table 6. Comparison of GPP under clear- and cloudy-sky conditions during the two crop growing seasons (PAR units: μmol m^{-2} s^{-1}).

	$d/t \leqslant 0.5$ GPP (g C m^{-2})			$d/t > 0.5$ GPP (g C m^{-2})		
	PAR<1000	PAR>1000	Total PAR	PAR<1000	PAR>1000	Total PAR
2007–08 wheat	305	2	307	146	223	369
2008 rice	213	25	238	22	75	97
2008–09 wheat	329	16	345	158	322	480
2009 rice	427	49	486	61	291	352
2009–10 wheat	286	16	302	234	108	342

chemicals (fertilizer, herbicides, insecticides and fungicides), from the use of machinery, and from the combustion of fuel, ag is the agriclural managements (Bao et al., 2014). According to previous research (West and Marland, 2002; Lal, 2004), we calculated the indirect carbon emissions from $C_{\rm ag}$ at our site. The emissions from fertilizer, herbicides and insecticides during the winter wheat season were 1.89, 0.07 and 0.04 g C m^{-2}, respectively. Fertilizer and herbicide emissions during the summer rice season were 1.92 and 0.01 g C m^{-2}, respectively. Although $C_{\rm ag}$ was a small part of the carbon emissions at our site, the impact could be far more substantial over a longer period of time, as highlighted by Maraseni et al. (2007), thus potentially influencing the assessment of the annual carbon budget.

It is also important to note that the global warming potential of methane (CH_4) is 23 times higher than that of CO_2 (Smith et al., 2010; Linquist et al., 2012a; IPCC, 2013). Previous studies have found that during the R–W rotation cycle the net CH_4 emissions are usually significant in the summer rice growing season but negligible in the winter wheat growing season. The CH_4 emissions rate reported in the literature ranges from 166 to 288 kg C hm^{-2} yr^{-1} (Ma et al., 2013; Yao et al., 2013). If CH_4 emissions of 100 g C m^{-2} are assumed for the rice paddy at our study site, according to previous studies (Wassmann and Aulakh, 2000; Xie et al., 2010; Wang et al., 2011; Linquist et al., 2012b), given that summer rice absorbs 120 g C m^{-2} on average (the average of 107 and 132 g C m^{-2}), the summer rice paddy system is in carbon balance, whereas the winter wheat field system remains a moderately strong carbon sink. It is also noted that carbon emissions from agrochemicals and fertilizers were not considered in this study.

5. Conclusions

In order to better understand surface carbon exchanges over R–W rotation fields in areas of subtropical semi-humid monsoon climate, the seasonal and interannual variation and controlling factors of carbon fluxes (e.g., NEE, GPP and $R_{\rm eco}$) over an R–W rotation system from 2007 to 2010 were analyzed using eddy-covariance measurements as well as measurements of meteorological variables.

Results indicate that exponential relationships using soil temperature explained 71% and 63% of the variation in nighttime NEE or $R_{\rm eco}$ of the winter wheat and summer rice. Seasonal changes in PAR explained about between 56 and 87% of the variability in daytime NEE of the two crops during the main growing seasons. The net carbon uptake was larger under cloudy-sky conditions in winter wheat growing seasons. The response of $R_{\rm eco}$ to soil temperature and the response of daytime NEE to light were closely affected by crop development and photosynthetic activity, respectively. Other factors, such as VPD and SWC also affected the variability of NEE. Interannual variability in NEE and GPP were mainly controlled by PAR and precipitation.

The annual NEE, GPP and $R_{\rm eco}$ values were -1021, 2210 and 1189 g C m^{-2}, respectively, for 2007–08 and -943, 2104 and 1161 g C m^{-2}, respectively, for 2008–09. On average, winter wheat contributed 56%, 54% and 56% to the annual totals of NEE, $R_{\rm eco}$ and GPP, respectively, while summer rice contributed 44%, 46% and 44%.

On average, NEE was negative over the whole cycle and the field behaved as a sink of 982 g C m^{-2} on average over the three-year period. The wheat field absorbed more carbon than the rice paddy, and it absorbed more CO_2 per unit of the grain yield, indicating a stronger carbon sink. Besides, winter wheat can produce more carbon per unit of water consumption. However, the average daily NEE of rice was much higher (-3.96 g C m^{-2} d^{-1}) than that of wheat (-2.35 g C m^{-2} d^{-1}) due to the longer growing season of winter wheat. When the carbon harvest was taken into account, the winter wheat field was a moderately strong carbon sink of 251–334 g C m^{-2} per season. as compared to the rice paddy, which acted as a weak carbon sink of 107–132 g C m^{-2} per season. These carbon flux results are in broad agreement with previous studies and the differences are mainly attributable to crop management, climatic conditions, soil conditions, and crop type.

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