

2016-02-13

Dear Editors and Reviewers, Thank you very much for your critical comments and great support! Please see the attached point-by-point answers and the manuscript with tracking system for your further evaluation.

Wish you a Happy Valentine's Day!

Sincerely yours,

Zhengqin (on behalf of all authors)

Referee #1

GENERAL COMMENTS The authors present an interesting and complete assessment on Global Warming Potential (GWP) and greenhouse gas intensity (GHGI) during three years in a rice-wheat rotation. The number of crop seasons, as well as the complete overview the sustainability of the agro-ecosystem (soil GHG emissions, SOC, CO₂ equivalents from inputs and operations, and crop yields) are, from my point of view, the main strengths of the this study, which fits well into the scope of the journal. Conversely, the manuscript requires additional details and explanation before it can be considered for publication. Moreover, I do not understand why the authors did not set some variables (e.g. Zn fertilization -which has been reported to influence crop yields and GHG emissions- plant density, water management...). That would have simplified the discussion and maybe would have allowed obtaining some conclusions about management techniques (and not only about the overall scenarios) and the possibilities of combining scenarios. The authors should also improve the Materials and Methods section, explaining much better the GWP calculations and other issues of major interest. The conclusions are adequately presented: since each scenario is a combination of several management techniques, the authors cannot recommend any single practice, only the full scenario. Conversely, ALL the management factors that could have influence the measured variables (yields, GHG fluxes, GWP) should be briefly discussed.

A: Thank you very much for your great support and critical comments. Those comments are all valuable and very helpful for revising and improving our paper, as well as further important guidance for our researches. We have made corrections which we hope to meet with approval. Please see the following point-by-point answers.

1. Yes, all of these variables such as Zn fertilization, plant density, and water management affect crop yields and GHG emissions. We are sorry that we did not set them as separate variables and just integrated them to realize our goal for better yield and NUE. According to your comments, we added some information for better understanding in discussion, such as on Page 10, Lines 262-265 and 270-275 for yield, Page 12, Lines 306-308 for GHG emissions.
2. It is really true that we update all possible components for calculating GWP as both of you Referee suggested. So, we put them in a better way on Page 6, Lines 149-173.
3. In conclusion, the ISSM scenarios could be adopted for both food security and environmental protection. We discussed scenarios in detail emphasizing the main components. Revised accordingly Page 14, Lines 385-388 and Page 16, Lines 430-432.

SPECIFIC COMMENTS

Abstract, lines 19-23. It seems that treatments only differ in N rate, and that is not true. Please indicate briefly other parameters that were different between treatments.

A: Thank you for your comment. Revised accordingly Page 2, Lines 18-20.

Lines 82-84. Include, if available, the information on clay, silt and sand contents and soil texture.

A: Thank you for your comment. Revised accordingly Page 4, Lines 90-91.

Lines 84-86. Please indicate the annual precipitation and mean temperature in each campaign. Were “normal years” with regard to these parameters, compared to the average values (15.5 °C and 1038 mm)? In any case, I think that this information fits better in the results section.

A: Yes, thank you. Revised accordingly Page 4, Lines 88-89.

Lines 88-98. What was the N source applied? What were the dates (or phenological stages) of N application in rice -4 split applications in some treatments-? What about the wheat? When was the N applied?

A: Urea was used as N fertilizer and 20 kg N ha⁻¹ in the form of rapeseed cake fertilizer was applied as N fertilizer for N3 and N4 treatments in this study. Revised accordingly Page 5, Lines 112-119.

Please indicate that Zn and Na₂SiO₃ fertilization, plant density and the use of an organic amendment were also management techniques for improving rice yield and NUE.

A: Thank you very much for your comment! According to your comments, we added some information for better understanding in discussion.

Did you consider the N supplied through rapeseed cake manure for NUE calculations (you should!)? In any case, please indicate in this section the composition of this residue, at least the C and N contents and C:N ratio.

A: We are sorry for the inconvenience. We recalculated the NUE according to your comment.. Revised accordingly Page 5, Line 102, Page 8, Lines 196-199 and Fig. 1.

Lines 99-104. What amount of irrigation water was applied during the rice growing season in each campaign? Was it different between scenarios (as could be deduced from line 329)?

A: The amount of irrigation water applied during the rice growing season in each campaign was as shown in Table 4. It was different between ISSM scenarios and FP and NN.

Please describe briefly the residue management at the end of rice and wheat growing season.

A: The rice and wheat straws were removed out of the field for all the treatments in this study. Revised accordingly Page 5, Lines 119-120.

Line 116. To my knowledge, it is not possible to measure N₂O with a flame ionization detector. Was not your GC equipped with an ECD detector? Please, clarify this crucial point.

A: We are sorry for the inconvenience. All of the gas samples were analyzed using a modified gas chromatograph (Agilent 7890A, Shanghai, China) equipped with two detectors. N₂O was detected by an electron capture detector (ECD). Argon-methane (5%) was used as the carrier gas at a flow rate of 40 ml min⁻¹ for the N₂O analysis. The temperatures of the column and the ECD were maintained at 40 °C and 300 °C, respectively. Revised accordingly Page 6, Lines 132-137.

Line 125. Can you reference this equation?

A: Yes. Revised accordingly Page 6, Line 142.

Lines 131-149. This section needs to be significantly improved. I recommend the authors to summarize the information in a DETAILED Table, indicating for each variable that is included in GWP calculations: Amount/number of labors/inputs, unit cost (kg CO₂ equivalents) and a reference.

A: Thank you very much for your comment! Please see the Table 4 for the detailed information.

The information on fertilizer rates is enough, but you should indicate the number of farm operations (labor passes, seeding, fertilizing, harvesting, irrigation –and amount of water applied-) in each treatment. Were the ZnSO₄ and Na₂SiO₃ considered for the GWP? (They should!)

A: Thank you for your comment. We added a new Table 4 for understanding the Eo and Ei components. The ZnSO₄ and Na₂SiO₃ were also considered for the GWP. There must have other uncertainties in selecting parameters. This is only preliminary evaluation within our understanding. Thank you very much for your great support!

What does the Ei involve? Only inputs application? Application + manufacture and transport?

A: Ei involve application + manufacture and transport.

What are the CO₂ equivalents for N₂O and CH₄ emissions? Please, indicate (with a reference).

A: Thank you for your comment. Revised accordingly Page 6, Line 152.

Lines 151-157. Were the normal distribution and variance uniformity checked? Did you use any non-parametric test for non-normally distributed data? If affirmative, please indicate how.

A: We have made the normal distribution and variance uniformity check. All data were conformed.

Line 167-168. I don't know what you meant here. According to Table 2, significant increases were observed... If this statement is referred to average wheat-rice values, please add "data not shown" in brackets.

A: Thank you for your comment. This statement was meant that significant increase was observed only in N4 scenario in wheat grain yields.

NUE: See my comment on lines 88-98 for NUE calculations in N3 and N4 scenarios (with rapeseed cake manure). Correct NUE for these cultivation patterns if the N from rapeseed was not considered.

A: We are sorry for the inconvenience. 20 kg N ha⁻¹ in the form of rapeseed cake fertilizer was applied as basal fertilizer and should be included in the total N rate. Revised accordingly Page 8, Lines 196-199 and Fig. 1.

Line 175-176. Please include this sentence "current ISSM strategy was only designed for rice production, not wheat production" in Materials and Methods.

A: Thank you for your comment. Revised accordingly Page 5, Lines 100-101.

Line 187-188. Avoid as possible the subjective statements (e.g. "due to the combined application of inorganic and organic fertilizers") in the results section. This sentence (from my point of view) fits better in the discussion.

A: Thank you for your comment. Deleted accordingly Page 9, Line 215.

Lines 189-196. The description of the N₂O evolution should be improved. You should indicate how many peaks or increments (if any) were reported in each crop, and if they were reported after fertilization events. Comparing emissions (CH₄ and N₂O) between crops (wheat versus rice) would be interesting.

A: Thank you for your comment. Revised accordingly Page 9, Lines 216-218.

"Correlations between seasonal cumulative N₂O emissions and fertilizer N application rates were also calculated": that should be indicated in Materials and Methods (Statistical Analysis section, in which you only explain that "linear relationships were determined"). About this regression, the N rate was not the only variable that could have influenced N₂O emissions, since other variables were not fixed. Moreover, the N rate in N3 and N4 is not correct (you have not considered rapeseed manure). Therefore, I recommend removing this figure.

A: Thank you for your comment. Deleted accordingly.

"Relative to the FP plot, the N1 and N2 scenarios decreased the annual N₂O emissions by an average of 41% and 22%, while the N4 scenario significantly increased it by 46% although there

was no significant difference between N3 and FP plots ($P < 0.05$)". This sentence is so confusing for me. Is this statement referred to wheat? If affirmative, please indicate and check the percentages of abatement/enhancement (looking at Table 2, average 2011-2013, I think there are some mistakes). You should describe also the results for the rice (in spite of the lack of significant differences between fertilized treatments). If these percentages are based on information of Table 2, please refer to this Table.

A: Sorry for the inconvenience. This statement referred to the annual N_2O emission rates including the results for both rice and wheat. Revised accordingly Page 9, Lines 222-323.

"With respect to the N application effect, the annual cumulative N_2O emissions in all four ISSM scenarios were significantly higher than in NN ($P < 0.05$)". In what crop? In wheat? Please indicate, because this is not observed for rice (Table 2, Average 2011-2013 fluxes).

A: Sorry for the inconvenience. The annual cumulative N_2O emissions indicate the average rates in rice-wheat rotations of 2011–2014.

Line 202-203. "Although N fertilizer increased annual CH_4 and N_2O emissions, they also increased SOC sequestration in this cropping system". Please change "N fertilizer" by "fertilized treatments". The idea that N fertilization can increase SOC sequestration is speculative, particularly in the Results section.

A: Thank you for your comment. Revised accordingly Page 9, Lines 233.

Lines 206-207: " CO_2 equivalents from machinery used for E_i (2449–4192 CO_2 -eq $ha^{-1} yr^{-1}$) were higher than E_o (1285–1697 CO_2 -eq $ha^{-1} yr^{-1}$) of the fertilized plots". The word "machinery" is confusing for me since you explain (in lines 123-133) that the E_i component accounted the CO_2 emissions from agrochemical inputs.

A: Sorry for the inconvenience. Revised accordingly Page 9, Lines 238.

Lines 211-212: "Consequently, the lowest NGWP was achieved under the N1 scenario for the ISSM." The NGWP in N1, N2 and FP was statistically similar. Please remove or correct this sentence.

A: Thank you for your comment. Deleted accordingly Page 9, Lines 243.

General comments on Discussion section: the Discussion should be significantly improved. First of all, the document (and particularly this section) should be reviewed by a native speaker. As explained above, each scenario is a combination of several management techniques, and even though authors cannot recommend any single practice (only the full scenario), ALL the management factors that could have influence the measured variables (yields, GHG fluxes, GWP) should be discussed:

A: Thank you for your comment. Revised accordingly throughout the discussion. We also asked AJE for re-editing the texts. Thank you for your patience. We added references (Kabata-Pendias and Mukherjee, 2007 ; Hossain et al., 2008) in the text.

- Fertilization: Not only different N rates were tried, but also different P, K, silicon and Zn. This fact may have directly affected crop yields, and also N_2O emissions indirectly (i.e. the more a crop grows, the more N is uptaken and the less N is likely to be lost as N_2O). Particularly, Zn has been reported to influence CH_4 and N_2O emissions (Glass and Orphan, 2012) and yields in some crops, e.g. rice (Hossain et al., 2008). The effects of silicon in rice physiology have also been described (Kabata-Pendias and Mukherjee, 2007).

Hossain, M. A., Jahiruddin, M., Islam, M. R., & Mian, M. H. (2008). The requirement of zinc for improvement of crop yield and mineral nutrition in the maize–mungbean–rice system. *Plant*

and soil, 306(1-2), 13-22.

Glass, J. B., & Orphan, V. J. (2012). Trace metal requirements for microbial enzymes involved in the production and consumption of methane and nitrous oxide. *Frontiers in microbiology*, 3.

Kabata-Pendias, A., & Mukherjee, A. B. (2007). Trace elements from soil to human. Springer Science & Business Media.

- The rapeseed cake manure is also an important variable. This organic amendment can substantially modify CH₄ and N₂O fluxes through the release of C and N. You should indicate the composition of this residue (C and N contents) and discuss better its influence on GHG emissions (Thangarajan et al., 2013) and C sequestration. Moreover, the residues from Brassicaceae have been reported to inhibit nitrification, thus affecting N₂O losses (Subbarao et al., 2015).

A: Thank you for your comment. Revised accordingly throughout the discussion. We added reference (Thangarajan et al., 2013) in the text.

Thangarajan, R., Bolan, N. S., Tian, G., Naidu, R., & Kunhikrishnan, A. (2013). Role of organic amendment application on greenhouse gas emission from soil. *Science of the Total Environment*, 465, 72-96.

Subbarao, G. V., Yoshihashi, T., Worthington, M., Nakahara, K., Ando, Y., Sahrawat, K. L., ... & Braun, H. J. (2015). Suppression of soil nitrification by plants. *Plant Science*, 233, 155-164.

- Plant density, split N application ratio and water regime were not the same in all treatments (I do not know why). Could these changes have modified GHG emissions and crop yields?

For instance, in lines 230-234, you consider that the changes in rice yields in N₁ and N₂ treatments as opposed to FP are due to changes in N fertilization rate. But the crop density and split ratio were different, and that could have also affected yields. In the reference that you provide (Peng et al., 2006) only the N rate is changed between treatments.

A: Thank you for your comment. Revised accordingly Page 10, Lines 262-265.

As indicated above, the N supplied through the manure should be taken into account for NUE calculations. Therefore, the NUE should be re-calculated and re-discussed.

A: Thank you for your comment. Revised accordingly Page 8, Lines 196-199 and Fig. 1.

Lines 239-240: "Possible explanations can be that organic fertilizer supplemented with adequate nutrients in combination with improved rice yield and efficient control of pests and diseases". As indicated above, many factors could have contributed to this higher yields and must be discussed (i.e. why the organic amendment increase yields? Maybe due to the higher supply of nutrients that you have not considered)... But what about the efficient control of pest and diseases? Were not efficiently controlled in the rest of treatments? This point needs to be clarified.

A: Thank you for your comment. Revised accordingly throughout the discussion.

Lines 248-252. Please split and/or rewrite this sentence for better understanding and be careful with the variables that were not measured (e.g. leaching and volatilization).

A: Thank you for your comment. Revised accordingly Page 11, Lines 282-285.

Line 277: add a reference for this statement.

A: Thank you for your comment. Revised accordingly Page 12, Lines 318.

Lines 278-279. Likely, the flooded conditions during rice season led to the reduction of N₂O to N₂ (complete denitrification).

A: Thank you for your comment.

Lines 280-282: add a reference for this statement.

A: Thank you for your comment. Revised accordingly Page 12, Lines 324.

Lines 286-287: as explained above, I recommend removing this correlation analysis.

A: Thank you for your comment. Deleted accordingly Page 12, Lines 328.

Lines 325-327: why the fertilized treatments could have increased SOC sequestration? That should be briefly discussed (maybe that could be related to residue management, which you should also explain).

A: Revised accordingly Page 14, Lines 368-369.

Line 343-344: I suggest adding a figure or table indicating the relative weight of each component in each crop. Were there any differences in Net GWP between years?

A: Thank you for your comment. The SOCSR was calculated through the long-term experiment of annual average carbon sequestration rate, not on the crop seasonal scale. We added a new Table 4 for understanding the Eo and Ei components. The GWP between years was similar.

Conclusions: you should indicate some results about wheat, not only about rice.

A: Thank you for your comment. The results include rice-wheat rotation system, not only about rice.

Lines 382-384: I guess that you are referring to one ISSM strategy in particular (N2), please indicate. Since you propose N2 as the most appropriate management strategy, I recommend describe briefly this scenario (10% reduction of N input, no rapeseed manure, no Zn or silicon addition, higher plant density...).

A: Thank you for your comment. Revised accordingly Page 16, Lines 428-429.

Table 2: please indicate with lowercase letters if there were significant differences between treatments in 2011, 2012 and 2013 (not only in the average).

A: Thank you for your comment. Revised accordingly Table 2.

Table 4: you must add the values for both wheat and rice in each component, and discuss in the text. Additionally, see my comment on lines 343-344.

A: Thank you for your comment. We added a new Table 4 for understanding the Eo and Ei components. We use the replicates for understand the uncertainties. There must have other uncertainties in selecting parameters. This is only preliminary evaluation within our understanding. Thank you very much for your great support!

Figure 2: You should delete figure 2a (this information is given on Table 2) and c (see the comment on lines 286-287). Add the standard errors (or deviations) to the columns in fig. 2b.

A: Thank you for your sincere advice! Revised accordingly Figure 1.

Figures 3 and 4. Indicate (e.g. with arrows) the times of N fertilization and the flooding cycles.

A: Thank you for your comment. Revised accordingly Figures 2 and 3.

TECHNICAL CORRECTIONS

Abstract: A widespread criteria is that non-standard or uncommon abbreviations should be avoided in the abstract. Therefore, you should remove some abbreviations that you only use once, e.g. Ei, Eo and SOC.

A: Thank you for your comment. Revised accordingly Page 2, Lines 22-23.

Avoid abbreviations at the beginning of the sentence (e.g. K in line 102, CO2 in line 206, CH4 in line 263).

A: Thank you for your comment. Revised accordingly.

Line 214: The word “Conversely” does not make sense there. Please rewrite the whole sentence.

A: Revised accordingly Page 10, Line 245-246.

Line 224: at the beginning of the sentence, change “A” by “The”.

A: Revised accordingly Page 10, Line 255.

Line 312: Although there were not significant differences...

A: Revised accordingly Page 13, Line 352.

Lines 314-316: In spite of producing. Change “considerable” by “similar”.

A: Revised accordingly Page 13, Line 355.

Line 333: per unit OF grain produced.

A: Revised accordingly Page 14, Line 375.

Line 355: the word “technologies” is repeated twice.

A: Revised accordingly Page 15, Line 399.

Line 362: the word “increment” is repeated twice.

A: Revised accordingly Page 15, Line 404.

Caption Table 2: and yields during rice and wheat cropping seasons...

A: Revised accordingly Table 2.

Footnote Table 2: significant differenceS.

A: Revised accordingly Table 2.

Table 3: I guess that you have considered MEAN fluxes and yields during the three cropping seasons (please indicate in the caption).

A: Yes, we considered mean fluxes and yields during the three cropping seasons. Revised accordingly Table 3.

Caption Table 4: global warming potential (without “s”)

A: Revised accordingly Table 5.

Be careful with the font and size in the figure captions.

A: Yes, we greatly revised the whole manuscript according to your valuable comments. We also improved our Figures for clarity. Thank you very much for your great help!

Referee #2

General Comments The authors have attempted to test agro-ecosystem dependent variables against a comprehensive set of controls related with the global perspective of GWP, and have tried to relate the study with the food security. The scope of this study is too large to detail all the measurements and their dynamics. Provided this paper is revised, it could be useful for relevant farming community, interesting to the scientific community and potentially important for the climate change studies. This paper should be published after filling up the significant gaps identified and correcting the specific and/or technical problems in the manuscript:

There are two major problems which need to be resolved before this research is published: 1. The C contents of the biomass (harvested crop=grains/paddy + straw) have gone un-accounted for in equations, although grain yield has been accounted for in equation 3 for GHGI calculation. However, in either case the crop straw is not mentioned (accounted). Crops grains as well as the wheat and rice straw accumulate a significant amount of C. As well, it is not clear how the total C balance of the agro-ecosystem was calculated. It is unclear how wheat grain and rice paddy and their straws have been accounted for in C balance and GWP calculations. The relative contributions of different GHGs on a global time scale are not even briefly mentioned. The “N” in the abbreviation “NGWP” is redundant. Instead negative GWP (cooling) and positive GWP

(warming) could be simpler to be used. 2. As the measurements were made from the same plots over years, therefore, repeated measures ANOVAs should be used, although year could also be taken as a fixed variable at the same time to see differences between years.

A: Thank you very much for your patience and your great support. We have tried our best to revise our manuscript according to your valuable comments. Please see the following point-by-point answers.

1. We determined the C balance by calculating the SOC changes in the integrated soil-crop system in this study as adopted by several researches (Shang et al., 2011; Zhang et al., 2014). We may adopt an alternative approach for calculating the C balance as suggested considering the C inputs from all parts including grains, straws, root exudates, manures etc. and outputs such as heterotrophic respiration. We compared these approaches and they agreed well with each other as reported by our previous publication (Zhang et al., 2014). We added some information according to your comments. Harvests included crop grains as well as the rice and wheat straws were removed out of the field for all the treatments in this study. Revised accordingly Page 5, Lines 119-120.
2. We deleted the “N” and “net” according to the Referee’s suggestion. Thus, we use GWP for all of our updated terminology. Thank you for your comments.
3. Considering the Referee’s suggestion, we have made correction in Table 3. A repeated-measures multivariate analysis of variance (MANOVA) was used to test cultivation patterns, cropping years and their interaction on GHG emissions and grain yields for the three annual rice-wheat rotations. Thank you very much for your indication. We therefore corrected the corresponding description according to the new MANOVA results.

Specific Comments

1. Authors have presented the conclusion in the abstract in a clear, concise and comprehensive manner

A: Thank you very much for your comment!

2. 5 years field study for this experiment is appropriate as it provides larger data set for processing to conclude with less uncertainty

A: Thank you so much for your support.

3. The terms GWP and Food Security are very important and need to be defined in introduction section

A: You are right. This is our major aim. We revised this point accordingly. Page 3, Lines 39-43 and Lines 52-55.

4. Please provide a brief rationale for this research with Food Security

A: You are right. Thank you very much! Revised accordingly Page 3, Lines 39-50.

5. The comments by the other referee are tired not be repeated here

A: Yes, thank you.

6. It could be very interesting if the GWPs be related to the annual (or seasonal) temperature and precipitation.

A: Thank you for your comment. The annual temperature and precipitation were similar over three years in this study. Further observations are essential to find out their relationship.

7. Fig. 1 may not be needed in this paper as the climate is not discussed in results section or related with other variables

A: Daily mean air temperature and precipitation were provided accordingly as Supplementary

resource 1.

8. In the title, “Net” is redundant

A: Thank you for your comment. We have deleted the “Net” in the title and the corresponding texts.

Page 18885 Line 6: add “equivalent” before “emissions” Line 7, 8: putting the abbreviations in brackets could be more meaningful Line 13: “, i.e., N1, N2, N3 and N4,” is redundant as these are already defined earlier Line 24: why is the word “cost” here? Page 18886 Line 4, 5, 6: Conclusion cannot be made on the basis of hypothesis, therefore, please remove this conclusion. Page 18887 Basal fertilizers- what was rate? Page 18888 Line 7: space or “.” Is required after mL Line 13: why different size brackets are used when same sized could be used? Table 2. The 2ND column CH4 values could be rounded off to no decimal point while the SD could be rounded off to a single decimal point.

A: We are sorry for the inconvenience. Revised accordingly Page 2, Lines 21-23, Line 26, Page 3, Line 50, Page 4, Line 77 and Table 2. The basal fertilizers rate was presented in Table 1 and Page 5, lines 112-116.

Thank you once again for your critical comments and great support!

Sincerely yours,

Zhengqin (on behalf of all authors)

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1 | Global warming potential and greenhouse gas intensity in rice agriculture driven by
2 | high yields and nitrogen use efficiency: A 5-year field study

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19 | **Abstract:** Our understanding of how global warming potential (GWP) and greenhouse gas
 20 | intensity (GHGI) is affected by management practices aimed at food security with respect to
 21 | rice agriculture remains limited. In the present study, a 5-year field experiment was conducted
 22 | in China to evaluate the effects of integrated soil-crop system management (ISSM) mainly
 23 | consisting of different nitrogen (N) fertilization rates and split, manure, Zn and Na₂SiO₃
 24 | fertilization and planting density on GWP and GHGI after accounting for carbon dioxide (CO₂)
 25 | equivalent emissions from all sources including methane (CH₄) and nitrous oxide (N₂O)
 26 | emissions, agrochemical inputs, and farm operations, and sinks (i.e., soil organic carbon
 27 | sequestration). For the improvement of rice yield and agronomic nitrogen use efficiency (NUE),
 28 | four ISSM scenarios consisting of different N_r rates relative to the local farmers' practice (FP)
 29 | rate were carried out, namely, N1 (25% reduction), N2 (10% reduction), N3 (FP rate) and N4
 30 | (25% increase). The results showed that compared with the FP, the four ISSM scenarios
 31 | significantly increased the rice yields by 10, 16, 28 and 41% and the agronomic NUE by 75, 67,
 32 | 74 and 73%, respectively. In addition, compared with the FP, the N1 and N2 scenarios
 33 | significantly reduced the GHGI by 14 and 18%, respectively, despite similar GWP. The N3
 34 | and N4 scenarios remarkably increased the GWP and GHGI by an average of 67 and 37%,
 35 | respectively. In conclusion, the ISSM strategies are promising for both food security and
 36 | environmental protection, and the ISSM scenario of N2 is the optimal strategy to realize high
 37 | yields and high NUE together with low environmental impacts for this agricultural rice field.
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61 **1 Introduction**

62 Rapid population growth and economic development place a growing pressure on increasing
63 food production (Barrett, 2010). An increase in global food production of 100% is the most
64 appropriate way to sustain the increase in human population and the consumption of animal
65 protein (Tilman et al., 2011). Rice is the staple food for nearly 50% of the world's people,
66 mainly in Asia. According to FAO (2010), approximately 600 million people in Asia-Pacific
67 region are suffering from hunger and malnutrition. With the region's population projected to
68 increase by another billion by mid-century, new approaches to increase food production are
69 needed. Within a limited land area, the intensive agricultural regions of China are facing
70 serious environmental problems due to large inputs of chemical fertilizers and low nitrogen
71 use efficiency (NUE) (Ju et al., 2009; Makino, 2011). Thus, integrated soil-crop system
72 management (ISSM), which redesigns the whole production system based on the local
73 environment and draws on appropriate fertilizer varieties and application ratios, crop
74 densities and advanced water regime management, has been advocated and developed to
75 simultaneously increase crop productivity and NUE with low carbon dioxide (CO₂)
76 equivalent emissions in China (Chen et al., 2014).

77 CO₂, methane (CH₄) and nitrous oxide (N₂O) are the most important greenhouse gases
78 (GHGs) that greatly contribute to global warming (IPCC, 2013). The concept of global
79 warming potential (GWP) was proposed based on the radiative properties of all the GHG
80 emissions and soil organic carbon (SOC) fixation, expressed as CO₂ eq. ha⁻¹ yr⁻¹ (Robertson
81 and Grace, 2004; Mosier et al., 2006). Although agriculture releases significant amounts of
82 CH₄ and N₂O into the atmosphere, the net emission of CO₂ equivalents from farming
83 activities can be partly offset by changing agricultural management to increase the soil
84 organic matter content and/or decrease the emissions of CH₄ and N₂O (Mosier et al., 2006;
85 Smith et al., 2008). If global agricultural techniques are improved, the mitigation potential of
86 agriculture (excluding fossil fuel offsets from biomass) is estimated to be approximately
87 5.5–6.0 Pg CO₂ eq. yr⁻¹ by 2030 (Smith et al., 2008). However, the release of CO₂ during the
88 manufacturing and application of N fertilizer to crops and from fuel used in machines for
89 farm operations can counteract these mitigation efforts (West and Marland, 2002). This
90 indicates that agricultural ecosystems are not only a very important source of GHG

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94 emissions but also present substantial opportunities for mitigation. Therefore, when
95 determining the GWP of GHG (CO₂, CH₄ and N₂O) emissions from agroecosystems, there is
96 a need to account for all sources including GHGs emissions, agrochemical inputs (Ei) and
97 farm operations (Eo) and sinks e.g. soil organic carbon (SOC) sequestration of CO₂
98 equivalents (Sainju et al., 2014).

99 Information on the effects of ISSM scenarios on GWP and greenhouse gas intensity
100 (GHGI) is limited in China (Ma et al., 2013; Liu et al., 2015). The annual rotation of summer
101 rice-upland crop is a dominant cropping system in China. Previous studies mainly
102 investigated the initial influences of ISSM practices but did not account for the contributions
103 of CO₂ emissions from Ei and Eo (Ma et al., 2013; Zhang et al., 2014). In this study, we
104 evaluated GWP and GHGI by taking CO₂ equivalents from all sources and sinks into
105 account for 5 years. We hypothesized that the ISSM strategies would reduce the overall
106 GWP and GHGI compared with local farmers' practices (FP). The specific objectives of this
107 study were to (i) evaluate the effects of different ISSM scenarios on GWP and GHGI; (ii)
108 determine the main sources of GWP and GHGI in a rice-wheat cropping system; and (iii)
109 elucidate the overall performance for each ISSM scenario for different targets to increase
110 grain yields and NUE and reduce GWP and GHGI.

111 2 Materials and Methods

112 2.1 Experimental site

113 A 5-year field experiment was conducted at the Changshu agro-ecological experimental
114 station (31°32'93"N, 120°41'88"E) in Jiangsu Province, China. This is a typical, intensively
115 managed agricultural area where the cropping regime is dominated by a flooding rice (*Oryza*
116 *sativa* L.)-drained wheat (*Triticum aestivum* L.) rotation system. The site is characterized by
117 a subtropical humid monsoon climate with a mean annual air temperature of 15.6, 15.2 and
118 15.8 °C and precipitation of 878, 1163 and 984 mm for three years, respectively. The soil of
119 the field is classified as an *Anthrosol* with a sandy loam texture of 6% sand (1–0.05 mm), 80%
120 silt (0.05–0.001 mm), and 14% clay (<0.001 mm), which developed from lacustrine
121 sediment. The major properties of the soil at 0–20 cm can be described as follows: bulk
122 density, 1.11 g cm⁻³; pH, 7.35; organic matter content, 35.0 g kg⁻¹; and total N, 2.1 g kg⁻¹.
123 The daily mean air temperatures and precipitation during the study period from June 15,

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删除的内容: ; thus, specific ISSM scenarios can be adopted by policy makers based on specific targets, such as high yield, high NUE and GHG mitigation

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147 2011, to June 15, 2014, are given in the supplementary resource 1,

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148 2.2 Experimental design and management

149 A completely randomized design was established in 2009 with four replicates of six
150 treatments, including no nitrogen (NN) and FP as controls, and four ISSM scenarios at
151 different N application rates relative to the local FP rate, namely N1 (25% reduction), N2 (10%
152 reduction), N3 (FP rate) and N4 (25% increase). The designed ISSM (only for rice but not
153 wheat production) including a redesign of a split N fertilizer application, a balanced fertilizer
154 application (rapeseed cake in additional 112.5 kg N ha⁻¹, C/N=8), additional phosphorus and
155 potassium application, and transplanting density, used as the main techniques for improving
156 rice yield and agronomic NUE (calculated as the difference in grain yield between the plots
157 that received N application and the NN plot, divided by the N fertilizer rate). The details of
158 the fertilizer applications, irrigation, and field management practices of the six different
159 treatments are presented in Table 1. Further detailed information was described previously
160 (Zhang et al., 2014). Each plot was 6 m × 7 m size with an independent drainage/irrigation
161 system.

162 One midseason drainage (about one week) and final drainage before harvest were used
163 during the rice-growing season, whereas the plots only received precipitation during the
164 wheat-growing season. The N fertilizer was split into a 6:2:0:2 or 5:1:2:2 ratio of basal
165 fertilizer and topdressings for the rice crop and a 6:1:3 ratio for the wheat crop. All of
166 phosphorous (P), silicon (Si), zinc (Zn), and rapeseed cake manure were applied as basal
167 fertilizers for both crops. Potassium (K) was added as a split (1:1) application to the rice
168 crop and all as basal fertilizer for the wheat crop. The basal fertilization occurred at the time
169 of rice transplanting and wheat seeding. The topdressing was applied at the tillering and
170 panicle stages of the rice crop and at the seedling establishment and elongation stages of the
171 wheat crop. Harvests included crop grains as well as the rice and wheat straws were removed
172 out of the field for all the treatments in this study.

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173 2.3 Gas sampling and measurements

174 We measured the CH₄ emissions and N₂O fluxes in each plot of the field experiment over
175 five annual cycles from the 2009 rice-growing season to the 2014 wheat-growing season.
176 The initial 2-yr measurements during the 2009–2011 rice-wheat rotational systems were

180 described in our previous study (Ma et al., 2013). Emissions were measured manually using
 181 the static-opaque chamber method. Each replicate plot was equipped with a chamber with a
 182 size of 50 cm × 50 cm × 50 cm or 50 cm × 50 cm × 110 cm, depending on the crop growth
 183 and plant height. The chamber was placed on a fixed PVC frame in each plot and wrapped
 184 with a layer of sponge and aluminum foil to minimize air temperature changes inside the
 185 chamber during the period of sampling.

186 The gas samples were analyzed for CH₄ and N₂O concentrations using a gas
 187 chromatograph (Agilent 7890A, Shanghai, China) equipped with two detectors. CH₄ was
 188 detected using a hydrogen flame ionization detector (FID), and N₂O was detected using an
 189 electron capture detector (ECD). Argon-methane (5%) and N₂ were used as the carrier gas at
 190 a flow rate of 40 ml min⁻¹ for N₂O and CH₄ analysis, respectively. The temperatures for the
 191 column and ECD detector were maintained at 40 °C and 300 °C, respectively. The oven and
 192 FID were operated at 50 °C and 300 °C, respectively.

193 2.4 Topsoil organic carbon sequestration measurements

194 To measure the organic carbon content of the topsoil as described by Zhang et al. (2014),
 195 soil samples were collected after the wheat harvest in 2009 and 2014 from all experimental
 196 plots at a plowing depth of 0–20 cm. The soil organic carbon sequestration rates (SOC SR)
 197 were calculated as follows (Liu et al., 2015):

$$198 \text{SOC SR (t C ha}^{-1} \text{ yr}^{-1}) = (\text{SOC}_t - \text{SOC}_0) / T \times \gamma \times (1 - \delta_{2\text{mm}}/100) \times 20 \times 10^{-1} \text{ (1)}$$

199 In Eq. (1), SOC_t and SOC₀ are the SOC contents measured in the soils sampled after the
 200 wheat was harvested in 2014 and 2009, respectively. T refers to the experimental period (yr).
 201 γ and $\delta_{2\text{mm}}$ are the average bulk density and the gravel content (>2 mm) of the topsoil (0–20
 202 cm), respectively.

203 2.5 GWP and GHGI measurements

204 To better understand the overall climatic effects of the ISSM strategies on rice-wheat
 205 rotation cropping system, the GWP and GHGI were updated using all possible components
 206 and calculated as the following equations (IPCC, 2013):

$$207 \text{GWP (kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}) = 25 \times \text{CH}_4 + 298 \times \text{N}_2\text{O} + \text{Ei} + \text{Eo} - 44/12 \times \text{SOC SR}$$

208 (2)

$$209 \text{GHGI (kg CO}_2 \text{ eq. kg}^{-1} \text{ grain yield yr}^{-1}) = \text{GWP} / \text{grain yield (3)}$$

删除的内容: a hydrogen flame ionization detector and an SS-2 m×2 mm Porapak Q (80/100 mesh) column. The oven temperature remained at 50 °C, and the detector was maintained at 300 °C. The carrier gas was purified N₂ with a flow rate of 35 ml min⁻¹.

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删除的内容: In addition to the CH₄ emissions and N₂O fluxes, we considered some 'hidden' CO₂ equivalent emissions, including agrochemical inputs (Ei), such as the manufacture and transportation of the N, P and K fertilizers (Snyder et al., 2009), and farm operations (Eo), such as the water used for irrigation (Zhang et al., 2013) and diesel fuel (Huang et al., 2013a). The CO₂ equivalent emissions of N fertilizer were calculated as the mean value of the C emissions of 1.3 kg C equivalent kg⁻¹ (Lal, 2004). Similarly, the CO₂ equivalent for irrigation was calculated from the total amount of water used during the rice-growing season; the coefficient for the C cost was 5.16 (kg C eq. cm⁻¹ ha⁻¹) (Lal, 2004). The CO₂ equivalents of other Ei (P and K fertilization, manure, herbicide, pesticide and fungicide applications) and Eo (tillage, planting, harvest, and farm machinery production) were recorded and estimated according to the methods

删除的内容: The NGWP of the cropland ecosystem equals the total CO₂ emission equivalents minus the SOC change. To better understand climatic effects of the

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281 In Eq. (2), E_i , E_o and SOCSR represent CO₂ equivalent emissions from the
282 agrochemical inputs, farm operations and soil organic carbon sequestration rate, respectively.
283 The global warming potential of 1 kg CH₄ and N₂O are equivalent to 25 and 298 kg CO₂
284 based on 100-year time scale, respectively (IPCC, 2013). The 12 and 44 are the molecular
285 weight of C and CO₂, respectively. The grain yield is expressed as the air-dried grain yield.

286 Therefore, the GWP of the cropland ecosystem equals the total CO₂ equivalent
287 emissions minus the SOC change. In addition to the CH₄ emissions and N₂O fluxes, we
288 considered the ‘hidden’ CO₂ equivalent emissions, including agrochemical inputs (E_i), such
289 as the manufacture and transportation of the N, P and K fertilizers (Snyder et al., 2009), and
290 farm operations (E_o), such as the water used for irrigation (Zhang et al., 2013) and diesel
291 fuel (Huang et al., 2013a). The CO₂ equivalent emissions of N fertilizer were calculated as
292 the mean value of the C emissions of 1.3 kg C equivalent kg⁻¹ (Lal, 2004). Similarly, the
293 CO₂ equivalent for irrigation was calculated from the total amount of water used during the
294 rice-growing season; the coefficient for the C cost was 5.16 (kg C eq. cm⁻¹ ha⁻¹) (Lal, 2004).
295 The CO₂ equivalents of other E_i (P and K fertilization, manure, herbicide, pesticide and
296 fungicide applications) and E_o (tillage, planting, harvest, and farm machinery production)
297 were recorded and estimated according to the methods provided by Lal (2004). We collected
298 data specific to China’s fertilizer manufacture and consumption, and then estimated C
299 emissions coefficients were 0.07 and 0.1 C cost (kg C eq. kg⁻¹ active ingredient) per applied
300 Si and Zn fertilizer, respectively.

301 2.6 Statistical analysis

302 Repeated-measures multivariate analysis of variance (MANOVA) and linear relationships
303 were determined using JMP 7.0, ver. 7.0 (SAS Institute, USA, 2007). The F-test was applied
304 to determine whether there were significant effects of the practices, years and their
305 interaction at $P < 0.05$. One-way analysis of variance was conducted to determine the
306 emissions of CH₄ and N₂O, and the grain yield among the different treatments. Tukey’s HSD
307 test was used to determine whether significant differences occurred between the treatments
308 at a significance level of $P < 0.05$. The results are presented as the means and standard
309 deviation (mean \pm SD, $n = 4$).

310 3 Results

删除的内容: using JMP, ver. 7.0 (SAS Institute, USA, 2007)

删除的内容: Repeated-measures multivariate analysis of variance (MANOVA) Two-way analysis of variance (ANOVA) and linear relationships were determined using JMP 7.0. The F-test was applied to determine whether there were significant effects of the practices, years and their interaction at $P < 0.05$.

321 3.1 Crop production and agronomic NUE

322 During the three cropping rotations from 2011 to 2014, the rice and wheat yields varied
323 significantly among these cultivation patterns; these results are shown in Table 2. The grain
324 yields ranged from 5.83 to 12.11 t ha⁻¹ for rice and 1.75 to 6.14 t ha⁻¹ for wheat (Table 2).

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325 On average over the three cycles, the annual rice yield of the FP was significantly lower than
326 that of the ISSM scenarios of N1, N2, N3 and N4. Compared with the FP, rice grain yields
327 increased by 10% and 16% for the N1 and N2 scenarios, respectively, i.e., with the lower N
328 input, by 28% for the N3 scenario with the same N input and by 41% for the N4 scenario
329 with the highest N input. However, we did not observe any significant increases in the
330 wheat-grain yields compared with the FP except for the N4 scenario. Statistical analysis
331 indicated that rice and wheat yields from the three years were not significantly influenced by
332 the interaction of cultivation patterns and cropping year (Table 3).

333 The agronomic NUE for the rice and wheat of the fertilized plots ranged from 9.2 to
334 16.1 and 19.5 to 24.7 kg grain kg⁻¹ N, respectively (Fig. 1). The higher NUE in the wheat
335 season was mainly due to the reduced N fertilizer (40%) during this season. As expected, the
336 rice agronomic NUE significantly increased by 75, 67, 74, and 73% for the N1, N2, N3 and
337 N4 scenarios, respectively, compared with the FP (Fig. 1). For the wheat crop, the agronomic
338 NUE merely increased by 12 and 14% for the N1 and N2 scenarios, respectively, and
339 decreased to some extent for the N3 and N4 scenarios compared with the FP, mainly because
340 the current ISSM strategy was only designed for rice and not wheat production.

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341 3.2 CH₄ and N₂O emissions

342 All plots showed similar CH₄ emission patterns, being a source in the rice season and
343 negligible in the wheat season. During the three annual rice-wheat rotations from 2011 to
344 2014, the CH₄ fluxes ranged from -3.89 to 99.67 mg C m⁻² h⁻¹ (Fig. 2). The seasonal CH₄

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345 emissions varied significantly among the treatments during the rice-growing season (Table 3,
346 Fig. 2). No significant difference was found between the FP, N1 and N2 plots. Temporal
347 variation was significant during the three cycles (Table 3, P < 0.001). Averaged across years,
348 the CH₄ emission was greater in the N3 and N4 plots than in the NN, FP, N1 and N2 plots
349 (Table 2, P < 0.05). However, compared with the NN plots, the FP, N1 and N2 plots with
350 inorganic fertilizer application resulted in increased CH₄ emission rates of 59.9, 41.9 and

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359 43.0%, respectively, averaged over the rice-growing seasons. The CH₄ emission rates were
360 further enhanced by 198.5% in the N3 plots and by 246.7% in the N4 plots.

删除的内容: due to the combined application of inorganic and organic fertilizers

361 The annual N₂O fluxes varied from -33.1 to 647.5 μg N₂O-N m⁻² h⁻¹, most of the N₂O
362 was emitted during the wheat-growing season after fertilization events, and there were
363 several small emission peaks during the rice-growing season (Fig. 3). With respect to the N
364 application effect, the annual cumulative N₂O emissions for all four ISSM scenarios were
365 significantly higher than in NN (*P* < 0.05). Relative to the FP plot, the N1 and N2 scenarios
366 decreased the annual N₂O emissions by an average of 41% and 22%, respectively. (Table 2).
367 The N4 scenario significantly increased it by 46% (*P* < 0.05) because they received
368 additional N via manure application compared to the FP practice, although there was no
369 significant difference between the N3 and FP plots.

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删除的内容: Correlations between seasonal cumulative N₂O emissions and fertilizer N application rates were also calculated and the seasonal cumulative N₂O emissions increased exponentially with an increase in the N application rate (Fig. 2c).

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370 3.3 Annual GWP and GHGI

371 Based on the perspective of the carbon footprint, we included the GHG emissions associated
372 with all of the inputs (E_i and E_o), and SOC sequestration was expressed as kg CO₂ eq. ha⁻¹
373 yr⁻¹. The emission of CO₂ equivalents for E_i and E_o are classified in Table 4. While
374 irrigation was a large proportion of farm operations, these were much less significant than
375 chemical inputs. The CO₂ equivalents rates from N fertilizer dominated not only the
376 chemical input section (67-76% of E_i) but also the total CO₂ equivalents from agricultural
377 management (46-51% of the sum of the E_i and E_o). The GWP ranged from 7871 to 20911,
378 kg CO₂ eq. ha⁻¹ yr⁻¹ for the NN and the N4 plots, respectively (Table 5). Although fertilized
379 treatments, increased the annual CH₄ and N₂O emissions, it also increased the SOC
380 sequestration in this cropping system. Of the main field GHGs that were directly emitted,
381 CH₄ accounted for 56-75% of the GWP in all plots. An increase in the annual SOC content
382 led to a significant decrease in the GWP (contributed to 5-10% of the GWP except in the
383 NN plot). The CO₂ equivalents from agricultural management practices, for E_i (2449-4256,
384 CO₂ eq. ha⁻¹ yr⁻¹) were higher than those for E_o (1285-1697CO₂ eq. ha⁻¹ yr⁻¹) in the
385 fertilized plots. There was no significant difference in the annual GWP observed between the
386 FP, N1 and N2 plots (Table 5). Across the three years, N1 and N2 slightly reduced the GWP
387 by 12 and 10%, respectively; however, N3 and N4 significantly increased the GWP by an
388 average of 52 and 81%, respectively, in comparison with the FP.

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删除的内容: Consequently, the lowest NGWPGWP was achieved under the N1 scenario for the ISSM.

418 The GHGI was used to express the relationship between GWP and grain yield. The
419 GHGIs in this study ranged from 664 to 1145 kg CO₂ eq. t⁻¹ (Table 5). The significant
420 difference in the annual GHGI was found between the FP and the ISSM strategies.
421 Compared with the FP, N1 and N2 significantly reduced the GHGI by 14 and 18%,
422 respectively, mainly due to the increased grain yield and SOC sequestration as well as
423 reduced GHG emissions for the ISSM strategies. Although N fertilizer or organic/inorganic
424 combination fertilizer application reduced the SOC losses caused by crop cultivation and
425 increased the grain yields, the GHGIs were generally higher for the N3 and N4 scenarios
426 than the N1 and N2 scenarios due to further increases in CH₄ and N₂O emissions.

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427 4 Discussion

428 4.1 Grain yield and agronomic NUE as affected by ISSM strategies

429 Grain yields are directly related to fertilizer management. The MANOVA results indicated
430 that the rice and wheat grain yields were significantly affected by the cultivation strategies
431 (Table 3, $P < 0.001$), which is in agreement with previous results (Chen et al., 2011; Zhang
432 et al., 2011). Compared with the FP plot, the rice yields were remarkably increased by all
433 four ISSM scenarios (Table 2). However, the wheat grain yield decreased significantly when
434 the N fertilizer rate was reduced by 25% (N1 scenario). It has been reported in previous
435 studies that ISSM strategies can effectively improve the rice grain yield (Ma et al., 2013; Liu
436 et al., 2015). First, the adjusted transplanting density for the N1, N2, and N3 scenarios would
437 produce a positive effect on rice yield by influencing rice colony structure, which agreed
438 with Wu et al. (2005). Second, reasonable N split for the N1, N2, N3 and N4 scenarios
439 would significantly increase rice yield and agronomic NUE which had been confirmed by
440 Liu et al. (2009). In the present study, N1 and N2 significantly increased annual rice
441 production by 10 and 16%, respectively, in comparison with the FP (Table 2). The finding is
442 consistent with the result of Peng et al. (2006), who reported that a 30% reduction in the
443 total N rate during the early vegetative stage did not reduce the yield but slightly increased it
444 when combined with the modified farmers' fertilizer practice. Third, integrated management
445 of three macronutrients: N, P and K as well as the two micronutrients: Si and Zn were
446 considered as essential for sustainable high crop yields. Additional Si and Zn fertilizers for

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451 the N3 and N4 scenarios would support better seedling establishment and reduce both biotic
452 and abiotic stress, thus produce higher yields (Wang et al., 2005; Slaton et al., 2005;
453 Kabata-Pendias and Mukherjee,
454 2007; Hossain et al., 2008). As expected, when the total N rate was at the FP rate and
455 increased by 25% and applied with rapeseed cake manure, the rice yield in these N3 and N4
456 plots remarkably increased by 28 and 41%, respectively. Based on a long-term fertilizer
457 experiment, Shang et al. (2011) reported that organic fertilizer incorporation significantly
458 increased the early rice grain yield. This may have resulted from the organic fertilizer
459 applied in combination with adequate nutrients, which improved the rice yield.

460 It has been suggested that N losses vary depending on the timing, rate, and method of N
461 application, as well as the source of N fertilizer (Zhu, 1997). In spite of the high proportion
462 and improper timing of N application, rapid N losses (via ammonia volatilization,
463 denitrification, surface runoff, and leaching) are important factors that cause low agronomic
464 NUE of irrigated rice in China (Peng et al., 2006). Compared with the FP plot, the rice
465 agronomic NUE was significantly increased by 75, 67, 74, and 73% under the N1, N2, N3
466 and N4 scenarios, respectively (Fig. 1). The higher rice agronomic NUE in our study over
467 the experimental period was primarily due to the greatly reduced N losses by leaching and
468 volatilization as well as the improvement of N bioavailability in the rice crop season.
469 Organic/inorganic combination fertilizer application also increases uptake by crops
470 compared with the traditional farmers' practice (Peng et al., 2006). These findings suggest
471 that the ISSM strategy is an effective method for improving grain yield and agronomic NUE
472 for future sustainable rice agriculture in China.

473 4.2 CH₄ and N₂O emissions as affected by ISSM strategies

474 During the three years, the annual cumulative CH₄ emissions, on average, varied from 133 to
475 469 kg C ha⁻¹yr⁻¹ (Table 2), and these values fell within the range of 4.1 to 1015.6 kg CH₄
476 ha⁻¹ observed previously in a rice field (Huang et al., 2004). The MANOVA results indicated
477 that obvious effects of cultivation patterns and years on CH₄ emissions were found during
478 the rice-wheat rotations (Table 3, *P* < 0.001). The CH₄ emissions were not significantly
479 affected by the cycles but affected by crop season (Table 5, Fig. 2). In this study, no
480 significant difference in CH₄ emission was observed between the FP, N1 and N2 plots.

删除的内容: and the efficient control of pests and diseases (Slaton et al., 2005; Wang et al., 2005)

删除的内容: The higher yields in N3 and N4 scenarios would have also attributed to the addition of 15 kg Zn ha⁻¹ for better seedling establishment and vigor according to Slaton et al. (2005) and the application of silicon to reduce both biotic and abiotic stress according to Wang et al. (2005).

删除的内容: In general, rapid N losses (via ammonia volatilization, denitrification, surface runoff, and leaching), the high application rate of fertilizer N and improper timing of N application are three important factors that cause low agronomic NUE of irrigated rice in China

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503 However, compared with the FP plot, the N3 and N4 scenarios emitted 87 and 118% more
504 CH₄ emissions, respectively (Table 5), which is probably due to the incorporation of the
505 organic rapeseed cake manure. Previous reports support the observations that CH₄ emissions
506 were significantly increased with the application of organic amendments (Ma et al., 2009;
507 [Thangarajan et al., 2013](#); Zou et al., 2005). [Additional application of Si and Zn fertilizers](#)
508 [had no significant effect on CH₄ and N₂O fluxes, which was consistent with the result of Xie](#)
509 [et al. \(2015\)](#). Moreover, rice growth was found to be significantly increased under the N3
510 and N4 scenarios. In this case, the organic matter inputs such as root litter and rhizodeposits
511 in the N3 and N4 scenarios were probably also higher than in the other plots, and thus soil C
512 input, which served as an additional source of substrates for the methanogens in the rice
513 paddies, likely contributed to the increase in CH₄ emissions (Ma et al., 2009). Finally,
514 because the rice plants acted as the main pathway for CH₄ transports from the soil to the
515 atmosphere, the higher biomass the more CH₄ emissions (Yan et al., 2005). The results
516 obtained in the present study revealed that both inorganic and organic fertilizer application
517 significantly increased the CH₄ emissions in the rice season (Table 2), which was probably
518 associated with the increase in the SOC content and crop biomass (Ma et al., 2013).

519 Denitrification and nitrification are the main processes that produce N₂O in the soil
520 ([Paul et al., 1993](#)). Changes in the soil water content strongly affected the soil N₂O
521 emissions and resulted in negligible N₂O emissions when the rice field was flooded (Fig. 3),
522 which is consistent with previous reports (Akiyama et al., 2005; Murdiyarso et al., 2010). A
523 relatively high N₂O peak was observed in the first two weeks of the wheat-growing season
524 (Fig. 3), possibly because soil changes from flooded to drained condition may have
525 enhanced N₂O release ([Deng et al., 2012](#)). Alternation of drainage and flooding may induce
526 large amounts of N₂O emissions, particularly in fertilized systems; this has commonly been
527 proved in earlier studies (Wang et al., 2013; Xiong et al., 2007; Zou et al., 2005). The
528 seasonal and annual rates of N₂O emission were significantly affected by the cultivation
529 practice patterns [and years](#) (Table 3). [Compared with the FP plot, the N2 scenario greatly](#)
530 [decreased the seasonal N₂O emissions in this study, which may have resulted from a](#)
531 [reduction in the N fertilizer rate \(Table 1, Table 2\)](#). The total N₂O emissions decreased by
532 7–38% and 26–42% in the rice and wheat seasons, respectively, when the conventional N

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删除的内容: Our results showed that the seasonal cumulative N₂O emissions increased exponentially with an increase in the N application rate (Fig. 2c).

539 management (300 kg N ha⁻¹ for rice and 180 kg N ha⁻¹ per crop for wheat) changed to
540 optimum N management (225–270 kg N ha⁻¹ for rice and 135–162 kg N ha⁻¹ per crop for
541 wheat). It is likely that more N₂O was emitted (Mosier et al., 2006) as a result of the
542 additional N made available to the soil microbes through N fertilizer application, which
543 probably increased the CH₄ emissions (Banger et al., 2013). Strategies that can reduce N
544 fertilization rates without influencing crop yields can inevitably lower GHG emissions
545 (Mosier et al., 2006).

546 4.3 GWP and GHGI as affected by ISSM strategies

547 The GWP in our study (10104–20911 kg CO₂ eq. ha⁻¹) with the ISSM strategies was higher
548 than that in a double-cropping cereal rotation (1346–4684 kg CO₂ eq. ha⁻¹) and a rice-wheat
549 annual rotation (290–4580 kg CO₂ eq. ha⁻¹) reported by Huang et al. (2013b) and Yang et al.
550 (2015), respectively. Dominant CH₄ emissions as well as additional CO₂ emitted by the
551 machinery/equipment used for irrigation and farm operations under the ISSM strategies may
552 increase the GWP more than in other cropping systems. However, the current GWP was still
553 much lower than that of a double-rice cropping system (13407–26066 kg CO₂ eq. ha⁻¹)
554 (Shang et al., 2011). The GHGIs, which ranged from 0.66 to 1.15 kg CO₂ eq. kg⁻¹ grain in
555 this study, were slightly higher than previous estimates of 0.24–0.74 kg CO₂ eq. kg⁻¹ grain
556 from rice paddies with midseason drainage and organic manure incorporation (Qin et al.,
557 2010; Li et al., 2006) but were lower than the DNDC model estimates for continuous
558 waterlogged paddies (3.22 kg CO₂ eq. kg⁻¹ grain) (Li et al., 2006). Differences in GWP or
559 GHGI were found in the cultivation patterns over the three rice-wheat rotations (Table 5).

560 Although there were not significant differences among the FP, N1 and N2 plots, the N1 and
561 N2 scenarios with optimized ISSM strategies led to a lower GWP than the FP (Table 5).
562 Compared with the FP, the N1 and N2 scenarios dramatically reduced the GHGI, which was
563 mainly due to higher yields. In spite of the similar GWP compared with the FP plot, the
564 lowest GHGI (0.66 kg CO₂ eq. kg⁻¹ grain) was obtained under the N2 scenario. This finding
565 is consistent with the suggestion made by Burney et al. (2010), i.e., that the net effect of
566 higher yields offsets emissions. It is well known that CH₄ emissions dominate the GWP in
567 rice paddies (Ma et al., 2013; Shang et al., 2011). In comparison to the GWP (11545 kg CO₂
568 eq. ha⁻¹yr⁻¹) and GHGI (0.81 kg CO₂ eq. kg⁻¹ grain) of the FP, the N3 and N4 scenarios

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582 increased both the GWP and GHGI, mainly because these scenarios notably increased the
583 CH₄ emissions compared with the FP, which resulted in relatively higher GWP (Table 5).

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584 Agricultural management practices that change one type of GWP source/sink may also
585 impact other sources/sinks and therefore change the GWP and GHGI (Mosier et al., 2006;
586 Shang et al., 2011). Although the N-fertilizer plots, especially those with the incorporation of
587 organic fertilizer, increased the annual CH₄ and N₂O emissions, they increased the SOC
588 sequestration in this cropping system, which is agreement with previous reports (Huang and
589 Sun, 2006). This was mainly due to the enhanced incorporation of rapeseed cake and crop
590 residue associated with higher crop productivity (Ma et al., 2013). In the present study, the
591 N₂ scenario with ISSM decreased the CH₄ and N₂O emissions as well as the energy
592 consumption related to irrigation and the manufacture and transport of N fertilizer
593 (depending on coal combustion), ultimately leading to a decrease in the GWP relative to the
594 FP plot. Moreover, despite the lower N fertilizer input, the grain yield did not decline and the
595 GHGI of the N₂ scenario was thus lower than of the FP plot, indicating less consumption of
596 CO₂ equivalents per unit of grain produced. We demonstrate that high yield and agronomic
597 NUE, together with low GWP, are not conflicting goals by optimizing ISSM strategies.

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598 4.4 Main components of GWP and GHGI and implementation significance for the ISSM
599 strategies

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600 Determining the main components of the GWP and GHGI in specific cropping systems is
601 very important for mitigating GHG emissions in the future because the benefits of C
602 sequestration would be negated by CH₄ and N₂O emissions and the CO₂ equivalents released
603 with the use of high N fertilizer application rates (Schlesinger, 2010). In the current study,
604 the five main components of the CO₂ equivalents for the GWP were ranked in decreasing
605 order of importance as follows: CH₄ emissions > agrochemical inputs of N fertilizer > farm
606 operations related to irrigation > SOC sequestration > N₂O emissions (Table 5). CH₄
607 emissions, the most important component of GWP in this typical rice-wheat rotation system,
608 could be further mitigated by some other strategies, such as reasonable irrigation (Zou et al.,
609 2005; Wang et al., 2012).

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610 Although N fertilizer application increased SOC sequestration when it was applied
611 with rapeseed cake manure, this benefit was consistently overshadowed, on a CO₂ equivalent

619 basis, by the increases in CH₄ and N₂O emissions (Table 5). Similar results have been
620 reported, i.e., GHG emissions substantially offset SOC increases (Six et al., 2004). It is
621 possible that the realization of reducing the GWP and GHGI in China should focus on
622 increasing the SOC and simultaneously decreasing the CO₂ equivalents from CH₄ emissions
623 and N fertilizer inputs. Several studies reported possible methods for these types of
624 mitigation strategies, such as optimizing the chemical fertilizer application amount and rate
625 (Ju et al., 2011), the amount of water used for irrigation (Gao et al., 2015), and the timing
626 and rate of N using the in-season N management approach, as well as improving the N
627 fertilizer manufacturing technologies (Zhang et al., 2013), and using nitrification inhibitors
628 or polymer-coated controlled-release fertilizers (Hu et al., 2013).

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629 China is a rapidly developing country that faces the dual challenge of substantially
630 increasing grain yields at the same time as reducing the very substantial environmental
631 impacts of intensive agriculture (Chen et al., 2011). We used the ISSM strategies to develop
632 a rice production system that achieved mean yields of 10.63 t ha⁻¹ (an increment of almost
633 24%) and an agronomic NUE of 16.33 kg grain kg⁻¹ N (an approximate doubling) in
634 long-term field experiments compared with current farmers' practices. The ISSM redesigned
635 the whole production system only for the rice crop based on the local environment and
636 drawing on appropriate fertilizer varieties and application ratios, crop densities and an
637 advanced water regime management. If the ISSM strategies were also developed for the
638 rotated wheat crop, the overall performance of the whole rice-wheat system would be much
639 improved, with further increases in yield and reductions in the GWP and GHGI. We
640 conclude that the ISSM strategies are promising, particularly the ISSM-N2 scenario, which
641 is the most favorable to realize higher yields with lower environmental impact. The proposed
642 ISSM strategies can provide substantial benefits to intensive agricultural systems and can be
643 applied feasibly using current technologies.

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644 5 Conclusions

645 Reasonable agricultural management practices are the key to reducing GHG emissions from
646 agricultural ecosystems. This study provided an insight into the complete GHG emission
647 accounting of the GWP and GHGI affected by different ISSM scenarios. After a five-year
648 field experiment, we found that the CH₄ emissions, production of N fertilizer, irrigation,

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653 SOC sequestration and N₂O fluxes were the main components of the GWP in a typical
654 rice-wheat rotation system. In contrast with the FP, N1 and N2 significantly reduced the
655 GHGI, though they resulted in similar GWPs, and N3 and N4 remarkably increased the
656 GWP and GHGI. By adopting the ISSM strategy, the conventional N application rate was
657 reduced by 10% while the rice yield was significantly increased by 16%, the NUE was
658 improved by 67% and the GHGI was lowered. ISSM scenarios could be adopted for both
659 food security and environmental protection with specific targets. We propose that the
660 ISSM-N2 scenario is the most appropriate management strategy (10% reduction of N input,
661 no rapeseed manure and higher plant density) for realizing higher yields and NUE, together
662 with some potential to reduce GHGI by integrated soil-crop management. For
663 simultaneously mitigating GHG emissions, further research on integrated soil-crop system
664 managements is required particularly for mitigating CH₄ emissions in sustainable rice
665 agriculture.
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删除的内容: , indicating that further research is required for mitigating GHG emissions when aiming to increasing rice yield and NUE

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Table 1

The establishment of different treatments for the annual rice-wheat rotations during the 2011–2014 cycle.

Scenario	NN ^a	FP	ISSM-N1	ISSM-N2	ISSM-N3	ISSM-N4
Rice-growing season						
Chemical fertilizer application rate (N:P ₂ O ₅ :K ₂ O:Na ₂ SiO ₃ :ZnSO ₄ , kg ha ⁻¹)	0:90:120:0:0	300:90:120:0:0	225:90:120:0:0	270:90:120:0:0	300:108:144:225:15	375:126:180:225:15
Split N application ratio		6:2:0:2	5:1:2:2	5:1:2:2	5:1:2:2	5:1:2:2
Rapeseed cake manure (t ha ⁻¹)	0	0	0	0	2.25	2.25
Water regime	F-D-F-M ^b	F-D-F-M	F-D-F-M	F-D-F-M	F-D-F-M	F-D-F-M
Planting density (cm)	20×20	20×20	20×15	20×15	20×15	20×20
Wheat-growing season						
Chemical fertilizer application rate (N:P ₂ O ₅ :K ₂ O, kg ha ⁻¹)	0:90:180	180:90:180	135:90:180	162:90:180	180:108:216	225:126:270
Split N application ratio		6:1:3	6:1:3	6:1:3	6:1:3	6:1:3
Seed sowing density (kg ha ⁻¹)	180	180	180	180	180	180

^aNN, no N application; FP, farmers' practice; The four integrated soil-crop system management (ISSM) practices at different nitrogen application rates relative to the FP rate of 300 kg N ha⁻¹ for the rice crop and 180 kg N ha⁻¹ for the wheat crop, namely, N1 (25% reduction), N2 (10% reduction), N3 (FP rate) and N4 (25% increase). Urea, calcium biphosphate and potassium chloride were used as N, P and K fertilizer respectively.

^bF-D-F-M, flooding-midseason drainage-re-flooding-moist irrigation.

Table 2

Seasonal CH₄ and N₂O emissions, and yields during rice and wheat cropping seasons, in the three cycles of 2011–2014.

Treatment	Rice season			Wheat season		
	CH ₄ (kg C ha ⁻¹)	N ₂ O (kg N ha ⁻¹)	Yield (t ha ⁻¹)	CH ₄ (kg C ha ⁻¹)	N ₂ O (kg N ha ⁻¹)	Yield (t ha ⁻¹)
2011						
NN	153±10.8 _c	0.03±0.05 _c	5.85±0.08 _f	-0.48±0.63 _a	0.45±0.09 _d	1.74±0.18 _d
FP	266±25.3 _b	0.11±0.08 _c	8.38±0.35 _e	-0.48±1.86 _a	1.43±0.19 _b	5.67±0.20 _b
ISSM-N1	212±30.3 _{bc}	0.08±0.03 _c	9.27±0.26 _d	0.78±0.97 _a	0.65±0.11 _{cd}	5.05±0.16 _c
ISSM-N2	220±32.5 _{bc}	0.17±0.11 _{bc}	9.79±0.44 _c	2.25±2.07 _a	0.80±0.06 _c	5.71±0.18 _b
ISSM-N3	518±58.9 _a	0.38±0.15 _{ab}	10.81±0.26 _b	0.04±3.23 _a	1.40±0.10 _b	5.31±0.26 _{bc}
ISSM-N4	561±50.9 _a	0.37±0.07 _a	11.76±0.24 _a	-0.09±1.40 _a	1.93±0.09 _a	6.15±0.15 _a
2012						
NN	149±25.8 _d	0.13±0.10 _c	5.80±0.22 _f	-4.32±7.29 _a	0.65±0.09 _d	1.73±0.11 _c
FP	239±34.5 _c	0.33±0.11 _{bc}	8.72±0.62 _e	4.85±10.30 _a	2.13±0.43 _{ab}	5.64±0.34 _{ab}
ISSM-N1	226±30.4 _{cd}	0.27±0.07 _{bc}	9.43±0.34 _d	1.46±6.38 _a	1.39±0.14 _c	4.94±0.38 _b
ISSM-N2	228±32.6 _{cd}	0.38±0.29 _{bc}	9.99±0.50 _c	-1.02±0.84 _a	1.77±0.38 _{bc}	5.78±0.59 _{ab}
ISSM-N3	431±26.8 _b	0.52±0.16 _{ab}	10.92±0.61 _b	2.45±8.35 _a	2.19±0.24 _{ab}	5.39±0.39 _{ab}
ISSM-N4	536±58.7 _a	0.78±0.13 _a	12.24±0.60 _a	5.91±6.18 _a	2.61±0.42 _a	6.10±0.49 _a
2013						
NN	101±39.2 _b	0.16±0.09 _b	5.84±0.15 _f	-1.45±1.34 _a	0.35±0.06 _c	1.80±0.03 _c
FP	141±25.2 _b	0.43±0.39 _{ab}	8.67±0.26 _e	-3.70±1.76 _a	0.80±0.20 _{ab}	5.70±0.30 _{ab}
ISSM-N1	135±15.7 _b	0.19±0.16 _{ab}	9.66±0.29 _d	-1.00±1.61 _a	0.49±0.16 _{bc}	5.15±0.20 _b
ISSM-N2	129±32.2 _b	0.26±0.13 _{ab}	10.15±0.07 _c	-0.79±1.60 _a	0.69±0.24 _{abc}	5.80±0.18 _{ab}
ISSM-N3	256±45.6 _a	0.59±0.42 _{ab}	11.14±0.10 _b	-0.62±1.14 _a	0.71±0.10 _{ab}	5.51±0.33 _{ab}
ISSM-N4	304±22.3 _a	0.74±0.40 _a	12.34±0.16 _a	0.55±1.68 _a	1.02±0.11 _a	6.19±0.63 _a
Average 2011–2013 ^a						
NN ^b	135±19.6 _d	0.11±0.05 _c	5.83±0.04 _f	-2.08±1.89 _a	0.48±0.07 _d	1.75±0.04 _d
FP ^b	215±19.9 _c	0.29±0.13 _{bc}	8.59±0.25 _e	0.22±3.96 _a	1.45±0.24 _b	5.67±0.16 _b
ISSM-N1 ^b	191±19.2 _c	0.18±0.06 _c	9.45±0.18 _d	0.42±2.77 _a	0.84±0.08 _c	5.04±0.08 _c
ISSM-N2 ^b	192±11.6 _c	0.27±0.12 _{bc}	9.98±0.25 _c	0.15±0.58 _a	1.08±0.12 _c	5.76±0.22 _{ab}
ISSM-N3 ^b	402±23.8 _b	0.50±0.16 _{ab}	10.95±0.13 _b	0.63±3.51 _a	1.43±0.05 _b	5.40±0.16 _{bc}
ISSM-N4 ^b	467±39.2 _a	0.68±0.15 _a	12.11±0.28 _a	2.12±2.57 _a	1.85±0.16 _a	6.14±0.35 _a

^aMean ± SD, different lower case letters within the same column for each item indicate significant differences at $P < 0.05$ according to Tukey's multiple range test.

^bSee Table 1 for treatment codes.

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Table 3

Repeated-measures analysis of variance (MANOVA) for the effects of cultivation patterns (P) and cropping year (Y) on mean CH₄ and N₂O emissions, and mean rice and wheat grain yields in the 2011–2014 cycle.

Crop season	Source	df	CH ₄ (kg C ha ⁻¹)	N ₂ O (kg N ha ⁻¹)	Yield (t ha ⁻¹)
Rice	<u>Between subjects</u>				
	P	5	35.3***	3.71***	123***
	<u>Within subjects</u>				
	Y	2	20.7***	0.88**	1.15**
	P×Y	10	6.73***	0.15	0.37
Wheat	<u>Between subjects</u>				
	P	5	0.26	14.8***	76.3***
	<u>Within subjects</u>				
	Y	2	0.55*	15.1***	0.08
	P×Y	10	0.83	4.39***	0.05
Rice-Wheat	<u>Between subjects</u>				
	P	5	37.2***	24.2***	153***
	<u>Within subjects</u>				
	Y	2	20.5***	5.83***	0.70*
	P×Y	10	6.50***	1.11	0.17

df – degrees of freedom, * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$ represent significant at the 0.05, 0.01 and 0.001 probability level, respectively.

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Two-way ANOVA for the effects of cultivation patterns (P) and cropping year (Y) on CH₄ and N₂O emissions, and rice and wheat grain yields for the three annual rice-wheat rotations of 2011–2014.
Crop season

Table 4

Agricultural management practices for chemical inputs and farm operations and contributions to carbon dioxide equivalents (kg CO₂ eq. ha⁻¹yr⁻¹) in the annual rice-wheat rotations from 2011 to 2014 (chemical inputs and farm operations used in each year were similar except for irrigation water).

Treatment	Chemical inputs (kg ha ⁻¹) ^a								Farm operations (kg ha ⁻¹) ^c							
	N	P	K	Si	Zn	Herbicide	Insecticide	Fungicide	Irrigation (cm) ^b			Tillage and raking	Crop planting	Farm manure	Crop harvest	Farm machinery production
									2011	2012	2013					
NN ^d	0	180	300	0	0	2	18	4	75	80	80	37	1	0	11	135
FP	480	180	300	0	0	2	20	4.4	75	80	80	37	1	0	11	147
ISSM-N1	360	180	300	0	0	2	20	4.4	50	65	55	37	1	0	11	139
ISSM-N2	432	180	300	0	0	2	20	4.4	50	65	55	37	1	0	11	177
ISSM-N3	480	216	360	225	15	2	27	6	50	65	55	37	1	2250	11	177
ISSM-N4	600	252	450	225	15	2	41	9	50	65	55	37	1	2250	11	275
	Chemical inputs (Ei)								Farm operations (Eo)							
NN	0	132	165	0	0	2	338	53	1419	1514	1514	127	12	0	37	36
FP	2288	132	165	0	0	2	375	59	1419	1514	1514	127	12	0	37	39
ISSM-N1	1716	132	165	0	0	2	375	59	946	1230	1041	127	12	0	37	37
ISSM-N2	2059	132	165	0	0	2	375	59	946	1230	1041	127	12	0	37	47
ISSM-N3	2288	158	198	58	6	2	506	79	946	1230	1041	127	12	62	37	47
ISSM-N4	2860	185	248	58	6	2	768	129	946	1230	1041	127	12	62	37	73

^aThe carbon emission coefficients were 1.3,0.2,0.15, 0.3, 5.1 and 3.9 C cost (kg C eq. kg⁻¹ active ingredient) per applied nitrogen fertilizer, phosphorus, potassium, herbicide, insecticide and fungicide, respectively, as referred to in Lal (2004). [We collected data specific to China's fertilizer manufacture and consumption, and then estimated carbon emissions coefficients were 0.07 and 0.1 C cost \(kg C eq. kg⁻¹ active ingredient\) per applied Si and Zn fertilizer, respectively.](#)

^bThe carbon emission coefficient for irrigation was 5.16 C cost (kg C eq. cm⁻¹ ha⁻¹) as referred to in Lal (2004).

^cThe carbon emission coefficients were 0.94, 3.2, 0.0075, 0.94 and 0.0725 C cost (kg C eq. kg⁻¹ active ingredient) for tillage and raking, crop planting, per farm manure application, harvesting, spraying and threshing, respectively, as referred to in Lal (2004).

^dSee Table 1 for treatment codes.

Table 5

Mean global warming potential (GWP) and greenhouse gas intensity (GHGI) over the three annual cycles of the 2011rice season–2014wheat season.

Treatment	CH ₄	N ₂ O	Ei	Eo	SOCSR	GWP ^a	Grain yield	GHGI ^b
	kg CO ₂ eq. ha ⁻¹ yr ⁻¹						t ha ⁻¹ yr ⁻¹	kg CO ₂ eq. t ⁻¹ grain
NN ^d	4418±628d ^c	276±29d	690	1694	- 792±327c	7871±646d	7.58±0.04d	1038±85b
FP	7181±766c	816±55b	3021	1697	1170±396ab	11545±505c	14.26±0.36c	810±23c
ISSM-N1	6381±633c	479±62c	2449	1285	491±435b	10104±930c	14.50±0.14c	697±63d
ISSM-N2	6421±379c	633±97c	2792	1295	709±193ab	10433±516c	15.74±0.44b	664±49d
ISSM-N3	13418±744b	906±87b	3295	1357	1383±503a	17593±688b	16.36±0.18b	1075±33ab
ISSM-N4	15630±1246a	1188±65a	4256	1383	1545±348a	20911±1289a	18.26±0.46a	1145±84a

^aGWP (kg CO₂ eq. ha⁻¹yr⁻¹) = 25 × CH₄ + 298 × N₂O + Ei + Eo - 44/12 × SOCSR, Ei (agrochemical inputs), Eo (farm operations), SOCSR (SOC sequestration rate)

^bGHGI (kg CO₂ eq. t⁻¹ grain) = GWP/grain yields

^cDifferent lower case letters within the same column for each item indicate significant differences at P<0.05 based on Tukey's multiple range tests.

^dSee Table 1 for treatment codes.

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Fig 1 Rice and wheat agronomic nitrogen use efficiency (NUE) in 2011–2014 in Changshu, China.

Different letters indicate a significant difference between treatments ($p < 0.05$). See Table 1 for treatment codes.

Fig 2 Seasonal variation of methane (CH_4) fluxes from the rice-wheat rotation cropping systems from

2011 to 2014. The black and gray part in figure separates different grain growth periods. See Table 1

for treatment codes. The solid arrows indicate fertilization.

Fig 3 Seasonal variation of nitrous oxide (N_2O) fluxes from rice-wheat rotation cropping systems in

three annual cycles over the period 2011–2014. The black and gray part in the figure separates

different growth periods. See Table 1 for treatment codes. The solid arrows indicate fertilization.

Supplementary resource 1 Daily mean air temperature and precipitation during the rice-wheat rotation in

2011–2014 in Changshu, China.

已下移 [1]: Fig 1 Daily mean air temperature and precipitation during the rice-wheat rotation in 2011–2014 in Changshu, China.

删除的内容: 2 (a)

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