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. N_2O 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 N_2O 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 $ZnSO_4$ and Na_2SiO_3 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 N2O 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 CH4 and N2O 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: "CO2 equivalents from machinery used for Ei (2449–4192 CO2-eq ha−1 yr−1) were higher than Eo (1285–1697 CO2-eq ha−1 yr−1) of the fertilized plots". The word "machinery" is confusing form me since you explain (in lines 123-133) that the Ei component accounted the CO2 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 N2O emissions indirectly (i.e. the more a crop grows, the more N is uptaken and the less N is likely to be lost as N2O). Particularly, Zn has been reported to influence CH4 and N2O 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 thorough 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 thorough 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, CO_2 in line 206, CH_4 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".

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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!

Thank you once again for your critical comments and great support! Wish you a Happy New Year!

Sincerely yours,

Zhengqin (on behalf of all authors)

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

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Abstract: Our understanding of how global warming potential (GWP) and greenhouse gas intensity (GHGI) is affected by management practices aimed at food security with respect to rice agriculture remains limited. In the present study, a 5-year field experiment was conducted in China to evaluate the effects of integrated soil-crop system management (ISSM) mainly consisting of different nitrogen (N) fertilization rates and split, manure, Zn and Na_2SiO_3 fertilization and planting density on GWP and GHGI after accounting for carbon dioxide (CO_2) equivalent emissions from all sources including methane (CH_4) and nitrous oxide (N_2O) emissions, agrochemical inputs and farm operations and sinks (i.e., soil organic carbon sequestration). For the improvement of rice yield and agronomic nitrogen use efficiency (NUE), four ISSM scenarios consisting of different N rates relative to the local farmers' practice (FP) rate were carried out, namely, N1 (25% reduction), N2 (10% reduction), N3 (FP rate) and N4 (25% increase). The results showed that compared with the FP, the four ISSM scenarios significantly increased the rice yields by 10, 16, 28 and 41% and the agronomic NUE by 75, 67, 74 and 73%, respectively. In addition, compared with the FP, the N1 and N2 scenarios significantly reduced the GHGI by 14 and 18%, respectively, despite similar GWPs. The N3 and N4 scenarios remarkably increased the GWP and GHGI by an average of 67 and 37%, respectively. In conclusion, the ISSM strategies are promising for both food security and environmental protection, and the ISSM scenario of N2 is the optimal strategy to realize high yields and high NUE together with low environmental impacts for this agricultural rice field.

1 Introduction

Rapid population growth and economic development place a growing pressure on increasing food production (Barrett, 2010). An increase in global food production of 100% is the most appropriate way to sustain the increase in human population and the consumption of animal protein (Tilman et al., 2011). Rice is the staple food for nearly 50% of the world's people, mainly in Asia. According to FAO (2010), approximately 600 million people in Asia-Pacific region are suffering from hunger and malnutrition. With the region's population projected to increase by another billion by mid-century, new approaches to increase food production are needed. Within a limited land area, the intensive agricultural regions of China are facing serious environmental problems due to large inputs of chemical fertilizers and low nitrogen use efficiency (NUE) (Ju et al., 2009; Makino, 2011). Thus, integrated soil-crop system management (ISSM), which redesigns the whole production system based on the local environment and draws on appropriate fertilizer varieties and application ratios, crop densities and advanced water regime management, has been advocated and developed to simultaneously increase crop productivity and NUE with low carbon dioxide (CO_2) equivalent emissions in China (Chen et al., 2014).

CO_2, methane (CH_4) and nitrous oxide (N_2O) are the most important greenhouse gases (GHGs) that greatly contribute to global warming (IPCC, 2013). The concept of global warming potential (GWP) was proposed based on the radiative properties of all the GHG emissions and soil organic carbon (SOC) fixation, expressed as CO_2 eq. ha^{-1} yr^{-1} (Robertson and Grace, 2004; Mosier et al., 2006). Although agriculture releases significant amounts of CH_4 and N_2O into the atmosphere, the net emission of CO_2 equivalents from farming activities can be partly offset by changing agricultural management to increase the soil organic matter content and/or decrease the emissions of CH_4 and N_2O (Mosier et al., 2006; Smith et al., 2008). If global agricultural techniques are improved, the mitigation potential of agriculture (excluding fossil fuel offsets from biomass) is estimated to be approximately 5.5–6.0 Pg CO_2 eq. yr^{-1} by 2030 (Smith et al., 2008). However, the release of CO_2 during the manufacturing and application of N fertilizer to crops and from fuel used in machines for farm operations can counteract these mitigation efforts (West and Marland, 2002). This indicates that agricultural ecosystems are not only a very important source of GHG emissions

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but also present substantial opportunities for mitigation. Therefore, when determining the GWP of GHG (CO_2, CH_4 and N_2O) emissions from agroecosystems, there is a need to account for all sources including GHGs emissions, agrochemical inputs (Ei) and farm operations (Eo) and sinks, e.g. soil organic carbon (SOC) sequestration of CO_2 equivalents (Sainju et al., 2014).

Information on the effects of ISSM scenarios on GWP and greenhouse gas intensity (GHGI) is limited in China (Ma et al., 2013; Liu et al., 2015). The annual rotation of summer rice-upland crop is a dominant cropping system in China. Previous studies mainly investigated the initial influences of ISSM practices but did not account for the contributions of CO_2 emissions from Ei and Eo (Ma et al., 2013; Zhang et al., 2014). In this study, we evaluated GWP and GHGI by taking CO_2 equivalents from all sources and sinks into account for 5 years. We hypothesized that the ISSM strategies would reduce the overall GWP and GHGI compared with local farmers' practices (FP). The specific objectives of this study were to (i) evaluate the effects of different ISSM scenarios on GWP and GHGI; (ii) determine the main sources of GWP and GHGI in a rice-wheat cropping system; and (iii) elucidate the overall performance for each ISSM scenario for different targets to increase grain yields and NUE and reduce GWP and GHGI.

2 Materials and Methods

2.1 Experimental site

A 5-year field experiment was conducted at the Changshu agro-ecological experimental station (31°32′93″N, 120°41′88″E) in Jiangsu Province, China. This is a typical, intensively managed agricultural area where the cropping regime is dominated by a flooding rice (*Oryza sativa* L.)-drained wheat (*Triticum aestivum* L.) rotation system. The site is characterized by a subtropical humid monsoon climate with a mean annual air temperature of 15.6, 15.2 and 15.8 ℃ and precipitation of 878, 1163 and 984 mm for three years, respectively. The soil of the field is classified as an *Anthrosol* with a sandy loam texture of 6% sand (1–0.05 mm), 80% silt (0.05–0.001 mm), and 14% clay (<0.001 mm), which developed from lacustrine sediment. The major properties of the soil at 0–20 cm can be described as follows: bulk 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}. The daily mean air temperatures and precipitation during the study period from June 15, 2011, to June 15, 2014,

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147 are given in the supplementary resource 1.

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 $\times$ 7 min 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 crop
168 and all as basal fertilizer for the wheat crop. The basal fertilization occurred at the time of rice
169 transplanting and wheat seeding. The topdressing was applied at the tillering and panicle
170 stages of the rice crop and at the seedling establishment and elongation stages of the wheat
171 crop. Harvests included crop grains as well as the rice and wheat straws were removed out of
172 the field for all the treatments in this study.

2.3 Gas sampling and measurements

174 We measured the CH$_4$ emissions and N$_2$O fluxes in each plot of the field experiment over five
175 annual cycles from the 2009 rice-growing season to the 2014 wheat-growing season. The
176 initial 2-yr measurements during the 2009–2011 rice-wheat rotational systems were described

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

The gas samples were analyzed for CH_4 and N_2O concentrations using a gas chromatograph (Agilent 7890A, Shanghai, China) equipped with two detectors. CH_4 was detected using a hydrogen flame ionization detector (FID), and N_2O was detected using an electron capture detector (ECD). Argon-methane (5%) and N_2 were used as the carrier gas at a flow rate of 40 ml min^{-1} for N_2O and CH_4 analysis, respectively. The temperatures for the column and ECD detector were maintained at 40 ℃ and 300 ℃, respectively. The oven and FID were operated at 50 ℃ and 300 ℃, respectively.

2.4 Topsoil organic carbon sequestration measurements

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

$$SOCSR \ (t \ C \ ha^{-1} \ yr^{-1}) = (SOC_t - SOC_0) \ / \ T \times \gamma \times (1 - \delta_{2mm}/100) \times 20 \times 10^{-1} \quad (1)$$

In Eq. (1), SOC_t and SOC_0 are the SOC contents measured in the soils sampled after the wheat was harvested in 2014 and 2009, respectively. T refers to the experimental period (yr). γ and δ_{2mm} are the average bulk density and the gravel content (>2 mm) of the topsoil (0–20 cm), respectively.

2.5 GWP and GHGI measurements

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

$$GWP \ (kg \ CO_2 \ eq. \ ha^{-1} \ yr^{-1}) = 25 \times CH_4 + 298 \times N_2O + Ei + Eo - 44/12 \times SOCSR \quad (2)$$

$$GHGI \ (kg \ CO_2 \ eq. \ kg^{-1} \ grain \ yield \ yr^{-1}) = GWP/grain \ yield \quad (3)$$

In Eq. (2), Ei, Eo and SOCSR represent CO_2 equivalent emissions from the

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281 agrochemical inputs, farm operations and soil organic carbon sequestration rate, respectively.

282 The global warming potential of 1 kg CH_4 and N_2O are equivalent to 25 and 298 kg CO_2

283 based on 100-year time scale, respectively (IPCC, 2013). The 12 and 44 are the molecular

284 weight of C and CO_2, respectively. The grain yield is expressed as the air-dried grain yield.

285   Therefore, the GWP of the cropland ecosystem equals the total CO_2 equivalent emissions

286 minus the SOC change. In addition to the CH_4 emissions and N_2O fluxes, we considered the

287 'hidden' CO_2 equivalent emissions, including agrochemical inputs (Ei), such as the

288 manufacture and transportation of the N, P and K fertilizers (Snyder et al., 2009), and farm

289 operations (Eo), such as the water used for irrigation (Zhang et al., 2013) and diesel fuel

290 (Huang et al., 2013a). The CO_2 equivalent emissions of N fertilizer were calculated as the

291 mean value of the C emissions of 1.3 kg C equivalent kg^{-1} (Lal, 2004). Similarly, the CO_2

292 equivalent for irrigation was calculated from the total amount of water used during the

293 rice-growing season; the coefficient for the C cost was 5.16 (kg C eq. cm^{-1} ha^{-1}) (Lal, 2004).

294 The CO_2 equivalents of other Ei (P and K fertilization, manure, herbicide, pesticide and

295 fungicide applications) and Eo (tillage, planting, harvest, and farm machinery production)

296 were recorded and estimated according to the methods provided by Lal (2004). We collected

297 data specific to China's fertilizer manufacture and consumption, and then estimated C

298 emissions coefficients were 0.07 and 0.1 C cost (kg C eq. kg^{-1} active ingredient) per applied

299 Si and Zn fertilizer, respectively.

300 2.6 Statistical analysis

301 Repeated-measures multivariate analysis of variance (MANOVA) and linear relationships

302 were determined using JMP 7.0, ver. 7.0 (SAS Institute, USA, 2007). The F-test was applied

303 to determine whether there were significant effects of the practices, years and their interaction

304 at $P < 0.05$. One-way analysis of variance was conducted to determine the emissions of CH_4

305 and N_2O, and the grain yield among the different treatments. Tukey's HSD test was used to

306 determine whether significant differences occurred between the treatments at a significance

307 level of $P < 0.05$. The results are presented as the means and standard deviation (mean $\pm$ SD,

308 n = 4).

309 **3 Results**

310 3.1 Crop production and agronomic NUE

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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 $P < 0.05$.

During the three cropping rotations from 2011 to 2014, the rice and wheat yields varied significantly among these cultivation patterns; these results are shown in Table 2. The grain 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). On average over the three cycles, the annual rice yield of the FP was significantly lower than that of the ISSM scenarios of N1, N2, N3 and N4. Compared with the FP, rice grain yields increased by 10% and 16% for the N1 and N2 scenarios, respectively, i.e., with the lower N input, by 28% for the N3 scenario with the same N input and by 41% for the N4 scenario with the highest N input. However, we did not observe any significant increases in the wheat-grain yields compared with the FP except for the N4 scenario. Statistical analysis indicated that rice and wheat yields from the three years were not significantly influenced by the interaction of cultivation patterns and cropping year (Table 3).

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

3.2 CH$_4$ and N$_2$O emissions

All plots showed similar CH$_4$ emission patterns, being a source in the rice season and negligible in the wheat season. During the three annual rice-wheat rotations from 2011 to 2014, the CH$_4$ fluxes ranged from –3.89 to 99.67 mg C m^{-2} h^{-1} (Fig. 2). The seasonal CH$_4$ emissions varied significantly among the treatments during the rice-growing season (Table 3, Fig. 2). No significant difference was found between the FP, N1 and N2 plots. Temporal variation was significant during the three cycles (Table 3, $P < 0.001$). Averaged across years, the CH$_4$ emission was greater in the N3 and N4 plots than in the NN, FP, N1 and N2 plots (Table 2, $P < 0.05$). However, compared with the NN plots, the FP, N1 and N2 plots with inorganic fertilizer application resulted in increased CH$_4$ emission rates of 59.9, 41.9 and 43.0%, respectively, averaged over the rice-growing seasons. The CH$_4$ emission rates were

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359 further enhanced by 198.5% in the N3 plots and by 246.7% in the N4 plots.

360 The annual N_2O fluxes varied from −33.1 to 647.5 µg N_2O-N m^{-2} h^{-1}, most of the N_2O

361 was emitted during the wheat-growing season after fertilization events, and there were several

362 small emission peaks during the rice-growing season (Fig. 3). With respect to the N

363 application effect, the annual cumulative N_2O emissions for all four ISSM scenarios were

364 significantly higher than in NN ($P < 0.05$). Relative to the FP plot, the N1 and N2 scenarios

365 decreased the annual N_2O emissions by an average of 41% and 22%, respectively (Table 2).

366 The N4 scenario significantly increased it by 46% ($P < 0.05$) because they received additional

367 N via manure application compared to the FP practice, although there was no significant

368 difference between the N3 and FP plots.

369 3.3 Annual GWP and GHGI

370 Based on the perspective of the carbon footprint, we included the GHG emissions associated

371 with all of the inputs (Ei and Eo), and SOC sequestration was expressed as kg CO_2 eq. ha^{-1}

372 yr^{-1}. The emission of CO_2 equivalents for Ei and Eo are classified in Table 4. While irrigation

373 was a large proportion of farm operations, these were much less significant than chemical

374 inputs. The CO_2 equivalents rates from N fertilizer dominated not only the chemical input

375 section (67–76% of Ei) but also the total CO_2 equivalents from agricultural management

376 (46–51% of the sum of the Ei and Eo). The GWP ranged from 7871 to 20911 kg CO_2 eq. ha^{-1}

377 yr^{-1} for the NN and the N4 plots, respectively (Table 5). Although fertilized treatments

378 increased the annual CH_4 and N_2O emissions, it also increased the SOC sequestration in this

379 cropping system. Of the main field GHGs that were directly emitted, CH_4 accounted for

380 56–75% of the GWP in all plots. An increase in the annual SOC content led to a significant

381 decrease in the GWP (contributed to 5–10% of the GWP except in the NN plot). The CO_2

382 equivalents from agricultural management practices for Ei (2449–4256 CO_2 eq. ha^{-1} yr^{-1})

383 were higher than those for Eo (1285–1697 CO_2 eq. ha^{-1} yr^{-1}) in the fertilized plots. There was

384 no significant difference in the annual GWP observed between the FP, N1 and N2 plots (Table

385 5). Across the three years, N1 and N2 slightly reduced the GWP by 12 and 10%, respectively;

386 however, N3 and N4 significantly increased the GWP by an average of 52 and 81%,

387 respectively, in comparison with the FP.

388 The GHGI was used to express the relationship between GWP and grain yield. The

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GHGIs in this study ranged from 664 to 1145 kg CO_2 eq. t^{-1} (Table 5). The significant difference in the annual GHGI was found between the FP and the ISSM strategies. Compared with the FP, N1 and N2 significantly reduced the GHGI by 14 and 18%, respectively, mainly due to the increased grain yield and SOC sequestration as well as reduced GHG emissions for the ISSM strategies. Although N fertilizer or organic/inorganic combination fertilizer application reduced the SOC losses caused by crop cultivation and increased the grain yields, the GHGIs were generally higher for the N3 and N4 scenarios than the N1 and N2 scenarios due to further increases in CH_4 and N_2O emissions.

4 Discussion

4.1 Grain yield and agronomic NUE as affected by ISSM strategies

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

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produce higher yields (Wang et al., 2005; Slaton et al., 2005; Kabata-Pendias and Mukherjee, 2007; Hossain et al., 2008). As expected, when the total N rate was at the FP rate and increased by 25% and applied with rapeseed cake manure, the rice yield in these N3 and N4 plots remarkably increased by 28 and 41%, respectively. Based on a long-term fertilizer experiment, Shang et al. (2011) reported that organic fertilizer incorporation significantly increased the early rice grain yield. This may have resulted from the organic fertilizer applied in combination with adequate nutrients, which improved the rice yield.

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

4.2 CH_4 and N_2O emissions as affected by ISSM strategies

During the three years, the annual cumulative CH_4 emissions, on average, varied from 133 to 469 kg C ha^{-1}yr^{-1} (Table 2), and these values fell within the range of 4.1 to 1015.6 kg CH_4 ha^{-1} observed previously in a rice field (Huang et al., 2004). The MANOVA results indicated that obvious effects of cultivation patterns and years on CH_4 emissions were found during the rice-wheat rotations (Table 3, $P < 0.001$). The CH_4 emissions were not significantly affected by the cycles but affected by crop season (Table 5, Fig. 2). In this study, no significant difference in CH_4 emission was observed between the FP, N1 and N2 plots. However, compared with the FP plot, the N3 and N4 scenarios emitted 87 and 118% more CH_4 emissions, respectively (Table 5), which is probably due to the incorporation of the organic

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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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502 rapeseed cake manure. Previous reports support the observations that CH_4 emissions were
503 significantly increased with the application of organic amendments (Ma et al., 2009;
504 Thangarajan et al., 2013; Zou et al., 2005). Additional application of Si and Zn fertilizers had
505 no significant effect on CH_4 and N_2O fluxes, which was consistent with the result of Xie et al.
506 (2015). Moreover, rice growth was found to be significantly increased under the N3 and N4
507 scenarios. In this case, the organic matter inputs such as root litter and rhizodeposits in the N3
508 and N4 scenarios were probably also higher than in the other plots, and thus soil C input,
509 which served as an additional source of substrates for the methanogens in the rice paddies,
510 likely contributed to the increase in CH_4 emissions (Ma et al., 2009). Finally, because the rice
511 plants acted as the main pathway for CH_4 transports from the soil to the atmosphere, the
512 higher biomass the more CH_4 emissions (Yan et al., 2005). The results obtained in the present
513 study revealed that both inorganic and organic fertilizer application significantly increased the
514 CH_4 emissions in the rice season (Table 2), which was probably associated with the increase
515 in the SOC content and crop biomass (Ma et al., 2013).

516 Denitrification and nitrification are the main processes that produce N_2O in the soil (Paul
517 et al., 1993). Changes in the soil water content strongly affected the soil N_2O emissions and
518 resulted in negligible N_2O emissions when the rice field was flooded (Fig. 3), which is
519 consistent with previous reports (Akiyama et al., 2005; Murdiyarso et al., 2010). A relatively
520 high N_2O peak was observed in the first two weeks of the wheat-growing season (Fig. 3),
521 possibly because soil changes from flooded to drained condition may have enhanced N_2O
522 release (Deng et al., 2012). Alternation of drainage and flooding may induce large amounts of
523 N_2O emissions, particularly in fertilized systems; this has commonly been proved in earlier
524 studies (Wang et al., 2013; Xiong et al., 2007; Zou et al., 2005). The seasonal and annual rates
525 of N_2O emission were significantly affected by the cultivation practice patterns and years
526 (Table 3). Compared with the FP plot, the N2 scenario greatly decreased the seasonal N_2O
527 emissions in this study, which may have resulted from a reduction in the N fertilizer rate
528 (Table 1, Table 2). The total N_2O emissions decreased by 7–38% and 26–42% in the rice and
529 wheat seasons, respectively, when the conventional N management (300 kg N ha^{-1} for rice
530 and 180 kg N ha^{-1} per crop for wheat) changed to optimum N management (225–270 kg N
531 ha^{-1} for rice and 135–162 kg N ha^{-1} per crop for wheat). It is likely that more N_2O was

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538 emitted (Mosier et al., 2006) as a result of the additional N made available to the soil

539 microbes through N fertilizer application, which probably increased the CH_4 emissions

540 (Banger et al., 2013). Strategies that can reduce N fertilization rates without influencing crop

541 yields can inevitably lower GHG emissions (Mosier et al., 2006).

542 4.3 GWP and GHGI as affected by ISSM strategies

543 The GWP in our study (10104–20911 kg CO_2 eq. ha^{-1}) with the ISSM strategies was higher

544 than that in a double-cropping cereal rotation (1346–4684 kg CO_2 eq. ha^{-1}) and a rice-wheat

545 annual rotation (290–4580 kg CO_2 eq. ha^{-1}) reported by Huang et al. (2013b) and Yang et al.

546 (2015), respectively. Dominant CH_4 emissions as well as additional CO_2 emitted by the

547 machinery/equipment used for irrigation and farm operations under the ISSM strategies may

548 increase the GWP more than in other cropping systems. However, the current GWP was still

549 much lower than that of a double-rice cropping system (13407–26066 kg CO_2 eq. ha^{-1})

550 (Shang et al., 2011).The GHGIs, which ranged from 0.66 to 1.15 kg CO_2 eq. kg^{-1} grain in this

551 study, were slightly higher than previous estimates of 0.24–0.74 kg CO_2 eq. kg^{-1} grain from

552 rice paddies with midseason drainage and organic manure incorporation (Qin et al., 2010; Li

553 et al., 2006) but were lower than the DNDC model estimates for continuous waterlogged

554 paddies (3.22 kg CO_2 eq. kg^{-1} grain) (Li et al., 2006). Differences in GWP or GHGI were

555 found in the cultivation patterns over the three rice-wheat rotations (Table 5). Although there

556 were not significant differences among the FP, N1 and N2 plots, the N1 and N2 scenarios with

557 optimized ISSM strategies led to a lower GWP than the FP (Table 5). Compared with the FP,

558 the N1 and N2 scenarios dramatically reduced the GHGI, which was mainly due to higher

559 yields. In spite of the similar GWP compared with the FP plot, the lowest GHGI (0.66 kg CO_2

560 eq. kg^{-1} grain) was obtained under the N2 scenario. This finding is consistent with the

561 suggestion made by Burney et al. (2010), i.e., that the net effect of higher yields offsets

562 emissions. It is well known that CH_4 emissions dominate the GWP in rice paddies (Ma et al.,

563 2013; Shang et al., 2011). In comparison to the GWP (11545 kg CO_2 eq. ha^{-1}yr^{-1}) and GHGI

564 (0.81 kg CO_2 eq. kg^{-1} grain) of the FP, the N3 and N4 scenarios increased both the GWP and

565 GHGI, mainly because these scenarios notably increased the CH_4 emissions compared with

566 the FP, which resulted in relatively higher GWP (Table 5).

567 Agricultural management practices that change one type of GWP source/sink may also

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impact other sources/sinks and therefore change the GWP and GHGI (Mosier et al., 2006; Shang et al., 2011). Although the N-fertilizer plots, especially those with the incorporation of organic fertilizer, increased the annual CH_4 and N_2O emissions, they increased the SOC sequestration in this cropping system, which is agreement with previous reports (Huang and Sun, 2006). This was mainly due to the enhanced incorporation of rapeseed cake and crop residue associated with higher crop productivity (Ma et al., 2013). In the present study, the N2 scenario with ISSM decreased the CH_4 and N_2O emissions as well as the energy consumption related to irrigation and the manufacture and transport of N fertilizer (depending on coal combustion), ultimately leading to a decrease in the GWP relative to the FP plot. Moreover, despite the lower N fertilizer input, the grain yield did not decline and the GHGI of the N2 scenario was thus lower than of the FP plot, indicating less consumption of CO_2 equivalents per unit of grain produced. We demonstrate that high yield and agronomic NUE, together with low GWP, are not conflicting goals by optimizing ISSM strategies.

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

Determining the main components of the GWP and GHGI in specific cropping systems is very important for mitigating GHG emissions in the future because the benefits of C sequestration would be negated by CH_4 and N_2O emissions and the CO_2 equivalents released with the use of high N fertilizer application rates (Schlesinger, 2010). In the current study, the five main components of the CO_2 equivalents for the GWP were ranked in decreasing order of importance as follows: CH_4 emissions > agrochemical inputs of N fertilizer > farm operations related to irrigation > SOC sequestration > N_2O emissions (Table 5). CH_4 emissions, the most important component of GWP in this typical rice-wheat rotation system, could be further mitigated by some other strategies, such as reasonable irrigation (Zou et al., 2005; Wang et al., 2012).

Although N fertilizer application increased SOC sequestration when it was applied with rapeseed cake manure, this benefit was consistently overshadowed, on a CO_2 equivalent basis, by the increases in CH_4 and N_2O emissions (Table 5). Similar results have been reported, i.e., GHG emissions substantially offset SOC increases (Six et al., 2004). It is possible that the realization of reducing the GWP and GHGI in China should focus on

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increasing the SOC and simultaneously decreasing the CO_2 equivalents from CH_4 emissions and N fertilizer inputs. Several studies reported possible methods for these types of mitigation strategies, such as optimizing the chemical fertilizer application amount and rate (Ju et al., 2011), the amount of water used for irrigation (Gao et al., 2015), and the timing and rate of N using the in-season N management approach, as well as improving the N fertilizer manufacturing technologies (Zhang et al., 2013), and using nitrification inhibitors or polymer-coated controlled-release fertilizers (Hu et al., 2013).

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

5 Conclusions

Reasonable agricultural management practices are the key to reducing GHG emissions from agricultural ecosystems. This study provided an insight into the complete GHG emission accounting of the GWP and GHGI affected by different ISSM scenarios. After a five-year field experiment, we found that the CH_4 emissions, production of N fertilizer, irrigation, SOC sequestration and N_2O fluxes were the main components of the GWP in a typical rice-wheat rotation system. In contrast with the FP, N1 and N2 significantly reduced the GHGI, though they resulted in similar GWPs, and N3 and N4 remarkably increased the GWP and GHGI. By

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adopting the ISSM strategy, the conventional N application rate was reduced by 10% while the rice yield was significantly increased by 16%, the NUE was improved by 67% and the GHGI was lowered. ISSM scenarios could be adopted for both food security and environmental protection with specific targets. We propose that the ISSM-N2 scenario is the most appropriate management strategy (10% reduction of N input, no rapeseed manure and higher plant density) for realizing higher yields and NUE, together with some potential to reduce GHGI by integrated soil-crop management. For simultaneously mitigating GHG emissions, further research on integrated soil-crop system managements is required particularly for mitigating CH_4 emissions in sustainable rice agriculture.

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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 ($N:P_2O_5:K_2O:Na_2SiO_3:ZnSO_4$, 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 ($N:P_2O_5:K_2O$, 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

[a]NN, 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.

[b]F-D-F-M, flooding-midseason drainage-re-flooding-moist irrigation.

Table 2

Seasonal CH_4 and N_2O 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_2O (kg N ha^{-1})	Yield (t ha^{-1})	CH_4 (kg C ha^{-1})	N_2O (kg N ha^{-1})	Yield (t ha^{-1})
2011						
NN	153 ±10.8c	0.03 ±0.05c	5.85 ±0.08f	- 0.48 ±0.63a	0.45 ±0.09d	1.74 ±0.18d
FP	266 ±25.3b	0.11 ±0.08c	8.38 ±0.35e	- 0.48 ±1.86a	1.43 ±0.19b	5.67 ±0.20b
ISSM-N1	212 ±30.3bc	0.08 ±0.03c	9.27 ±0.26d	0.78 ±0.97a	0.65 ±0.11cd	5.05 ±0.16c
ISSM-N2	220 ±32.5bc	0.17 ±0.11bc	9.79 ±0.44c	2.25 ±2.07a	0.80 ±0.06c	5.71 ±0.18b
ISSM-N3	518 ±58.9a	0.38 ±0.15ab	10.81 ±0.26b	0.04 ±3.23a	1.40 ±0.10b	5.31 ±0.26bc
ISSM-N4	561 ±50.9a	0.37 ±0.07a	11.76 ±0.24a	- 0.09 ±1.40a	1.93 ±0.09a	6.15 ±0.15a
2012						
NN	149 ±25.8d	0.13 ±0.10c	5.80 ±0.22f	- 4.32 ±7.29a	0.65 ±0.09d	1.73 ±0.11c
FP	239 ±34.5c	0.33 ±0.11bc	8.72 ±0.62e	4.85 ±10.30a	2.13 ±0.43ab	5.64 ±0.34ab
ISSM-N1	226 ±30.4cd	0.27 ±0.07bc	9.43 ±0.34d	1.46 ±6.38a	1.39 ±0.14c	4.94 ±0.38b
ISSM-N2	228 ±32.6cd	0.38 ±0.29bc	9.99 ±0.50c	- 1.02 ±0.84a	1.77 ±0.38bc	5.78 ±0.59ab
ISSM-N3	431 ±26.8b	0.52 ±0.16ab	10.92 ±0.61b	2.45 ±8.35a	2.19 ±0.24ab	5.39 ±0.39ab
ISSM-N4	536 ±58.7a	0.78 ±0.13a	12.24 ±0.60a	5.91 ±6.18a	2.61 ±0.42a	6.10 ±0.49a
2013						
NN	101 ±39.2b	0.16 ±0.09b	5.84 ±0.15f	- 1.45 ±1.34a	0.35 ±0.06c	1.80 ±0.03c
FP	141 ±25.2b	0.43 ±0.39ab	8.67 ±0.26e	- 3.70 ±1.76a	0.80 ±0.20ab	5.70 ±0.30ab
ISSM-N1	135 ±15.7b	0.19 ±0.16ab	9.66 ±0.29d	- 1.00 ±1.61a	0.49 ±0.16bc	5.15 ±0.20b
ISSM-N2	129 ±32.2b	0.26 ±0.13ab	10.15 ±0.07c	- 0.79 ±1.60a	0.69 ±0.24abc	5.80 ±0.18ab
ISSM-N3	256 ±45.6a	0.59 ±0.42ab	11.14 ±0.10b	- 0.62 ±1.14a	0.71 ±0.10ab	5.51 ±0.33ab
ISSM-N4	304 ±22.3a	0.74 ±0.40a	12.34 ±0.16a	0.55 ±1.68a	1.02 ±0.11a	6.19 ±0.63a
Average 2011–2013[a]						
NN[b]	135 ±19.6d	0.11 ±0.05c	5.83 ±0.04f	- 2.08 ±1.89a	0.48 ±0.07d	1.75 ±0.04d
FP[b]	215 ±19.9c	0.29 ±0.13bc	8.59 ±0.25e	0.22 ±3.96a	1.45 ±0.24b	5.67 ±0.16b
ISSM-N1[b]	191 ±19.2c	0.18 ±0.06c	9.45 ±0.18d	0.42 ±2.77a	0.84 ±0.08c	5.04 ±0.08c
ISSM-N2[b]	192 ±11.6c	0.27 ±0.12bc	9.98 ±0.25c	0.15 ±0.58a	1.08 ±0.12c	5.76 ±0.22ab
ISSM-N3[b]	402 ±23.8b	0.50 ±0.16ab	10.95 ±0.13b	0.63 ±3.51a	1.43 ±0.05b	5.40 ±0.16bc
ISSM-N4[b]	467 ±39.2a	0.68 ±0.15a	12.11 ±0.28a	2.12 ±2.57a	1.85 ±0.16a	6.14 ±0.35a

[a]Mean ± 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.

[b]See Table 1 for treatment codes.

Table 3

Repeated-measures analysis of variance (MANOVA) for the effects of cultivation patterns (P) and cropping year (Y) on mean CH$_4$ and N$_2$O 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	Between subjects				
	P	5	35.3***	3.71***	123***
	Within subjects				
	Y	2	20.7***	0.88**	1.15**
	P×Y	10	6.73***	0.15	0.37
Wheat	Between subjects				
	P	5	0.26	14.8***	76.3***
	Within subjects				
	Y	2	0.55*	15.1***	0.08
	P×Y	10	0.83	4.39***	0.05
Rice-Wheat	Between subjects				
	P	5	37.2***	24.2***	153***
	Within subjects				
	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.

Table 4

Agricultural management practices for chemical inputs and farm operations and contributions to carbon dioxide equivalents (kg CO_2 eq. ha^{-1}yr^{-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

[a]The 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.

[b]The carbon emission coefficient for irrigation was 5.16 C cost (kg C eq. cm^{-1} ha^{-1}) as referred to in Lal (2004).

[c]The 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).

[d]See 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_2O	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

^{a}GWP (kg CO_2 eq. ha^{-1}yr^{-1}) = 25 ×CH_4 +298 ×N_2O + Ei +Eo − 44/12 ×SOCSR, Ei (agrochemical inputs), Eo (farm operations), SOCSR (SOC sequestration rate)

^{b}GHGI (kg CO_2 eq. t^{-1} grain) = GWP/grain yields

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

^{d}See Table 1 for treatment codes.

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.