**The revised parts are highlighted by blue**

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

Quan Zhang[1,2], Huimin Lei[2], Dawen Yang[2], Lihua Xiong[1], Pan Liu[1], Beijing Fang[2,3]

[1]State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, China

[2]State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, China

[3]Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR, China

Correspondence to:

Q. Zhang (quan.zhang@whu.edu.cn) and H. Lei (leihm@tsinghua.edu.cn)

Tel: 86-(0)10-6278-3383

Fax: 86-(0)10-6279-6971

**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 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 ($R_{\mathrm{H}}$), above-ground autotrophic respiration ($R_{\mathrm{AA}}$), below-ground autotrophic respiration ($R_{\mathrm{AB}}$), 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 combining the eddy covariance technique and field carbon measurements associated with harvests and residue treatments (Ceschia et al., 2010; Kutsch et al., 2010). As detailed $CO_2$ budget might facilitate better predictions of agro-ecosystems' responses to climate change, the $CO_2$ budget evaluations in different croplands remain necessary.

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

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

Productivity (NEP), and Net Biome Productivity (NBP).

## Materials and methods

### Site description and field management

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

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

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

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

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 $ER_{ref}$ parameter in each of the four-day window by fitting the eq. (1), then $ER_{ref}$ 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),

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

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

$$\mathrm{z}_u = \mathrm{z}_m \left[ \ln\left(\frac{z_m}{z_0}\right) - 1 + \frac{z_m}{z_0} \right] \tag{4}$$

where $z_0$ represents the zero displacement 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 ($\theta$) (CS616-L, Campbell Scientific Inc.) for the top 5 cm soil; soil matric potential ($\psi$) (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 the meteorological station in 30-min intervals.

**Biometric measurements and crop samples**

To trace crop development and carbon storage, we measured canopy height ($H_C$), plant area index (PAI), 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 $H_C$ was measured with a ruler and PAI 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 Net Primary Productivity (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):

$$R_H = A\exp(BT_S)\cdot f(\theta), \tag{4}$$

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

where $\theta_f$ 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).

The $R_{AB}$ of wheat was assumed to be 0 before March 14$^{th}$ due to the negligible plant biomass; $R_{AB}$ 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,

$NEP_{CS}=NPP_{CS}-R_H$. (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 ($C_{gra}$),

$NBP=NEP-C_{gra}$, (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 $H_C$ and PAI reflecting the crop development for the full 2010-2011 cycle. The maximum PAI was 4.2 $m^2$ $m^{-2}$ for wheat and 3.6 $m^2$ $m^{-2}$ for maize. The variations in $H_C$ and PAI 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 $CO_2$ sink in most years except for 2012 and 2013 when NEE was positive (Fig. 7a). NEEs of both wheat and maize fields became less negative during the past decade (though not statistically significant), implying a progressive decline of the carbon sequestration potential of this cropland. The GPPs of both wheat and maize showed an increasing trend, though not statistically significant (Fig. 7b). The ERs of both wheat and maize also showed an increasing trend in these years, but only the trend of maize was significant (Fig. 7c). The decadal average of NEE, GPP and ER were −364 (±98), 1, 174 (±189) and 810 (±161) gC $m^{-2}$ for wheat, and −136 (±168), 1, 008 (±297), and 872 (±284) gC $m^{-2}$ for maize.

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

(Figs. 7&8 here)

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

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

**(Fig. 9 here)**

Fig. 10 shows the variations in ER and its components. During the wheat season, the variation in ER closely followed crop development and temperature, but there were two evident declines at the end of April and the start of May due to low temperatures associated with the inclement weather. During the early growing stage of maize, $R_H$ was the main component of 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.

Field measurements of the long term of $CO_2$ fluxes over croplands remain lacking, and we found the carbon sequestration capacity of this cropland has been progressively decreasing. The cropland has been widely suggested as a climate change mitigation tool (e.g., Lal, 2001), but the potential in the future is challenging. However, since the cropland management greatly impacts the carbon balance of cropland (Béziat et al., 2009; Ceschia et al., 2010), it remains required investigating if the management adjustment can foster the cropland carbon sink capacity over the long term.

The annual total NPP of 1, 345 gC $m^{-2}$ $yr^{-1}$ at our site is approximately twice the average of the model-estimated NPP for Chinese croplands (714 gC $m^{-2}$ $yr^{-1}$) with a rotation index of 2 (i.e., two crop cycles within one year) (Huang et al., 2007), more than three times the value estimated by MODIS (400 gC $m^{-2}$ $yr^{-1}$) (Zhao et al., 2005), and slightly higher than the value of the same crop rotation at the Luancheng site (1, 144 gC $m^{-2}$ $yr^{-1}$) (Wang et al., 2015). The higher NPP at our site may partially result from the sufficient irrigation and fertilization (Huang et al., 2007; Smith et al., 2014).

The contrasting respiration partitionings of the same crop in different regions (Table 2) indicate that the respiration processes may also be subject to climatic conditions and management practices. Though the ecosystem respiration to GPP at our site is comparable to other studies, the ratio of autotrophic respiration to GPP is much lower at our site, while the ratio of heterotrophic respiration to ecosystem respiration is greater at our site, these findings are different from those at the other sites with similar crop variety (Moureaux et al., 2008; Aubinet et al., 2009; Suleau et al., 2011; Wang et al., 2015; Demyan et al., 2016), as they 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 and 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 15$^{th}$, 2010 to March 8$^{th}$, 2011 (Fig. 12). These differences may result from the small wheat sample number. However, the sample number at harvest was sufficiently big and no discernible difference was found between the two NPPs at harvest. These two independent estimates of NPP were similar throughout the maize season (Fig. 12).

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

**(Fig. 12 here)**

## Conclusion

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

$CO_2$ loss in both wheat and maize season. This study provides detailed knowledge for estimating regional carbon emission over the North China 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), plant area index (PAI), net photosynthetically active radiation (PAR), and soil moisture ($\theta$) are the dominant factors. Hence, we select $T_a$, RH, PAI, PAR, and $\theta$ 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 ($T_s$), $\theta$ and PAI as explanatory variables of ER. PAI 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.

## 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.

## Acknowledgement

This research was supported by the NSFC-NSF collaboration (P. R. China-U.S.) funding (No. 51861125102), National Natural Science Foundation of China (Project Nos. 51509187, 51679120 and 51525902).

## Reference

Anthoni, P. M., Freibauer, A., Kolle, O., and Schulze, E. D.: Winter wheat carbon exchange in Thuringia, Germany, Agric. For. Meteorol., 121, 55-67, doi: 10.1016/s0168-1923(03)00162-x, 2004a.

Anthoni, P. M., Knohl, A., Rebmann, C., Freibauer, A., Mund, M., Ziegler, W., Kolle, O., and Schulze, E. D.: Forest and agricultural land-use-dependent $CO_2$ exchange in Thuringia, Germany, Global Change Biol., 10, 2005-2019, doi: 10.1111/j.1365-2486.2004.00863.x, 2004b.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology, Adv. Ecol. Res., 30, 113-175, 2000.

Aubinet, M., Moureaux, C., Bodson, B., Dufranne, D., Heinesch, B., Suleau, M., Vancutsem, F., and Vilret, A.: Carbon sequestration by a crop over a 4-year sugar beet/winter wheat/seed potato/winter wheat rotation cycle, Agric. For. Meteorol., 149, 407-418, doi: 10.1016/j.agrformet.2008.09.003, 2009.

Baker, J. M., and Griffis, T. J.: Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques, Agric. For. Meteorol., 128, 163-177, doi: 10.1016/j.agrformet.2004.11.005, 2005.

Baldocchi, D., Falge, E., Gu, L. H., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X. H., Malhi, Y., Meyers, T., Munger, W., Oechel, W., U, K. T. P., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, B Am. Meteorol. Soc., 82, 2415-2434, 2001.

Béziat, P., Ceschia, E., and Dedieu, G.: Carbon balance of a three crop succession over two cropland sites in South West France, Agric. For. Meteorol., 149, 1628-1645, doi: 10.1016/j.agrformet.2009.05.004, 2009.

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-

Campen, H., Muller, C., Reichstein, M., and Smith, B.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Global Change Biol., 13, 679-706, doi: 10.1111/j.1365-2486.2006.01305.x, 2007.

Cao, G., Scanlon, B.R., Han, D. and Zheng, C.: Impacts of thickening unsaturated zone on groundwater recharge in the North China Plain. J. Hydrol., 537, 260-270, doi: 10.1016/j.jhydrol.2016.03.049, 2016.

Ceschia, E., Béziat, P., Dejoux, J. F., Aubinet, M., Bernhofer, C., Bodson, B., Buchmann, N., Carrara, A., Cellier, P., Di Tommasi, P., Elbers, J. A., Eugster, W., Grunwald, T., Jacobs, C. M. J., Jans, W. W. P., Jones, M., Kutsch, W., Lanigan, G., Magliulo, E., Marloie, O., Moors, E. J., Moureaux, C., Olioso, A., Osborne, B., Sanz, M. J., Saunders, M., Smith, P., Soegaard, H., and Wattenbach, M.: Management effects on net ecosystem carbon and GHG budgets at European crop sites, Agric. Ecosyst. Environ., 139, 363-383, doi: 10.1016/j.agee.2010.09.020, 2010.

Chang, C. C., and Lin, C. J.: LIBSVM-A library for Support Vector Machines. http://www.csie.ntu.edu.tw/~cjlin/libsvm/, 2005.

Chen, Y. L., Luo, G. P., Maisupova, B., Chen, X., Mukanov, B. M., Wu, M., Mambetov, B. T., Huang, J. F., and Li, C. F.: Carbon budget from forest land use and management in Central Asia during 1961-2010, Agric. For. Meteorol., 221, 131-141, doi: 10.1016/j.agrformet.2016.02.011, 2016.

Ciais, P., Wattenbach, M., Vuichard, N., Smith, P., Piao, S. L., Don, A., Luyssaert, S., Janssens, I. A., Bondeau, A., Dechow, R., Leip, A., Smith, P. C., Beer, C., van der Werf, G. R., Gervois, S., Van Oost, K., Tomelleri, E., Freibauer, A., Schulze, E. D., and Team, C. S.: The European carbon balance. Part 2: croplands, Global Change Biol., 16, 1409-1428, doi: 10.1111/j.1365-2486.2009.02055.x, 2010.

Ciais, P., Gervois, S., Vuichard, N., Piao, S. L., and Viovy, N.: Effects of land use change and management on the European cropland carbon balance, Global Change Biol., 17, 320-338, doi: 10.1111/j.1365-2486.2010.02341.x, 2011.

Cristianini, N., and Shawe-Taylor, J.: An Introduction to SupportVector Machines and Other Kernel-Based Learning Methods, Cambridge Univ. Press, Cambridge, UK, pp. 189, 2000.

Demyan, M. S., Ingwersen, J., Funkuin, Y. N., Ali, R. S., Mirzaeitalarposhti, R., Rasche, F., Poll, C., Muller, T., Streck, T., Kandeler, E., and Cadisch, G.: Partitioning of ecosystem respiration in winter wheat and silage maize-modeling seasonal temperature effects, Agric. Ecosyst. Environ., 224, 131-144, doi: 10.1016/j.agee.2016.03.039, 2016.

de la Motte, L. G., Jérôme, E., Mamadou, O., Beckers, Y., Bodson, B., Heinesch, B., and Aubinet, M.: Carbon balance of an intensively grazed permanent grassland in southern Belgium, Agric. For. Meteorol., 228-229, 370-383, doi: 10.1016/j.agrformet.2016.06.009, 2016.

Dold, C., Büyükcangaz, H., Rondinelli, W., Prueger, J., Sauer, T., and Hatfield, J.: Long-term carbon uptake of agro-ecosystems in the Midwest, Agric. For. Meteorol., 232, 128-140, doi: 10.1016/j.agrformet.2016.07.012, 2017.

Drewniak, B. A., Mishra, U., Song, J., Prell, J., and Kotamarthi, V. R.: Modeling the impact of agricultural land use and management on US carbon budgets, Biogeosciences, 12, 2119-2129, doi: 10.5194/bg-12-2119-2015, 2015.

Eichelmann, E., Wagner-Riddle, C., Warland, J., Deen, B., and Voroney, P.: Comparison of carbon budget, evapotranspiration, and albedo effect between the biofuel crops switchgrass and corn, Agric. Ecosyst. Environ., 231, 271-282, doi: 10.1016/j.agee.2016.07.007, 2016.

Ekblad, A., Bostrom, B., Holm, A., and Comstedt, D.: Forest soil respiration rate and $\delta^{13}C$ is regulated by recent above ground weather conditions, Oecologia, 143, 136-142, doi: 10.1007/s00442-004-1776-z, 2005.

Eugster, W., Moffat, A. M., Ceschia, E., Aubinet, M., Ammann, C., Osborne, B., Davis, P. A., Smith, P., Jacobs, C., Moors, E., Le Dantec, V., Beziat, P., Saunders, M., Jans, W., Grunwald, T., Rebmann, C., Kutsch, W. L., Czerny, R., Janous, D., Moureaux, C., Dufranne, D., Carrara, A., Magliulo, V., Di Tommasi, P., Olesen, J. E., Schelde, K., Olioso, A., Bernhofer, C., Cellier, P., Larmanou, E., Loubet, B., Wattenbach, M., Marloie, O., Sanz, M. J., Sogaard, H., and Buchmann, N.: Management effects on European cropland respiration, Agric. Ecosyst. Environ., 139, 346-362, doi: 10.1016/j.agee.2010.09.001, 2010.

Falkowski, P., Scholes, R. J., Boyle, E. E. A., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Högberg, P., Linder, S., and Mackenzie, F. T.: The global carbon cycle: a test of our knowledge of earth as a system, Science, 290, 291-296, doi: 10.1126/science.290.5490.291, 2000.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grunwald, T., Hollinger, D., Jensen, N. O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, H., Moors, E., Munger, J. W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: Gap filling strategies for defensible annual sums of net ecosystem exchange, Agric. For. Meteorol., 107, 43-69, doi: 10.1016/S0168-1923(00)00225-2, 2001.

Falge, E., Baldocchi, D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Burba, G., Clement, R., Davis, K. J., Elbers, J. A., Goldstein, A. H., Grelle, A., Granier, A., Guomundsson, J., Hollinger, D., Kowalski, A. S., Katul, G., Law, B. E., Malhi, Y., Meyers, T., Monson, R. K., Munger, J. W., Oechel, W., Paw, K. T., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Valentini, R., Wilson, K., and Wofsy, S.: Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements, Agric. For. Meteorol., 113, 53-74, doi: 10.1016/S0168-1923(02)00102-8, 2002a.

Falge, E., Tenhunen, J., Baldocchi, D., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Bonnefond, J. M., Burba, G., Clement, R., Davis, K. J., Elbers, J. A., Falk, M., Goldstein, A. H., Grelle, A., Granier, A., Grunwald, T., Gudmundsson, J., Hollinger, D., Janssens, I. A., Keronen, P., Kowalski, A. S., Katul, G., Law, B. E., Malhi, Y., Meyers, T., Monson, R. K., Moors, E., Munger, J. W., Oechel, W., U, K. T. P., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Thorgeirsson, H., Tirone, G., Turnipseed, A., Wilson, K., and Wofsy, S.: Phase and amplitude of ecosystem carbon release and uptake potentials as derived from FLUXNET measurements, Agric. For. Meteorol., 113, 75-95, doi: 10.1016/S0168-1923(02)00103-X, 2002b.

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T., Cook-Patton, S. C., Ellis, P. W., Falcucci, A., Fourqurean, J. W., Gopalakrishna, T., Gu, H., Henderson, B., Hurteau, M. D., Kroeger, K. D., Kroeger, T., Lark, T. J., Leavitt, S. M., Lomax, G., McDonald, R. I., Megonigal, J. P., Miteva, D. A., Richardson, C. J., Sanderman, J., Shoch, D., Spawn, S. A., Veldman, J. W., Williams, C. A., Woodbury, P. B., Zganjar, C., Baranski, M., Elias, P., Houghton, R. A., Landis, E., McGlynn, E., Schlesinger, W. H., Siikamaki, J. V., Sutton-Grier, A. E., and Griscom, B. W.: Natural climate solutions for the United States, Sci Adv, 4, doi: 10.1126/sciadv.aat1869, 2018.

Fleisher, D. H., Timlin, D. J., and Reddy, V. R.: Elevated carbon dioxide and water stress effects on potato canopy gas exchange, water use, and productivity, Agric. For. Meteorol., 148, 1109-1122, doi: 10.1016/j.agrformet.2008.02.007, 2008.

Forkel, M., Carvalhais, N., Rödenbeck, C., Keeling, R., Heimann, M., Thonicke, K., Zaehle, S., and Reichstein, M.: Enhanced seasonal $CO_2$ exchange caused by amplified plant productivity in northern ecosystems, Science, 351, 696-699, doi: 10.1126/science.aac4971, 2016.

Freibauer, A., Rounsevell, M. D. A., Smith, P., and Verhagen, J.: Carbon sequestration in the agricultural soils of Europe, Geoderma, 122, 1-23, 10.1016/j.geoderma.2004.01.021, 2004.

Gao, X., Gu, F., Hao, W., Mei, X., Li, H., Gong, D., and Zhang, Z.: Carbon budget of a rainfed spring maize cropland with straw returning on the Loess Plateau, China, Science of The Total Environment, 586, 1193-1203, 10.1016/j.scitotenv.2017.02.113, 2017.

Gilmanov, T. G., Verma, S. B., Sims, P. L., Meyers, T. P., Bradford, J. A., Burba, G. G., and Suyker, A. E.: Gross primary production and light response parameters of four Southern Plains ecosystems estimated using long-term $CO_2$-flux tower measurements, Global Biogeochem. Cycles, 17, Artn 1071, doi: 10.1029/2002gb002023, 2003.

Grant, R. F., Arkebauer, T. J., Dobermann, A., Hubbard, K. G., Schimelfenig, T. T., Suyker, A. E., Verma, S. B., and Walters, D. T.: Net biome productivity of irrigated and rainfed maize-soybean rotations: Modeling vs. measurements, Agron. J., 99, 1404-1423, doi:

10.2134/agronj2006.0308, 2007.

Gray, J. M., Frolking, S., Kort, E. A., Ray, D. K., Kucharik, C. J., Ramankutty, N., and Friedl, M. A.: Direct human influence on atmospheric $CO_2$ seasonality from increased cropland productivity, Nature, 515, 398-401, doi: 10.1038/nature13957, 2014.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamaki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S. M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F. E., Sanderman, J., Silvius, M., Wollenberg, E., and Fargione, J.: Natural climate solutions, P. Natl. Acad. Sci. USA, 114, 11645-11650, doi: 10.1073/pnas.1710465114, 2017.

Heimann, M., and Reichstein, M.: Terrestrial ecosystem carbon dynamics and climate feedbacks, Nature, 451, 289-292, doi: 10.1038/Nature06591, 2008.

Hollinger, S. E., Bernacchi, C. J., and Meyers, T. P.: Carbon budget of mature no-till ecosystem in North Central Region of the United States, Agric. For. Meteorol., 130, 59-69, doi: 10.1016/j.agrformet.2005.01.005, 2005.

Hsieh, C. I., Katul, G., and Chi, T.: An approximate analytical model for footprint estimation of scaler fluxes in thermally stratified atmospheric flows, Adv. Water Resour, 23, 765-772, doi: 10.1016/S0309-1708(99)00042-1, 2000.

Huang, Y., Zhang, W., Sun, W. J., and Zheng, X. H.: Net primary production of Chinese croplands from 1950 to 1999, Ecol. Appl., 17, 692-701, doi: 10.1890/05-1792, 2007.

Hunt, J. E., Laubach, J., Barthel, M., Fraser, A., and Phillips, R. L.: Carbon budgets for an irrigated intensively grazed dairy pasture and an unirrigated winter-grazed pasture, Biogeosciences, 13, 2927-2944, doi: 10.5194/bg-13-2927-2016, 2016.

Hutchinson, J. J., Campbell, C. A., and Desjardins, R. L.: Some perspectives on carbon sequestration in agriculture, Agric. For. Meteorol., 142, 288-302, doi: 10.1016/j.agrformet.2006.03.030, 2007.

Iwasaki, H., Saito, H., Kuwao, K., Maximov, T. C., and Hasegawa, S.: Forest decline caused by high soil water conditions in a permafrost region, Hydrol. Earth Syst. Sc., 14, 301-307, doi: 10.5194/hess-14-301-2010, 2010.

Jans, W. W. P., Jacobs, C. M. J., Kruijt, B., Elbers, J. A., Barendse, S., and Moors, E. J.: Carbon exchange of a maize (*Zea mays* L.) crop: Influence of phenology, Agric. Ecosyst. Environ., 139, 316-324, doi: 10.1016/j.agee.2010.06.008, 2010.

Kang, M., Ichii, K., Kim, J., Indrawati, Y. M., Park, J., Moon, M., Lim, J. H., and Chun, J. H.: New gap-filling strategies for long-period flux data gaps using a data-driven approach, Atmosphere-Basel, 10, doi: 10.3390/Atmos10100568, 2019.

Kendy, E., Gerard-Marchant, P., Walter, M. T., Zhang, Y. Q., Liu, C. M., and Steenhuis, T. S.: A soil-water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain, Hydrol. Process., 17, 2011-2031, doi: 10.1002/hyp.1240, 2003.

Kim, Y., Johnson, M.S., Knox, S.H., Black, T. A., Dalmagro, H. J., Kang, M., Kim, J., Baldocchi, D.: Gap-filling approaches for eddy covariance methane fluxes: A comparison of three machine learning algorithms and a traditional method with principal component analysis. Global Change Biol., 26, 1-20 doi: 10.1111/gcb.14845, 2019.

Kutsch, W. L., Aubinet, M., Buchmann, N., Smith, P., Osborne, B., Eugster, W., Wattenbach, M., Schrumpf, M., Schulze, E. D., Tomelleri, E., Ceschia, E., Bernhofer, C., Beziat, P., Carrara, A., Di Tommasi, P., Grunwald, T., Jones, M., Magliulo, V., Marloie, O., Moureaux, C., Olioso, A., Sanz, M. J., Saunders, M., Sogaard, H., and Ziegler, W.: The net biome production of full crop rotations in Europe, Agric. Ecosyst. Environ., 139, 336-345, doi: 10.1016/j.agee.2010.07.016, 2010.

Lal, R.: World cropland soils as a source or sink for atmospheric carbon, Adv. Agron., 71, 145-191, 2001.

Latimer, R. N. C. and Risk, D. A.: An inversion approach for determining distribution of production and temperature sensitivity of soil respiration, Biogeosciences, 13, 2111-2122, doi: 10.5194/bg-13-2111-2016, 2016.

Lei, H. M., and Yang, D. W.: Seasonal and interannual variations in carbon dioxide exchange over a cropland in the North China Plain, Global Change Biol., 16, 2944-2957, doi: 10.1111/j.1365-2486.2009.02136.x, 2010.

Lei, H. M., Yang, D. W., Cai, J. F., and Wang, F. J.: Long-term variability of the carbon balance in a large irrigated area along the lower Yellow River from 1984 to 2006, Sci. China Earth Sci., 56, 671-683, doi: 10.1007/s11430-012-4473-5, 2013.

Li, J., Yu, Q., Sun, X. M., Tong, X. J., Ren, C. Y., Wang, J., Liu, E. M., Zhu, Z. L., and Yu, G. R.: Carbon dioxide exchange and the mechanism of environmental control in a farmland ecosystem in North China Plain, Sci. China Ser. D, 49, 226-240, doi: 10.1007/s11430-006-8226-1, 2006.

Luo, Y., He, C. S., Sophocleous, M., Yin, Z. F., Ren, H. R., and Zhu, O. Y.: Assessment of crop growth and soil water modules in SWAT2000 using extensive field experiment data in an irrigation district of the Yellow River Basin, J Hydrol, 352, 139-156, doi: 10.1016/j.jhydrol.2008.01.003, 2008.

Mauder, M., and Foken, T.: Documentation and instruction manual of the eddy covariance software package TK2. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse, 2004.

Mauder, M., and Foken, T.: Documentation and instruction manual of the eddy-covariance software package TK3, Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse 2011.

Moureaux, C., Debacq, A., Bodson, B., Heinesch, B., and Aubinet, M.: Annual net ecosystem carbon exchange by a sugar beet crop, Agric. For. Meteorol., 139, 25-39, doi: 10.1016/j.agrformet.2006.05.009, 2006.

Moureaux, C., Debacq, A., Hoyaux, J., Suleau, M., Tourneur, D., Vancutsem, F., Bodson, B., and Aubinet, M.: Carbon balance assessment of a Belgian winter wheat crop (*Triticum aestivum* L.), Global Change Biol., 14, 1353-1366, doi: 10.1111/j.1365-2486.2008.01560.x, 2008.

National Standards of Environmental Protection of the People's Republic of China: Soil – Determination of organic carbon – Combustion oxidation-titration method. HJ658-2013, 2013.

Özdoğan, M.: Exploring the potential contribution of irrigation to global agricultural primary productivity, Global Biogeochem. Cycles, 25, doi: 10.1029/2009GB003720, 2011.

Phillips, C. L., Nickerson, N., Risk, D. and Bond, B. J.: Interpreting diel hysteresis between soil respiration and temperature, Global Change Biol., 17, 515-527, doi: 10.1111/j.1365-

2486.2010.02250.x, 2011.

Piao, S. L., Ito, A., Li, S. G., Huang, Y., Ciais, P., Wang, X. H., Peng, S. S., Nan, H. J., Zhao, C., Ahlstrom, A., Andres, R. J., Chevallier, F., Fang, J. Y., Hartmann, J., Huntingford, C., Jeong, S., Levis, S., Levy, P. E., Li, J. S., Lomas, M. R., Mao, J. F., Mayorga, E., Mohammat, A., Muraoka, H., Peng, C. H., Peylin, P., Poulter, B., Shen, Z. H., Shi, X., Sitch, S., Tao, S., Tian, H. Q., Wu, X. P., Xu, M., Yu, G. R., Viovy, N., Zaehle, S., Zeng, N., and Zhu, B.: The carbon budget of terrestrial ecosystems in East Asia over the last two decades, Biogeosciences, 9, 3571-3586, doi: 10.5194/bg-9-3571-2012, 2012.

Poorter, H., Niklas, K. J., Reich, P. B., Oleksyn, J., Poot, P., and Mommer, L.: Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control, New Phytol, 193, 30-50, doi: 10.1111/j.1469-8137.2011.03952.x, 2012.

Poulter, B., Frank, D., Ciais, P., Myneni, R. B., Andela, N., Bi, J., Broquet, G., Canadell, J. G., Chevallier, F., Liu, Y. Y. and Running, S. W.: Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle, Nature, 509, 600-603, doi:10.1038/nature13376, 2014.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J. M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Global Change Biol., 11, 1424-1439, doi: 10.1111/j.1365-2486.2005.001002.x, 2005.

Sauerbeck, D. R.: $CO_2$ emissions and C sequestration by agriculture - perspectives and limitations, Nutr. Cycl. Agroecosys., 60, 253-266, doi: 10.1023/A:1012617516477, 2001.

Schmidt, M., Reichenau, T. G., Fiener, P., and Schneider, K.: The carbon budget of a winter wheat field: An eddy covariance analysis of seasonal and inter-annual variability, Agric. For. Meteorol., 165, 114-126, doi: 10.1016/j.agrformet.2012.05.012, 2012.

Shen, Y., Zhang, Y., Scanlon, B. R., Lei, H., Yang, D., and Yang, F: Energy/water budgets and productivity of the typical croplands irrigated with groundwater and surface water in the North China Plain, Agric. For. Meteorol., 181, 133-142, doi: 10.1016/j.agrformet.2013.07.013, 2013.

Smith, P.: Carbon sequestration in croplands: the potential in Europe and the global context, Eur. J. Agron., 20, 229-236, doi: 10.1016/j.eja.2003.08.002, 2004.

Smith, P., Lanigan, G., Kutsch, W. L., Buchmann, N., Eugster, W., Aubinet, M., Ceschia, E., Beziat, P., Yeluripati, J. B., Osborne, B., Moors, E. J., Brut, A., Wattenbach, M., Saunders, M., and Jones, M.: Measurements necessary for assessing the net ecosystem carbon budget of croplands, Agric. Ecosyst. Environ., 139, 302-315, doi: 10.1016/j.agee.2010.04.004, 2010.

Smith, W. K., Cleveland, C. C., Reed, S. C., and Running, S. W.: Agricultural conversion without external water and nutrient inputs reduces terrestrial vegetation productivity, Geophys. Res. Lett., 41, 449-455, doi: 10.1002/2013GL058857, 2014.

Suyker, A.E., Verma, S. B., Burba, G. G., and Arkebauer, T. J., Gross primary production and ecosystem respiration of irrigated maize and irrigated soybean during a growing season.

Agric. For. Meteorol., 31, 180-190, doi: 10.1016/j.agrformet.2005.05.007, 2005.

Suleau, M., Moureaux, C., Dufranne, D., Buysse, P., Bodson, B., Destain, J. P., Heinesch, B., Debacq, A., and Aubinet, M.: Respiration of three Belgian crops: Partitioning of total ecosystem respiration in its heterotrophic, above- and below-ground autotrophic components, Agric. For. Meteorol., 151, 633-643, doi: 10.1016/j.agrformet.2011.01.012, 2011.

Taylor, A. M., Amiro, B. D., and Fraser, T. J.: Net $CO_2$ exchange and carbon budgets of a three-year crop rotation following conversion of perennial lands to annual cropping in Manitoba, Canada, Agric. For. Meteorol., 182–183, 67-75, doi: 10.1016/j.agrformet.2013.07.008, 2013.

Terazawa, K., Maruyama, Y., and Morikawa, Y.: Photosynthetic and Stomatal Responses of Larix-Kaempferi Seedlings to Short-Term Waterlogging, Ecol. Res., 7, 193-197, doi: 10.1007/Bf02348500, 1992.

Tian, H., Melillo, J., Kicklighter, D., McGuire, A., and Helfrich, J.: The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric $CO_2$ in the United States, Tellus B, 51, 414-452, 1999.

Ueyama, M., Ichii, K., Iwata, H., Euskirchen, E. S., Zona, D., Rocha, A. V., Harazono, Y., Iwama, C., Nakai, T., and Oechel, W. C.: Upscaling terrestrial carbon dioxide fluxes in Alaska with satellite remote sensing and support vector regression, J. Geophys. Res-Biogeo., 118, 1266-1281, doi: 10.1002/jgrg.20095, 2013.

van Wesemael, B., Paustian, K., Meersmans, J., Goidts, E., Barancikova, G., and Easter, M.: Agricultural management explains historic changes in regional soil carbon stocks, P. Natl. Acad. Sci. USA, 107, 14926-14930, doi: 10.1073/pnas.1002592107, 2010.

Verma, S. B., Dobermann, A., Cassman, K. G., Walters, D. T., Knops, J. M., Arkebauer, T. J., Suyker, A. E., Burba, G. G., Amos, B., Yang, H. S., Ginting, D., Hubbard, K. G., Gitelson, A. A., and Walter-Shea, E. A.: Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems, Agric. For. Meteorol., 131, 77-96, doi: 10.1016/j.agrformet.2005.05.003, 2005.

Vick, E. S. K., Stoy, P. C., Tang, A. C. I., and Gerken, T.: The surface-atmosphere exchange of carbon dioxide, water, and sensible heat across a dryland wheat-fallow rotation, Agric. Ecosyst. Environ., 232,129-140, doi: 10.1016/j.agee.2016.07.018, 2016.

Wang, Y. Y., Hu, C. S., Dong, W. X., Li, X. X., Zhang, Y. M., Qin, S. P., and Oenema, O.: Carbon budget of a winter-wheat and summer-maize rotation cropland in the North China Plain, Agric. Ecosyst. Environ., 206, 33-45, doi: 10.1016/j.agee.2015.03.016, 2015.

Wolf, J., West, T. O., Le Page, Y., Kyle, G. P., Zhang, X., Collatz, G. J., and Imhoff, M. L.: Biogenic carbon fluxes from global agricultural production and consumption, Global Biogeochem. Cy., 29, 1617-1639, doi: 10.1002/2015gb005119, 2015.

Zhang, Q., Lei, H. M., and Yang, D. W.: Seasonal variations in soil respiration, heterotrophic respiration and autotrophic respiration of a wheat and maize rotation cropland in the North China Plain, Agric. For. Meteorol., 180, 34-43, doi: 10.1016/j.agrformet.2013.04.028, 2013.

Zhang, Q., Katul, G. G., Oren, R., Daly, E., Manzoni, S., and Yang, D. W.: The hysteresis response of soil $CO_2$ concentration and soil respiration to soil temperature, J. Geophys. Res-Biogeo., 120, 1605-1618, doi: 10.1002/2015JG003047, 2015a.

Zhang, Q., Lei, H.M., Yang, D.W., Bo H. B., and Cai, J. F.: On the diel characteristics of soil respiration over the North China Plain, J. Tsinghua University (Science and Technology), 55, 33-38, 2015b. (in Chinese with English abstract)

Zhang, Q., Phillips, R.P., Manzoni, S., Scott, R.L., Oishi, A.C., Finzi, A., Daly, E., Vargas, R. and Novick, K.A.: Changes in photosynthesis and soil moisture drive the seasonal soil respiration-temperature hysteresis relationship. Agric. For. Meteorol., 259:184-195, doi: 10.1016/j.agrformet.2018.05.005, 2018.

Zhang, Y. Q., Yu, Q., Jiang, J., and Tang, Y. H.: Calibration of Terra/MODIS gross primary production over an irrigated cropland on the North China Plain and an alpine meadow on the Tibetan Plateau, Global Change Biol., 14, 757-767, doi: 10.1111/j.1365-2486.2008.01538.x, 2008.

Zhao, M. S., Heinsch, F. A., Nemani, R. R., and Running, S. W.: Improvements of the MODIS terrestrial gross and net primary production global data set, Remote Sens. Environ., 95, 164-176, doi: 10.1016/j.rse.2004.12.011, 2005.

## 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 |

Table 2 Various ratios associated with carbon fluxes in croplands

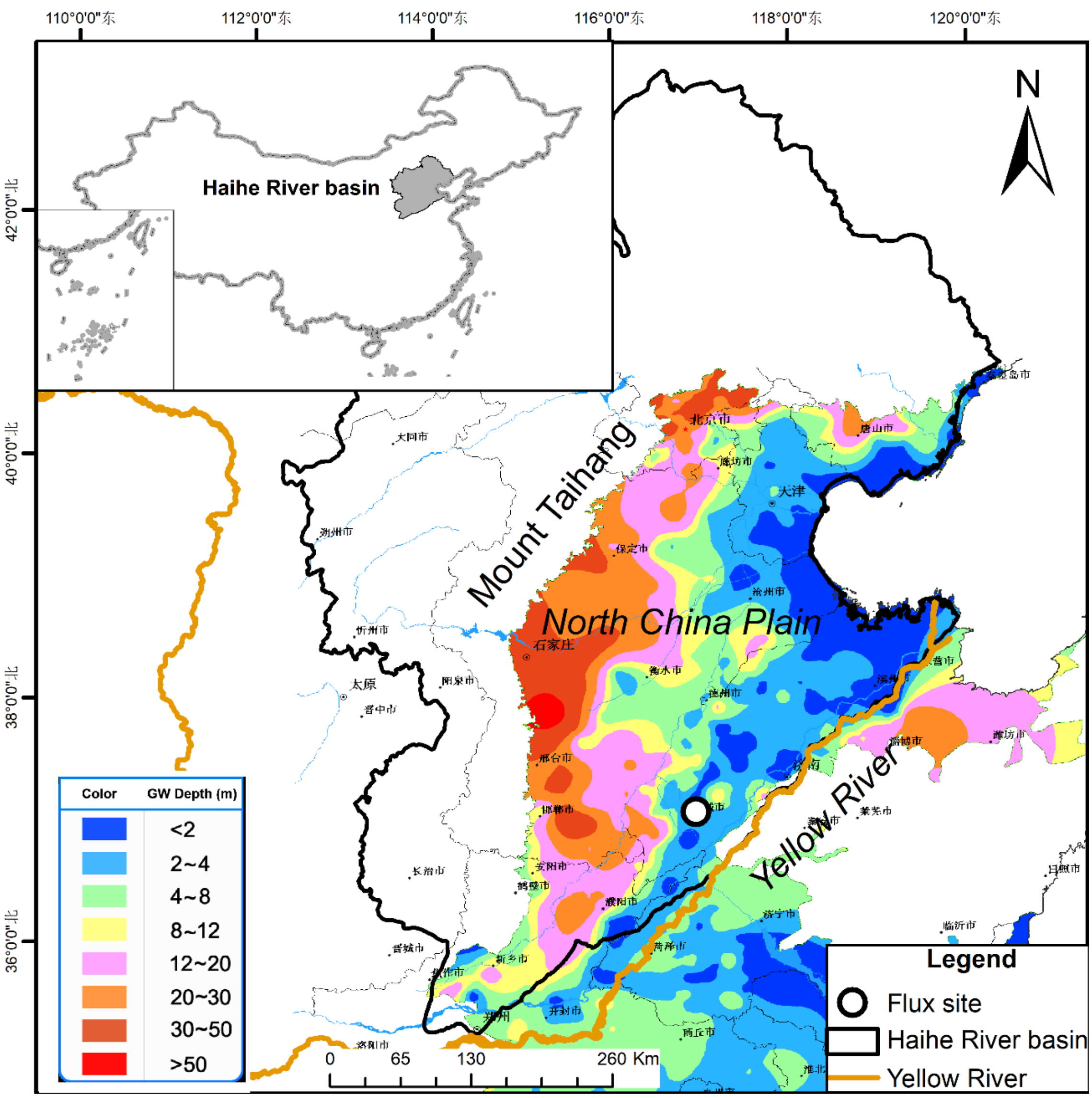
| crop species | ER/GPP | $R_A$/GPP[a] | $R_H$/ER | $R_{AB}$/ER | $R_{AA}$/ER | source |
|---|---|---|---|---|---|---|
| maize | 0.69 | 0.32 | 0.54 | 0.21 | 0.25 | **this study** |
| maize | 0.67 | 0.56 | 0.16 | 0.25 | 0.59 | Jans et al. (2010) |
| maize | 0.85 | 0.45 | 0.47 | 0.02 | 0.51 | Wang et al. (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) |

Note:

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

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

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

895



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

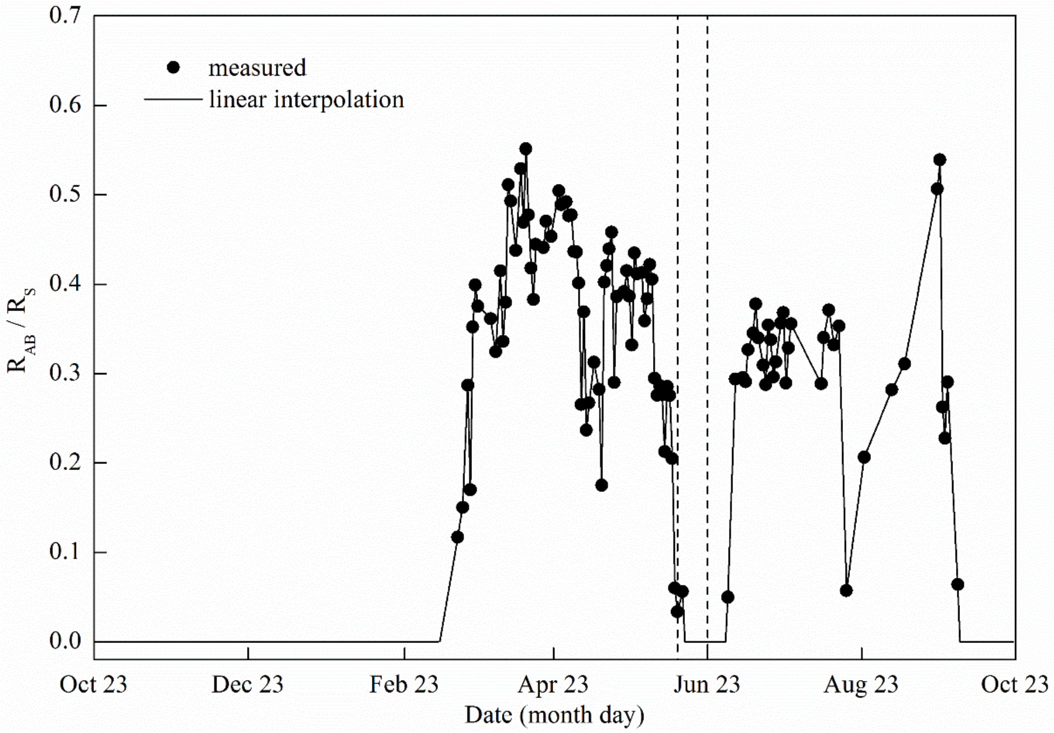
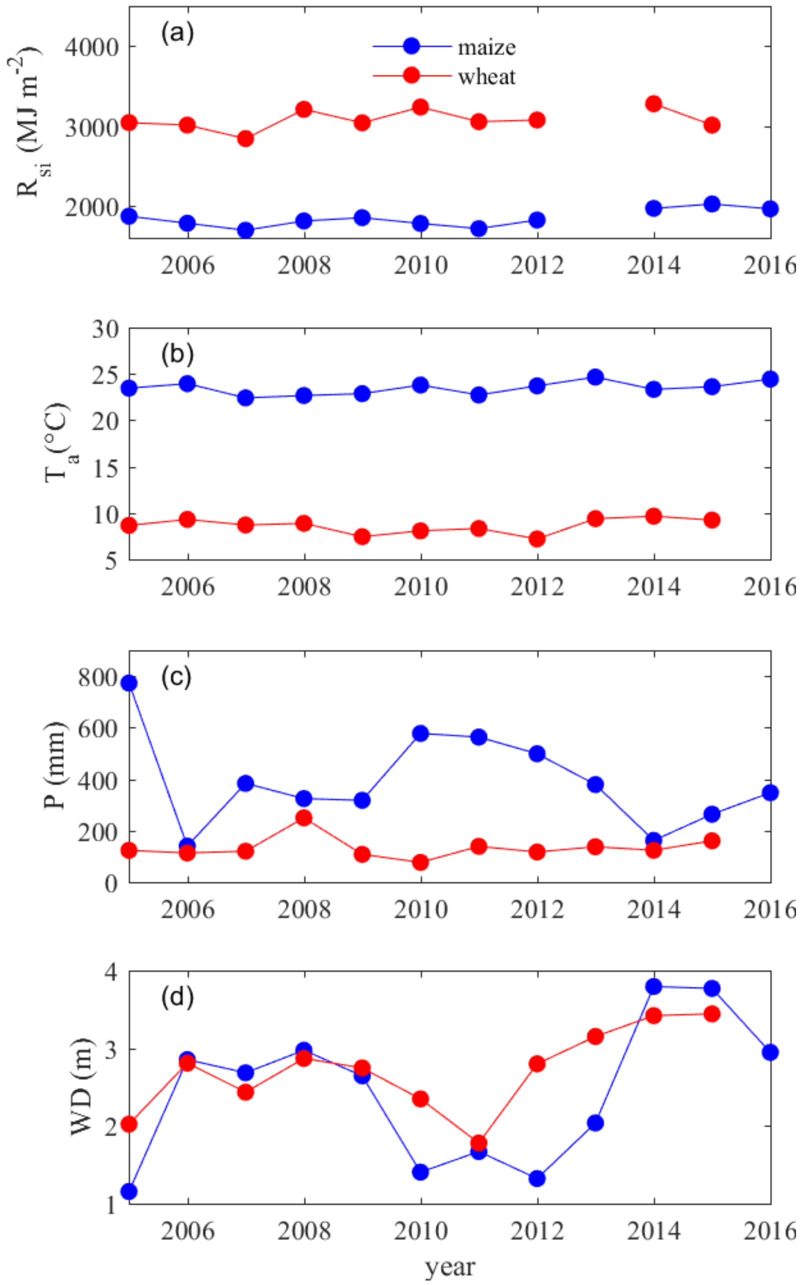



Fig. 2 Seasonal variations in the ratio of below-ground autotrophic respiration ($R_{AB}$) to total soil respiration ($R_S$). Two vertical dashed lines (hereafter) represent the date of harvesting wheat and sowing maize, respectively.




902

903 Fig. 3 The seasonal (a) total incoming short-wave radiation ($R_{si}$), (b) average air temperature

904 ($T_a$), (c) total precipitation (P) and (d) average groundwater depth (D) for both wheat and

905 maize evaluated for the period from 2005 through 2016. Note that incoming short-wave

906 radiation in the 2013 season was missing due to equipment malfunction.

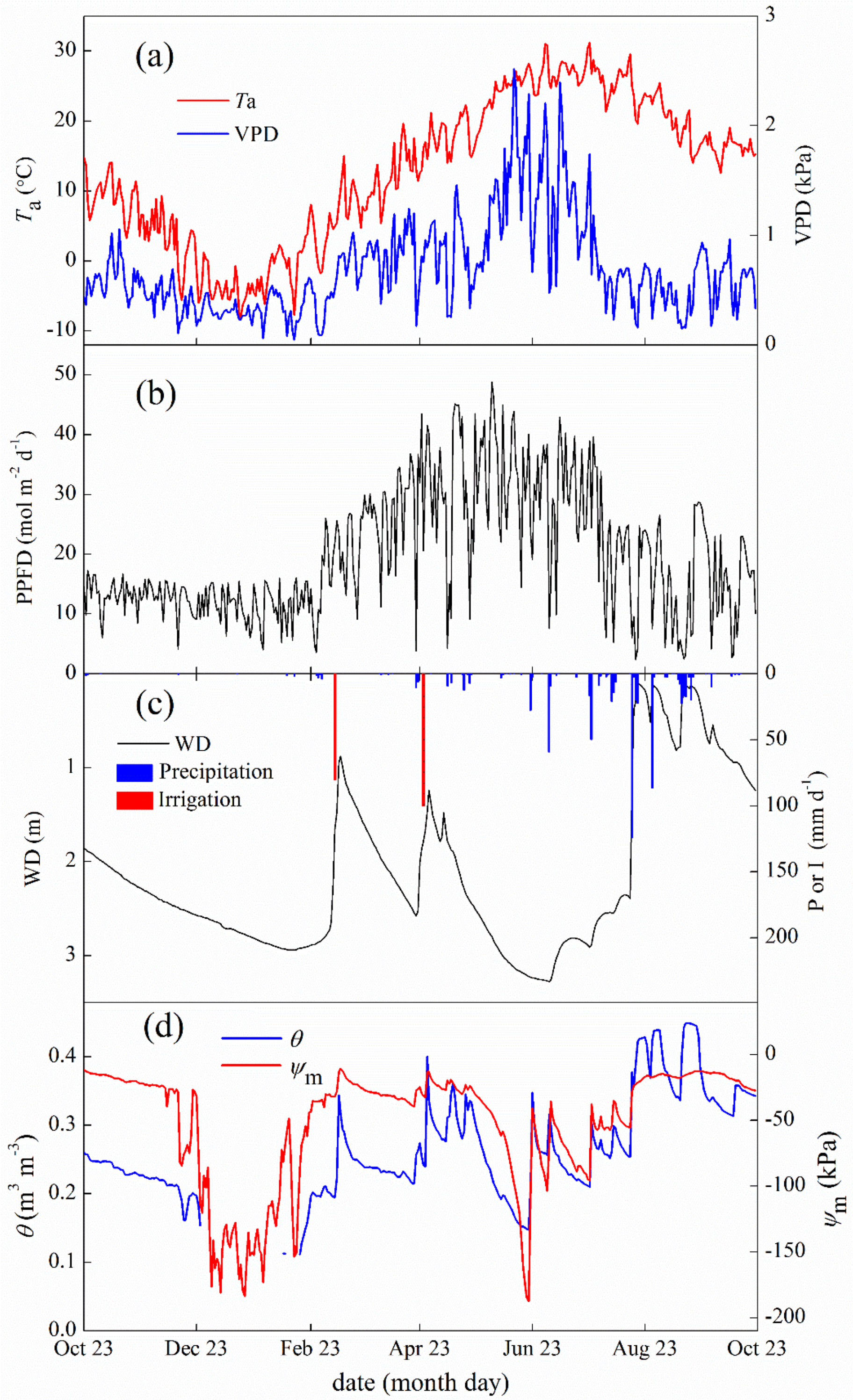



Fig. 4 Seasonal variations in the environmental variables of (a) air temperature ($T_a$), soil temperature at 5cm depth ($T_s$) and vapor pressure deficit (VPD), (b) photosynthetic photon flux density (PPFD), (c) precipitation (P), irrigation (I) and groundwater depth (WD), and (d) volumetric soil moisture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

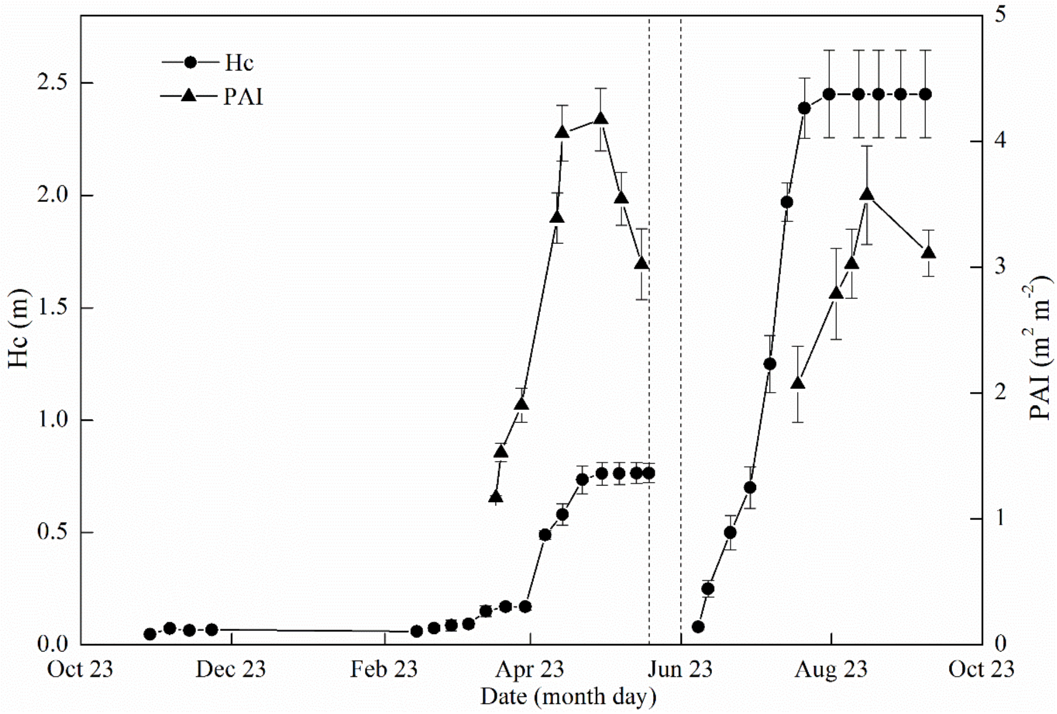



Fig. 5 Seasonal variations in canopy height ($H_C$) and plant area index (PAI). The error bars denote 1 standard deviation of the ten points.

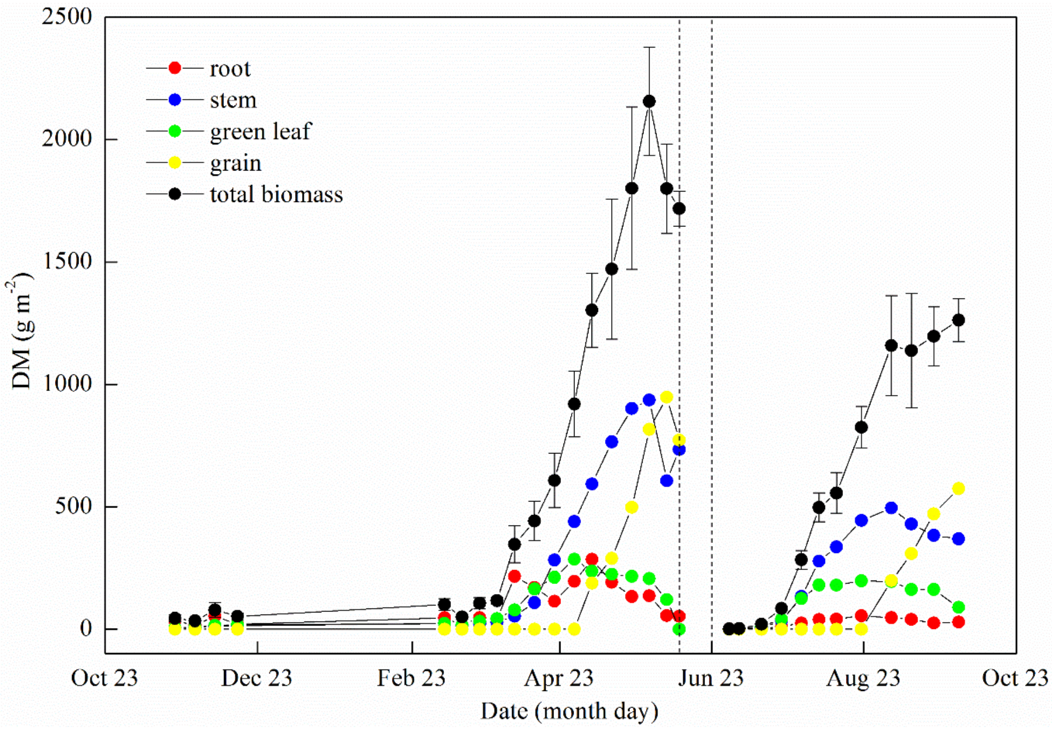



Fig. 6 Seasonal variations in the total dry biomass (DM) and its major parts of root, stem, green leaf and grain. The error bars of total biomass denote 1 standard deviation of the four sample points.

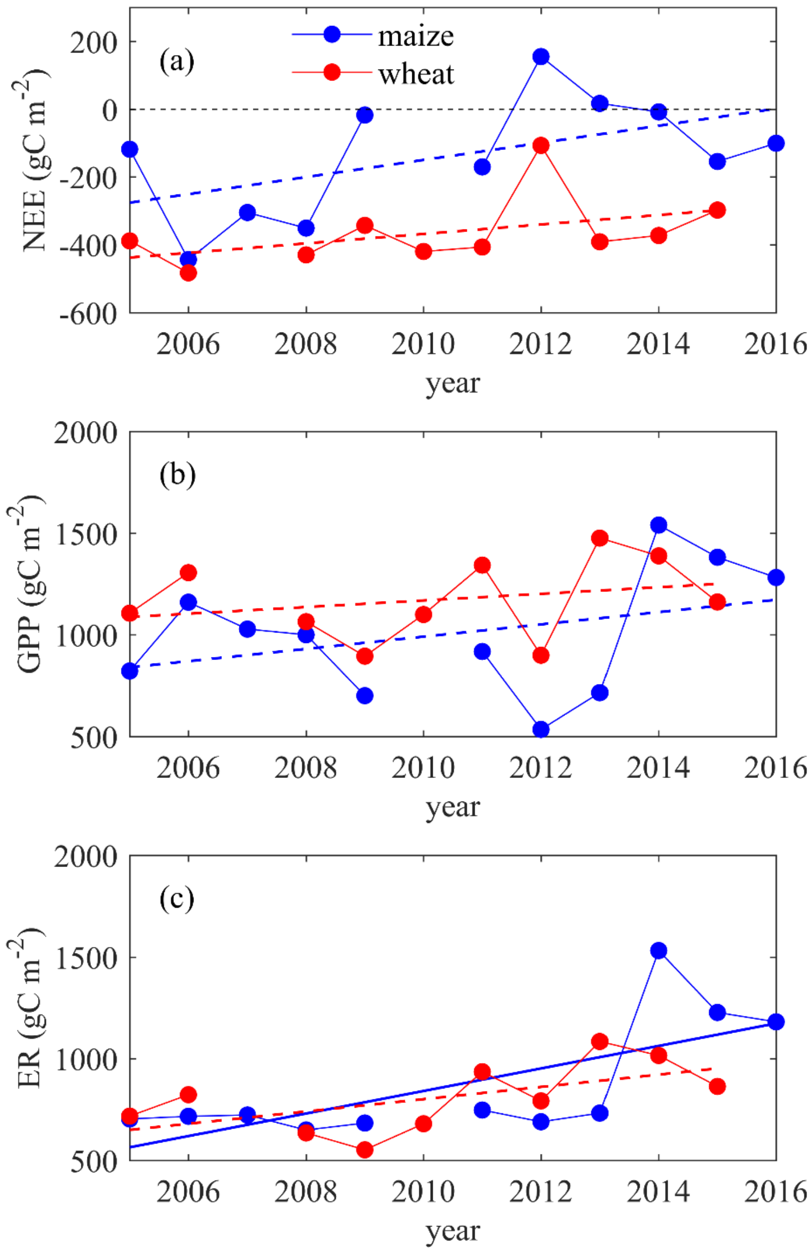



Fig. 7 The temporal trend of annual (a) Net Ecosystem Exchange (NEE), (b) Gross Primary Productivity (GPP) and (c) Ecosystem Respiration (ER) for both wheat and maize from 2005 through 2016. Note that though most gaps of carbon fluxes were filled, the wheat of 2007 was excluded as it had a large gap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

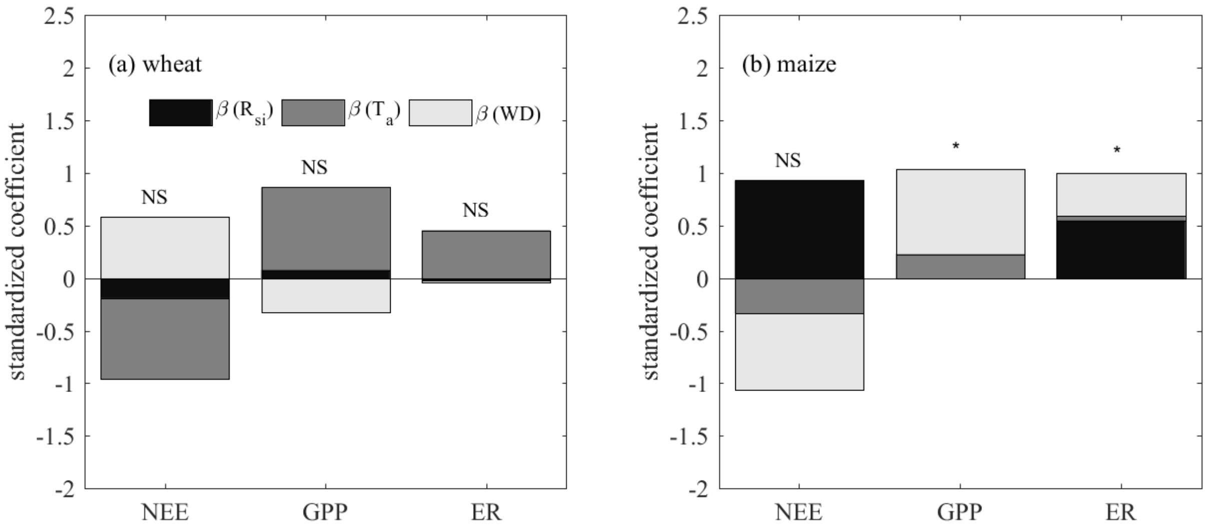



Fig. 8 The result of multipe regression for NEE, GPP and ER with incoming short-wave radiation ($R_{si}$), air temperature ($T_a$) and groundwater depth (WD) for both (a) wheat and (b) maize. Note that * denotes that the regression passes $p<0.05$ significance level, and NS indicates non-significant.

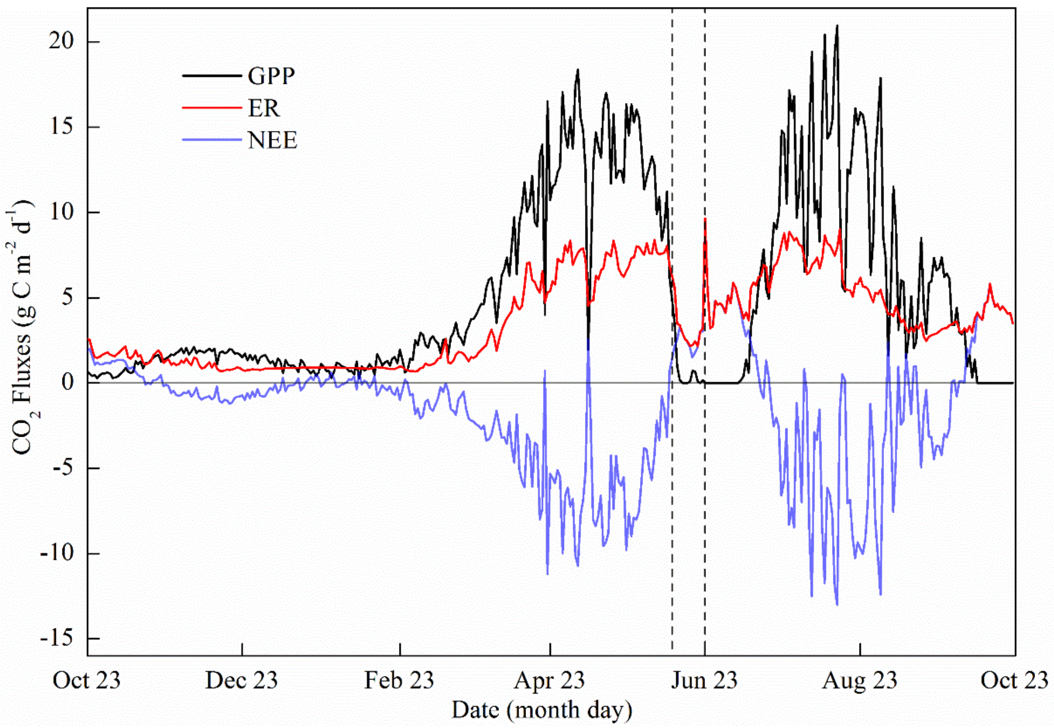



Fig. 9 Seasonal variations in Gross Primary Producrivity (GPP), Net Ecosystem Exchange (NEE) and Ecosystem Respiration (ER) (those before April 2nd were calculated with SVR method)

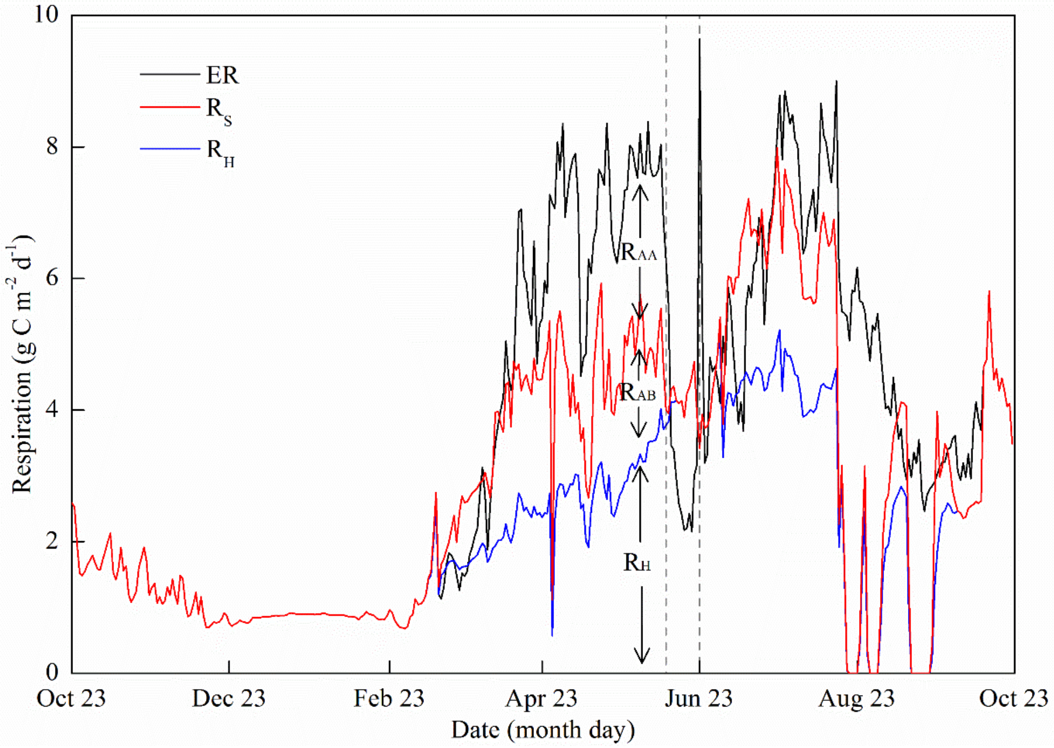



Fig. 10 Seasonal variations in the components of Ecosystem Respiration (ER), total soil respiration ($R_S$), soil heterotrophic respiration ($R_H$). The difference between ER and $R_S$ denotes above-ground autotrophic respiration ($R_{AA}$), and the difference between $R_S$ and $R_H$ denotes below-ground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

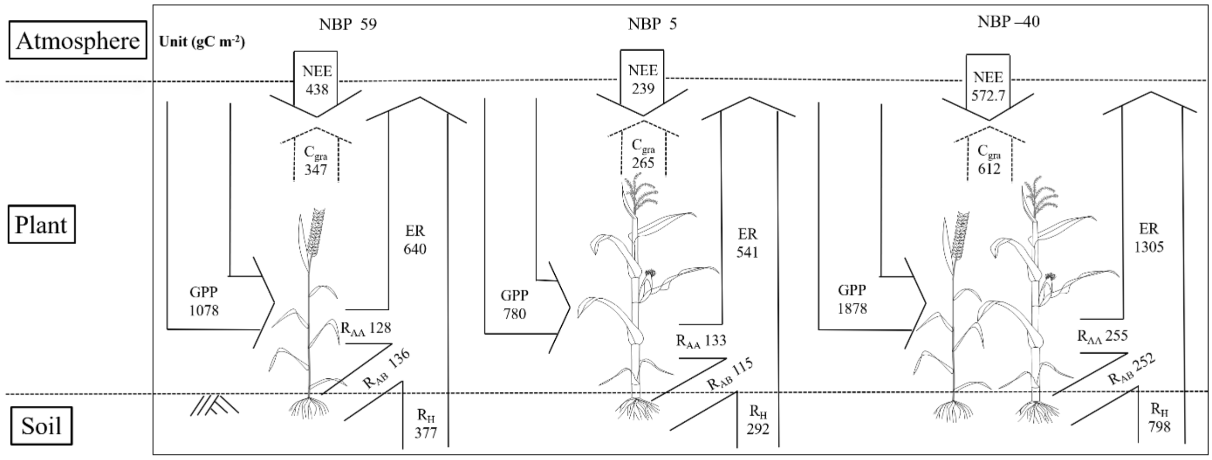



Fig. 11 Carbon budget of wheat (left), maize (middle) and the full wheat-maize rotation cycle with fallow periods included (right). Note that absolute value of NEE is shown here; NBPs of wheat and maize are the average of two independent methods (i.e, eddy covariance-based and crop sample-based)

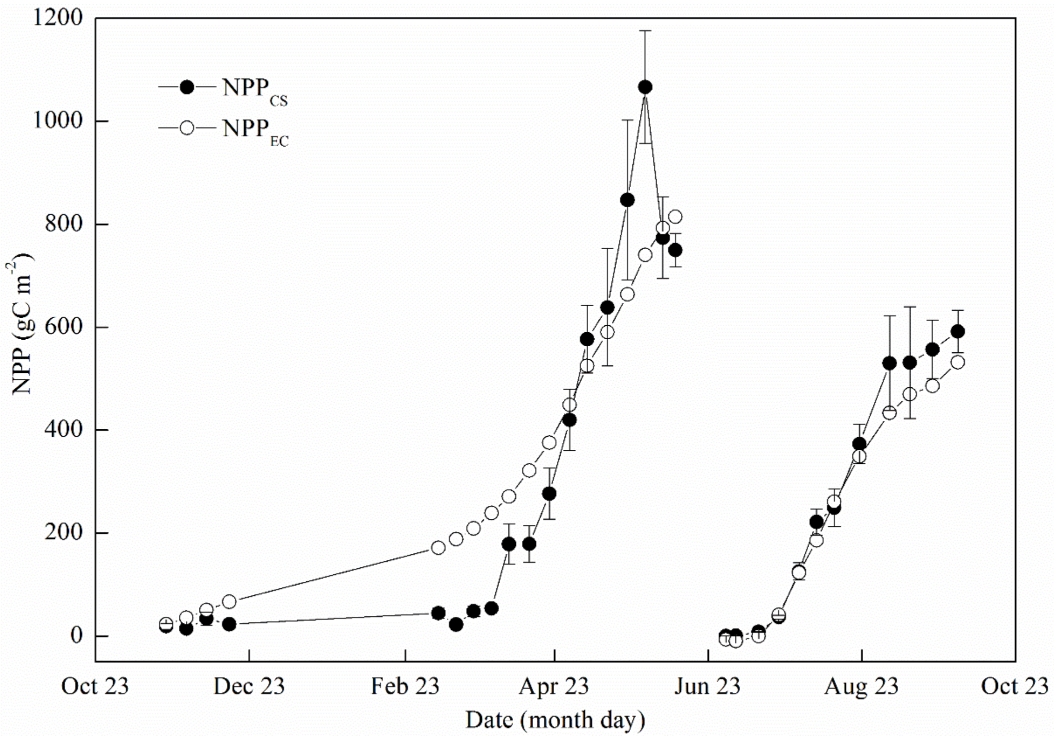



Fig. 12 Seasonal variations in the cumulative Net Primary Productivity (NPP) with two independent methods of Crop Sample ($NPP_{CS}$) and Eddy Covariance ($NPP_{EC}$) complemented with soil respiration measurements.