Title: Decadal variation of CO_2 fluxes and its budget in a wheat and maize rotation cropland over the North China Plain

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Abstract:

Carbon sequestration in agro-ecosystems has great potentials to mitigate global greenhouse gas emissions. To assess the decadal trend of CO_2 fluxes of an irrigated wheat-maize rotation cropland over the North China Plain, the net ecosystem exchange (NEE) with the atmosphere was measured by using an eddy covariance system from 2005 through 2016. To evaluate the detailed CO_2 budget components of this representative cropland, a comprehensive experiment was conducted in the full 2010-2011 wheat-maize rotation cycle by combining the eddy covariance NEE measurements, plant carbon storage samples, a soil respiration experiment that differentiated between heterotrophic and below-ground autotrophic respirations. Over the past decade from 2005 through 2016, the cropland exhibited a non-statistically significant decreasing carbon sequestration capacity; the average of total NEE, Gross Primary Productivity (GPP), Ecosystem Respiration (ER) for wheat were –364, 1174 and 810 gC m^{-2}, and were –136, 1008, and 872 gC m^{-2} for maize. The multiple regression revealed that, air temperature and groundwater depth showed pronounced correlation with the CO_2 fluxes for wheat; but in the maize season, incoming short-wave radiation and groundwater depth showed pronounced correlations with CO_2 fluxes. For the full 2010-2011 agricultural cycle, the CO_2 fluxes for wheat and maize were as follows: NEE –438 and –239 gC m^{-2}, GPP 1078 and 780 gC m^{-2}, ER 640 and 541 gC m^{-2}, soil heterotrophic respiration 377 and 292 gC m^{-2}, below-ground autotrophic respiration 136 and 115 gC m^{-2}, above-ground autotrophic respiration 128 and 133 gC m^{-2}; the net biome productivity was 59 gC m^{-2} for wheat and 5 gC m^{-2} for maize, indicating that wheat was a weak CO_2 sink and maize was close to CO_2 neutral to the atmosphere for this agricultural cycle. However, when considering the total CO_2 loss in

the fallow period, the net biome productivity was –40 gC m^{-2} yr^{-1} for the full 2010-2011 cycle, implying that the cropland was a weak CO_2 source. The investigations of this study showed that taking cropland as a climate change mitigation tool is challenging and further studies are required for the CO_2 sequestration potential of croplands.

Key words: Cropland; CO_2; Decadal trend; Maize; North China Plain; Wheat

Introduction

The widely used eddy covariance technique (Aubinet et al., 2000; Baldocchi et al., 2001; Falge et al., 2002b) has enabled us to better understand the terrestrial CO_2 exchange with the atmosphere, thereby forested our understanding of the mechanisms on how the terrestrial ecosystems contribute to mitigate the ongoing climate change (Falkowski et al., 2000; Gray et al., 2014; Poulter et al., 2014; Forkel et al., 2016). Agro-ecosystems play an important role in regulating the global carbon balance (Lal, 2001; Bondeau et al., 2007; Özdoğan, 2011; Taylor et al., 2013; Gray et al., 2014) and are believed to have great potentials to mitigate global carbon emissions through cropland management (Sauerbeck, 2001; Freibauer et al., 2004; Smith, 2004; Hutchinson et al., 2007; van Wesemael et al., 2010; Ciais et al., 2011; Schmidt et al., 2012), furthermore, some studies proposed the agro-ecosystems as the "natural climate solutions" to mitigate global carbon emission (e.g., Griscom et al., 2017; Fargione et al., 2018). The field management practices (e.g., irrigation, fertilization and residue removal, etc.) impact the cropland CO_2 fluxes (Baker and Griffis, 2005; Béziat et al., 2009; Ceschia et al., 2010; Eugster et al., 2010; Drewniak et al., 2015; de la Motte et al., 2016; Hunt et al., 2016; Vick et al., 2016), but their relative importance in determining the cropland CO_2 budget remain unclear because of limited field observations (Kutsch et al., 2010), motivating comprehensive CO_2 budget assessments across different cropland management styles.

Over the past two decades, CO_2 investigations of agro-ecosystems have mainly focused on the variations in the net ecosystem exchange with the atmosphere (i.e., NEE) or its two derived components (i.e., GPP and ER) using the eddy covariance. To date, these evaluations have

been widely conducted for wheat (Gilmanov et al., 2003; Anthoni et al., 2004a; Moureaux et al., 2008; Béziat et al., 2009; Vick et al., 2016), maize (Verma et al., 2005), sugar beet (Aubinet et al., 2000; Moureaux et al., 2006), potato (Anthoni et al., 2004b; Fleisher et al., 2008), soybean-maize rotation cropland (Gilmanov et al., 2003; Hollinger et al., 2005; Suyker et al., 2005; Verma et al., 2005; Grant et al., 2007), and winter wheat-summer maize cropland (Zhang et al., 2008; Lei and Yang, 2010). However, the long-term variations of the cropland CO_2 fluxes remain limited, leaving our knowledge of the cropland potential as the future climate change mitigation tool incomplete.

The widely used eddy covariance technique has fostered our understanding of the integrated fluxes of NEE, GPP and ER, but cannot provide the detailed CO_2 budget components, which consist of carbon assimilation (i.e., GPP), soil heterotrophic respiration (R_H), above-ground autotrophic respiration (R_{AA}), below-ground autotrophic respiration (R_{AB}), lateral carbon export at harvest and import at sowing or through organic fertilization (Ceschia et al., 2010). These different CO_2 components result from different biological and biophysical processes (Moureaux et al., 2008) that may respond differently to climatic conditions, environmental factors and management strategies (Ekblad et al., 2005; Zhang et al., 2013). Differentiating among these components is a prerequisite for understanding the response of terrestrial ecosystems to changing environment (Heimann and Reichstein, 2008), so the carbon budget evaluations have been reported for a few croplands (e.g., Moureaux et al., 2008; Ceschia et al., 2010; Wang et al., 2015; Demyan et al., 2016; Gao et al., 2017). In particular, to account for the literal carbon export, the Net Biome Productivity (NBP) is often estimated by

85 combining the eddy covariance technique and field carbon measurements associated with
86 harvests and residue treatments (Ceschia et al., 2010; Kutsch et al., 2010). As detailed CO_2
87 budget might facilitate better predictions of agro-ecosystems' responses to climate change, the
88 CO_2 budget evaluations in different croplands remain necessary.

89 The North China Plain (NCP) is one of the most important food production regions in China,
90 and it guarantees the national food security by providing more than 50% and 33% of the nation's
91 wheat and maize, respectively (Kendy et al., 2003). Irrigation by diverting water from the
92 Yellow River is common to alleviate the water stress during spring in the NCP, resulting in a
93 very shallow groundwater depth (usually range from 2 to 4 m) along the Yellow River (Cao et
94 al., 2016) (Fig. 1). Wang et al. (2015) suggested that a groundwater-fed cropland in the NCP
95 had been losing carbon, and other studies also reported croplands in this region as carbon
96 sources (e.g., Li et al., 2006; Luo et al., 2008). However, the long-term variations (e.g., >10
97 years) of the CO_2 fluxes over the NCP remain lacking, leaving the trend of carbon sequestration
98 capacity of this region unknow.

99 To this end, this study is designed to assess the long-term variation of CO_2 fluxes and its
100 budget of the representative wheat-maize rotation cropland in the NCP. The eddy covariance
101 system was used to measure the CO_2 exchange from 2005 through 2016. For the full 2010-
102 2011 agricultural cycle, we measured soil respiration and sampled crops to quantify the
103 detailed CO_2 budget components. These measurements allow to (1) investigate the decadal
104 CO_2 flux (NEE, GPP, and ER) trend over this cropland; (2) provide the detailed CO_2 budget
105 components; and (3) estimate the Net Primary Productivity (NPP), Net Ecosystem

106 Productivity (NEP), and NBP.

107 **Materials and methods**

108 **Site description and field management**

109 The experiment was conducted in a rectangular-shaped (460 m × 280 m) field of the
110 representative cropland over the NCP (36° 39' N, 116° 03' E, Weishan site of Tsinghua
111 University, Fig. 1). The soil is silt loam with the field capacity of 0.33 m^3 m^{-3} and saturation
112 point of 0.45 m^3 m^{-3} for the top 5 cm soil. The mean annual precipitation is 532 mm and the
113 mean air temperature is +13.3 °C. The winter wheat-summer maize rotation system is the
114 representative cropping style in this region. On average, the winter wheat is sown around
115 October 17th and harvested around June 16th of the following year with crop residues left on
116 the field; summer maize is sown following the wheat harvest around June 17th and harvested
117 around October 16th. Prior to sowing wheat of the next season, the field is thoroughly
118 ploughed to fully incorporate maize residues into the top 20 cm soil. The canopies of both
119 wheat and maize are very uniform across the whole season. Nitrogen fertilizer is commonly
120 applied at this site with the amount of 35 gN m^{-2} for wheat and 20 gN m^{-2} for maize. The crop
121 density is 775 plants m^{-2} for wheat with a ridge spacing of 0.26 m, and 4.9 plants m^{-2} for
122 maize with a ridge spacing of 0.63 m, on average. Wheat is commonly irrigated with water
123 diverted from the Yellow River and the irrigation is about 150 mm every year; maize is rarely
124 irrigated because of the high precipitation in the summer. During the 2010-2011 agricultural
125 cycle with CO_2 budget components evaluated, winter wheat was sown on October 23rd, 2010
126 and subsequently harvested on June 10th, 2011; summer maize was sown on June 23rd, 2011

and harvested on September 30th, 2011. The entire year from October 23rd, 2010 through October 22nd, 2011 was studied for the annual CO_2 budget evaluation.

(Fig. 1 here)

Eddy covariance measurements

A flux tower was set up at the center of the experiment field in 2005 (Lei and Yang, 2010; Zhang et al., 2013). The NEE was measured at 3.7m above ground with an eddy covariance system consisting of an infrared gas analyzer (LI-7500, LI-COR Inc., Lincoln, NE, USA) and a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA). The 30-min averaged NEE was calculated from the 10 Hz raw measurements with TK2 (Mauder and Foken, 2004) from 2005 through 2012 and TK3 software package (Mauder and Foken, 2011) from 2013 through 2016. The storage flux was calculated by assuming a constant CO_2 concentration profile. Nighttime measurements under stable atmospheric conditions with a friction velocity lower than 0.1 m s^{-1} were removed from the analysis (Lei and Yang, 2010). In the gap filling procedure, gaps less than 2 h were filled using linear regression, while other short gaps were filled using the Mean Diurnal Variation (MDV) method (Falge et al., 2001); gaps longer than 4 weeks were not filled. NEE was further partitioned to derive GPP and ER using the nighttime method (Reichstein et al., 2005; Lei and Yang, 2010), which assumes that daytime and nighttime ER follow the same temperature response, thereby estimates the daytime ER using the regression model derived from the nighttime measurements. In particular, this study adopted the method proposed by Reichstein (2005) to quantify the short-term temperature sensitivity of ER from nighttime measurements

as described by the Vant Hoff equation,

$$\mathrm{ER} = \mathrm{ER}_{\mathrm{ref}} \exp(bT_{\mathrm{S}}), \quad (1)$$

Where T_s is soil temperature, $\mathrm{ER}_{\mathrm{ref}}$ is the reference respiration at 0 °C, and b is a parameter associated with the commonly used temperature sensitivity coefficient Q_{10},

$$Q_{10} = \exp(10b). \quad (2)$$

The long-term temperature sensitivity b of the season (either wheat or maize) was determined by averaging all the estimated short-term b in each of the four-day window with the inverse of the standard error as a weighing factor. The long-term temperature sensitivity b was then used to estimate the $\mathrm{ER}_{\mathrm{ref}}$ parameter in each of the four-day window by fitting the eq. (1), then $\mathrm{ER}_{\mathrm{ref}}$ of each day was estimated by using the least square spline approximation (Lei and Yang, 2010).

To quantify the contribution of source areas to the CO_2 flux measurement of the eddy covariance, we used an analytical footprint model (Hsieh et al., 2000),

$$f(\chi, \mathrm{z}_m) = \frac{1}{\kappa^2 \chi^2} \mathrm{D}\, z_u^P |L|^{1-P} \exp\left(\frac{-1}{\kappa^2 \chi} \mathrm{D}\, z_u^P |L|^{1-P}\right) \quad (3)$$

where D=0.28 and P=0.59 are similarity constants for unstable condition (Hsieh et al., 2000), κ=0.4 is von Karman constant, χ represents the horizontal coordinate, L represents the Obukhov length, z_m represents the measurement height, and z_u represents the length scale expressed as,

$$z_u = z_m \left[\ln\left(\frac{z_m}{z_0}\right) - 1 + \frac{z_0}{z_m}\right] \quad (4)$$

where z_0 represents the roughness height set to be 0.1Hc (canopy height).

Note that the eddy covariance system failed from October 23, 2010 to April 1, 2011 during the wheat dormant season. To evaluate the seasonal CO_2 budget of this rotation cycle, the flux gap of this period was filled by using the machine learning Support Vector Regression (SVR) algorithm (Cristianini and Shave-Taylor, 2000), which has been proved to be an appropriate tool for flux gap fillings (e.g., Kang et al., 2019; Kim et al., 2019) (see Appendix A).

Meteorological and environmental condition measurements

The meteorological variables were measured at 30-min intervals by a standard meteorological station on the tower. Among these variables were the air temperature (T_a) and relative humidity (RH) (HMP45C, Vaisala Inc, Helsinki, Finland) at the height of 1.6 m, precipitation (P) (TE525MM, Campbell Scientific Inc), incoming short-wave radiation (R_{si}) (CRN1, Kipp & Zonen, Delft, Netherlands) and photosynthetic photon flux density (PPFD) (LI-190SA, LI-COR Inc) at the height of 3.7 m. The 30-min interval edaphic measurements included soil temperature (T_s) (109-L, Campbell Scientific Inc.), volumetric soil moisture (θ) (CS616-L, Campbell Scientific Inc.) for the top 5 cm soil; soil matric potential (ψ) (257-L, Campbell Scientific Inc.) was measured since 2010 at the same depth. The groundwater depth (WD) (CS420-L, Campbell Scientific Inc.) was measured at a location close to flux tower in 30-min intervals.

Biometric measurements and crop samples

To trace crop development and carbon storage, we measured canopy height (Hc), leaf area index (LAI), crop dry matter (DM), and carbon content of crop organs at an interval of 7-10 days in the footprint of eddy covariance. Due to inclement weather, measurement intervals

were occasionally extended to two weeks or longer. The Hc was measured with a ruler and LAI was measured with LAI-2000 (LI-COR Inc.) at ten locations randomly distributed in the field. For crop samples, four locations were randomly selected at the start of the growing season, crop samples were then collected close to these four locations throughout the experimental period. At each location, 10 crop samples were collected for wheat and 3 crop samples were collected from maize. To reduce the sample uncertainty at harvest, 200 crops and 5 crops were collected in each location for wheat and maize, respectively. The crop organs were separated and oven-dried at 105 °C for kill-enzyme torrefaction for 30 min, and then oven-dried at 75 °C until a constant weight. The crop samples were used to estimate the average field biomass (Dry Matter). The carbon content was analyzed using the combustion oxidation-titration method (National Standards of Environmental Protection of the People's Republic of China, 2013) to estimate carbon storage. The crop samples provided a direct estimate of the NPP.

Soil respiration measurements

Soil respiration was measured every day in the footprint of the eddy covariance between 13:00 and 15:00 from March through September of 2011 using a portable soil respiration system LI-8100 (LI-COR Inc.). Below-ground autotrophic respiration and heterotrophic respiration were differentiated using the root exclusion method (Zhang et al., 2013). The total soil respiration (R_S) and R_H were measured at treatments with and without roots, respectively, and the corresponding difference is R_{AB}. To reduce the uncertainty associated with spatial variability, we set three replicate pairs of comparative treatments (i.e., with root and without

root) randomly in the field. The uniform field condition contributes to reduce the measurement uncertainty associated with the spatial variability (see Zhang et al., 2013). To assess the seasonal variations and total amount of soil respirations, the seasonal continuous R_H was constructed using the Q_{10} model by incorporating soil moisture as follows (Zhang et al., 2013):

$$R_H = A\exp(BT_S)\cdot f(\theta), \quad (4)$$

$$f(\theta) = \begin{cases} 1, & \theta \le \theta_f \\ a(\theta-\theta_f)^2 + 1, & \theta > \theta_f \end{cases}, \quad (5)$$

where θ_f is the field capacity. The parameters were inferred by fitting the R_H and T_S measurements by using the least square method (see Zhang et al., 2013), where A=1.16, B=0.0503, and a= –44.9 (see Zhang et al., 2013). Note that because the plant biomass was negligible before March 14th, during which R_H was set to equal to the ecosystem respiration and the R_{AB} was assumed to be 0. R_{AB} of other periods was estimated based on the R_H measurement and the ratio of the R_{AB} to R_S estimated previously (Zhang et al., 2013), and the continuous R_{AB}/R_S ratio was interpolated from the daily records (Fig. 2). This estimation method is robust because the R_{AB}/R_S ratio is nearly constant around its diurnal average (Zhang et al., 2015b).

(Fig. 2 here)

Synthesis of the CO_2 budget components

The CO_2 budget components were derived by combining the eddy covariance measurements, soil respiration experiments and crop samples. Eddy covariance-measured NEE is the

difference between carbon assimilation (i.e., GPP) and carbon release (i.e., ER). The ER consists of R_H, R_{AB} (i.e., root respiration) and above-ground autotrophic respiration (R_{AA}). The total soil respiration is the sum of R_H and R_{AB},

$$R_S = R_H + R_{AB}. \quad (6)$$

The total autotrophic respiration (R_A) is the difference between the eddy covariance-derived ER and R_H,

$$R_A = ER - R_H. \quad (7)$$

The above-ground autotrophic respiration (R_{AA}) is the difference between the eddy covariance-derived ER and R_S in eq. (6),

$$R_{AA} = ER - R_S. \quad (8)$$

NPP is plant biomass carbon storage, and can be quantified as the difference between GPP and R_A,

$$NPP_{EC} = GPP - R_A, \quad (9)$$

where the subscript "EC" represents that the NPP is estimated from the eddy covariance-derived GPP. In parallel, NPP can also be directly inferred from biomass samples as,

$$NPP_{CS} = C_{cro}, \quad (10)$$

where the subscript "CS" indicates that NPP is based on crop samples, and C_{cro} is the plant biomass carbon storage at harvest. We used the average of the two independent NPPs as the measurement for this site.

NEP is commonly estimated by the NEE measurement ($NEP_{EC} = -NEE$). In this study, the crop

samples and soil respiration measurements also provided an independent estimate as,

$$NEP_{CS}=NPP_{CS}-R_H. \quad (11)$$

We used the average of the two NEPs as the measurement for this site.

At this site, there were no fire and insect disturbances, and there was no manure fertilizer application. The carbon input from seeds was negligible, and all crop residues were returned to the field. Thus, NBP can be quantified as the difference between NEP and grain export carbon loss (C_{gra}),

$$NBP=NEP-C_{gra}, \quad (12)$$

Results

Meteorological conditions and crop development

The inter-annual variations of major meteorological variables are shown in Fig. 3, and they showed no clear trend for both wheat and maize seasons. For the full 2010-2011 cycle with comprehensive experiments, the average R_{si} and T_a were very close to other years; however, the P during maize season was a little higher than other years (Fig. 3c), leading to a shallow WD in maize season (Fig. 3d). The intra-annual variations of field microclimates for the full 2010-2011 cycle are shown in Fig. 4. The seasonal maximum and minimum T_a occurred in July and January, respectively, and the variations in vapor pressure deficit (VPD) well followed the T_a. The WD mainly followed the irrigation events in winter and spring, but followed P in summer and autumn. In particular, the WD varied from 0 to 3 m throughout the year. The wet soil conditions prohibited the field from experiencing water stress (Fig. 4d)

because even the lowest soil matric potential (−187.6 kPa) remained a lot higher than the permanent wilting point of crops (around −1, 500.0 kPa).

(Fig. 3&4 here)

Fig. 5 shows the seasonal variations in Hc and LAI reflecting the crop development for the full 2010-2011 cycle. The maximum LAI was 4.2 m^2 m^{-2} for wheat and 3.6 m^2 m^{-2} for maize. The variations in Hc and LAI distinguished the different stages of crop development. During the wheat season, the stages of regreening, jointing, booting, heading, and maturity started approximately on March 1st, April 20th, May 1st, May 7th, and June 5th, respectively. The seasonal variations in DM agreed well with the crop stages (Fig. 6), and the wheat biomass mainly accumulated in April and May, while maize biomass mainly accumulated in July and August. The total DM was 1, 718 g m^{-2} for wheat and 1, 262 g m^{-2} for maize at harvest. Upon harvest, the wheat DM was distributed as: 3% root, 43% stem, 9% leaf and 45 % grain, while the maize DM was distributed as: 2% root, 29% stem, 7% green leaf, 5% dead leaf, 4% bracket, 7% cob, and 46% grain. The seasonal average carbon contents of the root, stem, green leaf, dead leaf, and grain were 410, 439, 486, 452 and 457 gC kg^{-1} DM for wheat and, 408, 438, 477, 457, and 456 gC kg^{-1} DM for maize (see Table 1 for the seasonal variation).

(Table 1 here)

(Figs. 5&6 here)

The inter-annual variations in the NEE, GPP and ER

For the period from 2005 through 2016, if grain export was not considered, the wheat was consistent CO_2 sink as the seasonal total NEEs were consistently negative, and the maize was

291 CO_2 sink in most years except for 2012 and 2013 when NEE was positive (Fig. 7a). NEEs of
292 both wheat and maize fields became less negative during the past decade (though not
293 statistically significant), implying a progressive decline of the carbon sequestration potential
294 of this cropland. The GPPs of both wheat and maize showed an increasing trend, though not
295 statistically significant (Fig. 7b). The ERs of both wheat and maize also showed an increasing
296 trend in these years, but only the trend of maize was significant (Fig. 7c). The decadal average
297 of NEE, GPP and ER were −364 (SD±98), 1, 174 (SD±189) and 810 (SD±161) gC m^{-2} for
298 wheat, and −136 (SD±168), 1, 008 (SD±297), and 872 (SD±284) gC m^{-2} for maize.

299 The NEE, GPP and ER for both wheat and maize were correlated with the three main
300 environmental variables of R_{si}, T_a and WD using the multiple regression (see Appendix B for
301 details). In the wheat season, T_a showed its relatively greater importance than R_{si} and WD to
302 all the three CO_2 fluxes with a higher T_a increasing both GPP and ER, and also enhancing
303 NEE (more negative) (Fig. 8a); WD correlated negatively with GPP, thereby reduced net
304 carbon uptake (less negative NEE); WD exhibited almost no effect on ER; R_{si} exhibited
305 almost no effect on all the three CO_2 fluxes. Therefore, T_a explained most of the inter-annual
306 variations in NEE, GPP and ER, followed by WD. In the maize season, WD had good
307 correlations with all the three fluxes of GPP, ER, and NEE, where a deeper WD contributed to
308 lower both GPP and ER, and also drive higher net carbon uptake (more negative NEE); T_a
309 showed almost no effect on all the three CO_2 fluxes; R_{si} had a positive correlation with ER,
310 but almost no correlation with GPP (Fig. 8b), ultimately, higher R_{si} in maize season lowered
311 the net carbon uptake (more positive NEE). Overall, R_{si} and WD showed their great

312 importance in influencing the inter-annual variation of maize NEE with R_{si} having a positive
313 correlation and WD having a comparable negative correlation (Fig. 8b).

314 (Figs. 7&8 here)

315 **Intra-annual variations in the NEE, GPP and ER**

316 The Intra-annual variations in NEE, GPP, and ER exhibited a bimodal curve corresponding
317 with the two crop seasons (Fig. 9). All the three CO_2 fluxes were almost in phase, with peaks
318 appearing at the start of May during the wheat season and in the middle of August during the
319 maize season. During some of the winter season, the field still sequestered a small amount of
320 CO_2 because of the weak photosynthesis, which was confirmed by leaf level gas exchange
321 measurement (data not shown). Net carbon emission happened during the fallow periods, in
322 addition to the start of the maize season when the plant was small and high temperature
323 enhanced heterotrophic respiration. During the wheat season, two evident spikes appeared on
324 April 21st and May 8th with positive NEE values (i.e., net carbon release). These spikes
325 resulted from the radiation decline during the inclement weather (Fig. 4b), which suppressed
326 the photosynthesis rate; similar phenomena also appeared during the maize season.

327 **(Fig. 9 here)**

328 Fig. 10 shows the variations in ER and its components. During the wheat season, the variation
329 in ER closely followed crop development and temperature, but there were two evident
330 declines at the end of April and the start of May due to low temperatures associated with the
331 inclement weather. During the early growing stage of maize, R_H was the main component of
332 ER. When water logging conditions occurred in late August and early September, both R_H and

R_{AB} were suppressed to zero.

(Fig. 10 here)

CO_2 budget synthesis in the 2010-2011 agricultural cycle

CO_2 budget analysis showed that this wheat-maize rotation cropland has the potential to uptake carbon from the atmosphere (Fig. 11). In the full 2010-2011 cycle, the total NEE, GPP and ER values were –438, 1078, and 640 gC m^{-2} for wheat, and –239, 780 and 541 gC m^{-2} for maize. The NPP values were 750 and 815 gC m^{-2} for wheat based on crop sample and the eddy covariance complemented with soil respiration measurements, respectively, and were 592 and 532 gC m^{-2} for maize based on the two methods. We used the average of these two methods for NPP measurements, which were 783 (SD±46) gC m^{-2} for wheat and 562 (SD± 43) gC m^{-2} for maize. We also used the average of NEP by two independent methods for the measurement, and the NEP was 406 gC m^{-2} for wheat and 269 gC m^{-2} for maize. Furthermore, when considering the carbon loss associated with the grain export, the NBP values were 59 gC m^{-2} for wheat and 5 gC m^{-2} for maize, respectively. Considering the net CO_2 loss of –104 gC m^{-2} during the two fallow periods, NBP of the whole wheat-maize crop cycle was –40 gC m^{-2} yr^{-1}, suggesting that the cropland was a weak carbon source to the atmosphere under the specific climatic conditions and field management practices.

(Fig. 11 here)

Discussion

This study investigated the decadal variations of the NEE, GPP and ER over an irrigated wheat-maize rotation cropland over the North China Plain, and the results exhibited a decreasing trend

of the CO_2 sink capacity during the past decade. The inter-annual variations of the carbon fluxes of wheat showed close dependence on temperature and groundwater depth, while those of maize were mostly regulated by the solar radiation and groundwater depth. Furthermore, the detailed CO_2 budget components were quantified for a full wheat-maize agricultural cycle. Investigating the decadal trend of the CO_2 fluxes and quantifying the detailed CO_2 budget components for this representative cropland will provide useful knowledge for the reginal greenhouse gas emission evaluation over the North China Plain.

Comparison with other croplands

The cropland has been reported as carbon neutral to the atmosphere (e.g., Ciais et al., 2010), carbon source (e.g., Anthoni et al., 2004a; Verma et al., 2005; Kutsch et al., 2010; Wang et al., 2015; Eichelmann et al., 2016), and also carbon sink (e.g., Kutsch et al., 2010). Such inconsistency probably results from the different crop types and management practices (residue removal, the use of organic manure, etc.), in addition to variations in the climatic conditions (Béziat et al., 2009; Smith et al., 2014) and fallow period length (Dold et al., 2017). Our results show that the fully irrigated wheat-maize rotation cropland with a shallow groundwater depth was a weak CO_2 sink during both the wheat and maize seasons in the full 2010-2011 cycle, but the CO_2 loss during the fallow period reversed the cropland from a sink into a weak source with an NBP of –40 gC m^{-2} yr^{-1}. These results are consistent with previous studies that reported the wheat-maize rotation cropland as a carbon source (Li et al., 2006; Wang et al., 2015). However, the net CO_2 loss was much lower at our site, most likely due to the shallow groundwater depth.

375 Field measurements of the long term of CO_2 fluxes over croplands remain lacking, and we
376 found the carbon sequestration capacity of this cropland has been progressively decreasing,
377 though it was not statistically significant. The cropland has been widely suggested as a
378 climate change mitigation tool (e.g., Lal, 2001), but the potential in the future is challenging.
379 However, since the cropland management greatly impacts the carbon balance of cropland
380 (Béziat et al., 2009; Ceschia et al., 2010), it remains required investigating if the management
381 adjustment can foster the cropland carbon sink capacity over the long term.
382 The annual total NPP of 1, 345 gC m^{-2} yr^{-1} at our site is approximately twice the average of
383 the model-estimated NPP for Chinese croplands (714 gC m^{-2} yr^{-1}) with a rotation index of 2
384 (i.e., two crop cycles within one year) (Huang et al., 2007), more than three times the value
385 estimated by MODIS (400 gC m^{-2} yr^{-1}) (Zhao et al., 2005), and slightly higher than the value
386 of the same crop rotation at the Luancheng site (1, 144 gC m^{-2} yr^{-1}) (Wang et al., 2015). The
387 higher NPP at our site may partially result from the sufficient irrigation and fertilization
388 (Huang et al., 2007; Smith et al., 2014).
389 The contrasting respiration partitioning of the same crop in different regions (Table 2) indicate
390 that the respiration processes may also be subject to climatic conditions and management
391 practices. Though the ecosystem respiration to GPP at our site is comparable to other studies,
392 the ratio of autotrophic respiration to GPP is much lower at our site, while the ratio of
393 heterotrophic respiration to ecosystem respiration is greater at our site, these findings are
394 different from those at the other sites with similar crop variety (Moureaux et al., 2008;
395 Aubinet et al., 2009; Suleau et al., 2011; Wang et al., 2015; Demyan et al., 2016), as they
396 showed that ecosystem respiration is usually dominated by below-ground and above-ground

autotrophic respirations. The higher soil heterotrophic respiration at our site probably results from the full irrigation and shallow groundwater which alleviates soil water stress.

(Table 2 here)

The effects of groundwater on carbon fluxes

The groundwater table at our site is much closer to the surface because of the irrigation by water diverted from the Yellow River, in contrast, the nearby Luancheng site (Wang et al., 2015) is groundwater-fed with a very deep groundwater depth (approximately 42 m) (Shen et al. 2013), and their CO_2 budget components had some difference with our study. Comparing the net CO_2 exchange of wheat, the GPP at our site is a little higher than the Luanchen site, implying the irrigation at our site may better sustain the photosynthesis rate for wheat; ER at our site is also a little higher than Luancheng site. For maize, both sites are not irrigated due to the high summer precipitation, GPP and ER at our site were comparable to Luancheng site, implying that the irrigation method prior to the maize season had no discernible effect on the integrated CO_2 fluxes for maize. However, the three components of ER in our study showed pronounced difference from the Luancheng site, where they reported the R_{AA} was 411 gC m^{-2} for wheat and 428 gC m^{-2} for maize, three times the results of our study (128 gC m^{-2} for wheat and 133 gC m^{-2} for maize). However, their R_{AB} for wheat (36 gC m^{-2}) and maize (16 gC m^{-2}) were less than a quarter of our results (136 gC m^{-2} for wheat and 115 gC m^{-2} for maize). Their R_H of wheat (245 gC m^{-2}) was less than our estimate (377 gC m^{-2}), but R_H of maize (397 gC m^{-2}) was greater than our result (292 gC m^{-2}). In general, the crop above-ground parts in our site respired more carbon than the Luancheng site, possibly because the shallow groundwater

depth at our site increased the above-ground biomass allocation but lowered the root biomass allocation (Poorter et al., 2012). These independent cross-site comparisons demonstrate that carbon budget components may be subject to the specific groundwater depth influenced by the irrigation type, and even the same crop under similar climatic conditions can behave differently in carbon consumption.

Our site experienced a short period of water logging during the 2010-2011 cycle due to the combined effects of full irrigation and the high precipitation during the summer. This distinct field condition reduced soil carbon losses in the maize season, potentially maintaining the CO_2 captured by the cropland. Water logging events were occasionally reported in upland croplands, for example, Terazawa et al. (1992) and Iwasaki et al. (2010) suggested that water logging causes damage to plants, resulting in a decline in GPP as reported by Dold et al. (2017) and our study. Our study further shows that water logging reduces ER to a greater degree than GPP possibly because of the low soil oxygen conditions, thereby reduces the overall cropland CO_2 loss. However, the CH_4 release in the short period may be pronounced in water-logged soils. As CH_4 emission in this kind of cropping system over the North China Plain cropland remains lacking, additional field experiments are required to understand how irrigation and water saturation field condition impact the overall carbon budget.

Uncertainty in the estimation and limitation of this study

In the comprehensive experiment period for the full 2010-2011 agricultural cycle, the NEE of wheat season from October 23rd, 2010 to April 1st, 2011 was calculated using a calibrated SVR model. The SVR model performs well in predicting GPP and ER with very high R^2 of

0.95 and 0.97 and an acceptable uncertainty level of 22.9% and 15.2% for GPP and ER, respectively. Hence, these estimates should have a negligible effect on the seasonal total carbon evaluation. The footprint analysis showed that 90% of the measured eddy flux comes from the nearest 420 m and 166 m in wheat and maize crops under unstable conditions, respectively, confirming that both soil respiration experiments and crop samples well paired with the EC measurements.

Root biomass was difficult to measure, but the uncertainty should be low, because the root ratio (the ratio of the root weight to the total biomass weight) accounts for 15-16 % of the crop for wheat and maize (Wolf et al., 2015), and our measurements are very close to these values, i.e., the averaged seasonal root ratio was 15% for wheat and10% for maize at our site. However, the relatively low root ratios (3% for wheat and 2% for maize) at harvest probably result from the root decay associated with plant senescence. The estimates of annual soil respiration are based on the Q_{10} model validated by the field measurements that may generate some uncertainty in the soil respiration budget due to the hysteresis response of soil respiration to temperature (Phillips et al., 2011; Zhang et al., 2015a; Zhang et al., 2018). However, the Q_{10} model remains robust in soil respiration estimations if well validated (Tian et al., 1999; Zhang et al., 2013; Latimer and Risk, 2016), allowing the confidence in the estimates.

During the wheat season, the cumulative curves of NPP_{EC} and NPP_{CS} were not perfectly consistent in the main growing season as clear differences emerged during the dormant season of wheat from December 15th, 2010 to March 8th, 2011 (Fig. 12). These differences may result

460 from the small wheat sample number. However, the sample number at harvest was sufficiently
461 big and no discernible difference was found between the two NPPs at harvest. These two
462 independent estimates of NPP were similar throughout the maize season (Fig. 12).

463 This study provides a comprehensive quantification of the CO_2 budget components of the
464 cropland, but it remains limited to a relatively wet year (see Fig. 3c and d). The integrated
465 carbon fluxes (NEE, GPP and ER) have pronounced inter-annual variations, also suggesting
466 further investigations are required on the inter-annual variations of the carbon budget
467 components.

468 **(Fig. 12 here)**

469 **Conclusion**

470 Based on the decadal measurements of CO_2 fluxes over an irrigated wheat-maize rotation
471 cropland over the North China Plain, we found the cropland was a strong CO_2 sink if grain
472 export was not considered. When considering the grain export, the cropland was a weak CO_2
473 source with the NBP of –40 gC m^{-2} yr^{-1} in the full 2010-2011 agricultural cycle. The net CO_2
474 exchange during the past decade from 2005 through 2016 showed a non-statistically
475 significant decreasing trend, implying a decreasing carbon sequestration capacity of this
476 cropland, discouraging the potential of taking agro-ecosystems as the mitigation tool of
477 climate change. In the wheat season, air temperature showed the best correlation with the CO_2
478 fluxes followed by the groundwater depth; while in the maize season, both short-wave
479 radiation and groundwater depth showed good correlation with the CO_2 fluxes. The
480 comprehensive investigation showed most of the carbon sequestration occurred during the

481 wheat season, while maize was close to being CO_2 neutral. Soil heterotrophic respiration in
482 this cropland contributes substantially to CO_2 loss in both wheat and maize season. This study
483 provides detailed knowledge for estimating regional carbon emission over the North China
484 Plain.

Appendix A. Flux calculation of the period with equipment failure

A1. Support Vector Regression method

Support Vector Regression (SVR) method is a machine-leaning technique-based regression, which transforms regression from nonlinear into linear by mapping the original low-dimensional input space to higher-dimensional space (Cristianini and Shave-Taylor, 2000). SVR method has two advantages: 1) the model training always converges to global optimal solution with only a few free parameters to adjust, and no experimentation is needed to determine the architecture of SVR; 2) SVR method is robust to small errors in the training data (Ueyama et al., 2013). The SVM software package obtained from LIBSVM (Chang and Lin, 2005) is used in this study.

A2. Data processing and selection of explanatory variables

Gross Primary Productivity (GPP) is influenced by several edaphic, atmospheric, and physiological variables, among which air temperature (T_a), relative humidity (RH), llant area index (LAI), net photosynthetically active radiation (PAR), and soil moisture (θ) are the dominant factors. Hence, we select T_a, RH, LAI, PAR, and θ as explanatory variables of GPP. Ecosystem Respiration (ER) consists of total soil respiration and above-ground autotrophic respiration. The total soil respiration is largely influenced by soil temperature and soil moisture, while above-ground autotrophic respiration is largely influenced by air temperature and above-ground biomass. So we select T_a, soil temperature at 5 cm (T_s), θ and LAI as explanatory variables of ER. LAI is estimated from the Wide Dynamic Range Vegetation Index derived from the MOD09Q1 reflectance data (250 m, 8-d average,

https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod09q1, also see Lei et al. 2013).

The three wheat seasons of 2005-2006, 2009-2010, and 2010-2011 are selected for model training, and the original half-hourly measurements of GPP and ER together with the explanatory variables are averaged to the daily scale, but we remove days missing more than 25% of half-hourly data. We have GPP available from 466 days and ER from 483 days for model training. The explanatory variables for the equipment failure are also averaged into daily scale, which will be used to calculate GPP and ER with the trained model described in the following section.

A3. SVR model training and flux calculation

In order to eliminate the impact of variables with different absolute magnitudes, we rescale all the variables in training-data set to the [0, 1] range prior to SVR model training. In the training process, the radial basis function (RBF, a kernel function of SVR) is used and the width of insensitive error band is set as 0.01. The SVR model training follows these steps:

(1) All training data samples are randomly divided into five non-overlapping subsets, and four of them are selected as the training sets (also calibration set), the remaining subset is treated as the test set (also validation set). Such process is repeated five times to ensure that every subset has a chance to be the test set.

(2) For the selected training set, the SVR parameters (cost of errors c and kernel parameter σ) are determined using a grid search with a five-fold cross-validation training process. In this approach, the training set is further randomly divided into five non-overlapping subsets.

Training is performed on each of the four subsets within this training set, with the remaining subset reserved for calculating the Root Mean Square Error (RMSE), and model parameters (c and σ) yielding the minimum RMSE value are selected.

(3) The SVR model is trained based on the training set from step (1) and initialized by the parameters (c and σ) derived from step (2).

(4) The test set from the step (1) is used to evaluate the model obtained from the step (3) by using the coefficient of determination (R^2) and RMSE.

(5) The model is trained with all of the available samples with good performance achieved, as R^2 are 0.95 and 0.97 for GPP and ER, respectively, and the mean RMSE are 1.28 gC m^{-2} d^{-1} and 0.44 gC m^{-2} d^{-1}. The RMSE can be further used as a metric quantifying uncertainty, which accounts for 22.9% and 15.2% for the averaged GPP and ER, respectively. GPP and ER during equipment failure period are then calculated with the trained model complemented with the observed explanatory variables, and NEE is derived as the difference of GPP and ER.

Appendix B. Multiple regression for NEE, GPP and ER with microclimate variables

The flux of NEE, GPP or ER is correlated with incoming short-wave radiation (R_{si}), air temperature (T_a) and groundwater depth (WD) as $flux=aR_{si}+bT_a+cWD+d$, where flux is NEE, GPP, or ER; a, b, c, and d are regression parameters. All the variables are normalized to derive their z-score before the regression, where z-score is to subtract the mean from the data and divide the result by standard deviation. The coefficient of each variable represents the relative importance of the corresponding variable in contributing to the dependent variable.

Data availability

The data of this study are available for public after a request to the corresponding author (H. Lei).

Author contributions

Q.Z. and H.L. designed the study and methodology with substantial input from all co-authors. Q.Z. conducted the field experiment. B.F. conducted the SVR calculation for gap filling. All authors contributed to interpretation of the results. Q.Z. drafted the manuscript, and all authors edited and approved the final manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Tables and figures

Table 1 Carbon content of different parts (gC kg^{-1} DM)

crop	date	root	stem	green leaf	dead leaf	grain
wheat	3/15/2011	416	413	488	-	-
	3/22/2011	454	-	476	-	-
	3/29/2011	-	436	451	-	-
	4/5/2011	527	431	534	-	-
	4/13/2011	348	417	457	-	-
	4/21/2011	434	415	522	-	-
	4/29/2011	410	443	510	-	-
	5/6/2011	434	423	481	-	-
	5/14/2011	275	445	485	-	-
	5/22/2011	380	474	-	538	470
	5/29/2011	461	515	503	444	479
	6/5/2011	393	432	439	400	432
	6/10/2011	393	429	-	426	449
maize	7/4/2011	339	351	476	-	-
	7/13/2011	370	392	455	-	-
	7/21/2011	389	418	463	-	-
	7/29/2011	406	432	462	-	-
	8/5/2011	399	429	481	-	-
	8/12/2011	443	439	469	-	-
	8/22/2011	403	462	469	-	-
	9/3/2011	386	466	499	-	446
	9/11/2011	466	465	505	-	460
	9/20/2011	445	481	481	-	454
	9/30/2011	439	481	489	457	462

894 Table 2 Various ratios associated with carbon fluxes in croplands

crop species	ER/GPP	R_A/GPP[a]	R_H/ER	R_{AB}/ER	R_{AA}/ER	source
maize	0.69	0.32	0.54	0.21	0.25	**this study**
maize	0.67	0.56	0.16	0.25	0.59	Jans et al. (2010)
maize	0.85	0.45	0.47	0.02	0.51	Wang et al. (2015)
maize	0.80	0.65	0.19	0.21	0.60	Demyan et al. (2016)[b]
wheat	0.59	0.24	0.59	0.21	0.20	**this study**
wheat	0.71	0.49	0.31	0.19	0.50	Demyan et al. (2016)[b]
wheat	0.61	0.46	0.24	0.31	0.45	Moureaux et al. (2008)
wheat (2005)	0.60	0.44	0.26	0.74		Aubinet et al. (2009)[c]
wheat (2007)	0.57	0.48	0.15	0.85		Aubinet et al. (2009)[c]
wheat	0.57	0.45	0.21	0.17	0.62	Suleau et al. (2011)
wheat	0.66	0.43	0.35	0.05	0.59	Wang et al. (2015)
potato	0.48	0.37	0.24	0.76		Aubinet et al. (2009)[c]
potato	0.47	0.32	0.33	0.14	0.53	Suleau et al. (2011)
sugar beet	0.44	0.30	0.31	0.69		Aubinet et al. (2009)[c]
sugar beet	0.36	0.22	0.37	0.25	0.36	Suleau et al. (2011)

895 Note:

896 a- the values in parentheses indicate that the value is calculated by the equation R_A/GPP=1–NPP/GPP.

897 b- The data was from 2012, and the estimation is based on the average of the static and dynamic methods

898 c- R_A as well as R_H is the averaged values of their two corresponding methods

899

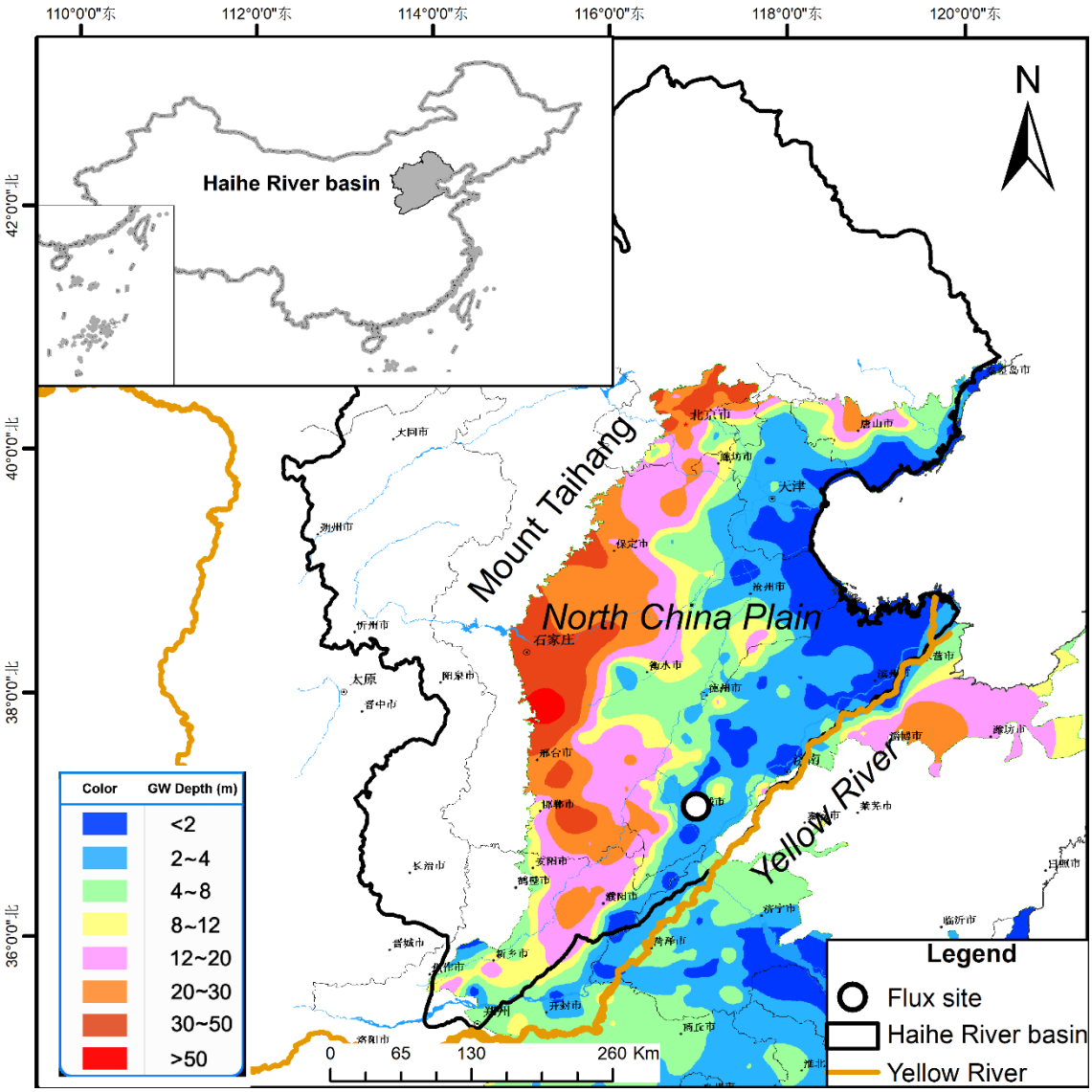
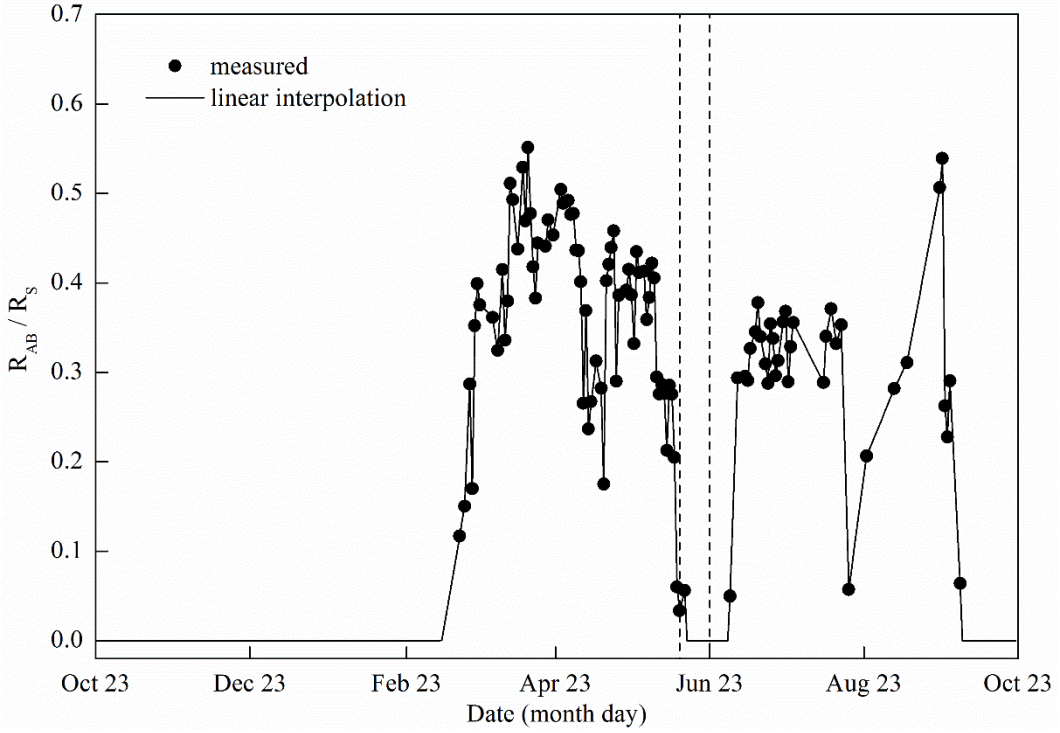


Fig. 1 Location of the experimental site. The background is the shallow groundwater depth in early September of 2011 (modified from http://dxs.hydroinfo.gov.cn/shuiziyuan/)



903

904 Fig. 2 Seasonal variations in the ratio of below-ground autotrophic respiration (R_{AB}) to total
905 soil respiration (R_S). Two vertical dashed lines (hereafter) represent the date of harvesting
906 wheat and sowing maize, respectively.

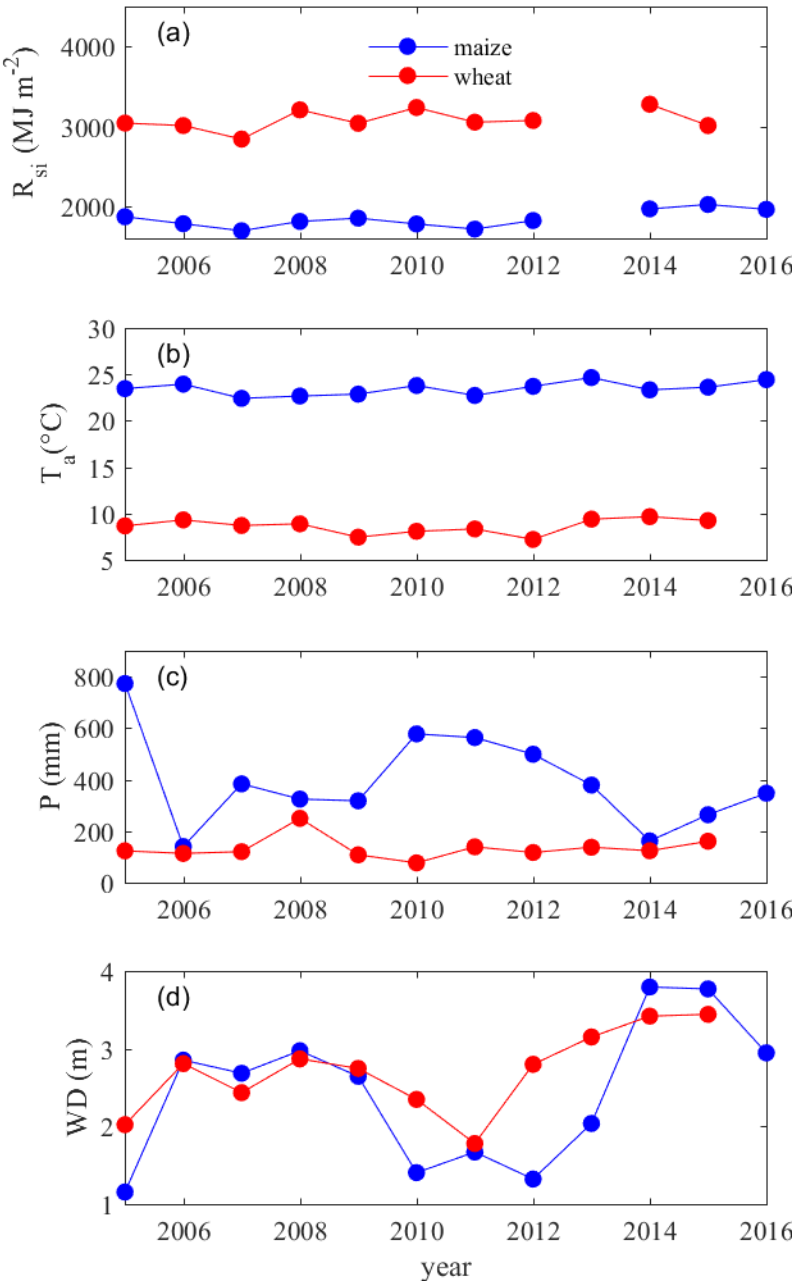
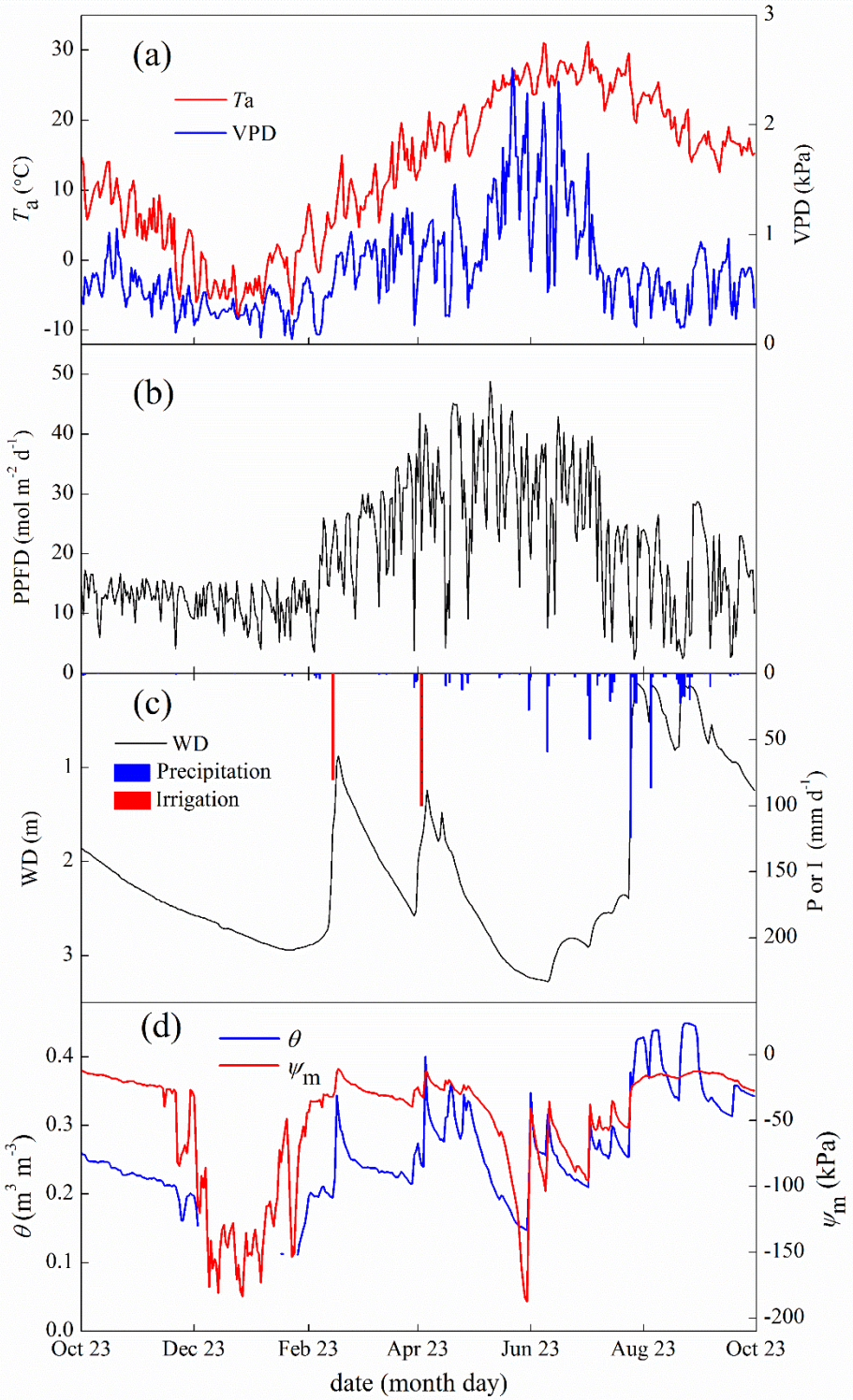


Fig. 3 The seasonal (a) total incoming short-wave radiation (R_{si}), (b) average air temperature (T_a), (c) total precipitation (P) and (d) average groundwater depth (D) for both wheat and maize evaluated for the period from 2005 through 2016. Note that incoming short-wave radiation in the 2013 season was missing due to equipment malfunction.



912

913 Fig. 4 Seasonal variations in the environmental variables of (a) air temperature (T_a), soil
914 temperature at 5cm depth (T_s) and vapor pressure deficit (VPD), (b) photosynthetic photon
915 flux density (PPFD), (c) precipitation (P), irrigation (I) and groundwater depth (WD), and (d)
916 volumetric soil moisture (θ) and soil matric potential (ψ_m).

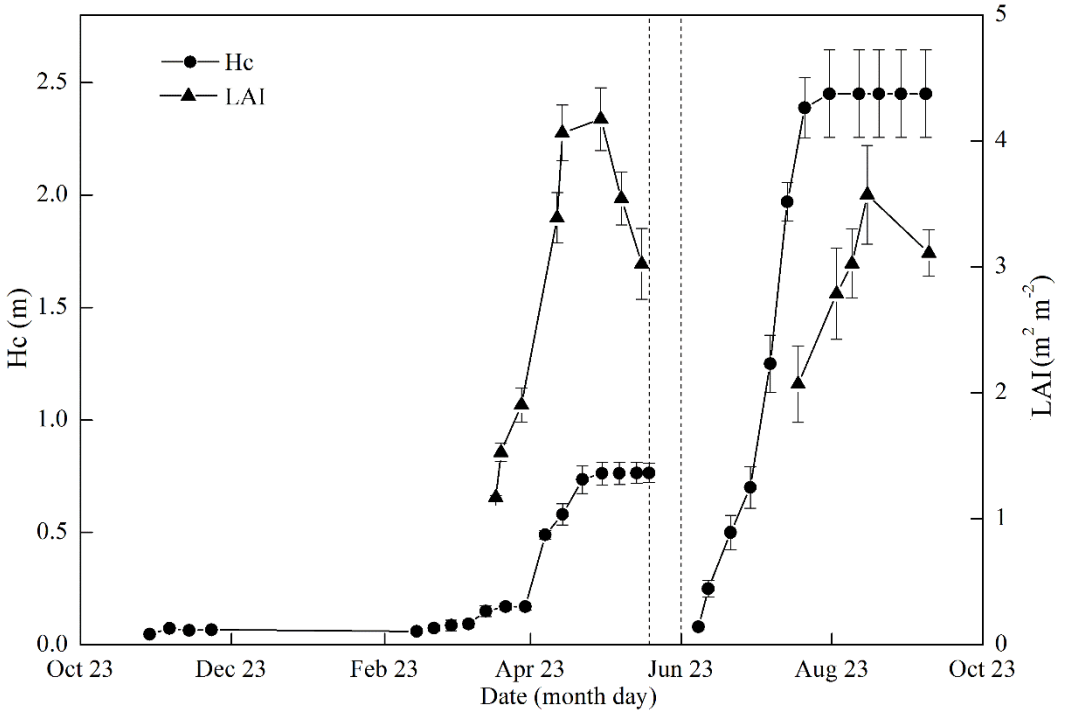


Fig. 5 Seasonal variations in canopy height (Hc) and leaf area index (LAI). The error bars denote 1 standard deviation of the ten points.

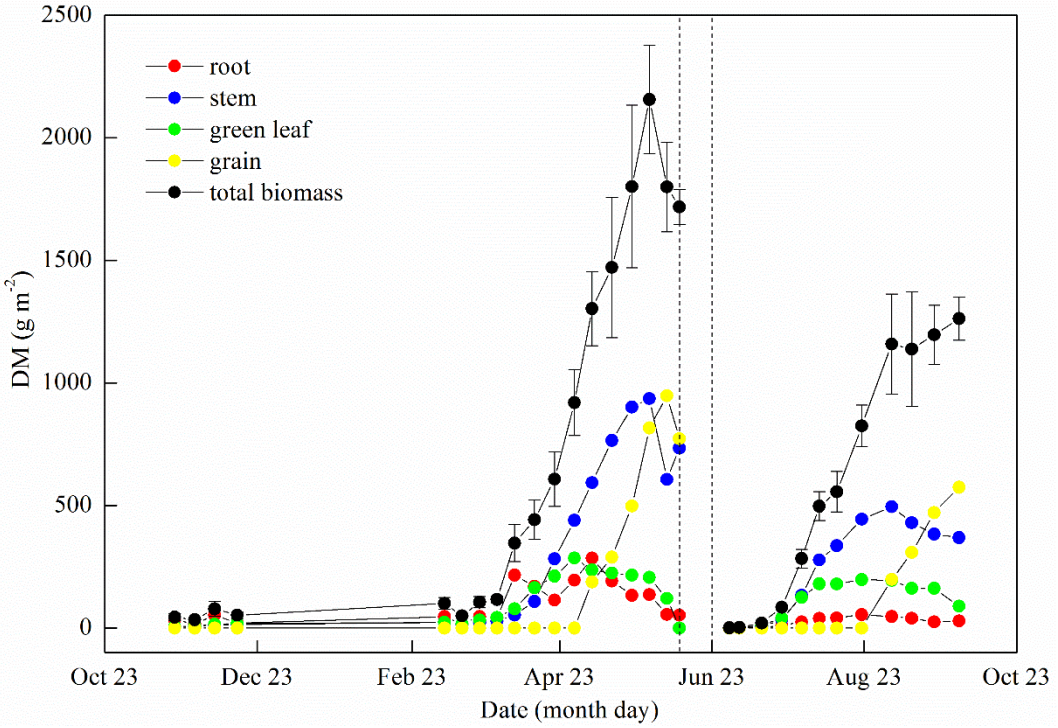
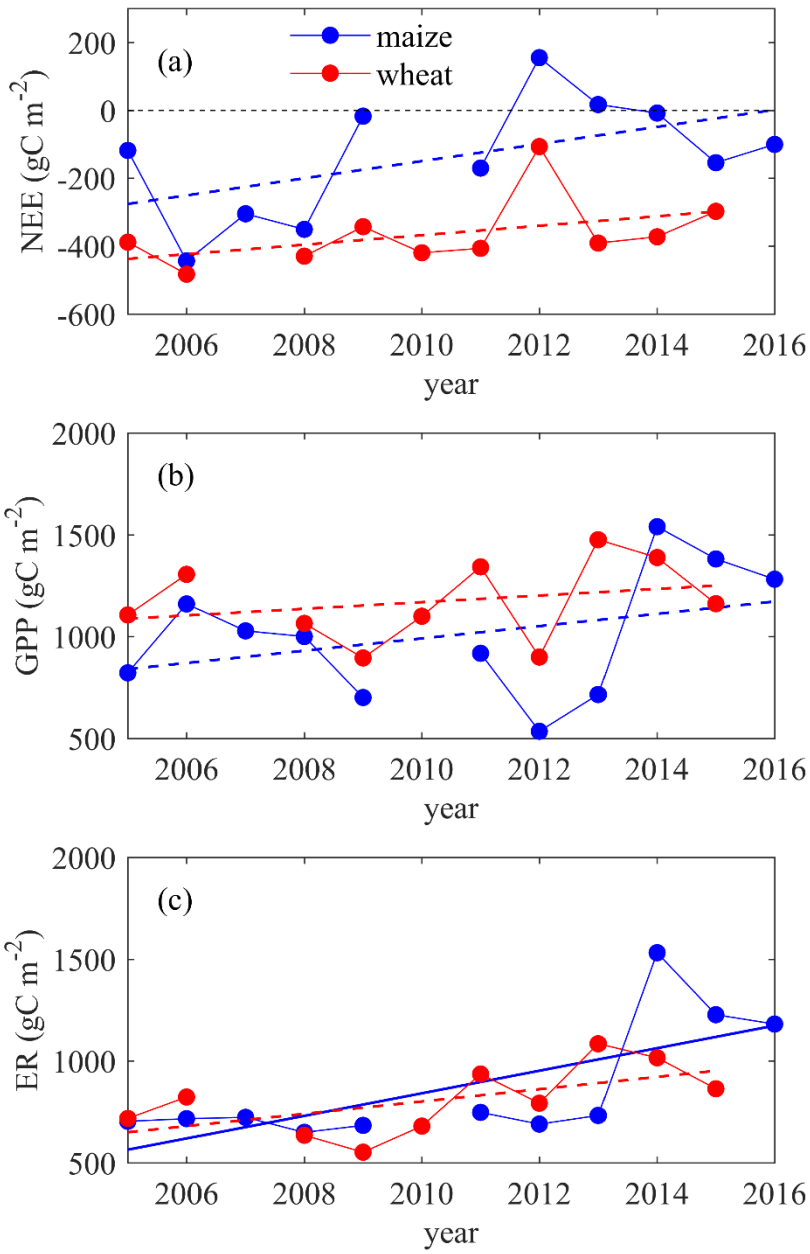


Fig. 6 Seasonal variations in the total dry biomass (DM) and its major parts of root, stem, green leaf and grain. The error bars of total biomass denote 1 standard deviation of the four sample points.



924

925 Fig. 7 The temporal trend of annual (a) Net Ecosystem Exchange (NEE), (b) Gross Primary
926 Productivity (GPP) and (c) Ecosystem Respiration (ER) for both wheat and maize from 2005
927 through 2016. Note that though most gaps of carbon fluxes were filled, the wheat of 2007 was
928 excluded as it had a large gap accounting for 26 % of annual records unable to fill; maize was
929 not planted in the growing season of 2010. Note that the solid line represents the temporal
930 trend passes F-test at $p<0.05$ significance level, while the dashed line represents the temporal
931 trend does not pass the F-test at $p<0.05$ level.

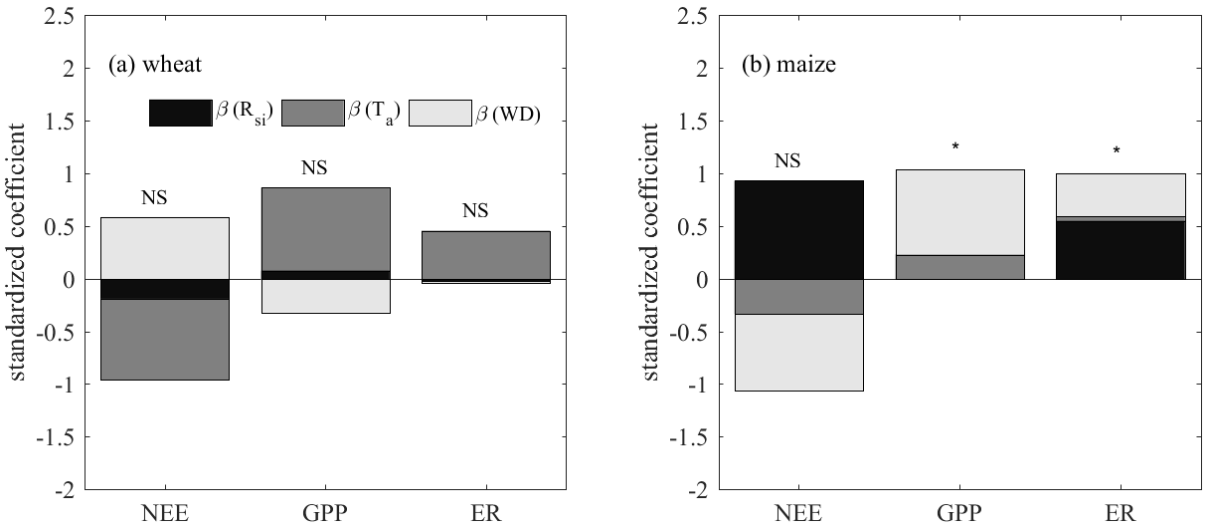


Fig. 8 The result of multipe regression for NEE, GPP and ER with incoming short-wave radiation (R_{si}), air temperature (T_a) and groundwater depth (WD) for both (a) wheat and (b) maize. Note that * denotes that the regression passes $p<0.05$ significance level, and NS indicates non-significant.

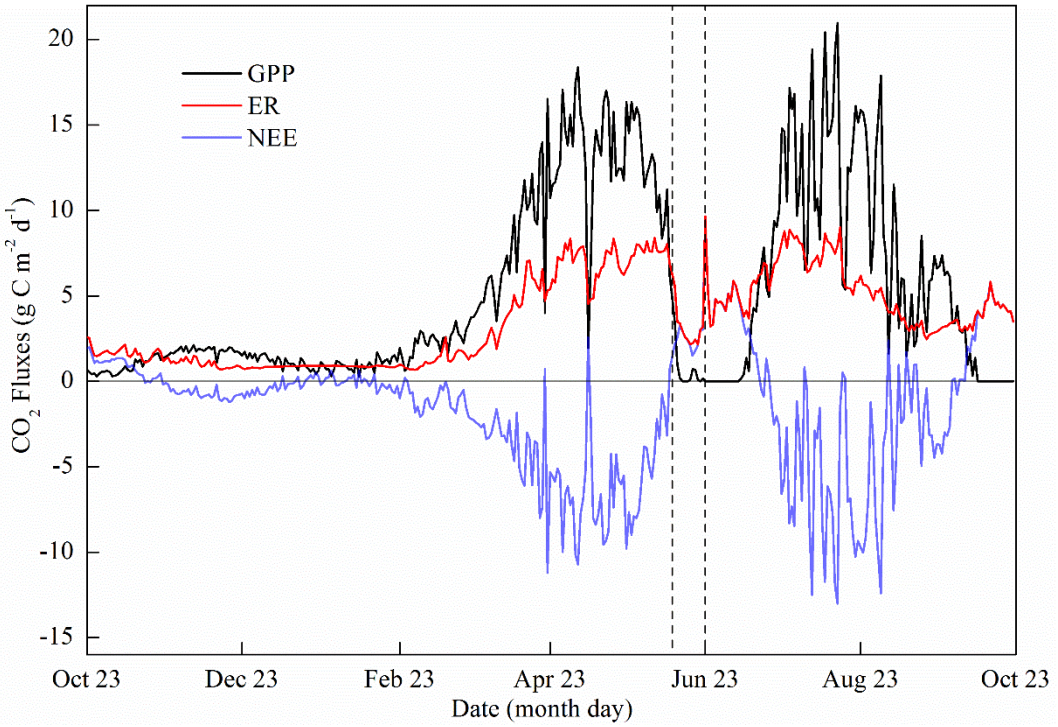


Fig. 9 Seasonal variations in Gross Primary Producrivity (GPP), Net Ecosystem Exchange (NEE) and Ecosystem Respiration (ER) (those before April 2nd were calculated with SVR method)

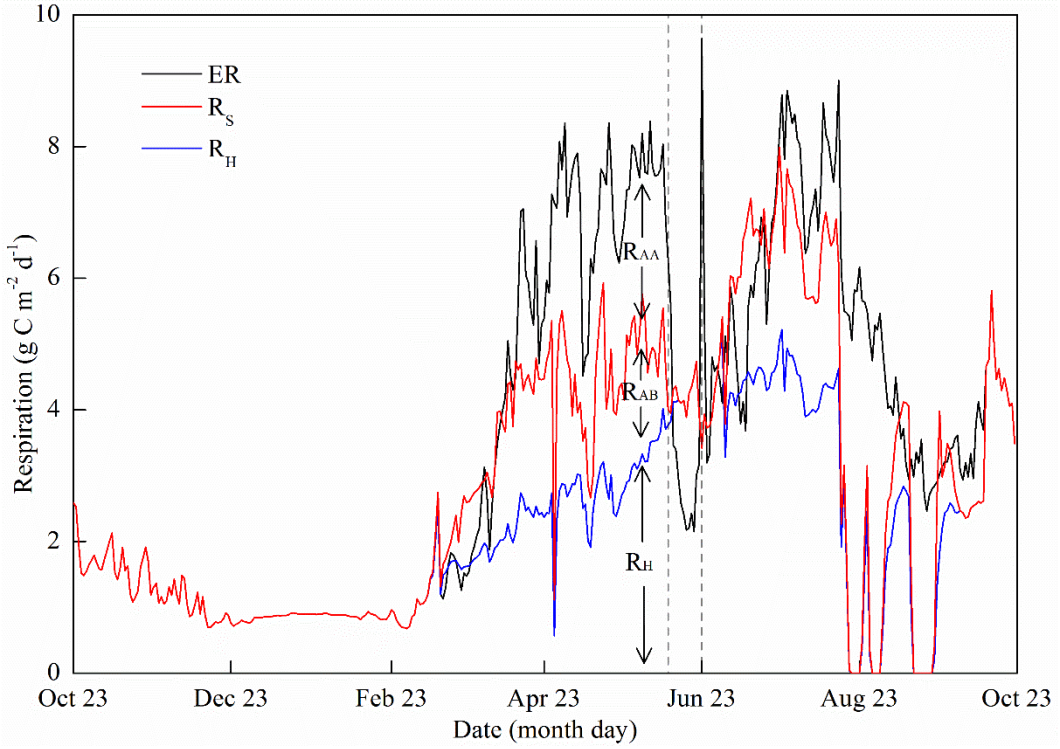


Fig. 10 Seasonal variations in the components of Ecosystem Respiration (ER), total soil respiration (R_S), soil heterotrophic respiration (R_H). The difference between ER and R_S denotes above-ground autotrophic respiration (R_{AA}), and the difference between R_S and R_H denotes below-ground autotrophic respiration (R_{AB}).

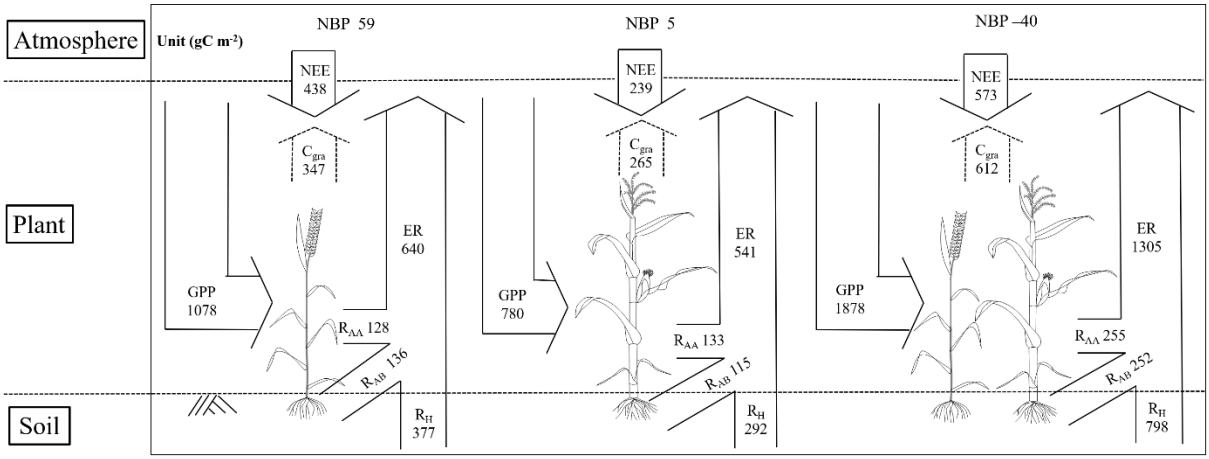


Fig. 11 Carbon budget of wheat (left), maize (middle) and the full wheat-maize rotation cycle with fallow periods included (right). Note that absolute value of NEE is shown here; NBPs of wheat and maize are the average of two independent methods (i.e, eddy covariance-based and crop sample-based)

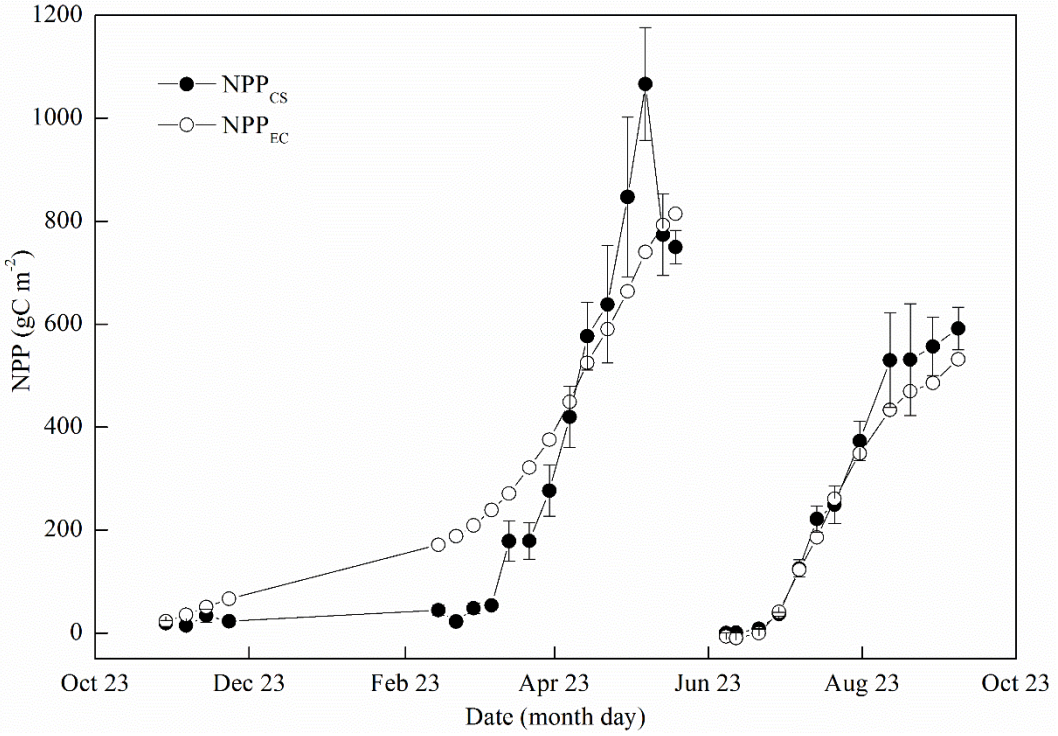


Fig. 12 Seasonal variations in the cumulative Net Primary Productivity (NPP) with two independent methods of Crop Sample (NPP_{CS}) and Eddy Covariance (NPP_{EC}) complemented with soil respiration measurements.