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Decadal variation of CO_2 flux 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 CO_2 sequestration and the decadal trend of an irrigated wheat-maize rotation cropland, the net ecosystem exchange (NEE) with the atmosphere was measured by using an eddy covariance system from 2005 through 2016 over the North China Plain. To evaluate the detailed CO_2 budget components of this typical cropland, a comprehensive experiment was conducted in the full 2010-2011 wheat-maize rotation cycle by combining the eddy covariance NEE measurements, a soil respiration experiment that differentiated between heterotrophic and below-ground autotrophic respirations, plant carbon storage samplings and soil organic carbon measurements. Over the past decade from 2005 through 2016, the average of total NEE, Gross Primary Productivity (GPP), Ecosystem Respiration (ER) for wheat were –363.6 (±SD 97.8) gC m^{-2}, 1173.9 (±189.1) gC m^{-2} and 810.0 (±161.0) gC m^{-2}, and were –135.8 (±168.2) gC m^{-2}, 1007.6 (±296.5) gC m^{-2}, and 871.8 (±283.5) gC m^{-2} for maize. The multiple regression revealed that, air temperature was the dominant factor of CO_2 fluxes for wheat; but in the maize season, incoming short-wave radiation and groundwater table were the dominant factors. For the full 2010-2011 cultural cycle, the CO_2 fluxes for wheat and maize were as follows: NEE –437.9 and –238.8 gC m^{-2}, GPP 1078.2 and 779.7 gC m^{-2}, ER 640.4 and 540.8 gC m^{-2}, soil heterotrophic respiration 376.8 and 292.2 gC m^{-2}, below-ground autotrophic respiration 135.5 and 115.4 gC m^{-2}, above-ground autotrophic respiration 128.0 and 133.2 gC m^{-2}. The net biome productivity was 58.8 (±SD 45.8) gC m^{-2} for wheat and 3.9 (±42.9) 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 cultural cycle.

However, when considering the total CO_2 loss in the fallow period, the net biome productivity was −41.2 (±3.1) gC m^{-2} yr^{-1} for the full 2010-2011 cycle, implying that the cropland was a weak CO_2 source in this period. The detailed investigation of the CO_2 budget components of this study provides valuable knowledge for sustainable cropland management in the context of climate change.

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

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

Biogeosciences Discussions

Introduction

There have been growing interests to investigate the terrestrial ecosystem CO_2 budget in the context of climate change (Falkowski et al., 2000; Poulter et al., 2014; Forkel et al., 2016), especially when the eddy covariance system is widely used to assess the carbon exchange of terrestrial ecosystems with the atmosphere (Aubinet et al., 2000; Baldocchi et al., 2001; Falge et al., 2002b). The eddy covariance technique only measures the Net Ecosystem Exchange (NEE) with the atmosphere. Despite appropriate algorithms are able to partition NEE into its two integrated components of Gross Primary Productivity (GPP) and Ecosystem Respiration (ER) (Falge et al., 2002a; Reichstein et al., 2005), lacking the detailed CO_2 budget hampers an in-depth understanding of the mechanisms underlying the terrestrial ecosystem carbon processes.

Numerical models are popular for evaluating large-scale CO_2 budget (Piao et al., 2012; Chen et al., 2016; Thompson et al., 2016). But models are usually difficult to calibrate due to limited direct measurements of the 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, therefore, required to not only calibrate models but also understand the

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

response of terrestrial ecosystems to changing climatic and environmental conditions (Heimann and Reichstein, 2008). Nevertheless, the most recent efforts of evaluating the detailed CO_2 budget components only appeared in limited studies for forests (Iglesias et al., 2013; Wu et al., 2013) and agro-ecosystems (Moureaux et al., 2008; Ceschia et al., 2010; Wang et al., 2015; Demyan et al., 2016; Gao et al., 2017).

Agro-ecosystems play an important role in regulating the global carbon balance (Lal, 2001; Bondeau et al., 2007; Özdoğan, 2011; Taylor et al., 2013) and 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; Torres et al., 2015). The field management practices (e.g., irrigation, fertilization and residue removal, etc.) impact the cropland CO_2 budget (Baker and Griffis, 2005; Béziat et al., 2009; Ceschia et al., 2010; Eugster et al., 2010; Soni et al., 2013; Drewniak et al., 2015; de la Motte et al., 2016; Hunt et al., 2016; Vick et al., 2016), but the key factors determining the cropland CO_2 budget remain unclear because of limited field observations (Kutsch et al., 2010), prompting the interest on comprehensive CO_2 budget assessments across different cropland management styles.

Over the past two decades, CO_2 evaluations of agro-ecosystems have mainly focused on the variations in the integrated 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 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

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

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 eddy covariance technique alone cannot capture lateral carbon fluxes associated with harvesting, residue treatment, and manure addition, which greatly impact the CO_2 budget in agro-ecosystems (Kutsch et al., 2010). To overcome this problem, several studies investigated Net Biome Productivity (NBP) using the eddy covariance technique complemented with auxiliary carbon measurements (i.e, harvest, residue, manure etc.) (Ceschia et al., 2010; Kutsch et al., 2010). Only a few studies reported the detailed CO_2 budget components (Moureaux et al., 2008; Aubinet et al., 2009; Jans et al., 2010; Wang et al., 2015; Demyan et al., 2016; Gao et al., 2017), but the results remain diverse regarding whether agro-ecosystems are carbon sinks or sources. Therefore, the CO_2 budget evaluation remains necessary to understand the contribution of agro-ecosystems to the global carbon balance (Smith et al., 2010).

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 is a common practice in the NCP to reduce the water stress in spring droughts. There are two major irrigation methods in the NCP, one is pumping groundwater to the surface which dramatically lowers the groundwater table (more than 20 m) for the piedmont plain of the Mount Taihang, and the other is withdrawing water from the Yellow River, resulting in a relatively higher groundwater table (range from 2

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Preprint. Discussion started: 2 January 2020

Biogeosciences Discussions
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to 4 m) along the Yellow River (Cao et al., 2016) (Fig. 1). Such high groundwater table along the Yellow River is the major difference from the groundwater-fed cropland (Shen et al., 2013). Wang et al. (2015) suggested that the groundwater-fed croplands in the piedmont plain of Mount Taihang (Luancheng site in Fig. 1) were losing carbon at the rate of 77 gC m^{-2} yr^{-1}, and other studies also reported that the cropland in this region was a carbon source (Li et al., 2006; Luo et al., 2008; Lei and Yang, 2010). However, it remains unknown whether such conclusion holds across the whole NCP region with diverse microclimates and management practices. Lacking such knowledge limits our understanding of how this typical wheat-maize cropland contributes to the regional carbon cycle, motivating this study.

To assess the long-term variation of CO_2 fluxes and its budget of the typical wheat-maize rotation cropland in the NCP, we conducted a comprehensive field experiment. The eddy covariance system was used to measure the CO_2 exchange from 2005 through 2016. For the full 2010-2011 cultural cycle, we also conducted soil respiration measurements and plant carbon samplings to quantify the detailed CO_2 budget components. These measurements (1) allow for evaluating the long-term CO_2 flux (NEE, GPP, and ER) trend over this cropland; (2) provide the detailed CO_2 budget components; and (3) allow for estimating the Net Primary Productivity (NPP), Net Ecosystem Productivity (NEP), and Net Biome Productivity (NBP).

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

Materials and methods

Site description and field management

The experiment was conducted in a rectangular-shaped (460 m × 280 m) field of the typical 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 typical cropping style in this region. On average, the winter wheat is sown around October 17th and harvested around June 16th of the following year with crop residues left on the field; summer maize is sown following the wheat harvest around June 17th and harvested around October 16th. 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, where the use of nitrogen is 35 gN m^{-2} for wheat and 20 gN m^{-2} for maize according to the field inventory. The plant density of wheat is about 775 plants m^{-2} with a ridge spacing of 0.26 m, and the plant density of maize is about 4.9 plants m^{-2} with a ridge spacing of 0.63 m.

Wheat is commonly irrigated with water diverted from the Yellow River and the irrigation is ~150 mm every year; maize is rarely irrigated because of precipitation is usually sufficeint. The water withdrawal from the Yellow River results in an elevated groundwater table (fluctuating between 0 and 4 m) in this region (Fig. 1).

(Fig. 1 here)

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

Eddy covariance measurements

A flux tower was set up in the center of the experiment field in 2005 (Let and Yang et al., 2011; 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 within 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, and ER_{ref} is the reference respiration at 0 °C, and b is the

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

temperature sensitivity 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 ER_{ref} parameter in each of the four-day window by fitting the Eq. (1), and ER_{ref} of each day was finally estimated by using the least square spline approximation (Lei and Yang, 2010).

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

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

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,

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

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 total CO_2 budget of this rotation cycle, the

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

Support Vector Regression (SVR) method was used to calculate GPP and ER directly for this period (Cristianini and Shave-Taylor, 2000) and NEE was derived accordingly as the difference between GPP and ER (see Appendix A for details).

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.) at the depth of 5 cm; soil matric potential (ψ) (257-L, Campbell Scientific Inc.) was measured since 2010 at the same depth. The groundwater table (WT) (CS420-L, Campbell Scientific Inc.) was measured at a location close to the meteorological station in 30-min intervals.

Biometric measurements and crop samplings

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

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

field. For crop samplings, four locations were randomly selected at the start of the growing season, crop samples were then collected in these four locations throughout the experimental period. At each location, 10 crop samples were collected in the wheat season and 3 crop samples were collected during the maize season. To reduce the sampling uncertainty at harvest, 200 crops and 5 crops were collected in each location during the wheat season and maize season, respectively. The crop organs were separated and oven-dried at 105 °C for kill-enzyme torrefaction for 30 min, and then were oven-dried at 75 °C until a constant weight. The crop samplings allowed for directly estimating 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 samplings allowed for a direct estimate of the Net Primary Productivity (NPP).

Soil respiration measurements

Soil respiration was measured every day in the footprint of 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 (R_{AB}) and heterotrophic respiration (R_{H}) were differentiated using the root exclusion method (Wan and Luo, 2003; Jassal et al., 2012; 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 spatial

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

representativeness of soil respiration measurements was guaranteed by the uniform crops and field conditions (see Zhang et al., 2013). To assess the seasonal variations and total amount of soil respiration, 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 other parameters were inferred from the R_H measurements, where A=1.16, B=0.0503, and a= –44.9 (Zhang et al., 2013).

The R_{AB} of wheat was assumed to be 0 before March 14 due to the negligible plant biomass, while R_{AB} of other periods was estimated based on the R_H record and the contribution ratio of the R_{AB} to R_S estimated previously (Zhang et al., 2013). The continuous contribution ratio of R_{AB} was interpolated from the daily records (Fig. 2). This estimation method is robust because the ratio of R_{AB} to R_S is nearly constant around its diurnal average (Zhang et al., 2015b).

In order to estimate the decay rate of soil organic carbon (SOC), we took soil samples from the top 20 cm soil at 10 different locations randomly distributed in the field every 2-3 weeks from March to November in 2011. The SOC was then analyzed by using the combustion oxidation-titration method (National Standards of Environmental Protection of the People's Republic of China, 2013). The SOC decay ultimately turns into R_H, and is able to provide an independent estimate of the seasonal total R_H.

(Fig. 2 here)

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

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 samplings. 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 the carbon storage in plant biomass, and can be calculated as the difference between eddy covariance-derived 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. Meanwhile, NPP can also be directly inferred from biomass samplings by,

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

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

Biogeosciences Discussions
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where the subscript "CS" indicates that NPP is based on crop samplings, and C_{cro} is the amount of carbon storage in biomass at harvest.

NEP is commonly estimated by the NEE measurement (NEP_{EC}=–NEE). In this study, the crop samplings and soil respiration measurements provided another independent estimate as,

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

At the site, there were no disturbances related to fire and insect, and there was no manure fertilization application. The carbon input from seeds was negligible, and all crop residues were returned to the field. Thus, NBP can be estimated as the difference between NEP and carbon loss associated with the grain export,

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

where C_{gra} is the amount of carbon loss due to grain export at harvest. NEP can be estimated using two independent methods as aforementioned, therefore, we had two independent NBP estimates and used the standard deviation of the two measurements to quantify the overall uncertainty of the CO_2 budget evaluation. During the 2010-2011 cultural cycle with CO_2 budget components evaluated, winter wheat was sown on October 23rd, 2010 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 for this cultural cycle.

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

Results

Meteorological conditions and crop development

The inter-annual variations of major meteorological variables were 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 R_{si} and T_a were very close to other years; however, the P during maize season was higher than other years (Fig. 3c), leading to a shallow WT in maize season (Fig. 3d). The intra-annual variations of field microclimates for the full 2010-2011 cycle were 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 WT mainly followed the irrigation events in winter and spring, but followed precipitation in summer and autumn. In particular, the WT varied from 0 to 3 m throughout the year. The wet soil conditions prohibited the field from experiencing water stress (Fig. 4d) because 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 values were 4.2 and 3.6 m^2 m^{-2} for wheat and maize, respectively. 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 1, April 20, May 1, May 7, and June 5, respectively. The seasonal variations in DM agreed well with the crop stages (Fig. 6), and the

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

wheat biomass mainly accumulated in April and May, while maize biomass mainly accumulated in July and August. The total DM was 1, 717.5 g m^{-2} for wheat and 1, 262.4 g m^{-2} for maize at harvest. Upon harvest, the wheat DM was distributed as: 3.0 % root, 42.7 % stem, 9.3 % leaf and 45.0 % grain, while the maize DM was distributed as: 2.3 % root, 29.2% stem, 7.1% green leaf, 4.6% dead leaf, 4.0% bracket, 7.3% cob, and 45.5% grain. The average carbon contents of the root, stem, green leaf, dead leaf, and grain were 410.4, 439.4, 486.0, 452.0 and 457.5 gC kg^{-1} DM for wheat and, 407.7, 437.8, 477.2, 457.0, and 455.5 gC kg^{-1} DM for maize (Table 1).

(Table 1 here).

(Figs. 5&6 here)

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

From 2005 through 2016, if grain export was not considered, the wheat field was a consistent CO_2 sink as seasonal total NEE was consistently negative, and the maize field 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 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 are −363.6 (±97.8) gC m^{-2}, 1173.9 (±189.2) gC m^{-2} and 810.3 (±161.0) gC m^{-2} for wheat, and −135.8 (±168.2) gC m^{-2}, 1007.6 (±296.5) gC m^{-2}, and 871.8 (±283.5) gC m^{-2}

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

for maize, respectively. The NEE, GPP and ER for both wheat and maize were correlated with the three main environmental variables of R_{si}, T_a and WT using multiple regression (see Appendix B for details). In the wheat season, T_a was the dominant factor in controlling all the three CO_2 fluxes, and a higher T_a increased both GPP and ER, and also enhanced NEE (Fig. 8a); R_{si} showed negligible effect to all the three CO_2 fluxes; higher WT contributed to decrease GPP, thereby reduce NEE. In the maize season, WT had pronounced contribution to both GPP and ER, as well as to NEE; the contribution of T_a was moderate to GPP, but was negligible to ER; in contrast, the contribution of R_{si} was pronounced to ER, but was negligible to GPP (Fig. 8b). Overall, R_{si} was the dominant factor controlling inter-annual variation of maize followed by the WT and T_a (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 the wheat dormant season, the field still sequestered carbon though in a low magnitude; 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 and May 8 with positive NEE (i.e., net carbon release). These spikes resulted from the inclement weather and the radiation decline (Fig. 4b), which suppressed the crop metabolism

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

rate; similar phenomena 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 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

CO_2 budget analysis showed that this wheat-maize rotation cropland has a great potential to uptake carbon from the atmosphere (Fig. 11). In the full 2010-2011 cycle, the total NEE, GPP and ER values were −437.9, 1078.2, and 640.4 gC m^{-2} for wheat, and −238.8, 779.7 and 540.8 gC m^{-2} for maize. The NPP values were 749.9 and 814.7 gC m^{-2} for wheat based on crop sampling and the eddy covariance complemented with soil respiration measurements, respectively, and were 591.6 and 531.9 gC m^{-2} for maize based on the two methods. Considering carbon loss in the form of R_H, NEP values for wheat were 373.1 and 437.9 gC m^{-2} based on the crop sampling and eddy covariance measurements, and were 299.4 and 238.8 gC m^{-2} for maize based on the two methods. Furthermore, the carbon loss associated with the grain export was 346.7 and 265.2 gC m^{-2} for wheat and maize, respectively. Therefore, the NBP values was 26.4 and 91.2 gC m^{-2} for wheat based on the two methods, and 34.2 and

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

−26.4 gC m^{-2} for maize based on the two methods. Averaging the results of the two methods resulted in the following estimates of NPP, NEP and NBP: 782.3, 405.5, and 58.8 (±45.8) gC m^{-2} for the wheat season and 561.8, 269.1, and 3.9 (±42.9) gC m^{-2} for the maize season. Considering the net CO_2 loss of −103.9 gC m^{-2} during the two fallow periods, NBP values of the whole wheat-maize crop cycle were −43.3 and −38.9 gC m^{-2} yr^{-1} based on the two methods. Averaging the values from the two methods resulted in an NBP of −41.2 (±3.1) gC m^{-2} yr^{-1}, suggesting that the cropland was a weak carbon source to the atmosphere.

(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, furthermore, the detailed CO_2 budget components were quantified for a full wheat-maize cultural cycle. The inter-annual variations of the carbon fluxes of wheat showed close dependence on temperature, while those of maize were mostly regulated by the groundwater table. The detailed quantifications of the CO_2 budget of this typical cropland will not only provide useful knowledge for reginal greenhouse gas emission evaluation, but also provide insights to improve the development of carbon models for such typical wheat-maize rotation croplands.

Comparison with other croplands

No consensus has been reached regarding the role of cropland plays in global carbon cycle, some studies reported cropland as carbon neutral to the atmosphere (e.g, Ciais et al., 2010), but some believed it to be a source (e.g., Anthoni et al., 2004a; Verma et al., 2005; Kutsch et

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

al., 2010; Wang et al., 2015; Eichelmann et al., 2016), and others reported it as a carbon sink (e.g., Kutsch et al., 2010). Such inconsistency probably results from the different crop types and management strategies (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 high groundwater table was a weak CO_2 sink during both the wheat and maize seasons in the full 2010-2011 cycle, but the carbon loss during the fallow period reversed the cropland from a sink to a weak carbon source with an NBP of −41.2 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 losses were much lower at our site, most likely due to the different cropland management strategies and edaphic conditions.

The annual total NPP of 1, 344.1 gC m^{-2} yr^{-1} at our site is approximately twice the average of the model-estimated NPP for Chinese croplands (714.0 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 a 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 carbon content of wheat is comparable to the average value of 430 gC kg^{-1} DM from another study (Moureaux et al., 2008). The carbon content of maize organs are different from

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

the findings of Jans et al. (2010) that reported the carbon contents of the root, stem, leaf and grain as 316, 252, 452 and 468 gC kg^{-1} DM (converted from the unit of %). The carbon contents of root and stem reported by Jans et al. (2010) are much lower than our results. These contrasting results suggest that the carbon content of crops may depend on climatic and environmental conditions.

The effects of groundwater on carbon fluxes

Our site experienced short-period of water logging due to the combined effects of full irrigation and the high precipitation during the summer maize season. 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 considerate in water-logged soils. Additional field experiments remain required to understand how irrigation and water saturation field condition impact the overall carbon budget.

The three components of ER in our study also showed pronounced difference with the results of Wang et al. (2015) at the nearby Luancheng site, where they report the R_{AA} is 411 gC m^{-2} for wheat and 428 gC m^{-2} for maize, three times the results of our study (128.0 gC m^{-2} for wheat and 133.2 gC m^{-2} for maize). However, their R_{AB} is 36 gC m^{-2} for wheat and 16 gC m^{-2}

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

for maize, less than a quarter of our results (135.5 gC m^{-2} for wheat and 115.4 gC m^{-2} for maize). Their R_H of wheat (245 gC m^{-2}) is less than our estimate (376.8 gC m^{-2}), but R_H of maize (397 gC m^{-2}) is greater than our result (292.2 gC m^{-2}). These independent cross-site comparisons demonstrate that carbon budget components may be subject to the specific cropland management strategies, and even the same crop under similar climatic conditions can behave differently in carbon uptake. The groundwater table at our site is considerably high because of the water withdrawal for irrigation from the Yellow River, but the Luancheng site (Wang et al., 2015) is groundwater-fed with a very deep groundwater table (approximately 42 m) (Shen et al. 2013), characterizing a major difference between these two sites in the North China Plain with similar crop types, fertilization practices, and fallow periods etc. The water logging events and the associated high soil moisture at our site, contribute to the lower GPP and ER during the maize season (Fig. 8b). However, ER was reduced by a greater degree than GPP, thereby contributing to the lower CO_2 loss during the maize season. In contrast, Verma et al. (2005) reported that irrigation reversed a maize cropland from a carbon sink to a source because irrigation enhanced the corn production, which was ultimately exported from the cropland. No consensus has been reached on how irrigation impacts the cropland carbon behavior, and these comparisons point to the necessity of investigating how irrigation may change the cropland carbon budget.

Field managements influence the carbon budget feature

Globally, the carbon use efficiency (NPP/GPP) of crops (Table 2) is relatively higher than the average value of 0.53 of forests (the slope of NPP against GPP, Delucia et al., 2007) (Griffis

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

et al., 2004; Jassal et al., 2007; Wu et al., 2013) and the average of 0.52 of terrestrial ecosystems (Zhang et al., 2009). In particular, comparisons with the results of Delucia et al. (2007) show that cropland is more efficient in sequestering CO_2 from the atmosphere than forests. The carbon use efficiency estimates at our site (0.73 for wheat and 0.72 for maize) are higher than the average value of 0.58 for croplands (Zhao et al., 2005) and for most other croplands of the same variety (0.54 for a wheat cropland in the study of Moureaux et al. , 2008; 0.45 and 0.56 for wheat cropland in the study by Aubinet et al., 2009; 0.55 for a wheat cropland in the study by Suleau et al., 2011; 0.57 for a wheat cropland and 0.55 for a maize cropland by Wang et al., 2015; 0.51 and 0.35 for a wheat cropland and maize cropland in Demyan et al., 2016). Considering the intense cropland management at our site, these results imply that full irrigation and fertilization may contribute to a higher carbon use efficiency. The carbon use efficiencies in our study are comparable with those of chickpea (0.74), sorghum (0.70), sunflower (0.68) and wheat (0.77) reported by Albrizio and Steduto (2003). The consistently high carbon use efficiencies of various species in our study and those reported by Albrizio and Steduto (2003) suggest that the carbon use efficiency may depend on both the site-specific microclimates and management strategies.

The contrasting respiration partitionings of the same crop in different regions (e.g, wheat in our study compared with Moureaux et al., 2008, Aubinet et al., 2009, Suleau et al., 2011, Wang et al., 2015 and Demyan et al., 2016) (Table 2) indicate that the respiration processes may also be subject to climatic conditions and management practices. In particular, the ratio of heterotrophic respiration to ecosystem respiration (R_H/ER) is greater in our study than

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

others, probably because of the full irrigation and shallow groundwater table prohibiting the soil from water stress. 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 show that ecosystem respiration is usually dominated by below-ground and above-ground autotrophic respirations. Higher autotrophic respiration (R_{AA}+R_{AB}) in those studies return a higher percentage of the assimilated carbon (i.e., GPP) to the atmosphere, thereby resulting in a relatively lower carbon use efficiency.

(Table 2 here)

Uncertainty in the estimation and limitation of this study

In the comprehensive experiment period for the full 2010-2011 cultural cycle, the NEE of wheat season from October 23, 2010 to April 1, 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 samplings 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 only 10 % of the crop (Jackson et al., 1996). The relatively low root ratios at harvest probably result from the

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

Biogeosciences Discussions

root decay due to 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 (Bahn et al., 2008; Phillips et al., 2010; 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; Latimer and Risk, 2016), allowing the confidence in the estimates. Furthermore, the SOC samplings showed that the surface 20 cm soil had been losing carbon at a rate of 0.0077 gC kg^{-1} soil d^{-1} (Fig. 12). The bulk soil density is about 1, 300 kg m^{-3}, then the SOC decay will release 1.93 μmol m^{-2} s^{-1} CO_2 - an amount of 730.7 gC m^{-2} yr^{-1} soil heterotrophic respiration if integrated to the annual scale. The value is very close to 789.2 gC m^{-2} yr^{-1} estimated by soil respiration measurements, again allowing the confidence of the estimation quality.

(Fig. 12 here)

During the wheat season, the cumulative curves of NPP_{EC} and NPP_{CS} were not perfectly consistent in the main growing season because clear differences emerged during the dormant period of winter wheat from December 15, 2010 to March 8, 2011 (Fig. 13). These differences may result from the insufficient wheat sampling. However, the samples at harvest were sufficient and no discernible differences was found between the two NPPs at harvest. These two independent estimates of NPP were similar throughout the maize season (Fig. 13). Crop sampling and eddy covariance methods provided consistently positive NBP estimates for wheat, implying that wheat was a robust carbon sink. However, the two methods provided opposite results for maize-one of them showing maize as a carbon sink while the other as a

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

carbon source. The average of these two methods implies that maize is close to being carbon neural. The uncertainty analysis indicates an overall good quality of the CO_2 budget evaluation.

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 inter-annual variations of CO_2 budget components remain to be explored in the future. The integrated carbon fluxes (NEE, GPP and ER) have pronounced inter-annual variations, also suggesting further investigations remain required on the inter-annual variations of the carbon budget components.

(Fig. 13 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 is a strong CO_2 sink with mean annual NEE of –493.3 (±292.6) gC m^{-2} yr^{-1} if grain export was not considered. But the carbon sequestration capacity of this cropland became weaker during the past decade. In the comprehensive experiment conducted in the full 2010-2011 cultural cycle, we found the cropland was a weak CO_2 source with an NBP of –41.2 gC m^{-2} yr^{-1} when considering the grain export. In this full cultural cycle, most of the carbon sequestration occurred during the wheat season with an NBP of 58.8 gC m^{-2}, while maize was close to being CO_2 neutral with an NBP of 3.9 gC m^{-2}. The net CO_2 loss (103.9 gC m^{-2}) in the two fallow periods significantly diminished the carbon sink. The NPP values were 782.3 and 561.8 gC m^{-2} for wheat and

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

maize, respectively. Considering the carbon loss associated with the soil heterotrophic respiration, the NEP values were 405.5 and 269.1 gC m^{-2} for wheat and maize. Air temperature was the dominant factor controlling the inter-annual variations of CO_2 fluxes in the wheat season, while groundwater table played an important role in maize season. This study provides valuable knowledge not only for carbon model development, but also for the sustainable cropland management to mitigate global carbon emission.

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

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 (θ) are the dominant factors. Hence, we select T_a, RH, PAI, PAR, and θ as explanatory variables of GPP. Ecosystem Respiration (ER) consists of total soil respiration and above-ground autotrophic respiration, 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 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://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

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.

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

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 table (WT) as flux=aR_{si}+bT_a+cWT+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. All authors contributed to interpretation of results. Q.Z. drafted the manuscript. All authors edited and approved the final manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Biogeosciences Discussions

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Biogeosciences Discussions
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947 **Tables and figure**

948 Table 1 Carbon content of different crop organs (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

949

https://doi.org/10.5194/bg-2019-494
Preprint. Discussion started: 2 January 2020

Table 2 Various ratios associated with carbon behaviors in different ecosystems

plant type or species	NPP/GPP[a]	ER/GPP	R_A/GPP[a]	C_{gra}/NPP	R_H/ER	R_{AB}/ER	R_{AA}/ER	source
aspen	0.54	0.76	(0.46)	-	(0.73)[b]		0.27[c]	Griffis et al. (2004)
deciduous forest	0.38	0.86	0.62	-	0.28	0.72[d]		Wu et al. (2013)
douglas-fir	0.47	0.86	(0.53)	-	(0.63)[b]		0.37[c]	Jassal et al. (2007)
chickpea	0.74	-	(0.26)	-	-	-	-	Albrizio and Steduto (2003)
maize	0.72	0.69	0.32	0.47	0.54	0.21	0.25	**this study**
maize	0.44	0.67	0.56	-	0.16	0.25	0.59	Jans et al. (2010)
maize	0.55	0.85	0.45	0.57	0.47	0.02	0.51	Wang et al. (2015)
maize	(0.35)	0.80	0.65	-	0.19	0.21	0.60	Demyan et al. (2016)[e]
potato	0.60	0.48	0.37	0.81[f]	0.24	0.76		Aubinet et al. (2009)[g]
potato	(0.68)	0.47	0.32	-	0.33	0.14	0.53	Suleau et al. (2011)
sorghum	0.70	-	(0.30)	-	-	-	-	Albrizio and Steduto (2003)
sugar beet	0.71	0.44	0.30	0.62[f]	0.31	0.69		Aubinet et al. (2009)[g]
sugar beet	(0.78)	0.36	0.22	-	0.37	0.25	0.36	Suleau et al. (2011)
sunflower	0.68	-	(0.32)	-	-	-	-	Albrizio and Steduto (2003)
wheat	0.73	0.59	0.24	0.44	0.59	0.21	0.20	**this study**
wheat	0.77	-	(0.23)	-	-	-	-	Albrizio and Steduto, (2003)
wheat	0.54	0.61	0.46	-	0.24	0.31	0.45	Moureaux et al. (2008)
wheat (2005)	0.56	0.60	0.44	0.42	0.26	0.74		Aubinet et al. (2009)[g]
wheat (2007)	0.45	0.57	0.48	0.41	0.15	0.85		Aubinet et al. (2009)[g]
wheat	(0.55)	0.57	0.45	-	0.21	0.17	0.62	Suleau et al. (2011)
wheat	0.57	0.66	0.43	0.45	0.35	0.05	0.59	Wang et al. (2015)
wheat	(0.51)	0.71	0.49	-	0.31	0.19	0.50	Demyan et al. (2016)[e]

Note:

a- NPP+R_A=GPP, we list both of NPP/GPP and R_A/GPP, the values in parentheses indicate that the value is calculated by the aforementioned closed equation. Our study estimates NPP with two methods so that the equation is not closed, estimates in Aubinet et al. (2009) are not closed either because they used different models to estimate respirations.

b- Ratio of total soil respiration to ecosystem respiration, i.e, R_S/ER or (R_H + R_{AB})/ER

c- Obtained as 1−R_S/ER

d- Ratio of autotrophic respiration to ecosystem respiration, i.e, R_A/ER=1−R_H/ER

e- The data was from 2012, and the estimation is based on the averaged carbon flux (ER and GPP) of both static and dynamic methods

f- The 'grain' production refers to the production of sugar beet root

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

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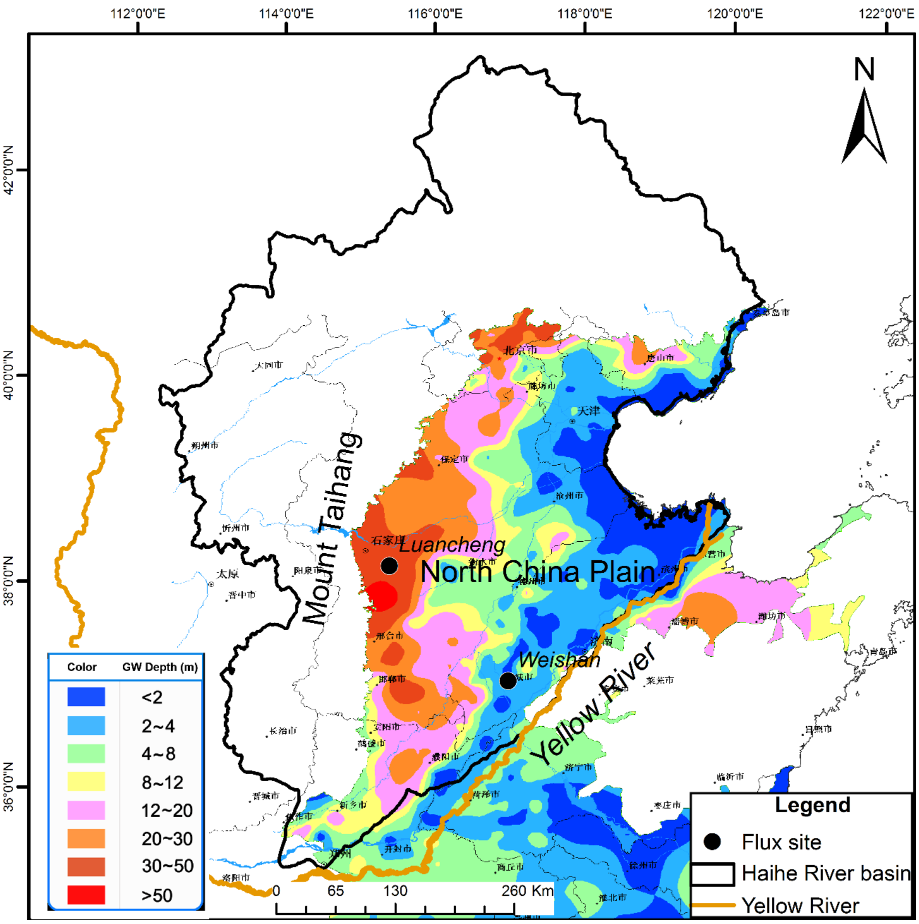
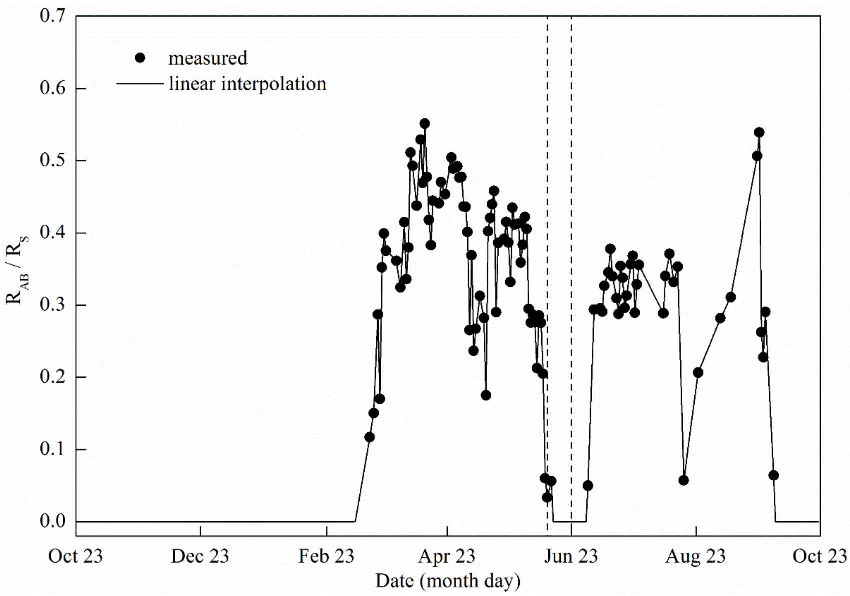


Fig. 1 Location of the experimental site. The background is the shallow groundwater depth in early September of 2011 (source: http://dxs.hydroinfo.gov.cn/shuiziyuan/)



955

956 Fig. 2 Seasonal variations in the ratio of below-ground autotrophic respiration (R_{AB}) to total

957 soil respiration (R_S). Two vertical dashed lines (here and after) represent the date of harvesting

958 wheat and sowing maize, respectively.

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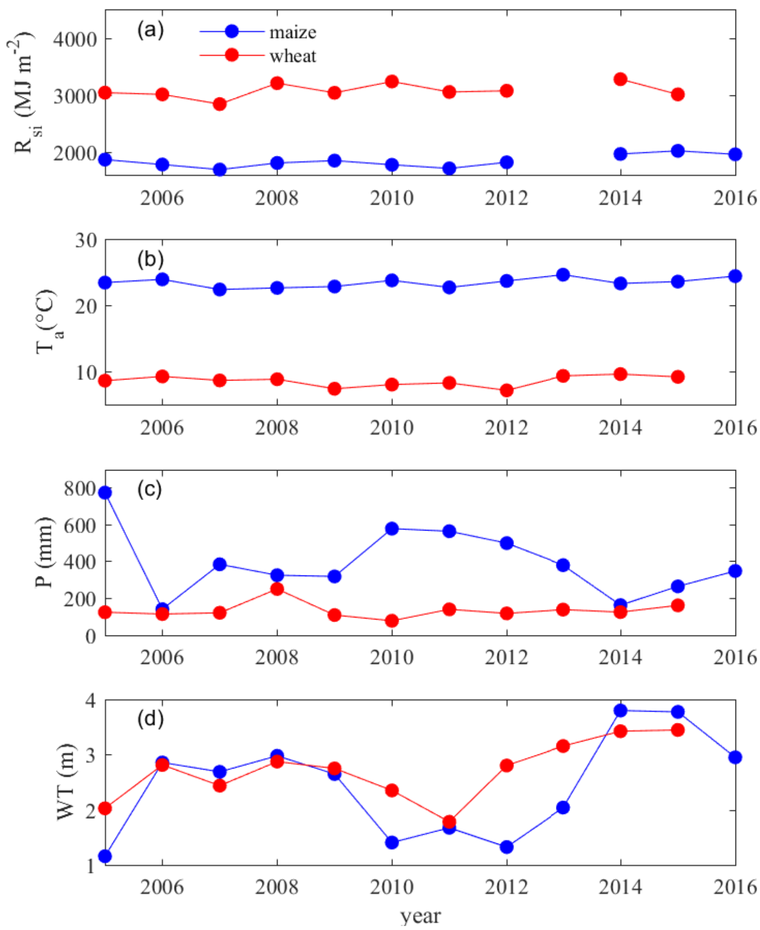

959

960 Fig. 3 The seasonal total incoming short-wave radiation (a), average air temperature (b), total
961 precipitation (c) and average groundwater table (d) for both wheat and maize evaluated for the
962 period from 2005 through 2016. Note that incoming short-wave radiation in the 2013 season
963 was missing due to euqipment malfunction.

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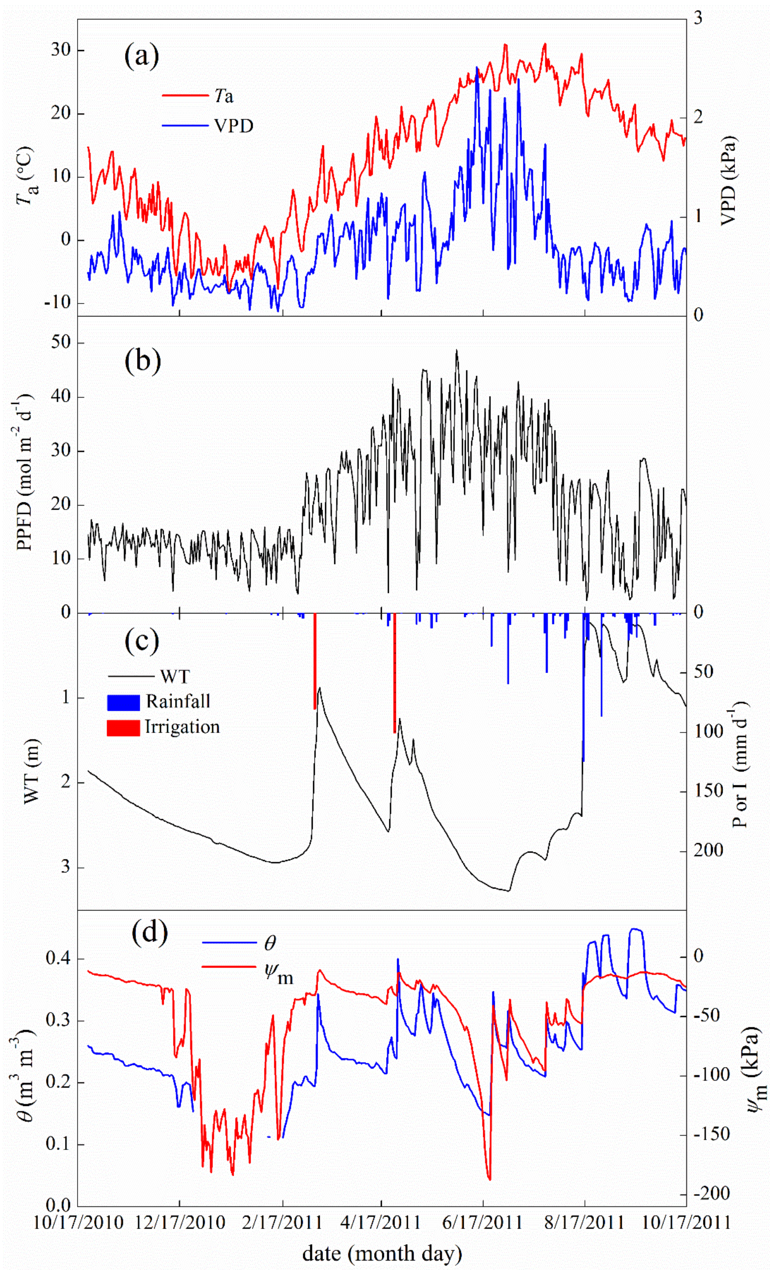

Fig. 4 Seasonal variations in the environmental variables of (a) air temperature (T_a), soil temperature at 5cm depth (T_s) and vapor pressure deficit (VPD), (b) photosynthetic photon flux density (PPFD), (c) precipitation (P), irrigation (I) and groundwater table (WT) and (d)

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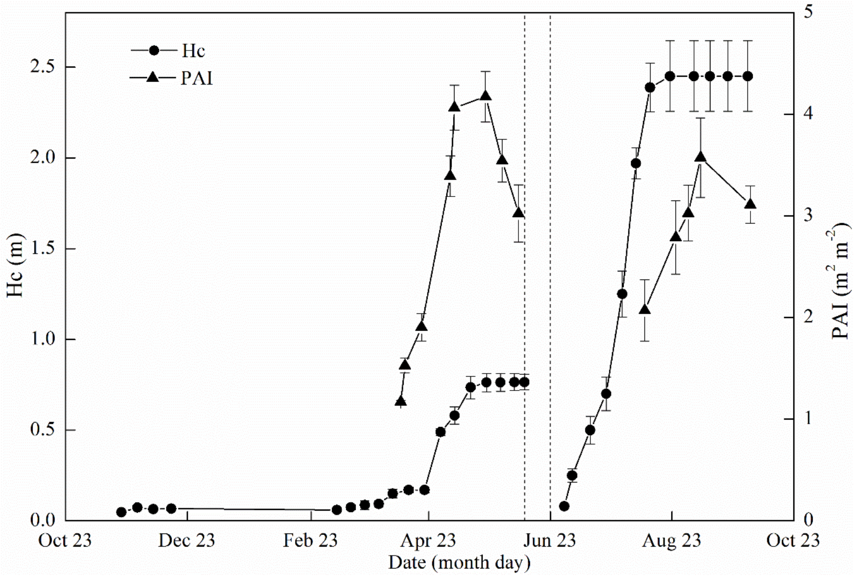
968 volumetric soil moisture (θ) and soil matric potential (ψ_m).

969 

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

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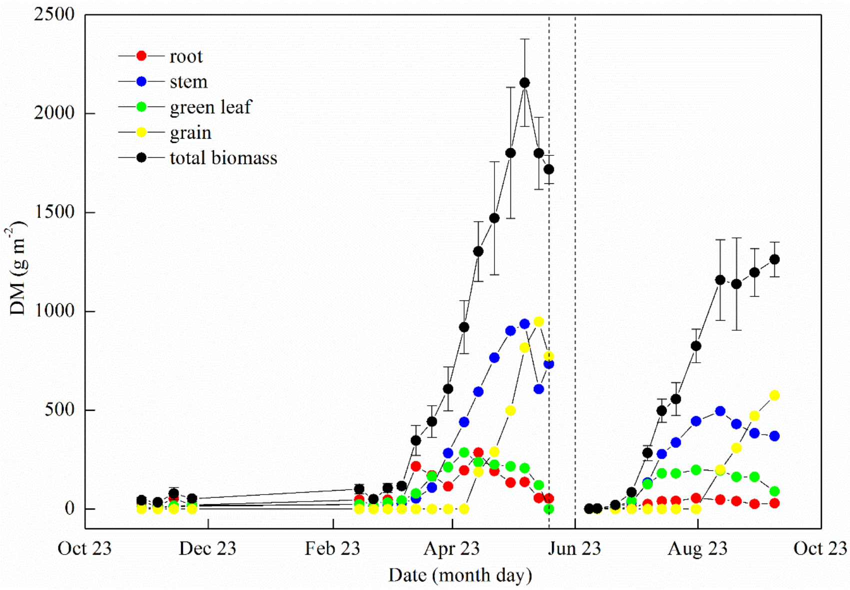

Fig. 6 Seasonal variations in the total dry biomass (DM) and its major parts of root, stem, green leaf and grain. The error bars of total biomass denote 1 standard deviation of the four sampling points.

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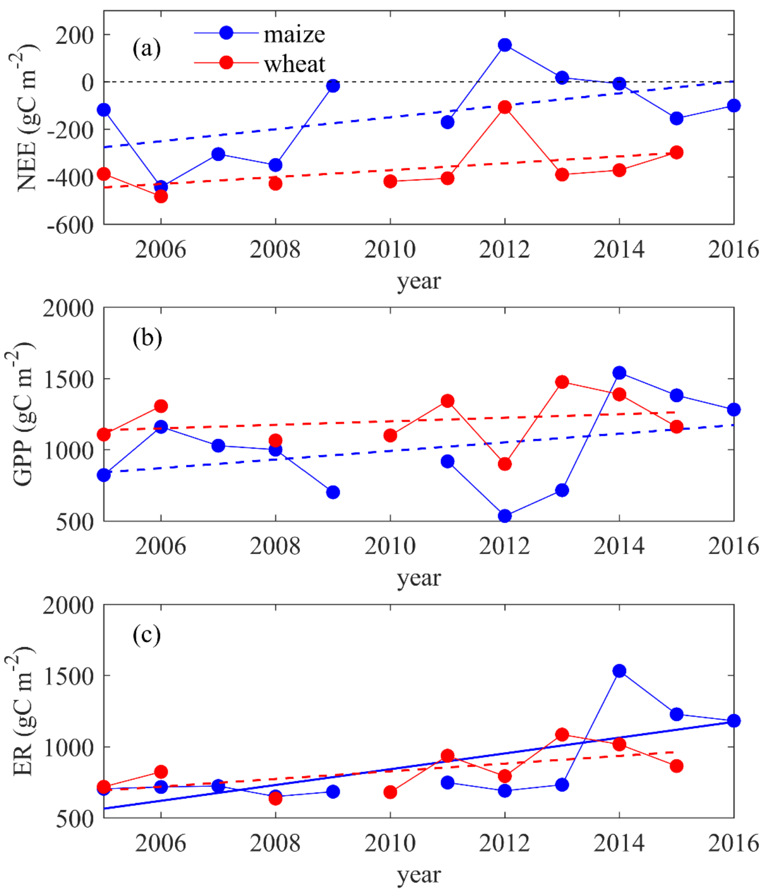
Preprint. Discussion started: 2 January 2020



976

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

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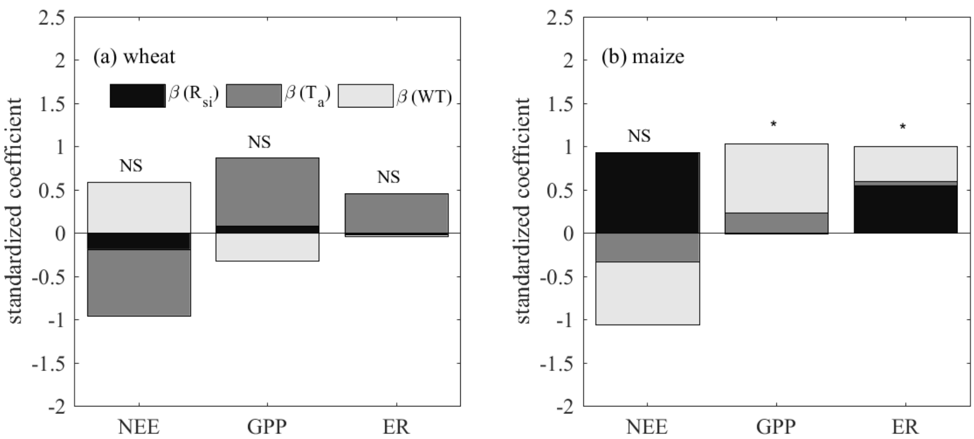

Fig. 8 The result of multipe regression for NEE, GPP and ER with incoming short-wave radiation (R_{si}), air temperature (T_a) and groundwater table (WT) for both (a) wheat and (b) maize. Note that * denotes that the regression passes $p<0.05$ significance level, and NS indicates non-significant.

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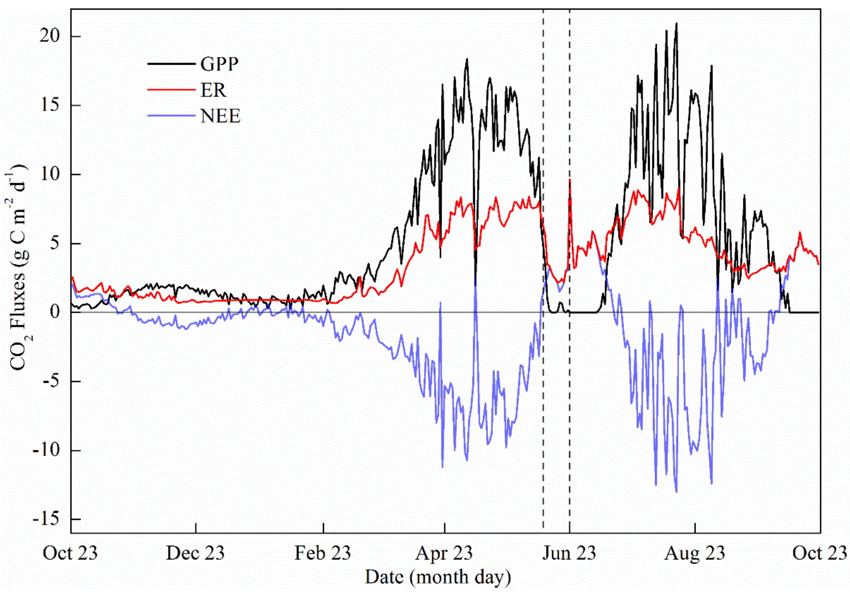

991

992 Fig. 9 Seasonal variations in gross primary producrivity (GPP), net ecosystem exchange
993 (NEE) and ecosystem respiration (ER) (those before April 2 were calculated with SVR
994 method.

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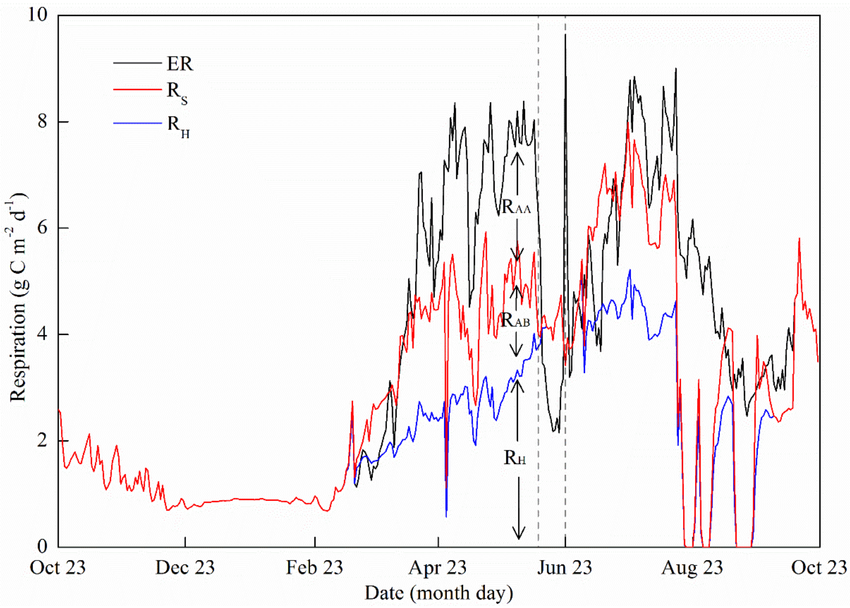

Fig. 10 Seasonal variations in the components of ecosystem respiration (ER), total soil respiration (R_S), soil heterotrophic respiration (R_H). The difference between ER and R_S denotes above-ground autotrophic respiration (R_{AA}), and the difference between R_S and R_H denotes below-ground autotrophic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

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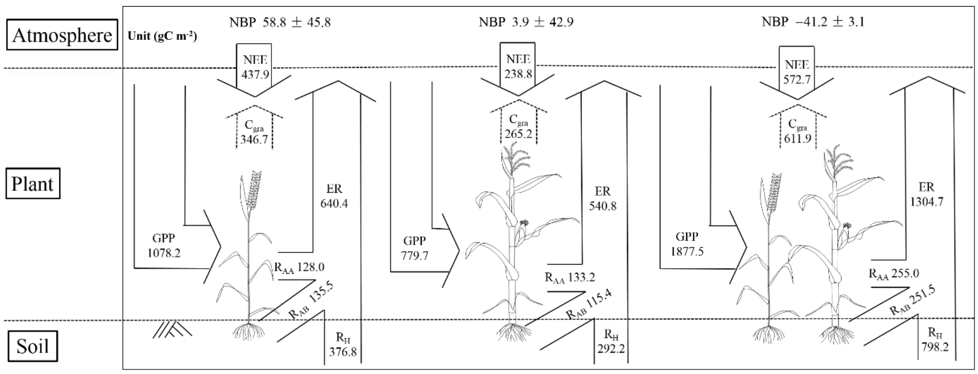

Fig. 11 Carbon budget of wheat (left), maize (middle) and the full wheat-maize rotation cycle with fallow periods included (right). Note that NEE shown here is measured by eddy covariance to maintain the carbon balance, and NBPs of wheat and maize are the average of two independent methods with standard deviation provided (i.e, eddy covariance-based and crop sampling-based)

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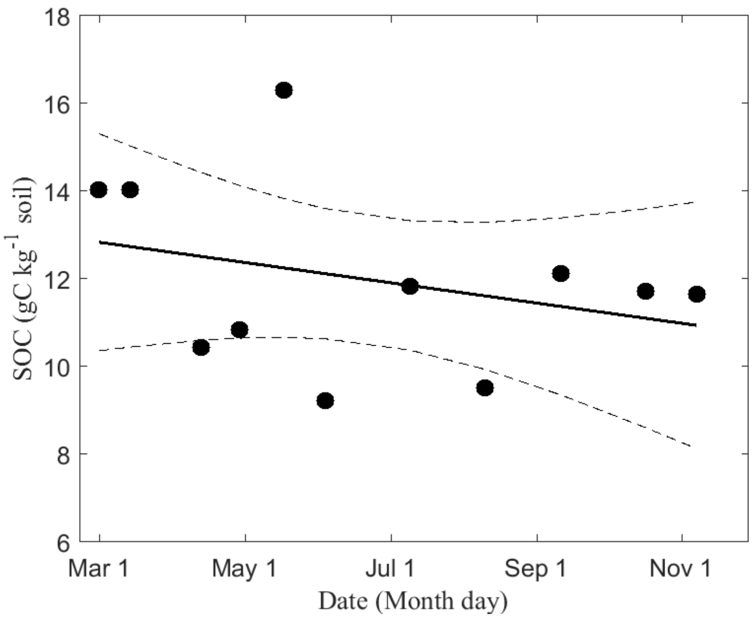

1007

1008 Fig. 12 The decay rate of soil organic carbon (SOC) of the top 20cm soil in 2011. The thick

1009 black line denotes the linear regression, and the two dashed lines denote the 95% confidence

1010 interval. The slope of the linear regression is –0.0077 gC kg^{-1} soil d^{-1} with R^2=0.10.

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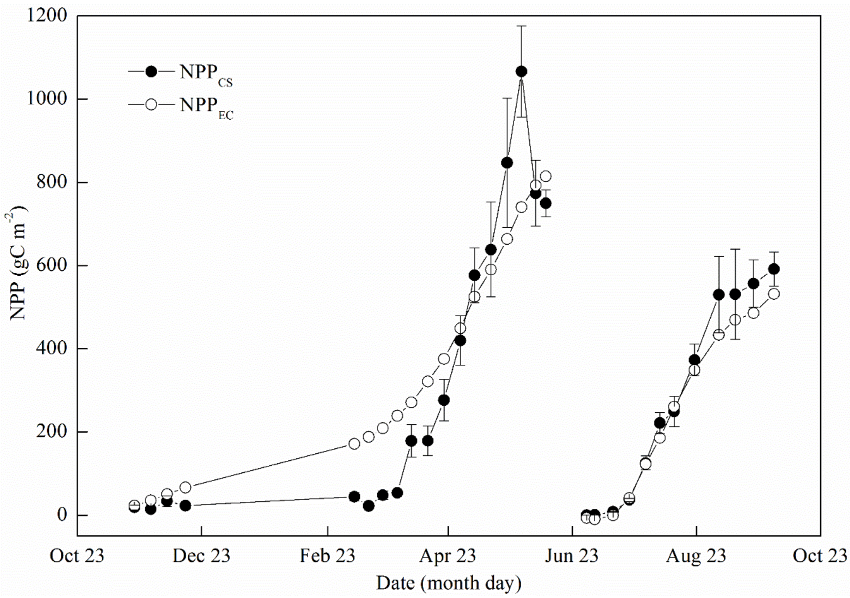

1012
1013 Fig. 13 Seasonal variations in the cumulative Net Primary Productivity (NPP) with two
1014 independent methods of Crop Sampling (NPP_{CS}) and Eddy Covariance (NPP_{EC})
1015 complemented with soil respiration measurements.