Dear editor P. C. Stoy, reviewers Dr. R. Scott and S. Spawn,

We thank you for providing the insightful and constructive comments. We carefully edited the paper according to these comments and suggestions. We hope the revised version of the manuscript is to your satisfaction, and of course, we are more than happy to improve the manuscript if new comments and suggestions might arise.

Reviewer: 1

This paper presents an assessment of the 10 yr carbon budget of wheat/corn crop rotation along with a much more detailed component assessment over the course of one year in China. The authors use both long-term eddy covariance observations along with respiration measurements and a comprehensive array of biophysical ones for their analysis. The main result is a comprehensive carbon budget for this cropping system as well as some estimates of the controlling drivers and a comparison with previously published agroecosystem C budgets.

The paper is well written. The results are clearly presented and the discussion is well framed. There is a great need for these kinds of studies so that the large uncertainty in carbon budgets of agroecosystems can be reduced. I have no major objections to this paper being published. The weakest part of the paper is its consideration of uncertainty. Ideally, it would be great to see confidence intervals given on the detailed crop budgets, but this is difficult to address and not easy to improve. I have just a few stylistic suggestions to improve the paper's presentation.

Response

We appreciate your positive evaluation and constructive comments. We have revised the manuscript thoroughly according to all the comments. Please see our response to the specific comments.

1. Throughout the paper, "groundwater table" is used to indicate "depth to groundwater" or "water table depth" or even "groundwater depth". One of these later terms should be used. (e.g., L. 27). Likewise, "cultural" is used to indicate "agricultural". This should be changed to "crop" or "agricultural" cycle.

Response

All these suggestions are adopted and all the texts are updated. We use "groundwater depth" and “agricultural” in the revised manuscript.

2. All throughout the paper, C balance figures are reported down to the 1/10th’s of a g C. I’d suggest rounding these off to the nearest whole number which would make it easier to read as well as not convey such high level of confidence in their accuracy (maybe even consider rounding the nearest 10’s).

Response:

We appreciate the comment, we round the figures to the nearest whole number, which is commonly adopted in literatures reporting the carbon balance figures.

Figure 1. There are two dots on the map to indicate location of one flux site. Also, would be nice to have a smaller inset map that shows a more zoomed out region to indicate where in China we’re zoomed into.

Response:

We updated the figure and pasted it below for your convenience.

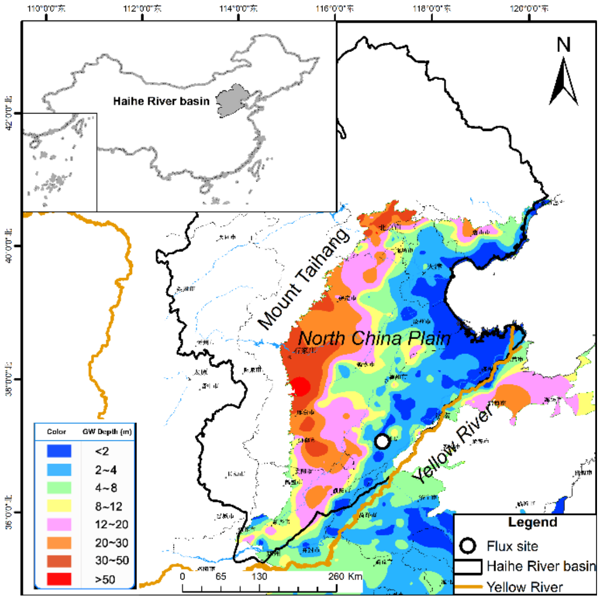

Fig. R1 Location of the experimental site. The background is the shallow groundwater depth in early September of 2011 (modified from http://dxs.hydroinfo.gov.cn/shuiziyuan/)

L151. "gaps less than 2 h" L274. "as previously mentioned" L283. "were" to "are". Also see L288 and elsewhere.

Response:

We appreciate the comments, all these are corrected in the revised manuscript.

L323-332. Here and elsewhere, correlation is being used to indicate causation. The text should be changed to correct this.

Response:

We appreciate the comment, the texts are updated to focus on the correlation alone. The updated texts are pasted below for your convenience (L298-312):

"The NEE, GPP and ER for both wheat and maize were correlated with the three main environmental variables of R_{si}, Ta and WD using the multiple regression (see Appendix B for details). In the wheat season, Ta 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, Ta 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); Ta showed almost no effect on all the three CO2 fluxes; Rsi 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)."

L338-339. Wondering if this cold season uptake might be caused by IRGA self-heating as shown previously by Burba et al. Did you consider this?

Response:

We appreciate the reviewer for this comment, we did not consider this. But the winter wheat at our site has green leaves in winter, and our leaf level gas exchange measurement in winter shows that photosynthesis happens in winter. In addition, wheat is also reported to have photosynthesis under low temperature in winter in other studies, e.g., Savitch et al. (1997). These allow us the confidence of the measurement. By addressing this concern from the reviewer, we added the text for explanation (L318-320), which is pasted below for your convenience:

"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)."

L413. "a short period of" L421 considered L422 "are required" L423 "is much closer to the surface because..."

Response:

We appreciate the reviewer's comment. All these have been corrected in the revised manuscript.

L454-464. Rather than reporting all these values in the text again, I'd suggest just referring to the values in the table.

Response:

We appreciate the comment, the texts are corrected accordingly.

L522. Rather than just reiterating these numerical results I'd suggest trying to write what some of the broader implications of your work are.

Response:

We appreciate the comment, we have thoroughly revised the conclusion, which is pasted below for your convenience:

"**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."

Reviewer: 2

The authors present a 10-year time-series of eddy covariance-derived NEE from a representative (wheat-maize double-cropped annual rotation) cropping system in the North China Plain. They find their system to be a net CO2 sink (negative NEE) but also that the strength of this sink has progressively declined throughout their observational record. Disproportionate increases in ecosystem respiration relative to gross primary production appear to be responsible for this trend and, interestingly, the authors assert that – at least during the maize season – changes in water table depth and shortwave radiation (not air temperature) are the proximate drivers of change. In addition, the authors embark to further partition ecosystem respiration into its autotrophic and both above- and below-ground heterotrophic components by coupling eddy covariance measurements to a concurrent year's worth of daily, in situ soil respiration measurements. While the authors demonstrate that such partitioning can be done successfully, results are presented in site specific manner and it's unclear to me whether they reveal anything that can be generalized to other sites. Finally, the authors compare their eddy covariance derived C balance to biometric proxies and concurrent changes in soil organic carbon concentrations.

Response

We appreciate the reviewer for the constructive comments. The research is indeed carried out at site level. Given the site we selected is representative over the North China Plain in terms of cropping style and tillage management etc, we are of the opinion that the site-specific research of this study can represent the general carbon characteristics of the winter wheat/summer maize cropping system over the North China Plain. We added the representativeness of this study by incorporating the reviewer's other comments, please also see our response to the detailed comments.

I feel that either story could be a valuable contribution to the literature but, at present, the potential of neither is fully realized. The former narrative (weakening sink) aligns with hypothesized metabolic responses to climate warming, though interestingly the authors suggest that temperature may not be the proximate driver – I'd like to see a more thorough assessment of these patterns/drivers and a richer discussion if the authors choose to pursue this narative.

Likewise, the latter story – as the authors explain well in their introduction – has great potential to unveil ecological mechanisms that could inform process-based predictions of agroecosystem responses to change. Unfortunately, the study does not seem to dig into this much and thereby does not reveal generalities to that end. This narrative dichotomy is manifest in the manuscript's current structure. The introduction suggests that the focus will be on flux partitioning. By the end, though, the decadal trends – that have no apparent connection to the partitioning exercise – emerge as the dominate discussion. I encourage the authors to choose one narrative, focus all manuscript sections accordingly, and substantially expand the associated discussion. I've provided specific comments and suggestions below that are largely agnostic towards which ever story is ultimately emphasized.

Response

We appreciate the reviewer for the comments.

We need to note that the current manuscript is a re-submission to BG. Our previous manuscript focused on the second narrative of flux partitioning, but a previous reviewer suggested that one-year measurement was insufficient for a paper for BG, so we added the decadal variation of CO_2 flux to this study. We agree with the reviewer's concern regarding the paper structure, and we realized the structure of the manuscript can be improved. By incorporating the reviewer's advice, we revised the introduction and rewrote the result section to make the story more consistent. In particular, we balanced the contents between decadal variation of CO_2 fluxes and the detailed budget components throughout the manuscript. Now the manuscript reports the CO_2 fluxes at the inter-annual timescale, then the CO_2 budget components are described for a representative year. We believe the revised manuscript is coherent by incorporating the reviewer's comments.

The revised introduction is pasted here for your convenience:

"**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; Torres et al., 2015), 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; Soni et al., 2013; Drewniak et al., 2015; de la Motte et al., 2016; Hunt et al., 2016; Vick et al., 2016), but their relative importance in determining the cropland CO_2 budget remain unclear because of limited field observations (Kutsch et al., 2010), motivating comprehensive CO_2 budget assessments across different cropland management styles.

Over the past two decades, CO_2 investigations of agro-ecosystems have mainly focused on the variations in the net ecosystem exchange with the atmosphere (i.e., NEE) or its two derived components (i.e., GPP and ER) using the eddy covariance. To date, these evaluations have been widely conducted for wheat (Gilmanov et al., 2003; Anthoni et al., 2004a; Moureaux et al., 2008; Béziat et al., 2009; Vick et al., 2016), maize (Verma et al., 2005), sugar beet (Aubinet et al., 2000; Moureaux et al., 2006), potato (Anthoni et al., 2004b; Fleisher et al., 2008), soybean-maize rotation cropland (Gilmanov et al., 2003; Hollinger et al., 2005; Suyker et al., 2005; Verma et al., 2005; Grant et al., 2007), and winter wheat-summer maize cropland (Zhang et al., 2008; Lei and Yang, 2010). However, the long-term variations of the cropland CO_2 fluxes remain limited, leaving our knowledge of the cropland potential as the future climate change mitigation tool incomplete.

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

Specific Comments:

Line 17: Here and throughout (e.g. lines 110, 112, 122, etc.), it's not clear what "typical" means. I'd suggestion changing to something like "representative" and defining in a sentence or too (the definition can be provided in the main text and doesn't need to occupy space in the abstract).

Response

We modified it to representative.

Line 27: Here and throughout, "cultural" should be changed to "agricultural".

Response

Revised.

Lines 36-38: There is no discussion in the body of the text about the management implications of a more detailed understanding of the CO2 budget. I recommend that this concluding sentence be changed to better reflect what is actually discussed in the manuscript.

Response

We modified the concluding sentence to (L38-40):

"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.

Lines 41-54: I recommend framing these opening sentences less as though interest in terrestrial C-cycle's role in the climate system is new but instead that the advent of the eddy covariance method has changed the way we study it. People have long recognized and studied land-atmosphere C fluxes (Houghton et al (1983) is an early example but by no means the first or only one). Reframing in this way would then smoothly transition to your accurate assertion that the growing number of eddy flux studies further necessitate a mechanistic understanding of the processes that underly the integrative fluxes measured by the eddy system.

Response

We appreciate the reviewer for the comment. We revised it accordingly.

We open the paragraph now by (L43-47) "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)."

Line 42: Gray et al (2014) may also be a good reference here as it directly addresses the role of agriculture as a diver of variation in the global C cycle.

Response

We appreciate the reviewer for the paper recommendation. It is incorporated.

Line 67: Gray et al (2014) may also be a good reference here.

Response

We appreciate the reviewer for the paper recommendation. It is incorporated.

Lines 68-70: You might consider mentioning some of the emerging "natural climate solutions" literature. Griscom et al (2017) show that agroecosystems have a large potential to mitigate C emissions, globally. Fargione et al (2018) further show that agroecosystems can be a particularly cost-effective means of mitigating C emissions.

Response

We appreciate the reviewer for the paper recommendation. It is incorporated.

We added the text to mention such effort as (L52-54) "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)."

Lines 73-74: Please change "the key factors" to "their relative importance in".

Response

Revised.

Lines 92-95: These sentences seem to imply that agroecosystems are monolithic and might collectively be generalized as source or sink with the help of a few more CO2 budgets. Diversity in source/sink behavior among studies is almost surely an artifact of differences in management and edaphics. Instead, I'd suggest emphasizing that detailed budgets might facilitate better prediction of systems' responses to change.

Response

We appreciate the reviewer's constructive comment. It is revised accordingly. The updated text (L86-88) is pasted here for your convenience:

"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."

Lines 107-111: This study's central question needs to be clarified. Here the question seems to be something like 'how does variation in microclimate and management influence the source/sink status of croplands. This is a question that doesn't seem to necessitate the detailed C budget that distinguishes your study and could instead be inferred from [spatial] patterns of NEE. But back in lines 73-74 the question seems more about the proximate drivers influencing individual C cycle fluxes. Which is it?

Response

We revised the introduction to better clarify the question.

Our aim is to: report the inter-annual variations of the CO_2 fluxes in a representative cropland over the North China Plain, and investigate the detailed CO_2 budget components.

In fact, both are the reasons that drive this study, but now we revised the introduction thoroughly to better clarify our question. Please refer to our revised introduction in response to previous comments.

Line 182: Is this a standard gap filling procedure? I'm not familiar. Perhaps add a sentence to the text?

Response

This is a machine learning algorithm, which has been recently shown to have the capability to fill gaps of eddy covariance data (see Kang et al., 2019; Kim et al., 2019).

We modified it to (L169-172) "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)"

Line 194: Please change "groundwater table" to "groundwater table depth".

Response

We modified it to "groundwater depth", which is also suggested by the first reviewer.

Line 210: Here and throughout the text, "samplings" should be changed to "samples".

Response

Revised.

Line 224: "guaranteed" is too strong of a term here. It ignores inevitable underlying heterogeneity in soil characteristics.

Response

The agree with the reviewer. We modified it to (L209-210) "The uniform field condition contributes to reduce the measurement uncertainty associated with the spatial variability (see Zhang et al., 2013)".

Line 230: How were parameters "inferred"?

Response

The parameters were inferred by using the least square method. We modified it to (L216-217) "The parameters were inferred by fitting the R_H and T_S measurements by using the least square method (see Zhang et al., 2013)". See Fig. R2 (figure in Zhang et al. 2013) pasted below.

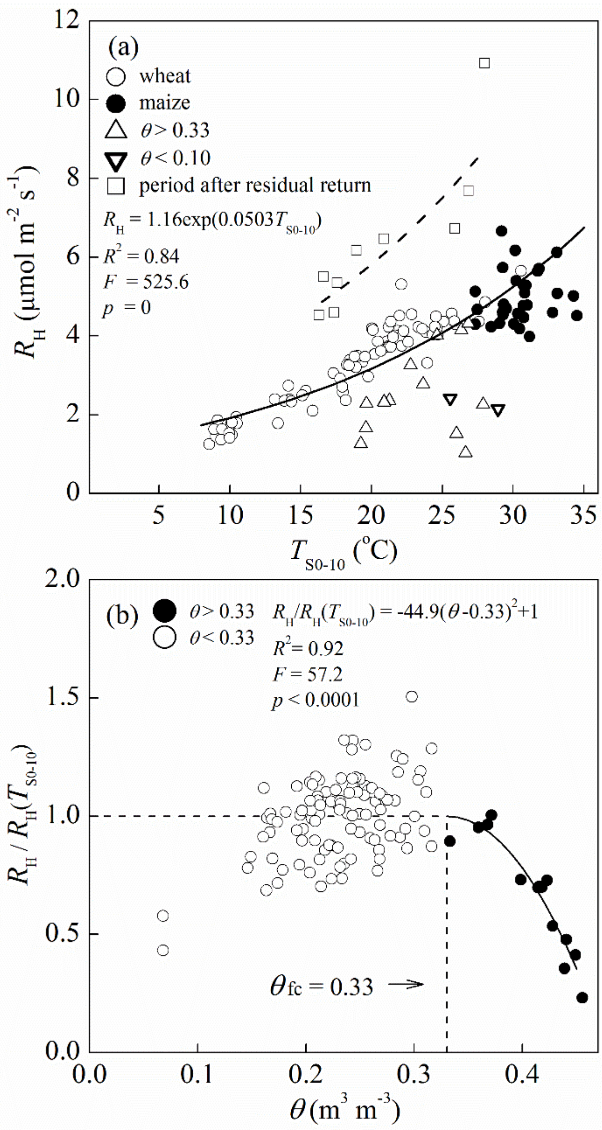

Fig. R2 (a) Relation between heterotrophic respiration (R_H) and soil temperature of the upper 10 cm ($T_{S0–10}$) (b) relation between temperature-standardized heterotrophic respiration ($R_H/R_H(T_{S0–10})$) and mean soil water content of the upper 5 cm (θ), vertex of the fitting quadratic curve was set to 1.0 at θ_{fc} . Dashed line in (a) was the fitting temperature dependence curve for the period of 3 weeks following the crop residual return.

Line 233: Please define the “contribution ratio”.

Response

The contribution ratio of R_{AB} to R_S is the ratio R_{AB}/R_S, we revised this to make it clearer as (L220-222)

"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).

Lines 237-242: This is a remarkably narrow time period (1-year) within which to measure SOC changes in response to management. I'm highly skeptical a signal will emerge through the inevitable noise of heterogenous soil. Were samples taken at the same location every time? The regression technique used to calculate the rate of change needs to be reported and must account for the variance among samples on each sampling date. Was bulk density measured with each sample? If not, please clarify that these are measurements SOC concentration, not SOC stocks.

Response

This analysis was removed by incorporating the reviewer's other comment. Nevertheless, to respond to the reviewer's concerns, we sampled soil from 10 fixed locations each time and pooled them before SOC analysis. The soil bulk density is the average value of the soil measurements in this cropland, so we did not measure it for each soil sample. We analyzed the SOC concentration to estimate the SOC stock.

Line 244: You might consider adding a conceptual figure showing the C-cycle as inferred in this study and highlighting the fluxes/drivers of interest.

Response

We appreciate this advice. We actually have the CO_2-cycle in figure 11, a new conceptual figure might be repetitive. We are inclined to reduce the figure count to use figure 11 for this purpose.

Lines 277-279: This could be moved to the site description at the beginning of the methods section.

Response

We revised accordingly.

Lines 307-309: Consider reporting these as percentages.

Response

This part is removed when we thoroughly revised the discussion.

Lines 327-328: As I see Figure 8, WT increased wheat NEE (positive coefficient) and decreased GPP (negative coefficient). But you say "decreased GPP, thereby reduce NEE". What am I missing? Also, please elaborate on the maize trends. Currently you say, "WT had a pronounced contribution to both GPP and ER, as well as to NEE." Please provide a more detailed description that includes the directions of changes.

Response

We revised this part.

The confusion is due to the sign of NEE. We adopted the commonly used sign system to use negative NEE as ecosystem carbon uptake (atmosphere carbon removel). For wheat, groundwater depth (WD) has positive correlation with NEE, implying the decrease of carbon uptake along with increasing groundwater depth, and we can further find that this result from the decrease of GPP under high WD value (Fig. 8a). We modified the expression to (L301-302) "WD correlated negatively with GPP, thereby reduced net carbon uptake (less negative NEE)" to avoid the confusion. We also provided a more detailed description of maize.

We also thoroughly revised this part, and the updated texts are pasted here for your convenience (L297-311): "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)."

Line 373: There is very little discussion of the flux partitioning work that was so heavily emphasized in the introduction. Why?

Response

By incorporating the reviewer's advice, we thoroughly revised the introduction. In particular, we expanded the introduction to the general CO_2 researches and measurements of cropland. Please also see our introduction pasted in response to previous comments. We now balance the contents of flux partitioning and inter-annual variation.

Lines 383-384: Similar to my critique of lines 92-95, I don't get the impression that the scientific community is seeking a consensus on whether or not croplands are C sources or sinks. I would remove this assertion. It's well accepted (and demonstrated in the literature) that, like so many ecosystem processes, source/sink status is contingent upon management and landscape heterogeneity across scales and domains.

Response

We agree with the reviewer and removed this expression. We also thoroughly revised the whole introduction.

Line 390: As with all C-cycle assessments, results depend on the system boundaries. Since your results suggest that the sink status of your focal croplands is contingent upon irrigation water, I'd suggest including a brief discussion of the implications that emissions from irrigation pumping might have for the source/sink status of your croplands. Such a discussion may be more appropriately situated in the "Effects of ground water on carbon fluxes" section.

Response

We appreciate the constructive comment.

Our cropland is irrigated by diverting water from the Yellow River, we compared with a nearby cropland with similar cropping system but irrigated by pumping the groundwater (Wang et al., 2015). The updated texts (L399-420) were pasted below for your convenience:

"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."

Line 398: These numbers are remarkably precise. Is that true to the precision of your instruments? What is the uncertainty associated with your numbers?

Response

We followed reviewer1's advice and round the data to the nearest whole number. Our NPPs of both wheat and maize were estimated based on two independent methods, and they gave very close estimations. The NPP was 783 (SD±46) gC m^{-2} for wheat and 562 (SD±43) gC m^{-2} for maize, which has already been described in the text (L337-341) and we pasted it here for your convenience: "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."

Line 403: What is "sufficient"?

Response

We revised it to full irrigation.

Line 405: This paragraph needs a topic sentence.

Response

This part is removed when we thoroughly revised the discussion.

Lines 419-420: This was not reported in the results. Please add. Figure 8 shows standardized results so it cannot simply be inferred from the figure.

Response

We appreciate the comment. We provided more explanation regarding the effect of groundwater depth on the CO_2 fluxes, but the water logging effect discussion is removed as no direct measurements can provide strong support to our assertation. We present such results in the "The inter-annual variations in the NEE, GPP and ER" sub-section (L297-311) and has been pasted as the response to previous comments, please refer to our detailed response to that comment.

Lines 421-423: Given that the paper is framed within the context of the climate change mitigation, this is an important caveat and one on which you should elaborate further. Can you provide a sense from your work or from nearby studies on how large methane emissions might be and – when converted to CO2-equivalents – what they might imply for their source/sink status?

Response

We appreciate the reviewer for this comment. We did a literature search and realized that CH_4 measurement remains lacking for similar cropping system in the area. So we did not expand the discussion that much, instead, we added such text to motivate future study as (L430-432) "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."

Lines 451-452: "cropland is more efficient in sequestering CO2 from the atmosphere than forest" - this is a terribly misleading statement and should be removed. In fact, this whole carbon use efficiency section and table 2 should be removed. It doesn't relate to either of the questions you pose in the introduction. Moreover, It's well established that the principle source of greenhouse gas emissions from croplands is not CO2 but N2O a greenhouse gas (e.g. Carlson et al 2017) and any assessment of relative climate impacts should fully account for that. Simply comparing NPP to GPP is thus not a relevant way of assessing sequestration potential. It also says nothing of the longevity of any sequestered C. Carbon sequestered in forests, for example, is likely to remain stored on the landscape for far longer than cropland residue (which may only persist for a year or two). This is why agriculture has been attributed to the rising annual variance in northern hemisphere CO2 concentrations (Gray et al 2014, Zeng et al 2014) – there are lots of really productive plants (high NPP) – that are then abruptly removed from the land surface and quickly decomposed.

Response

We appreciate the comment. We removed this related content of carbon use efficiency. However, we sustained other parts of the table, which gave us the information of a few important ratios of the CO_2 budget components. We pasted the corresponding texts here for your convenience (387-396):

"The contrasting respiration partitioning 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."

Line 489: The Jackson et al (1996) number here is relatively low in comparison to crop specific estimates for corn (15%) and wheat (17%) compiled in (Wolf et al 2015).

Response

We appreciate the comment. We cited the recommended paper in the revision. Furthermore, we analyzed the root ratios for our crops and found that the averaged root/biomass ratio is about 10% for maize and 15% for wheat close to the values in Wolf et al. (2015). The root/biomass ratios decreased until harvest at our site, and the minimal ratio at harvest possibly resulted from root decay during crop senescence. (See Fig. R3). We revised this part as (L443-448)

"Root biomass was difficult to measure, but the uncertainty should be low, because the root ratio (the ratio of the root weight to the total biomass weight) accounts for 15-16 % of the crop for wheat and maize (Wolf et al., 2015), and our measurements are very close to these values, i.e., the averaged seasonal root ratio was 15% for wheat and 10% 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."

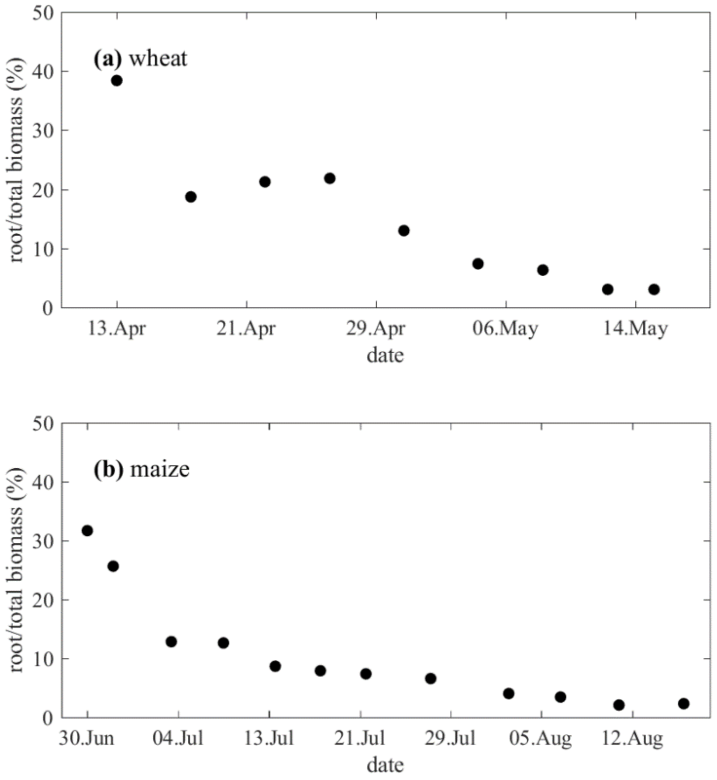

Fig. R3 The seasonal variation in the root/total biomass ratio of wheat (a) and maize (b) for the main growing season.

Line 495: Was your Q10 model "well validated"? If so that validation should be reported in the results section. If not, that should be discussed here.

Response

We appreciate the comment. The soil respiration Q_{10} model was validated by a previous independent study (see the Fig. R2). Please also see response to previous comments.

Lines 496-499: These SOC comparisons should instead be reported in the results section. What is the p-value of the SOC loss rate? If not less than 0.05, this section should be removed. How was bulk density calculated? You say that it is "about" 1,300 – does that mean that this is an approximation? If so, based on what? Since this value is used to calculate the SOC stock with which you 'validate' your soil respiration results, it's critical to know from where this number is coming.

Response

The correlation did not pass the significance test. We removed this part by following the reviewer’s advice. Nevertheless, the bulk density of the soil was measured independently.

Line 503-514: Once again, these data should have been reported in the results section.

Response

We appreciate the comment. We moved this part to results section.

Line 507: What does “sufficient” mean here? And “insufficient” in the line preceding it?

Response

“Sufficient” means the sample number is big enough, and the “insufficient” means the number of samples is small. We revised these expressions to (L457-459) “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.”

Lines 511-514: This is not an acceptable ‘validation’. The cause of the difference in signs (+/-) between the two independent estimates needs to be determined before deciding whether maize is a source or a sink. Simply calculating an average is not acceptable in this case. Doing so bases your final determination of source/sink on which ever estimate has the greater absolute value regardless of whether it was right or wrong. Why is one positive and the other negative?

Response

We realized our explanation of the analysis had some problem. As we used two independent methods to estimate NPP, so we used the averaged NPP of the two; we also used the averaged NEP of the two methods to estimate NBP to avoid the confusion. The updated texts (L339-347) are pasted here for your convenience:

“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.”

Line 513: This is not an “uncertainty analysis”. Nor is it a true “validation” If anything, it would be a “comparison” of methods.

Response

We agree with the reviewer. According to the previous comment, we removed such discussion.

Line 526: This seems like a key finding to me.

Response

We appreciate the comment, we highlight this in the abstract. We also present this in the results section.

Figure 12: A p-value needs to be reported here. Please also add error bars to illustrate the variation associated with the 10 measurements from each date. If the slope of this relationship is not significantly different than zero ($p > 0.05$), it should not be used to ‘validate’ your heterotrophic respiration numbers.

Response

By incorporating the reviewer’s previous comments, we removed this part as the correlation did not pass the significance level $p<0.05$.

Main references used in this response:

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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

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Abstract:

Carbon sequestration in agro-ecosystems has great potentials to mitigate global greenhouse gas emissions. To assess the decadal trend of CO_2 fluxes of an irrigated wheat-maize rotation cropland over the North China Plain, the net ecosystem exchange (NEE) with the atmosphere was measured by using an eddy covariance system from 2005 through 2016. To evaluate the detailed CO_2 budget components of this representative cropland, a comprehensive experiment was conducted in the full 2010-2011 wheat-maize rotation cycle by combining the eddy covariance NEE measurements, plant carbon storage samples, a soil respiration experiment that differentiated between heterotrophic and below-ground autotrophic respirations. Over the past decade from 2005 through 2016, the cropland exhibited a non-statistically significant decreasing carbon sequestration capacity; the average of total NEE, Gross Primary Productivity (GPP), Ecosystem Respiration (ER) for wheat were –364, 1174 and 810 gC m^{-2}, and were –136, 1008, and 872 gC m^{-2} for maize. The multiple regression revealed that, air temperature and groundwater depth showed pronounced correlation with the CO_2 fluxes for wheat; but in the maize season, incoming short-wave radiation and groundwater depth showed pronounced correlations with CO_2 fluxes. For the full 2010-2011 agricultural cycle, the CO_2 fluxes for wheat and maize were as follows: NEE –438 and –239 gC m^{-2}, GPP 1078 and 780 gC m^{-2}, ER 640 and 541 gC m^{-2}, soil heterotrophic respiration 377 and 292 gC m^{-2}, below-ground autotrophic respiration 136 and 115 gC m^{-2}, above-ground autotrophic respiration 128 and 133 gC m^{-2}; the net biome productivity was 59 gC m^{-2} for wheat and 5 gC m^{-2} for maize, indicating that wheat was a weak CO_2 sink and maize was close to CO_2 neutral to the atmosphere for this agricultural cycle. However, when considering the total CO_2 loss in the fallow period, the net biome productivity was –40 gC m^{-2} yr^{-1} for the full 2010-2011 cycle, implying that the cropland was a weak CO_2 source. The investigations of this study showed that taking cropland as a climate change mitigation tool is challenging and further studies are required for the CO_2 sequestration potential of croplands.

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

Introduction

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

Over the past two decades, CO_2 investigations of agro-ecosystems have mainly focused on the variations in the net ecosystem exchange with the atmosphere (i.e., NEE) or its two derived components (i.e., GPP and ER) using the eddy covariance. To date, these evaluations have been widely conducted for wheat (Gilmanov et al., 2003; Anthoni et al., 2004a; Moureaux et al., 2008; Béziat et al., 2009; Vick et al., 2016), maize (Verma et al., 2005), sugar beet (Aubinet et al., 2000; Moureaux et al., 2006), potato (Anthoni et al., 2004b; Fleisher et al., 2008), soybean-maize rotation cropland (Gilmanov et al., 2003; Hollinger et al., 2005; Suyker et al., 2005; Verma et al., 2005; Grant et al., 2007), and winter wheat-summer maize cropland (Zhang et al., 2008; Lei and Yang, 2010). However, the long-term variations of the cropland CO_2 fluxes remain limited, leaving our knowledge of the cropland potential as the future climate change mitigation tool incomplete.

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

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

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

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 $\mathrm{ER}_{\mathrm{ref}}$ parameter in each of the four-day window by fitting the eq. (1), then $\mathrm{ER}_{\mathrm{ref}}$ of each day was estimated by using the least square spline approximation (Lei and Yang, 2010).

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

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

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

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

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

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

Meteorological and environmental condition measurements

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

Biometric measurements and crop samples

To trace crop development and carbon storage, we measured canopy height (H_C), leaf area index (LAI), crop dry matter (DM), and carbon content of crop organs at an interval of 7-10 days in the footprint of eddy covariance. Due to inclement weather, measurement intervals were occasionally extended to two weeks or longer. The H_C was measured with a ruler and LAI was measured with LAI-2000 (LI-COR Inc.) at ten locations randomly distributed in the field. For crop samples, four locations were randomly selected at the start of the growing season, crop samples were then collected close to these four locations throughout the experimental period. At each location, 10 crop samples were collected for wheat and 3 crop samples were collected from maize. To reduce the sample uncertainty at harvest, 200 crops and 5 crops were collected in each location for wheat and maize, respectively. The crop organs were separated and oven-dried at 105 °C for kill-enzyme torrefaction for 30 min, and then oven-dried at 75 °C until a constant weight. The crop samples were used to estimate the average field biomass (Dry Matter). The carbon content was analyzed using the combustion oxidation-titration method (National Standards of Environmental Protection of the People's Republic of China, 2013) to estimate carbon storage. The crop samples provided a direct estimate of the NPP.

Soil respiration measurements

Soil respiration was measured every day in the footprint of the eddy covariance between 13:00 and 15:00 from March through September of 2011 using a portable soil respiration system LI-8100 (LI-COR Inc.). Below-ground autotrophic respiration and heterotrophic respiration were differentiated using the root exclusion method (Zhang et al., 2013). The total soil respiration (R_S) and R_H were measured at treatments with and without roots, respectively, and the corresponding difference is R_{AB}. To reduce the uncertainty associated with spatial variability, we set three replicate pairs of comparative treatments (i.e., with root and without root) randomly in the field. The uniform field condition contributes to reduce the measurement uncertainty associated with the spatial variability (see Zhang et al., 2013). To assess the seasonal variations and total amount of soil respirations, the seasonal continuous R_H was constructed using the Q_{10} model by incorporating soil moisture as follows (Zhang et al., 2013):

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

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

where θ_f is the field capacity. The parameters were inferred by fitting the R_H and T_S measurements by using the least square method (see Zhang et al., 2013), where A=1.16, B=0.0503, and a= –44.9 (see Zhang et al., 2013).

The R_{AB} of wheat was assumed to be 0 before March 14th 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},

$$R_S=R_H+R_{AB}. \tag{6}$$

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

$$R_A=ER-R_H. \tag{7}$$

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

$$R_{AA}=ER-R_S. \tag{8}$$

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

$$NPP_{EC}=GPP-R_A, \tag{9}$$

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,

$$NPP_{CS}=C_{cro}, \tag{10}$$

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,

$$NEP_{CS}=NPP_{CS}-R_H. \tag{11}$$

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}),

$$NBP=NEP-C_{gra}, \tag{12}$$

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

(Table 1 here)

(Figs. 5&6 here)

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

For the period from 2005 through 2016, if grain export was not considered, the wheat was consistent CO_2 sink as the seasonal total NEEs were consistently negative, and the maize was 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 21st and May 8th 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, though it was not statistically significant. 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 partitioning 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 $\mathrm{NPP}_{\mathrm{EC}}$ and $\mathrm{NPP}_{\mathrm{CS}}$ were not perfectly consistent in the main growing season as clear differences emerged during the dormant season of wheat from December 15th, 2010 to March 8th, 2011 (Fig. 12). These differences may result 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 non-statistically significant 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), leaf area index (LAI), net photosynthetically active radiation (PAR), and soil moisture (θ) are the dominant factors. Hence, we select T_a, RH, LAI, PAR, and θ as explanatory variables of GPP. Ecosystem Respiration (ER) consists of total soil respiration and above-ground autotrophic respiration. The total soil respiration is largely influenced by soil temperature and soil moisture, while above-ground autotrophic respiration is largely influenced by air temperature and above-ground biomass. So we select T_a, soil temperature at 5 cm (T_s), θ and LAI as explanatory variables of ER. LAI is estimated from the Wide Dynamic Range Vegetation Index derived from the MOD09Q1 reflectance data (250 m, 8-d average, https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod09q1, also see Lei et al. 2013).

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

A3. SVR model training and flux calculation

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

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

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

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

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

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

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

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

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

Data availability

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

Author contributions

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

Competing interests

The authors declare that they have no conflict of interest.

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Tables and figures

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

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

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

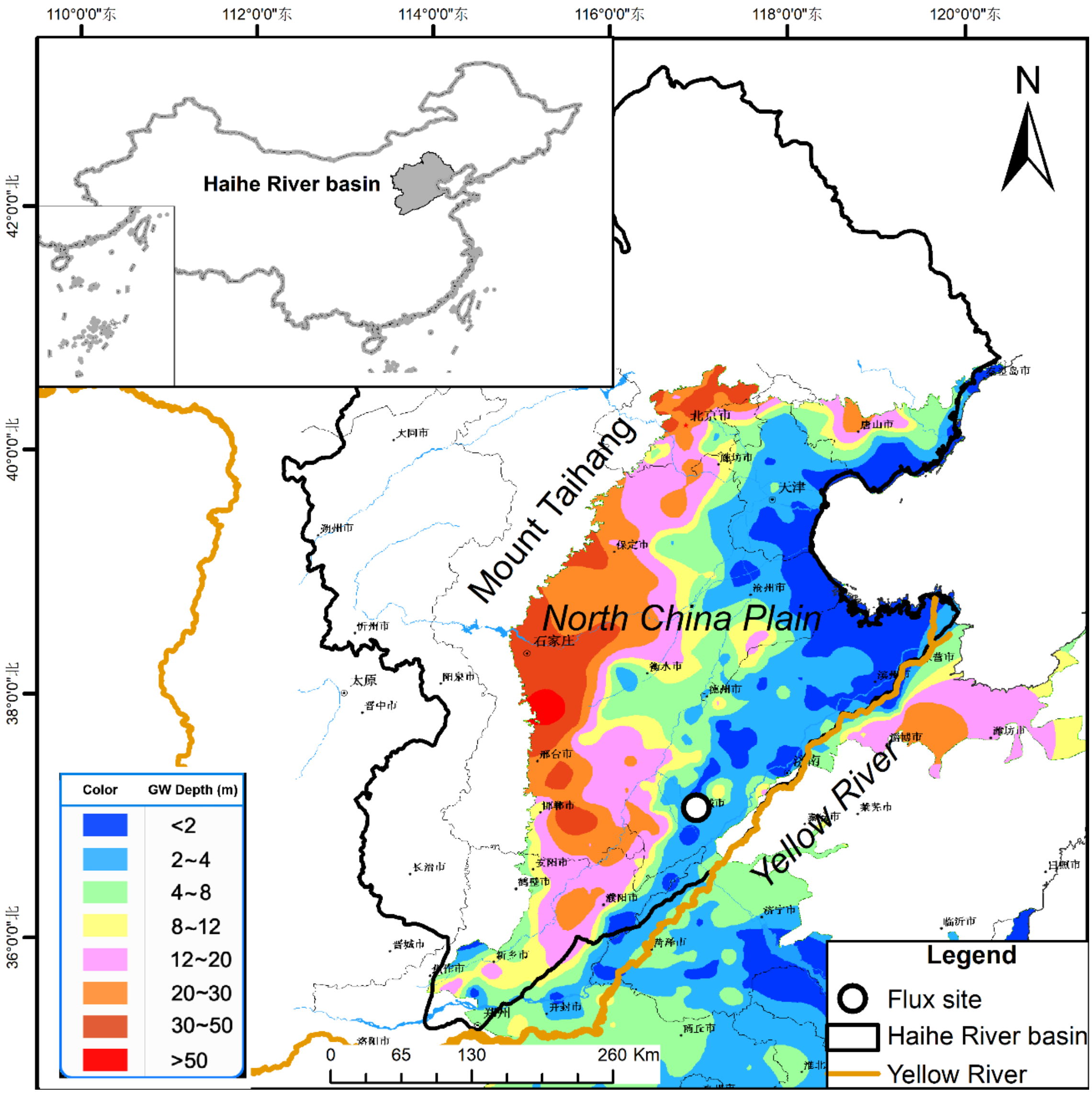

Fig. 1 Location of the experimental site. The background is the shallow groundwater depth in early September of 2011 (modified from http://dxs.hydroinfo.gov.cn/shuiziyuan/)

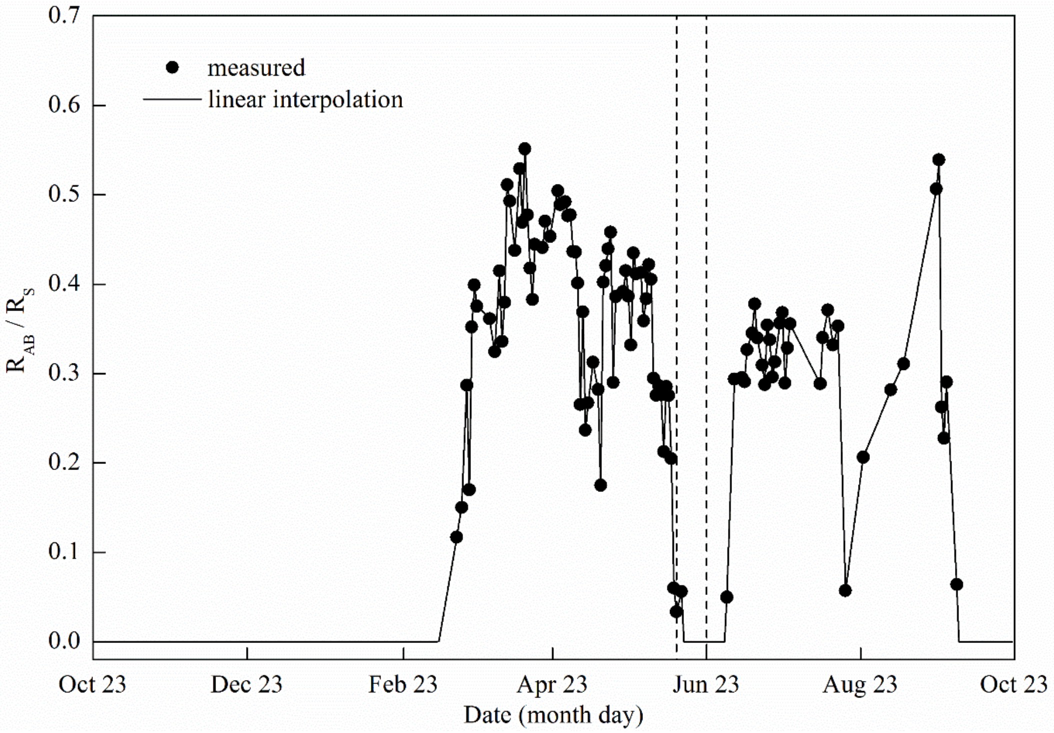

Fig. 2 Seasonal variations in the ratio of below-ground autotrophic respiration (R_{AB}) to total soil respiration (R_S). Two vertical dashed lines (hereafter) represent the date of harvesting wheat and sowing maize, respectively.

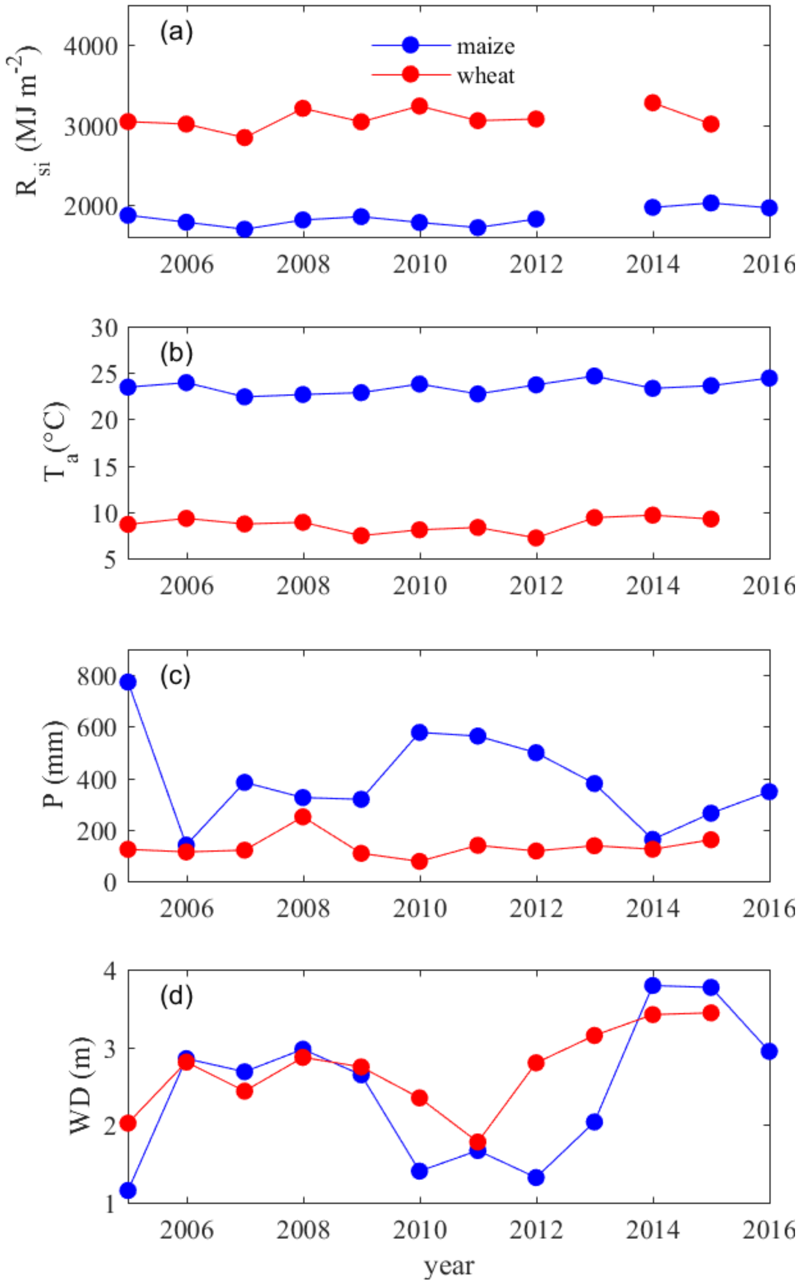

Fig. 3 The seasonal (a) total incoming short-wave radiation (R_{si}), (b) average air temperature (T_a), (c) total precipitation (P) and (d) average groundwater depth (D) for both wheat and maize evaluated for the period from 2005 through 2016. Note that incoming short-wave radiation in the 2013 season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

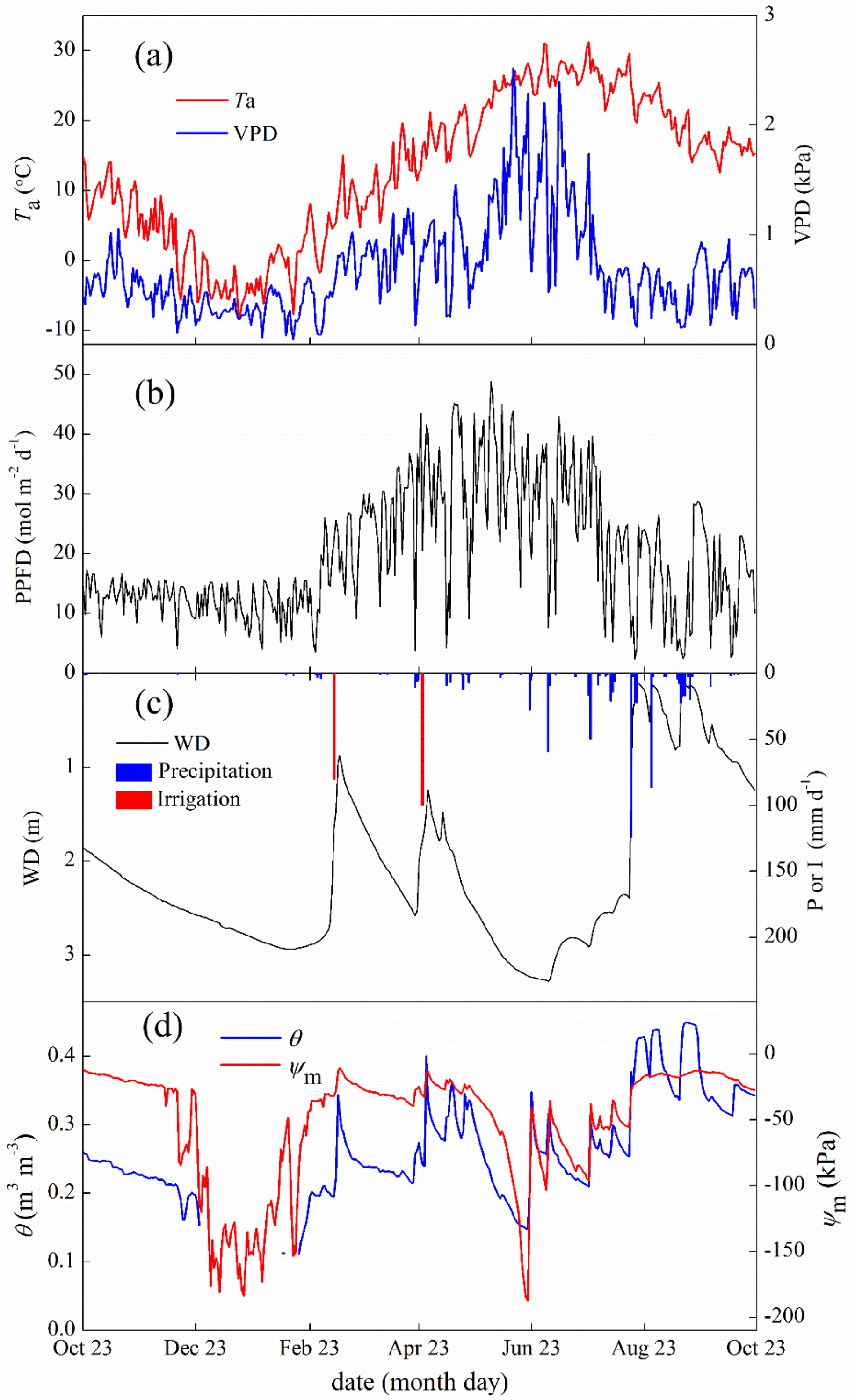

Fig. 4 Seasonal variations in the environmental variables of (a) air temperature (T_a), soil temperature at 5cm depth (T_s) and vapor pressure deficit (VPD), (b) photosynthetic photon flux density (PPFD), (c) precipitation (P), irrigation (I) and groundwater depth (WD), and (d) volumetric soil moisture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

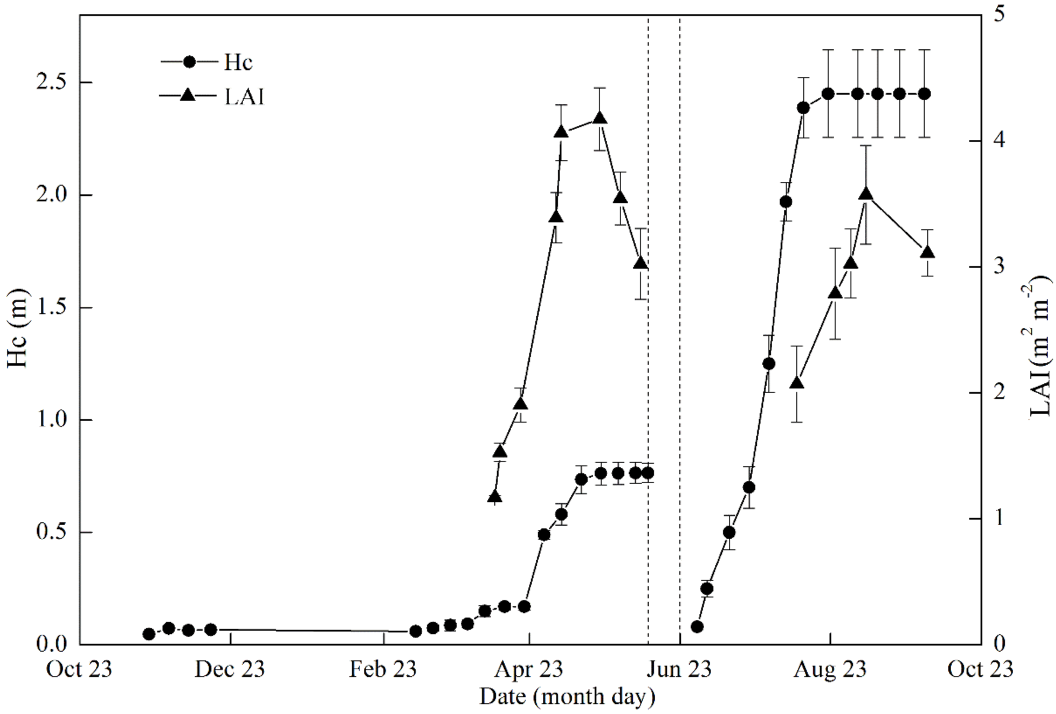

Fig. 5 Seasonal variations in canopy height (H_C) and leaf area index (LAI). The error bars denote 1 standard deviation of the ten points.

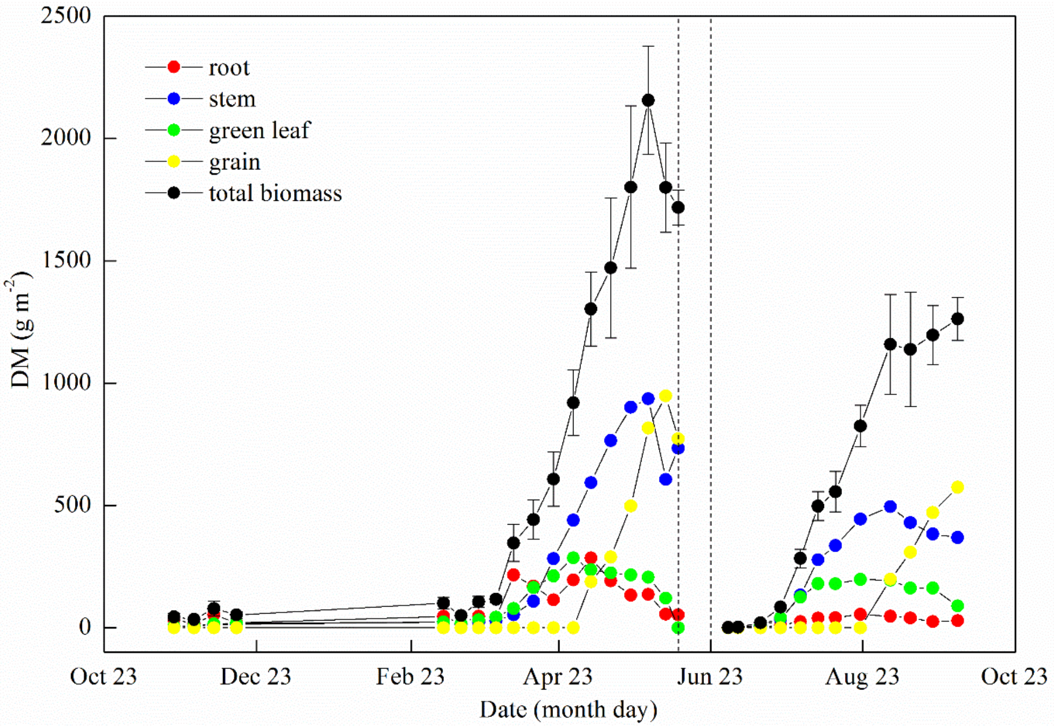

Fig. 6 Seasonal variations in the total dry biomass (DM) and its major parts of root, stem, green leaf and grain. The error bars of total biomass denote 1 standard deviation of the four sample points.

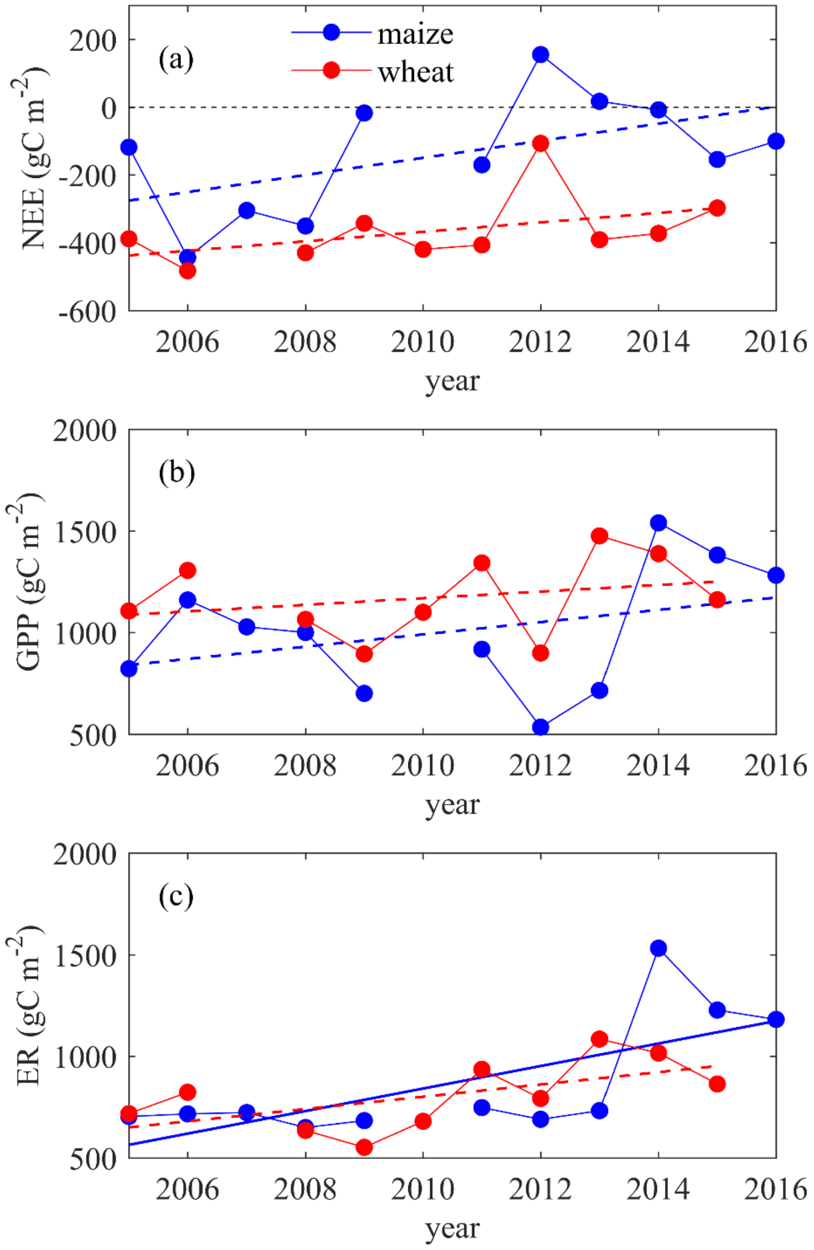

Fig. 7 The temporal trend of annual (a) Net Ecosystem Exchange (NEE), (b) Gross Primary Productivity (GPP) and (c) Ecosystem Respiration (ER) for both wheat and maize from 2005 through 2016. Note that though most gaps of carbon fluxes were filled, the wheat of 2007 was excluded as it had a large gap 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.

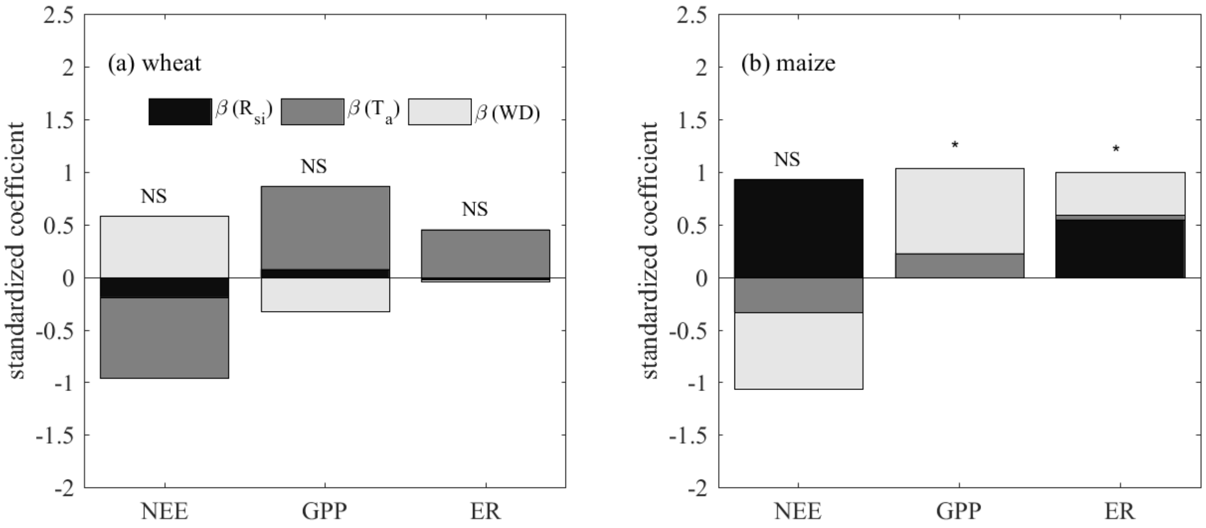

Fig. 8 The result of multipe regression for NEE, GPP and ER with incoming short-wave radiation (R_{si}), air temperature (T_a) and groundwater depth (WD) for both (a) wheat and (b) maize. Note that * denotes that the regression passes $p<0.05$ significance level, and NS indicates non-significant.

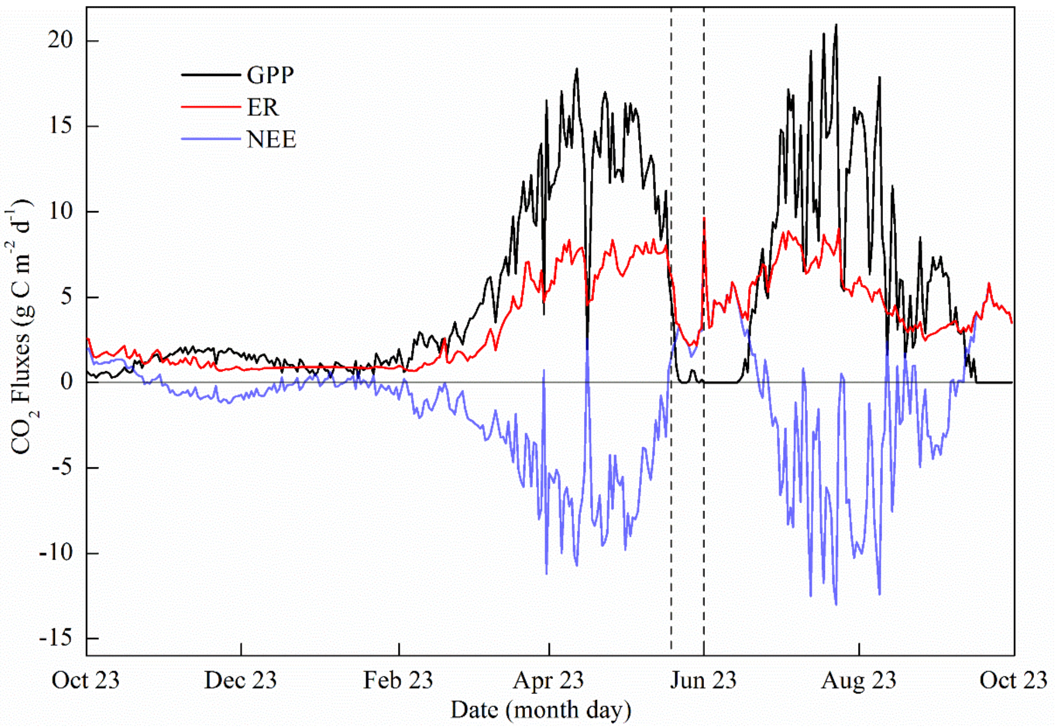

Fig. 9 Seasonal variations in Gross Primary Producrivity (GPP), Net Ecosystem Exchange (NEE) and Ecosystem Respiration (ER) (those before April 2nd were calculated with SVR method)

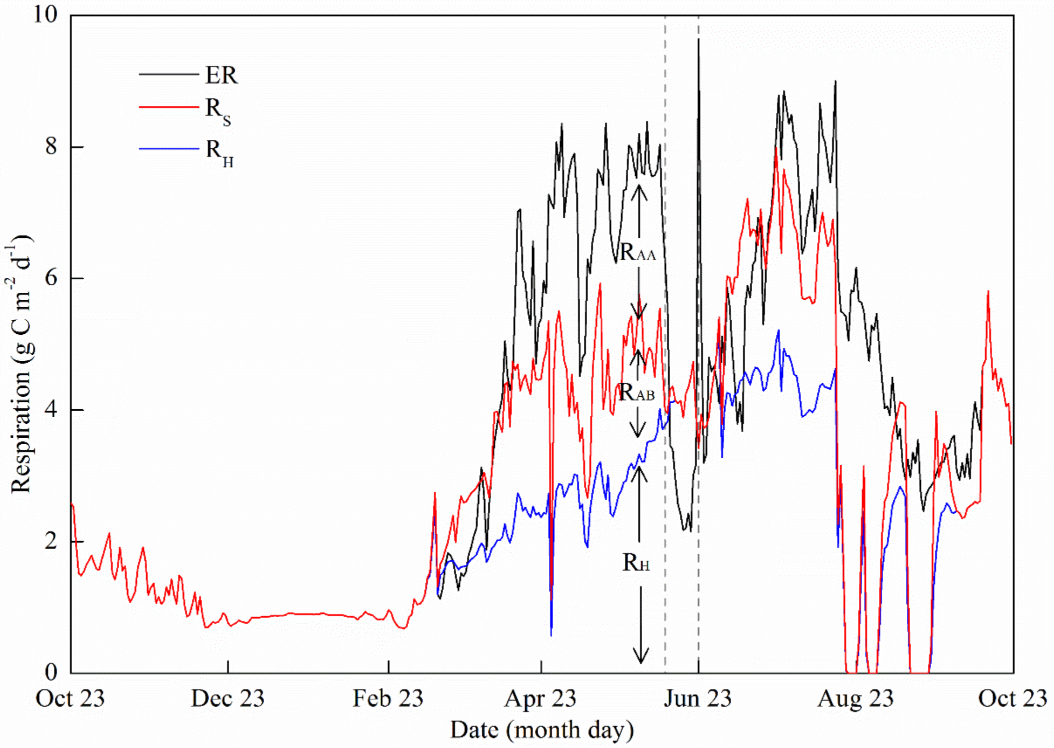

Fig. 10 Seasonal variations in the components of Ecosystem Respiration (ER), total soil respiration (R_S), soil heterotrophic respiration (R_H). The difference between ER and R_S denotes above-ground autotrophic respiration (R_{AA}), and the difference between R_S and R_H denotes below-ground autotrophic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

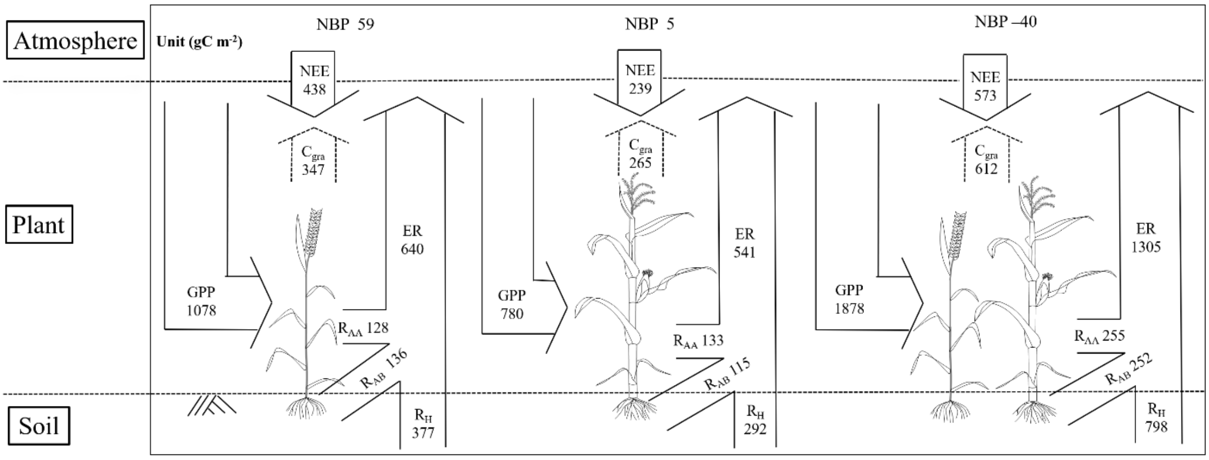

Fig. 11 Carbon budget of wheat (left), maize (middle) and the full wheat-maize rotation cycle with fallow periods included (right). Note that absolute value of NEE is shown here; NBPs of wheat and maize are the average of two independent methods (i.e, eddy covariance-based and crop sample-based)

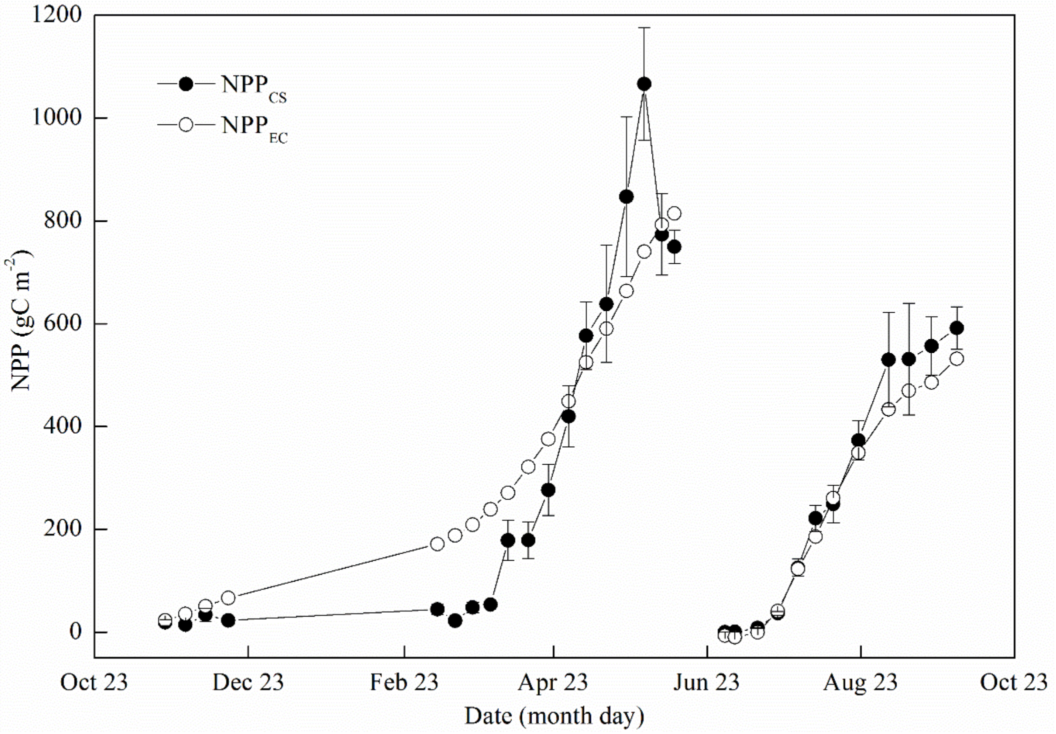

Fig. 12 Seasonal variations in the cumulative Net Primary Productivity (NPP) with two independent methods of Crop Sample (NPP$_{CS}$) and Eddy Covariance (NPP$_{EC}$) complemented with soil respiration m easurements.