Response to referee #1

The quality of the manuscript has been significantly improved. The authors are aware that the variables of each management system cannot be analyzed separately, and that they should discuss what system is the best and how the different variables could have caused these results. I congratulate the authors for the inclusion of Table 4, which is very useful for the readers. Moreover, the quality of the English and the writing has been clearly enhanced. I consider that the paper is now suitable for publication in Biogeosciences if the following changes are addressed.

A: Thank you very much for your positive comments and your great support! We have tried our best to revise our manuscript according to your valuable comments.

Specific comments:

Lines 149-158: I recommend using the current CO2 equivalents for CH4 (24) and N2O (265) (Myhre et al., 2013).

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 659-740.

A: Thank you for your comment. We have cited the reference (Myhre et al., 2013) and updated the current CO_2 equivalents for CH_4 (28, not 24) and N_2O (265).

Line 385: Methane instead of CH4 at the beginning of the sentence. Please, review the whole manuscript checking possible similar mistakes.

A: Thank you for your comment. Revised accordingly throughout the whole manuscript on Page 3, Line 56, Page 6, Line 141 and Page 16, Line 425.

I do not understand your answer: "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". If 20 kg N ha-1 were applied as urea, that is not consistent with the rates in Table 1 (225-375). If this was the N rate applied through rapeseed, this is not consistent with the 112.5 kg N ha-1 that you indicated in line 154. Please, clarify this and indicate in the text (not only in the footnote of Table 1) that urea was the synthetic N source.

A: Sorry for the inconvenience due to our negligence. It was 112.5 kg N ha^{-1}, not 20 kg N ha^{-1}. The total N rate included urea fertilizer and rapeseed cake fertilizer. Revised accordingly Page 5, Line 109-112 and Table 1.

"We have made the normal distribution and variance uniformity check. All data were conformed". Please, indicate in the manuscript that you checked normal distribution and variance uniformity and how.

A: Thank you for your comment. Revised accordingly Page 8, Line 198-199.

You have included Table 4 indicating how you calculated GWP. I appreciated that, but the TABLE 5 still lacks a comparative between two crops (what were all these components for rice and wheat). I think that you must include it, at least as Supplementary Material. If you did that you would provide valuable information about the relative weight of each component in each crop (for instance, CH4 and irrigation are important for rice, but less important for wheat, in which N2O losses are expected to have a higher weight) aiming to find specific mitigation strategies. Please include also in the text a brief statement about the crop and year effect (even if there was not a year effect) on GWP.

A: Thank you for your comment. We added a new Table 5 for understanding the GWP components for rice and wheat, respectively. Revised accordingly Page 15, Line 423-425.

Lines 287-289: “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”. Be careful! You are explaining higher NUE values using variables that you did not measure (leaching, volatilization). I recommend changing “was primarily” by “could be”, and I would add a reference(s) of lower leaching and volatilization with similar improved management strategies.

A: Thank you for your comment. Revised accordingly Page 12, Line 317. We have added a new reference (Zhao et al., 2015) to explain it.

CH4 emissions were highest during rice season, but only during the flooding period. Please indicate this in the results and discuss briefly why highest CH4 fluxes were observed during flooding periods (I know that it seems obvious but maybe is not the same for all readers). Maybe the paper of Le Mer and Roger (2001) could be a nice reference.

Le Mer, J., & Roger, P. (2001). Production, oxidation, emission and consumption of methane by soils: a review. European Journal of Soil Biology, 37(1), 25-50.

A: Thank you for your comment. We added this reference in our manuscript. Revised accordingly Page 12, Line 325-329.

Lines 306-308: you cannot state that “Additional application of Si and Zn fertilizers HAD NO SIGNIFICANT effect on CH4 and N2O fluxes, which was consistent with the result of Xie et al. (2015)”. Because of your experimental design, you cannot attribute the effect of a management system (with several variables) to only one of these variables. I recommend adding the word “Apparently” at the beginning of the sentence.

A: Thank you for your comment. Revised accordingly Page 13, Line 338.

Line 321: From my point of view, you should add a brief explanation about why N2O fluxes during rice seasons were negligible (reduction of N2O to N2 thorough complete denitrification) and a reference. Accordingly, I would include a brief statement explaining why N2O emissions were higher during wheat seasons (as opposed to rice seasons) and which processes could have been involved (incomplete denitrification and nitrification –so for discuss that I would include soil moisture data during wheat season, if available-).

A: Thank you for your comment. Revised accordingly Page 13, Line 348-349, Page 13, Line 352-354.

Lines 368-369: “This was mainly due to the enhanced incorporation of rapeseed cake and crop residue associated with higher crop productivity (Ma et al., 2013)”. Good explanation, but in the materials and methods you say that “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”. Please clarify this.

A: Thank you for your comment. The aboveground part is consisted of grain and straw. When we removed the aboveground part, the root system as crop residue still remained in the soil. Revised accordingly Page 5, Line 125-126.

Line 405: 16.33 “kg grain kg N-1” instead of “kg grain kg−1 N”.

A: Thank you for your comment. Revised accordingly Page 8, Line 215, Page 16, Line 445 and Fig 1.

Line 421: were, IN DECREASING ORDER, the main components of the GWP… By the way, great conclusions section (and the end of the discussion)!

A: Thank you for your comment. Yes, I wrote the main components of the GWP in decreasing order.

Table 4: As indicated above, congratulations for Table 4. One just further recommendation: in the farm operations section, you have indicated that the units are kg/ha and I guess, that in the case of tillage, planting, etc, you present the number of operations (in the case of manure I guess you present kg ha-1). Please clarify this, and indicate below (in Eo/Ei) the units (kg CO2 eq/ha, kg C-CO2 eq/ha??).

A: Thank you for your comment. Revised accordingly Table 4.

Fig. 2 and 3. Flooding period instead of floodin. Please include the flooding period in the three years. I also recommend using the same scale in the Y axis for the three years.

A: We are sorry for the inconvenience. Revised accordingly Figures 2 and 3.

Thank you very much once again for all of your nice comments and great support!

Sincerely yours,

Zhengqin (on behalf of all authors)

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Response to referee #3

The authors present an interesting study on the global warming potential and greenhouse gas intensity of typical farmer's practice and 4 alternative management packages for rice-wheat cropping systems in China. I very much appreciate the effort to estimate greenhouse gas emissions from inputs and farm practices, in addition to direct greenhouse gas emissions from soil, to make a comprehensive greenhouse gas budget. I also like the comparison of complete management packages as an integrated soil crop system management approach. However, I think the materials and methods section should include the equations and emission factors used to calculate emissions from inputs and farm operations, with a reference for each of the emission factors. Furthermore, the manuscript would benefit from some more background on ISSM and a rationale on why exactly these 4 improved management practices were selected, and what the main objectives and anticipated outcomes where for the 4 management packages (for example, highest yield, resource conservation, balanced nutrient inputs, etc.).

A: Thank you very much for your positive comments and great interest. Those comments are all valuable and very helpful for revising and improving our manuscript, as well as further important guidance for our researches. We have made corrections which we hope to meet with approval. Revised accordingly Page 3, Line 51-55. Please see the following point-by-point answers.

Detailed comments

Abstract

Line 21: It is stated that this is a 5 year study, but data from only 3 years is shown, while the first 2 years appear to be published elsewhere. Would it make more sense to do the analyses on the full 5 year dataset?

A: Thank you for your comment. Since the field study of ISSM strategies was consistently conducted for 5 years and the SOC changes were measured over the 5-year period of 2009–2014, we would still like to state that this study is a '5-year study'. for calculating GWP and GHGI, we would still like to state that this study is a '5-year study' (Page 6, Line 150-158). Yes, the other measurements were focused on the late three years and those from the initial 2-yr measurements were published in Ma et al. (2013) as indicated in our manuscript (Page 6, Line 129-131). Thank you very much for your kind understanding!

Line 28: N-rate is not the only factor that is different between the management practices. Can you give the management packages different names, that reflect their full objective, rather than N-rate alone?

A: Thank you for your comment. You are right. We used integrated soil-crop system management (ISSM) mainly consisting of different chemical nitrogen (N) fertilization rates and split, manure, Zn and Na_2SiO_3 fertilization and planting density. Four ISSM scenarios consisting of different chemical N rates relative to the local farmers' practice (FP) rate were carried out, namely, ISSM-N1 (25% reduction), ISSM-N2 (10% reduction), ISSM-N3 (FP rate) and ISSM-N4 (25% increase).

Line 34: When you write 'increased', is that relative to the farmers' practice?

A: Yes. It is relative to the local farmers' practice (FP).

Introduction

Line 96: are there any estimations of N leaching and indirect N_2O emissions from these systems? This seems an important missing component in the GHG budget. If there are no estimations, it should be stated that this has not been considered due to lack of data.

A: Thank you for your comment. Nitrogen leaching and volatilization are the important components of reactive nitrogen releases but not included in the current GHG budget. Revised accordingly Page 14, Line 370-372.

Materials and methods

Line 118: how do the average annual precipitation and temperatures for the measurement years compare to long term averages, and does the variability in weather help explain some of the year-to-year variability in the measured yields and GHG emissions.

A: The average annual precipitation and temperatures for the measurement years were similar to those of the multiyear, with insignificant effect on yields and GHG emissions.

Line 153: why is it stated that ISSM did not apply to the wheat, even though nutrient input rates do vary between treatments in the wheat crop. What are those adjustments based on then?

A: Thank you for your comment. Since the optimized ISSMs packages were mainly designed and developed for the rice crop, we stated that ISSM did not apply to the wheat. For the following wheat crop, we only used the corresponding total N reduction level strategy, not all packages.

Line 156: it would be interesting to look at N removal by the crop, and determine NUE as the difference in aboveground N uptake in the fertilized and non-fertilized crop relative to N applied.

A: Thank you for your comment. NUE could be calculated as the difference in aboveground N uptake in the fertilized and non-fertilized crop relative to N applied. But calculation result of this method can not accurately express crop N absorption from fertilizer. Firstly, non-fertilized crop N absorbed is not entirely from soil N while another source is from atmospheric N deposition; Secondly, the amount of aboveground N uptake in the fertilized crop is not related to the non-fertilized treatment. Therefore, we used agronomic NUE in this manuscript.

Line 160: replace min. by m.

A: Revised accordingly Page 5, Line 115.

Line 169-170: there are 4 numbers listed for topdressing, but only 2 phenological stages named. What are the other 2?

A: Except basal fertilizer, there are 3 numbers listed for topdressing named tillering, elongation and panicle stages. Revised accordingly Page 5, Line 124.

Line 301-309: as far as I can tell, the authors conducted a 2-way anova with year and practice as factors, and not a multivariate data analysis.

A: As the measurements were made from the same plots over years, therefore, we used the repeated measures ANOVAs, although year could also be taken as a fixed variable at the same time to see differences between years.

Results

Line 333-334: it is not clear if the rapeseed cake N was included in this calculation. I think it should. In any case, would be helpful to list the nutrient input from rapeseed cake.

A: Thank you for your comment. The rapeseed cake N was also included in this calculation. The nutrient input from rapeseed cake was list in Materials and methods. Revised accordingly Page 5, Line 107 and 109-112.

Line 347: how confident are you in averaging across years, if there is a significant year by practice interaction?

A: Thank you for your comment. Repeated-measures multivariate analysis of variance (MANOVA) were used in this manuscript and taken the year as a fixed variable at the same time to see differences between practice treatments. Thank you for your understanding!

Line 378-380: increase relative to what?

A: It is relative to the NN plot. Revised accordingly Page 10, Line 256.

Discussion

Line 444: what is meant with ‘the modified farmers’ fertilizer practice’?

A: Compared with the farmers’ N-fertilizer practices, other N management strategies such as real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM) were used.

Line 467-486: Did you measure N losses by leaching and volatilization, and N uptake in the rice? I suggest to provide a reference to the measured data, or tone down the statement in case it is merely a speculation.

A: Thank you for your comment. We didn’t measure N losses by leaching and volatilization. Revised accordingly Page 12, Line 317. We have added a new reference (Zhao et al., 2015) to explain it.

Line 479: what is meant with ‘cycles’ here?

A: The ‘cycles’ meant three annual cycles of the 2011rice season–2014wheat season.

Line 507-508: you can not statistically test for this effect in your study, because other factors changed.

A: Thank you for your comment. Revised accordingly Page 13, Line 338.

Line 515: did you mean to say biomass, or number of tillers?

A: Yes. ‘the higher biomass the more CH_4 emissions’ there the biomass was mean to say the aboveground biomass.

Line 527: I would suggest to replace ‘proved’ by ‘shown’. Strictly speaking, a hypothesis can only be rejected, not proven.

A: Thank you for your comment. Revised accordingly Page 13, Line 358.

line 574-550: the GWP in this study seems to be a lot higher than the 2 other studies. Why is this? Were emissions from farm operations and inputs also included in the cited studies?

A: The emissions from farm operations and inputs were not included in the 2 other cited studies. Thus, the GWP in our study seems to be a lot higher.

Line 553: I wouldn’t say it was much lower in the current study than in Shang et al. 2011. It seems to be in the same range.

A: Yes. Revised accordingly Page 14, Line 381.

Line 560-563: there are some contradictions in these lines.

A: Thank you for your comment. We have rewritten the sentence. Revised accordingly Page 14, Line 388-389.

Line 582-583: but they also increased N2O

A: Relative to FP, the ISSM-N3 scenario produced similar sizes of N_2O.

Line 608: what do you mean with reasonable irrigation?

A: A water regime of flooding-midseason drainage-re-flooding-moist intermittent irrigation but without water logging (F-D-F-M).

Line 656: but that was not the case for all ISSM strategies.

A: Revised accordingly Page 17, Line 464.

Thank you very much once again for all of your nice comments and great support!

Sincerely yours,

Zhengqin (on behalf of all authors)

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Response to referee #4

Comments and suggestions for the Manuscript BG- 2015-478 (Global warming potential and greenhouse gas intensity in rice agriculture driven by high yields and nitrogen use efficiency: A 5-year field study).

Recommendation:

This manuscript reports results from a multi-year field experiment aimed at evaluating the effect of several 'integrated soil-crop system management (ISSM) scenarios (consisted of different rates of nitrogen fertilizer supplied by split application to synchronize in-season N supply with crop demand, with or without supplementary organic manure, Zn and Na2SiO3 fertilizer and different planting densities) on global warming potential (GWP) and greenhouse gas emissions intensity (GHGI) of grain (rice and wheat) production. For calculating GWP and GHGI, the analysis accounts for all GHG sources (i.e. CH4 and N2O and CO2 emissions associated with agrochemical inputs and farm operations) and sinks (i.e., soil organic carbon sequestration).

Considering the global priority of developing cropping systems that are capable of increasing food production while minimizing the environmental impact, the manuscript is suitable for publication in the journal Biogeosciences. However, I find several issues (listed below), that must be addressed to improve the quality of the manuscript. Once these general comments and the specific comments on the manuscript text are satisfactorily addressed, the manuscript should be accepted for publication in this Journal.

A: Thank you very much for your positive comments and your great support! Those comments are all valuable and very helpful for revising and improving our manuscript, as well as leading guidance for our further researches. We have tried our best to revise our manuscript according to your valuable comments. Please see the following point-by-point answers.

General comments:

(1). It is stated that this study is a '5-year study'; however, the data presented in this paper covers only the last three years (2011 - 2014, Table 2 and 4) of the field experiment. Authors have simply reported the experiment was started in 2009 (Line 97) and the results for the first 2-yr were published in Ma et al. (2013) in lines 122-123; however, no attempt has been taken to analyze the overall 5-yr results. Therefore, the reference to '5-year study' is not supported by the results presented. I suggest, to call it as a '3-year study' or to include the first 2-year data in the overall analysis and then call it as a '5-year study' in the title and relevant locations elsewhere in the manuscript.

A: Thank you for your comment. Since the field experiment of the ISSM strategies was consistently conducted for 5 years (2009-2014) and the SOC changes were measured over the 5-year period of 2009–2014 for calculating GWP and GHGI, we would still like to state that this study is a '5-year study' (Lines 150-158). Yes, the other measurements were focused on the late three years and those from the initial 2-yr measurements were published in Ma et al. (2013) as indicated in our manuscript (Page 6, Line 129-131). Thank you very much for your kind understanding!

(2). I have several questions related to the emission factors used for the calculation of CO_2 emissions from agricultural inputs and farm management operations as explained below. These issues must be addressed and clarified in the manuscript text and/or in Table 4.

Line 165 - 167: Please explain how the emission factor for irrigation water (i.e. 5.16 kg C eq. cm^{-1} ha^{-1}) was calculated, because Lal, 2004 provides several emission factors for irrigation water, depending on the amount of total irrigation water supplied and the type of irrigation system used. It is clear that this emission factor was based on the original value of 257.8 kg CE ha-1 for a 50 cm of irrigation provided in Lal 2004. However, Authors need to explain briefly the applicability of this emission factor for the irrigation system used in this experiment. Please revise the text accordingly, to include this information.

A: Thank you for your comment. Yes, it is more appropriate to use specific emission factors for all calculations. Since we didn't investigate all of these factors, the emission factor of 5.16 kg C eq. cm^{-1} ha^{-1} was used in this experiment. We will try our best to obtain specific emission factor. We provided such information on Page 7, Line 180-182.

Line 168: Please check the C emission factor used for herbicide. According to Lal (2004), it should be 6.3 kg CE per kg active ingredient, NOT 0.3 kg CE per kg active ingredient, used in Table 4. This should be corrected.

A: Sorry for the inconvenience due to our negligence. Revised accordingly Table 4.

Line 169: The following several issues (listed a to f) related to the method of calculating CO2 emissions associated with farm operations need to be clarified to improve the clarity of the methodology:

(a) Briefly explain the field operations such as tillage, planting, and harvest. The C emission factor for each of these operations will depend on the type of the machinery used. For example, it is necessary to mention how tillage was done. Was it done using one pass of rotary tiller and one pass of raking? There are two events of tillage: one for rice, one for wheat: two different systems. Explain briefly what was done to understand the applicability of the emission factor used.

A: We are sorry for the inconvenience. The C emission factor for these farm operations depends on the fuel used or electricity. The type of fuel used for the machinery is diesel. We also added a Supplementary resource 2 for understanding the Eo and Ei components for rice and wheat, respectively. We agree that there must have some uncertainties in selecting parameters. This is only preliminary evaluation. Thank you very much for your great support!

(b) It is not clear what is presented as: 1 (one) kg/ha for all treatments in the column for crop planting in Table 4. Does it mean: 1 kg diesel fuel/ ha was used for crop planting? If that is the case, C emission factor for diesel fuel is 0.94 kg CE per kg diesel (Lal 2004). If it is '1' event, then 3.2 kg CE/ha (which authors have used) is correct; however, there are 2 events of planting per year (one event for rice, another event for wheat). It appears that only one event of crop planting is accounted in the Table 4. Please clarify.

A: We are sorry for the inconvenience. It should be 2 events of planting per year. Revised accordingly Table 4.

(c) Was the emission factor for manure application used in Table 4, obtained from Lal 2004? (I am not sure Lal 2004 provided this emission factor).

A: Thank you for your comment. We obtained the emission factor for manure application from Lal 2004, "In contrast to chemical fertilizers, energy input is much less for nutrients from animal manure (Stout, 1990). The CE of fresh manure is estimated at 7–8 g/kg manure." Thus, we adopted the average value of 7.5 g/kg for manure.

(d) Similarly, there are two harvest events per year (one for rice, one for wheat). Was the 11 kg/ha diesel use reported in Table 4 for both harvest events? Please clarify.

A: Thank you for your comment. Revised accordingly as Supplementary resource 2.

(e) It is not correct to apply the emission factor for spraying and thrashing (0.0725 kg CE/kg active ingredient) for calculating CO2 emissions from 'farm machinery production' as presented in Table 4.

Please correct.

A: Thank you for your comment. We used electricity energy units of Kilowatt hour (0.0725 kg CE/kg active ingredient) for calculating CO_2 emissions from 'farm machinery production' as presented in Table 1 of Lal 2004.

(f) Was there any machinery used for fertilizer application? If machinery was used, split fertilizer application requires 3 or 4 passes for each crop, depending on how many split applications were done for rice and for wheat in each treatment. The C emission factors for fertilizer i.e. 1.3, 0.2, and 0.15 kg CE/kg of N, P2O5 and K2O, respectively (taken from Table 5, Lal, 2004) do not include C emissions associated with fertilizer application (attributable to fuel use in machinery). Please clarify.

A: Thank you for your comment. There was no machinery used for fertilizer application. Chemical fertilizers were hand spraying broadcasted for each fertilization event. Revised accordingly Page 8, Line 188-189.

Authors should clarify the issues mentioned above by briefly explaining the facts in the relevant section under the Materials and Methods.

A: Thank you for your comment. Revised accordingly as well as a Supplementary resource 2.

Specific comments on the manuscript text:

Line 37 – 39: Please re-phrase the sentence starting 'An increase in global food production....'

For example: 'An increase in global crop production of 100% would be necessary to sustain the projected demand for human food and livestock feed in 2050 (Tilman et al., 2011).

A: Thank you for your comment. We have re-phrased the sentences. Revised accordingly Page 3, Line 38-39.

Line 40: Please add a reference to support the statement: 'Rice is the staple food for nearly 50% of the world's people, mainly in Asia.'

A: Thank you for your comment. We have added a new reference to support the statement. Revised accordingly Page 3, Line 41.

Line 42: Please add a reference to support the statement: 'With the region's population projected to increase by another billion by mid-century (reference?), ...'

A: Thank you for your comment. Revised accordingly Page 3, Line 44.

Line 43: Please change: 'With a limited agricultural land area, the intensive.....'

A: Thank you for your comment. Revised accordingly Page 3, Line 44.

Line 44: .... fertilizer... (not fertilizers)

A: Revised accordingly Page 3, Line 46.

Line 47: ...appropriate fertilizer compounds...

A: Revised accordingly Page 3, Line 48.

Line 48: ...advanced water management regimes,...

A: Revised accordingly Page 3, Line 49.

Line 49 – 50: Authors should indicate here exactly what they mean by: low carbon dioxide (CO2) equivalent emissions per unit product or per unit land area?

A: Thank you for your comment. Revised accordingly Page 3, Line 51.

Line 51: Please do not start a sentence with an abbreviation. Should be: Carbon dioxide, methane (CH4) and...'

A: Thank you for your comment. Revised accordingly Page 3, Line 56. And we have reviewed the whole manuscript checking possible similar mistakes.

Line 52: delete the word: 'greatly'. Should be: ...the most important greenhouse gases (GHGs) that contribute to global warming...'

A: Revised accordingly Page 3, Line 57.

Line 52 – 55: Rephrase the sentence. For example: 'The concept of global warming potential (GWP) has been applied to agricultural lands by taking in to account of the radiative properties of all GHG emissions associated with agricultural production and soil organic carbon (SOC) sequestration, expressed as CO_2 eq. ha^{-1} yr^{-1} (Robertson and Grace, 2004; Mosier et al., 2006).'

A: Thank you for your comment. Revised accordingly Page 3, Line 57-60.

Line 63 – 65: the following sentence seems to be out of place and break the 'line of reasoning' you are building as justification, consider deleting it:

'This indicates that agricultural ecosystems are not only a very important source of GHG emissions but also present substantial opportunities for mitigation.'

A: Thank you for your comment. Revised accordingly Page 4, Line 69.

Line 65 – 69: Re-phrase this sentence. For example: Therefore, when determining the GWP of agroecosystems, there is a need to account for all sources of GHG emissions, including the emissions associated with agrochemical inputs (Ei) and farm operations (Eo) and sinks, e.g. soil organic carbon (SOC) sequestration (Sainju et al., 2014).

A: Thank you for your comment. Revised accordingly Page 4, Line 69-72.

Line 70 – 71: ...and greenhouse gas intensity (GHGI) of agricultural systems is limited in China (...

A: Revised accordingly Page 4, Line 74.

Line 72: Previous studies were mainly focused on the....

A: Revised accordingly Page 4, Line 76.

Line 72: A part of sentence is missing here. Should read as:.. influences of ISSM practices on CH4 and N2O emissions, but did not account for the...

A: Thank you for your comment. Revised accordingly Page 4, Line 76-77.

Line 74 – 76: The sentence is not complete. Should read as:

'In this study, we evaluated GWP and GHGI of rice-wheat crop rotation managed under several scenarios of ISSM by taking CO2 equivalent emissions from all sources and sinks into account for 5 years.'

A: Thank you for your comment. Revised accordingly Page 4, Line 78-79.

Line 76: Please see my general comment on '5-year study'. Revise accordingly.

A: Thank you for your comment.

Line 84: Please see my general comment on '5-year study'. Revise accordingly.

A: Thank you for your comment.

Line 86: ...flooded rice...

A: Revised accordingly Page 4, Line 90.

Line 88 – 89: Here only three-years weather data are presented as per my general comment. If it is a 5-year study, authors should provide the readers about where other two years data can be found. (Ma et al 2013?).

A: Yes. The other two years data can be found by Ma et al 2013. Revised accordingly Page 6, Line 129-131.

Line 97: 'A completely randomized block design' or 'A completely randomized plot design' please explain.

A: Revised accordingly Page 5, Line 101. It means that the distribution of each treatment in the field is randomly arranged (with four replicates of six treatments).

Line 99: Provide within parenthesis the N rate for local FP rate: Should read as: ...local FP rate (300 kg N ha-1)

A: Revised accordingly Page 5, Line 103.

Line 100 - 105: Re-phrase the sentence. For example:

'The designed ISSM scenarios (only for rice but not for wheat) included a redesigned split N fertilizer application, a balanced fertilizer application that included sodium silicate, zinc sulphate, rapeseed cake (C/N=8) providing an additional 112.5 kg N ha−1, and additional phosphorus and potassium, and different transplanting densities, used as the main techniques for improving rice yields...'

A: Thank you for your comment. Revised accordingly Page 5, Line 105-108.

Line 107: delete: 'detailed'. Should reads as: Further information was...

A: Revised accordingly Page 5, Line 114.

Line 114 – 115: ... rapeseed cake manure were applied as basal fertilizers for both crops. Does this mean that rapeseed cake was applied to both crops? If so, it is missing in Table 1.

A: Sorry for the inconvenience due to our negligence. Rapeseed cake manure was applied for rice crop only. Revised accordingly Page 5, Line 120-121.

Line 119 – 120: Re-write to be consistent (example): 'Harvests included crop grains and rice and wheat straws which were removed out of the fields of all the treatments in this study.'

A: Thank you for your comment. Revised accordingly Page 5, Line 125-126.

Line 122: Please re-phrase (example): We measured the CH4 and N2O emissions from each plot...

A: Revised accordingly Page 6, Line 128.

Line 125 – 130: Somewhere under this section, please explain briefly the following: gas sampling frequency, length of chamber deployment, gas sample drawing time interval (e.g. 0, 10, 20, 30 minutes) and sample volume, gas sample storage length until analysis). Alternatively, you may provide a previous paper related to this study, that explains these details.

A: Thank you for your comment. Revised accordingly Page 6, Line 136-139.

Line 137: somewhere here, explain briefly gas flux calculation method used (Alternatively, you may provide a previous paper related to this study, that explains these details).

A: Thank you for your comment. Revised accordingly Page 6, Line 146-148.

Line 144: Provide units for SOCt and SOC0.

A: Revised accordingly Page 6, Line 155.

Line 149: Re-phrase (for example): 'To better understand the overall GHG impact of the rice-wheat crop rotation managed under different ISSM scenarios, the GWP and GHGI were calculated...'

A: Thank you for your comment. Revised accordingly Page 7, Line 160-161.

Line 154: Provide units for each: Ei, Eo and SOCSR.

A: Revised accordingly Page 7, Line 165-166.

Line 156: ...The global warming potential of 1 kg CH4 and 1 kg of N2O are 25 and 298 kg CO2 equivalents respectively, based on 100-yr time scale (...

A: Revised accordingly Page 7, Line 168-169.

Line 157: It is not correct to write as: The 12 and 44... You could write as (for example): 'In the equation 2, 12 and 44 refers to molecular weights of C and CO2, respectively.

A: Revised accordingly Page 7, Line 169-170.

Line 160:...SOC change per unit land area.

A: Revised accordingly Page 7, Line 173.

Line 160 - 164: It is not correct to say ‘hidden CO2 equivalent emissions’. It is well known that agricultural inputs and farm operations produce greenhouse gas emissions. Please re-phrase part of the sentence (for example you may revise this as):

In addition to CH_4 and N_2O emissions, we considered CO_2 equivalent emissions associated with the use of agrochemical inputs (Ei), such as...

A: Thank you for your comment. Revised accordingly Page 7, Line 173-174.

Line 165 - 167: Please explain how the emission factor for irrigation water (i.e. 5.16 kg C eq. cm^{-1} ha^{-1}) was calculated, because Lal, 2004 provides several values for irrigation water, depending on the amount of total irrigation water supplied and the type of irrigation system used. It clear to me that this emission factor was calculated from the original value of 257.8 kg CE ha-1 for a 50 cm of irrigation provided in Lal 2004. However, you need to explain briefly the applicability of this emission factor for the irrigation system used in this experiment. Revise the sentence accordingly to include this information.

A: Thank you for your comment. We responded this question in general comments.

Line 168: Please check the C emission factor used for herbicide. It should be 6.3 kg CE per kg active ingredient (Lal 2004), NOT 0.3 kg CE per kg active ingredient, you have used in Table 4.

A: Sorry for the inconvenience due to our negligence. Revised accordingly Table 4.

Line 169: I have number of questions related to how the CO2 emissions were calculated for farm operations. The questions (a to f) are listed below. Please revise the text to explain briefly the main type of farm operations listed in Table 4 in order to clarify the emission factors used and how CO2 emissions were calculated.

(a) What type of machinery was used for field operations such as tillage, planting, and harvest? The C emission factor for each of these operations will depend on the type of the machinery used. This information is important. For example, it is necessary to mention how tillage was done. One passes of rotary tiller and one passes of raking? There will be two events of tillage: one for rice, one for wheat.

(b) It is not clear what it means: 1 (one) kg/ha given for all treatments in the column for crop planting in Table 4. Does it mean: 1 kg diesel fuel/ ha was used for crop planting? If that is the case C emission factor for diesel fuel is 0.94 kg CE per kg diesel according to Lal 2004. If it is 1 event, then 3.2 kg CE/ha (which you have used) is correct; however, there are 2 events of planting per year (one event for rice, another event for wheat). It appears that only one event of crop planting is accounted in the Table 4.

(c) Was the emission factor for manure application used in Table 4 taken from Lal 2004? (I am not sure Lal 2004 provided this emission factor).

(d) Similarly, there are two harvest events per year (one for rice, one for wheat). Was the 11 kg/ha diesel use reported in Table 4 for both harvest events?

(e) It is not correct to apply the emission factor for spraying and thrashing (0.0725 kg CE/kg active ingredient) for calculating CO2 emissions from ‘farm machinery production’ as presented in Table 4.

(f) Was there machinery used for fertilizer spreading? Split fertilizer application requires 3 or 4 passes for each crop depending on how many split applications were used for rice and for wheat in each treatment.

A: Thank you very much for your great comments. We answered these questions in the previous general comments.

Line 170 – 173: Rephrase the sentence. (for example): ‘We collected the data specific to China’s fertilizer manufacture and consumption, and calculated the C emission coefficients to be 0.07 and 0.1

kg C eq. kg^{-1} of active ingredient for Si and Zn fertilizer, respectively. These coefficients were used to estimate the CO_2 equivalent emissions associated with applied Si and Zn fertilizer.'

A: Revised accordingly Page 8, Line 186-187.

That is a good approach. Please explain why this approach was not possible to be done for other fertilizer types used in this experiment, given the fact that coefficients published in Lal (2004) were largely based on European and North American studies.

A: Thank you for your comment. Surely, it is more appropriate to use targeted emission factor in China, but we didn't investigate other fertilizer types used in this experiment. After that, we will try our best to obtain new emission factor. Anyway, these coefficients published in Lal (2004) are also applicable to China, as cited in Jia et al. (2012).

Line 176: Please check: SAS Institute, USA, 2007 (missing in the reference list).

A: Thank you for your comment. It is the version of JMP, not a reference.

Line 177: should read as: ...to determine whether there were significant differences among treatments, years, and their interactions at $p<0.05$.

A: Revised accordingly Page 8, Line 194.

Line 180 - 181: should read as: …determine whether significant differences occurred between the treatments at a level of $p<0.05$.

A: Revised accordingly Page 8, Line 198.

Line 186: Revise the line to include reference to the Table 2. (for example): …varied significantly among the treatments (Table 2).

A: Revised accordingly Page 8, Line 204.

Line 187: delete the reference to Table 2 here, once you do the above revision in line 186.

A: Revised accordingly Page 8, Line 205.

Line 197- 198: Revise the sentence. For example, it should read as: 'The higher NUE in the wheat season was mainly due to the relatively lower N fertilizer (40%) rates used for wheat compared with that for rice.'

A: Revised accordingly Page 9, Line 216-217.

Line 201: delete the word: 'merely'. The difference between FP vs. N1 and N2 is statistically significant, as indicated by different letters (b vs. a and a) in Fig 1.

A: Thank you for your comment. Revised accordingly Page 9, Line 219.

Line 201: should read as …NUE increased by 12 and 14% in the N1 and N2 scenarios, respectively, and slightly decreased in the N3 and N4 scenarios…

A: Revised accordingly Page 9, Line 219-220.

Line 206: Include the reference to Fig 2 here at the end of line: …wheat season (Fig 2).

A: Revised accordingly Page 9, Line 225.

Line 207: delete the reference to Fig 2 here, once you do the revision above in line 206.

A: Revised accordingly Page 9, Line 226.

Line 216 – 217: should read as: 'The annual N_2O fluxes varied from −33.1 to 647.5 μg N2O-N m^{-2} h^{-1}, with most N_2O emissions occurring during the wheat-growing season after fertilization events, and several smaller emission peaks during the rice-growing season (Fig. 3).'

A: Revised accordingly Page 9, Line 236-237.

Line 220: ...higher than that in NN...

A: Revised accordingly Page 9, Line 240.

Line 222: should read as: 'The N4 scenario significantly increased the cumulative N2O emissions by

46% ($P < 0.05$), because this system received additional...

A: Revised accordingly Page 9, Line 242-244.

Line 222 – 224: Was additional N received from rape seed cake the main reason for highest cumulative N2O emissions in the N4 scenario relative to FP? N3 scenario also received additional N as rape seed cake, but there was no significant difference in cumulative N2O emissions in N3 vs. FP. It seems the main reason for highest cumulative N2O emissions in N4 is highest inorganic N fertilizer (25% higher than that in FP) rate it received. Please explain all the possibilities.

A: Thank you for your comment. Revised accordingly Page 9, Line 243-244.

Line 228: Should be ...'The CO2 equivalent emissions associated with Ei and Eo...'

A: Revised accordingly Page 10, Line 249.

Line 228: replace the word 'classified' with 'presented'.

A: Revised accordingly Page 10, Line 249.

Line 228-229: Results in Table 5 indicates that irrigation contributed 19 – 31% of the total CO2 equivalent emissions from agricultural management (Ei + Eo). Yes, it is lower than the CO2 equivalent contribution from N fertilizer (which were 46 – 51% Ei+Eo), but you cannot say that it is much less important. I would say it is the second largest source of CO2 equivalents associated with agricultural management after N fertilizer.

A: Thank you for your comment. Revised accordingly Page 10, Line 252-253.

Line 234-235: Please check the **negative** or **positive** symbol for the values of CO2 equivalent emissions due to SOC sequestration presented in Table 5. A negative value indicates soil is a sink for C sequestration and a positive value indicates a soil as a source for CO2 emissions from SOC loss.

A: Thank you for your comment. The GWP is calculated as equation: GWP (kg CO_2 eq. ha^{-1} yr^{-1}) = $GWP_{(CH4 + N2O + Ei + Eo)}$ − GWP_{SOCSR}. Thus, negative value indicates soil as a source for CO_2 emissions from SOC loss and a positive value indicates soil is a sink for C sequestration as presented in Table 5.

Line 235: ...in these cropping systems.

A: Revised accordingly Page 10, Line 256-257.

Line 237: ...(contributed 5 – 10% decrease of the GWP except in the NN plot).

A: Revised accordingly Page 10, Line 259.

Line 238: Of the CO2 equivalents from agricultural management practices, emissions associated with Ei (2449-4256 CO2 eq. ha-1 yr-1) were higher than those associated with Eo (...

A: Revised accordingly Page 10, Line 260-261.

Line 245: The GHGIs (kg CO2 eq. Mg-1 grain)...

A: Revised accordingly Page 10, Line 268.

Line 245-246: Significant differences in the GHGIs of grain was found...

A: Revised accordingly Page 10, Line 269.

Line 248: reduced GHG emissions (relative to FP) were only observed in N1 and N2. Please revise the sentence to correctly reflect the results.

A: Revised accordingly Page 10, Line 272-273.

Line 258: Should be: 'Compared with the FP, rice yields increased significantly by all four ISSM...

A: Revised accordingly Page 11, Line 283.

Line 264-265: What is the meaning of reasonable N split? I would say 'N split application to match the crop demand'. Please revise or clarify. For example:

'Second, split application of N fertilizer to match crop demand in the N1, N2, N3 and N4 scenarios would significantly increase agronomic NUE and rice yield which had been reported previously by Liu et al. (2009).

A: Thank you for your comment. Revised accordingly Page 11, Line 289-291.

Line 267: This finding is consistent with the results...

A: Revised accordingly Page 11, Line 293.

Line 270: What are the ‘modified farmer’s practice’ in that study?

A: Compared with the farmers’ N-fertilizer practices, other N management strategies such as real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM) were used.

Line 274: ...produced higher yields (...

A: Revised accordingly Page 11, Line 300.

Line 275 – 277: Was applying rape seed cake manure with FP rate or with 25% higher N was the only reason for higher rice grain yields in N3 and N4? P, and K were higher, in combination with Si and Zn fertilizer as well as a different planting density (in N3).

Should read as: As expected, when the total N rate was at the FP rate and/or increased by 25%, in combination with other ISSM strategies (e.g. rapeseed cake manure, additional P and K, applying Si and Zn fertilizer), the rice grain yield in N3 and N4 systems increased substantially by 28 and 41%, respectively.’

A: Revised accordingly Page 11, Line 302-304.

Line 279-280: This may have resulted from the organic fertilizer applied in combination with adequate nutrients contributing to alleviate potential yield limiting factors of rice.

A: Revised accordingly Page 12, Line 307-308.

Line 282 – 285: It is not clear exactly what you are explaining in this sentence. Especially, I could not understand the phrase: ‘**In spite of the high proportion**...’ Do you mean to say the following?:

‘In addition to **high rates** of N 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).’

Please revise the lines 282-285.

A: Revised accordingly Page 12, Line 310.

Line 287 - 289: You did not measure N leaching and volatilization losses. You cannot be certain about this and therefore, the use of the word: ‘primarily’ is not correct. Please revise. May be you can say:

‘The higher rice agronomic NUE in our study over the experimental period was **likely** due to the decreased N losses and improved N uptake realized through the better synchrony of N supply and crop N demand, due to the split application of N fertilizer in the rice cropping season.’

A: Revised accordingly Page 12, Line 316.

Line 303: delete the word ‘emissions’. ...scenarios emitted 87 and 118% more CH4, respectively (...

A: Revised accordingly Page 12, Line 334.

Line 313 – 314: ...the higher biomass may have facilitated more CH4 emissions (...

A: Revised accordingly Page 13, Line 346.

Line 314-317: This is a repetition of the same, you have already discussed in previous several sentences. Avoid repetition.

A: Deleted accordingly Page 13, Line 346.

Line 319: ...strongly influenced the soil N2O...

A: Revised accordingly Page 13, Line 350.

Line 323: ...conditions may have enhanced...

A: Revised accordingly Page 13, Line 356.

Line 324 – 325: What is the likely reason for increased N2O emissions due to alternative of drainage and flooding? Coupled nitrification and dentrification?

A: Thank you for your comment. Water regimes affect the relative importance of the nitrification and denitrification processes as sources of N_2O. When the soil water content is below saturation, N_2O emissions increase with soil moisture; however, N_2O emissions gradually decrease with the soil saturation condition. As such, denitrification and nitrification are carried out alternately that produce N_2O in the soil.

Line 326: Please check: Wang et al., 2013. In the reference list it is listed as 2012.

A: Sorry for the inconvenience. The reference is Wang et al., 2012. Revised accordingly Page 13, Line 359.

Line 327: ...N2O emissions...cultivation practices and years (Table 3).

A: Revised accordingly Page 13, Line 360.

Line 328: Replace the word 'greatly' with the word 'significantly'.

A: Revised accordingly Page 13, Line 361.

Line 335: ...which also probably contributed increased CH4 emissions (Banger et al. 2013).

A: Revised accordingly Page 14, Line 368.

Line 342: ...as well as additional CO2 emissions due to the use of machinery/equipment for irrigation...

A: Revised accordingly Page 14, Line 377-378.

Line 339 – 344: If possible, please provide an approximate quantity of additional CO2 emitted due to ISSM strategies in the present study relative to studies cited here.

A: Revised accordingly Page 14, Line 379-380.

Thank you very much once again for all of your nice comments and great support!

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 chemical N rates relative to the local farmers' practice (FP) rate were carried out, namely, ISSM-N1 (25% reduction), ISSM-N2 (10% reduction), ISSM-N3 (FP rate) and ISSM-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~~ 35 and ~~73~~40%, respectively. In addition, compared with the FP, the ISSM-N1 and ISSM-N2 scenarios significantly reduced the GHGI by 14 and 18%, respectively, despite similar GWPs. The ISSM-N3 and ISSM-N4 scenarios remarkably increased the GWP and GHGI by an average of 69~~7~~ and 39~~7~~%, respectively. In conclusion, the ISSM strategies are promising for both food security and environmental protection, and the ISSM scenario of ISSM-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~~ An increase in global crop production of 100% would be necessary to sustain the projected demand for human food and livestock feed in 2050 (Tilman et al., 2011). Rice is the staple food for nearly 50% of the world's people, mainly in Asia (Frolking et al., 2002). 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 (Chen et al., 2014). With~~in~~ a limited agricultural land area, the intensive agricultural regions of China are facing serious environmental problems due to large inputs of chemical fertilizer~~s~~ 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 compounds~~varieties~~ and application ratios, crop densities and advanced water management regimes ~~management~~, has been advocated and developed to simultaneously increase crop productivity and NUE with low carbon dioxide (CO_2) equivalent emissions per unit product in China (Chen et al., 2014). The key points of the ISSM are to integrate soil and nutrient management with high-yielding cultivation systems, to integrate the utilization of various nutrient sources and match nutrient supply to crop requirements, and to take all soil quality improvement measures into consideration (Zhang et al., 2011).

~~CO_2~~Carbon dioxide, 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}~~ The concept of global warming potential (GWP) has been applied to agricultural lands by taking in to account of the radiative properties of all GHG emissions associated with agricultural production and soil organic carbon (SOC) sequestration, 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 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 Therefore, when determining the GWP of agroecosystems, there is a need to account for all sources of GHG emissions, including the emissions associated with agrochemical inputs (Ei) and farm operations (Eo) and sinks, e.g. soil organic carbon (SOC) sequestration (Sainju et al., 2014).

Information on the effects of ISSM scenarios on GWP and greenhouse gas intensity (GHGI) of agricultural systems 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 were mainly focused onmainly investigated the initial influences of ISSM practices on CH_4 and N_2O emissions, 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 of rice-wheat crop rotation managed under several scenarios of ISSM by taking CO_2 equivalents emissions 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 flooded~~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 °C 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, are given in the supplementary resource 1.

2.2 Experimental design and management

A completely randomized block design was established in 2009 with four replicates of six treatments, including no nitrogen (NN) and FP as controls, and four ISSM scenarios at different chemical N fertilizer application rates relative to the local FP rate (300 kg N ha^{-1}) , namely ISSM-N1 (25% reduction), ISSM-N2 (10% reduction), ISSM-N3 (FP rate) and ISSM-N4 (25% increase). The designed ISSM scenarios (only for rice but not for wheat) included a redesigned split N fertilizer application, a balanced fertilizer application that included sodium silicate, zinc sulphate, rapeseed cake (C/N=8) providing an additional 112.5 kg N ha^{-1}, and additional phosphorus and potassium, and different transplanting densities~~The designed ISSM (only for rice but not wheat production) including a redesign of a split N fertilizer application, a balanced fertilizer application (rapeseed cake in additional 112.5 kg N ha⁻¹, C/N=8), additional phosphorus and potassium application, and transplanting density~~, used as the main techniques for improving rice yield and agronomic NUE. The agronomic NUE was– ~~(~~calculated as the difference in grain yield between the plots that received N application and the NN plot, divided by the total N ~~fertilizer~~ rate which included chemical N fertilizer and rapeseed cake in the ISSM-N3 and ISSM-N4 scenarios~~)~~. The details of the fertilizer applications, irrigation, and field management practices of the six different treatments are presented in Table 1. Further ~~detailed~~ information was described previously (Zhang et al., 2014). Each plot was 6 m × 7 m in size with an independent drainage/irrigation system.

One midseason drainage (about one week) and final drainage before harvest were used during the rice-growing season, whereas the plots only received precipitation during the wheat-growing season. The N fertilizer was split into a 6:2:0:2 or 5:1:2:2 ratio of basal fertilizer and topdressings for the rice crop and a 6:1:3 ratio for the wheat crop. All of phosphorous (P), silicon (Si), zinc (Zn) ~~and rapeseed cake manure~~ were applied as basal fertilizers for both crops and rapeseed cake manure was applied for rice crop. Potassium (K) was added as a split (1:1) application to the rice crop and all as basal fertilizer for the wheat crop. The basal fertilization occurred at the time of rice transplanting and wheat seeding. The topdressing was applied at the tillering, elongation and panicle stages of the rice crop and at the seedling establishment and elongation stages of the wheat crop. Aboveground biomass including crop grains and straws were removed out of the fields for all the treatments.~~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.~~

2.3 Gas sampling and measurements

We measured the CH_4 and N_2O emissions ~~and N_2O fluxes in~~from each plot of the field experiment over five annual cycles from the 2009 rice-growing season to the 2014 wheat-growing season. The initial 2-yr measurements during the 2009–2011 rice-wheat rotational systems were described 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. Gas samples were collected from 9:00 to 11:00 am using an airtight syringe with a 20-ml volume at intervals of 10 min (0, 10, 20 and 30 min after chamber closure). The fluxes were measured once a week and more frequently after fertilizer application or a change in soil moisture.

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~~ Methane 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 °C and 300 °C, respectively. The oven and FID were operated at 50 °C and 300 °C, respectively. The CH_4 and N_2O fluxes rate were calculated using a linear increase in the two gas concentrations over time described by Jia et al. (2012).

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):

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

In Eq. (1), SOC_t (g C kg^{-1}) and SOC_0 (g C kg^{-1}) 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 GHG impact of the rice-wheat crop rotation managed under different ISSM scenarios, the GWP and GHGI were calculated ~~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 (Myhre et al.~~IPCC~~, 2013):

GWP (kg CO_2 eq. ha^{-1} yr^{-1}) = 28~~5~~ × CH_4 + 265~~98~~ × N_2O + Ei + Eo − 44/12 × SOCSR (2)

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

In Eq. (2), Ei (kg CO_2 eq. ha^{-1} yr^{-1}), Eo (kg CO_2 eq. ha^{-1} yr^{-1}) and SOCSR (kg C ha^{-1} yr^{-1}) represent CO_2 equivalent emissions from the agrochemical inputs, farm operations and soil organic carbon sequestration rate, respectively. The global warming potential of 1 kg CH_4 and 1 kg N_2O are ~~equivalent to~~ 28~~5~~ and 265~~98~~ kg CO_2 equivalents respectively (without inclusion of climate-carbon feedbacks), based on 100-y~~ea~~r time scale~~, respectively~~ (Myhre et al.~~IPCC~~, 2013). ~~The~~ 12 and 44 refers to ~~are the~~ molecular weights of C and CO_2, respectively. The grain yield is expressed as the air-dried grain yield.

Therefore, the GWP of the cropland ecosystem equals the total CO_2 equivalent emissions minus the SOC change per unit land area. In addition to CH_4 and N_2O emissions, we considered CO_2 equivalent emissions associated with the use of agrochemical inputs (Ei), ~~In addition to the CH_4 emissions and N_2O fluxes, we considered the 'hidden' CO_2 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 CO_2 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 CO_2 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}) originated from the value of 257.8 kg C eq. ha^{-1} for a 50 cm of irrigation provided by ~~(~~Lal~~,~~ (2004)~~)~~. The CO_2 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 also estimated by coefficients provided by Lal (2004) since no specific coefficients were available. We collected the data specific to China's fertilizer manufacture and consumption, and obtained the C emission coefficients to be 0.07 and 0.1 kg C eq. kg^{-1} of active ingredient for Si and Zn fertilizer, respectively. The C emission factor for these farm operations depends on diesel used as fuel or electricity. Chemical fertilizers were hand spraying broadcasted for each fertilization event. Detailed information of each Ei and Eo component for rice and wheat crop season was presented in Supplementary resource 2.~~and then estimated C emissions coefficients were 0.07 and 0.1 C cost (kg C eq. kg^{-1} active ingredient) per applied Si and Zn fertilizer, respectively.~~

2.6 Statistical analysis

Repeated-measures multivariate analysis of variance (MANOVA) and linear relationships were determined using JMP 7.0, ver. 7.0 (SAS Institute, USA, 2007). The F-test was applied to determine whether there were significant differences among~~effects of the~~ practices, years and their interaction at $P < 0.05$. One-way analysis of variance was conducted to determine the emissions of CH_4 and N_2O, and the grain yield among the different treatments. Tukey's HSD test was used to determine whether significant differences occurred between the treatments at a ~~significance~~ level of $P < 0.05$. Normal distribution and variance uniformity were checked and all data were consistent with the variance uniformity ($P > 0.05$) within each group. The results are presented as the means and standard deviation (mean ± SD, n = 4).

3 Results

3.1 Crop production and agronomic NUE

During the three cropping rotations from 2011 to 2014, the rice and wheat yields varied significantly among the treatments~~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 ISSM-N1, ISSM-N2, ISSM-N3 and ISSM-N4. Compared with the FP, rice grain yields increased by 10% and 16% for the ISSM-N1 and ISSM-N2 scenarios, respectively, i.e., with the lower N input, by 28% for the ISSM-N3 scenario with the same N input and by 41% for the ISSM-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 ISSM-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^{-1}, respectively (Fig. 1). The higher NUE in the wheat season was mainly due to the relatively lower N fertilizer (40%) rates used for wheat compared with that for rice~~reduced N fertilizer (40%) during this season~~. As expected, the rice agronomic NUE significantly increased by 75, 67, 35~~74~~ and 40~~73~~% for the ISSM-N1, ISSM-N2, ISSM-N3 and ISSM-N4 scenarios, respectively, compared with the FP (Fig. 1). For the wheat crop, the agronomic NUE ~~merely~~ increased by 12 and 14% in~~for~~ the ISSM-N1 and ISSM-N2 scenarios, respectively, and slightly decreased ~~to some extent for~~in the ISSM-N3 and ISSM-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_2O emissions

All plots showed similar CH_4 emission patterns, being a source in the rice season and negligible in the wheat season (Fig. 2). 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, ISSM-N1 and ISSM-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 ISSM-N3 and ISSM-N4 plots than in the NN, FP, ISSM-N1 and ISSM-N2 plots (Table 2, $P < 0.05$). However, compared with the NN plots, the FP, ISSM-N1 and ISSM-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 further enhanced by 198.5% in the ISSM-N3 plots and by 246.7% in the ISSM-N4 plots.

The annual N_2O fluxes varied from −33.1 to 647.5 μg N_2O-N m^{-2} h^{-1}, with most~~most of the~~ N_2O emissions occurring~~was emitted~~ during the wheat-growing season after fertilization events, and ~~there were~~ several small emission peaks during the rice-growing season (Fig. 3). With respect to the N application effect, the annual cumulative N_2O emissions for all four ISSM scenarios were significantly higher than that in NN ($P < 0.05$). Relative to the FP plot, the ISSM-N1 and ISSM-N2 scenarios decreased the annual N_2O emissions by an average of 41% and 22%, respectively (Table 2). The ISSM-N4 scenario significantly increased the cumulative N_2O emissions~~it~~ by 46% ($P < 0.05$) because this system~~they~~ received highest inorganic N fertilizer (25% higher than that in FP) and ~~–~~additional N via manure application compared to the FP practice, although there was no significant difference between the ISSM-N3 and FP plots.

3.3 Annual GWP and GHGI

Based on the perspective of the carbon footprint, we included the GHG emissions associated with all of the inputs (Ei and Eo), and SOC sequestration was expressed as kg CO_2 eq. ha^{-1} yr^{-1}. The CO_2 equivalent emissions associated with ~~The emission of CO_2 equivalents for~~ Ei and Eo are presented~~classified~~ in Table 4. ~~While irrigation was a large proportion of farm~~

operations, these were much less significant than chemical inputs. The CO_2 equivalents rates from N fertilizer dominated not only the chemical input section (67–756% of Ei) but also the total CO_2 equivalents from agricultural management (456–501% of the sum of the Ei and Eo). And irrigation was the second largest source of CO_2 equivalents associated with agricultural management after N fertilizer (19–31% of the sum of the Ei and Eo). The GWP ranged from 84257871 to 2270911 kg CO_2 eq. ha^{-1} yr^{-1} for the NN and the ISSM-N4 plots, respectively (Table 5). Although fertilized treatments increased the annual CH_4 and N_2O emissions in comparison with the NN plot, it also increased the SOC sequestration in thesethis cropping systems. Of the main field GHGs that were directly emitted, CH_4 accounted for 596–785% of the GWP in all plots. An increase in the annual SOC content led to a significant decrease in the GWP (contributed to 5–910% decrease of the GWP except in the NN plot). The CO_2 equivalents from agricultural management practices, –emissions associated withfor Ei (249349–4300256 CO_2 eq. ha^{-1} yr^{-1}) were higher than those associated withfor Eo (129685–1708 697CO_2 eq. ha^{-1} yr^{-1}) in the fertilized plots. There was no significant difference in the annual GWP observed between the FP, ISSM-N1 and ISSM-N2 plots (Table 5). Across the three years, ISSM-N1 and ISSM-N2 slightly reduced the GWP by 12 and 10%, respectively; however, ISSM-N3 and ISSM-N4 significantly increased the GWP by an average of 552 and 841%, respectively, in comparison with the FP.

The GHGI was used to express the relationship between GWP and grain yield. The GHGIs (kg CO_2 eq. t^{-1} grain) in this study ranged from 712664 to 12145 kg CO_2 eq. t^{-1} grain (Table 5). The significant difference in the annual GHGI of grain was found between the FP and the ISSM strategies. Compared with the FP, ISSM-N1 and ISSM-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 of reasonable N fertilizer management and suitable planting density. 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 ISSM-N3 and ISSM-N4 scenarios than the ISSM-N1 and ISSM-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 significantly 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 ISSM-N1, ISSM-N2, and ISSM-N3 scenarios would produce a positive effect on rice yield by influencing rice colony structure, which agreed with Wu et al. (2005). Second, split application of N fertilizer to match crop demand in the ISSM-N1, ISSM-N2, ISSM-N3 and ISSM-N4 scenarios would significantly increase agronomic NUE and rice yield which had been reported previously by Liu et al. (2009).~~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, ISSM-N1 and ISSM-N2 significantly increased annual rice production by 10 and 16%, respectively, in comparison with the FP (Table 2). This ~~The~~ finding is consistent with the results 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 ISSM-N3 and ISSM-N4 scenarios would support better seedling establishment and reduce both biotic and abiotic stress, thus produced 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/or increased by 25%, in combination with other ISSM strategies (e.g. rapeseed cake manure, additional P and K, applying Si and Zn fertilizer)~~and applied with rapeseed cake manure~~, the rice yield in these ISSM-N3 and ISSM-N4 plots ~~remarkably~~ increased substantially 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 contributing to alleviate potential yield limiting factors of rice~~, 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 addition to high rates of N~~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~~ 35 and 40~~73~~% under the ISSM-N1, ISSM-N2, ISSM-N3 and ISSM-N4 scenarios, respectively (Fig. 1). The higher rice agronomic NUE in our study over the experimental period could be~~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 (Zhao et al., 2015). 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). Methane emissions were highest during rice season, but only during the flooding period. Mainly because CH_4 was produced in the anaerobic zones of submerged soils by methanogens and is oxidized into CO_2 by methanotrophs in the aerobic zones of wetland soils and in upland soils (Le Mer and Roger, 2001). 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, ISSM-N1 and ISSM-N2 plots. However, compared with the FP plot, the

ISSM-N3 and ISSM-N4 scenarios emitted 87 and 118% more CH_4 ~~emissions~~, respectively (Table 5), which is probably due to the incorporation of the organic rapeseed cake manure. Previous reports support the observations that CH_4 emissions were significantly increased with the application of organic amendments (Ma et al., 2009; Thangarajan et al., 2013; Zou et al., 2005). Apparently, a~~A~~dditional application of Si and Zn fertilizers had no significant effect on CH_4 and N_2O fluxes, which was consistent with the result of Xie et al. (2015). Moreover, rice growth was found to be significantly increased under the ISSM-N3 and ISSM-N4 scenarios. In this case, the organic matter inputs such as root litter and rhizodeposits in the ISSM-N3 and ISSM-N4 scenarios were probably also higher than in the other plots, and thus soil C input, which served as an additional source of substrates for the methanogens in the rice paddies, likely contributed to the increase in CH_4 emissions (Ma et al., 2009). Finally, because the rice plants acted as the main pathway for CH_4 transports from the soil to the atmosphere, the higher biomass may have facilitated~~the~~ more CH_4 emissions (Yan et al., 2005). ~~The results obtained in the present study revealed that both inorganic and organic fertilizer application significantly increased the CH_4 emissions in the rice season (Table 2), which was probably associated with the increase in the SOC content and crop biomass (Ma et al., 2013).~~

Denitrification and nitrification are the main processes that produce N_2O in the soil (Paul et al., 1993). The N_2O emission patterns varied during the rice and wheat growing seasons which were partially associated with the anaerobic conditions prevailing in a rice paddy. Changes in the soil water content strongly influenced~~affected~~ the soil N_2O emissions and resulted in negligible N_2O emissions when the rice field was flooded (Fig. 3), which is consistent with previous reports (Akiyama et al., 2005; Murdiyarso et al., 2010). When the soil water content was below saturation, N_2O emissions increase with soil moisture; however, N_2O emissions gradually decreased with the soil saturation condition (Rudaz et al., 1999). A relatively high N_2O peak was observed in the first two weeks of the wheat-growing season (Fig. 3), possibly because soil changes from flooded to drained conditions may have enhanced N_2O release (Deng et al., 2012). Alternation of drainage and flooding may induce large amounts of N_2O emissions, particularly in fertilized systems; this has commonly been shown~~proved~~ in earlier studies (Wang et al., 2012~~3~~; Xiong et al., 2007; Zou et al., 2005). The seasonal and annual rates of N_2O emissions were significantly affected by the cultivation practices patterns and years (Table 3). Compared with the FP plot, the ISSM-N2 scenario significantlygreatly decreased the seasonal N_2O emissions in this study, which may have resulted from a reduction in the N fertilizer rate (Table 1, Table 2). The total N_2O emissions decreased by 7–38% and 26–42% in the rice and wheat seasons, respectively, when the conventional N management (300 kg N ha^{-1} for rice and 180 kg N ha^{-1} per crop for wheat) changed to optimum N management (225–270 kg N ha^{-1} for rice and 135–162 kg N ha^{-1} per crop for wheat). It is likely that more N_2O was emitted (Mosier et al., 2006) as a result of the additional N made available to the soil microbes through N fertilizer application, which also probably contributed increased the CH_4 emissions (Banger et al., 2013). Strategies that can reduce N fertilization rates without influencing crop yields can inevitably lower GHG emissions (Mosier et al., 2006). Nitrogen leaching and volatilization are the important components of reactive N releases but not included in the current GHG budget.

4.3 GWP and GHGI as affected by ISSM strategies

The GWP in our study (10871104–2270911 kg CO_2 eq. ha^{-1}) with the ISSM strategies was higher than that in a double-cropping cereal rotation (1346–4684 kg CO_2 eq. ha^{-1}) and a rice-wheat annual rotation (290–4580 kg CO_2 eq. ha^{-1}) reported by Huang et al. (2013b) and Yang et al. (2015), respectively. Dominant CH_4 emissions as well as additional CO_2 emissions due to the use of emitted by the machinery/equipment used for irrigation and farm operations under the ISSM strategies may increase the GWP more than in other cropping systems (emit more CO_2 equivalent emissions of 2439–5694 kg CO_2 eq. ha^{-1} for agricultural management practices in the present study). However, the current GWP was comparable tostill much lower than that of a double-rice cropping system (13407–26066 kg CO_2 eq. ha^{-1}) (Shang et al., 2011).The GHGIs, which ranged from 0.7166 to 1.215 kg CO_2 eq. kg^{-1} grain in this study, were slightly higher than previous estimates of 0.24–0.74 kg CO_2 eq. kg^{-1} grain from rice paddies with midseason drainage and organic manure incorporation (Qin et al., 2010; Li et al., 2006) but were lower than the DNDC model estimates for continuous waterlogged paddies (3.22 kg CO_2 eq. kg^{-1} grain) (Li et al., 2006). Differences in GWP or GHGI were found in the cultivation patterns over the three rice-wheat rotations (Table 5). The ISSM-N1 and ISSM-N2 scenarios with optimized ISSM strategies led to a lower GWP than the FP by a certain extent,

~~Although~~ but there were not significant differences among the FP, ISSM-N1 and ISSM-N2 plots~~, the N1 and N2 scenarios with optimized ISSM strategies led to a lower GWP than the FP~~ (Table 5). Compared with the FP, the ISSM-N1 and ISSM-N2 scenarios dramatically reduced the GHGI, which was mainly due to higher yields. In spite of the similar GWP compared with the FP plot, the lowest GHGI (0.71~~66~~ kg CO_2 eq. kg^{-1} grain) was obtained under the ISSM-N2 scenario. This finding is consistent with the suggestion made by Burney et al. (2010), i.e., that the net effect of higher yields offsets emissions. It is well known that CH_4 emissions dominate the GWP in rice paddies (Ma et al., 2013; Shang et al., 2011). In comparison to the GWP (12371~~1545~~ kg CO_2 eq. $ha^{-1}yr^{-1}$) and GHGI (0.87~~1~~ kg CO_2 eq. kg^{-1} grain) of the FP, the ISSM-N3 and ISSM-N4 scenarios increased both the GWP and GHGI, mainly because these scenarios notably increased the CH_4 emissions compared with the FP, which resulted in relatively higher GWP (Table 5).

Agricultural management practices that change one type of GWP source/sink may also 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 ISSM-N2 scenario with ISSM strategies 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 ISSM-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). In each crop, CH_4 and irrigation were important for rice, but less important for wheat, in which N_2O losses were expected to have a higher weight (Supplementary resource 2). ~~CH_4~~ Methane 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 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 13.20~~6.33~~ kg grain kg^{-1} N^{-1} (an increment of 43%~~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, ISSM-N1 and ISSM-N2 significantly reduced the GHGI, though they resulted in similar GWPs, and ISSM-N3 and ISSM-N4 remarkably increased the GWP and GHGI. By adopting the ISSM-N2 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[c]	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, ISSM-N1 (25% reduction), ISSM-N2 (10% reduction), ISSM-N3 (FP rate) and ISSM-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.

[c]112.5 kg N ha^{-1} in the form of rapeseed cake was applied as basal fertilizer and included in the total N rate for calculating agronomic NUE.

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_2O emissions, and mean rice and wheat grain yields in the 2011–2014 cycle.

Crop season	Source	*df*	CH_4 (kg C ha^{-1})	N_2O (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 (event)	Farm manure	Crop harvest	Farm machinery production
									2011	2012	2013					
NN[d]	0	180	300	0	0	2	18	4	75	80	80	37	2~~1~~	0	11	135
FP	480	180	300	0	0	2	20	4.4	75	80	80	37	2~~1~~	0	11	147
ISSM-N1	360	180	300	0	0	2	20	4.4	50	65	55	37	2~~1~~	0	11	139
ISSM-N2	432	180	300	0	0	2	20	4.4	50	65	55	37	2~~1~~	0	11	177
ISSM-N3	480	216	360	225	15	2	27	6	50	65	55	37	2~~1~~	2250	11	177
ISSM-N4	600	252	450	225	15	2	41	9	50	65	55	37	2~~1~~	2250	11	275
	Chemical inputs (Ei) (kg CO_2 eq. ha^{-1})								Farm operations (Eo) (kg CO_2 eq. ha^{-1})							
NN	0	132	165	0	0	46~~2~~	338	53	1419	1514	1514	127	23~~12~~	0	37	36
FP	2288	132	165	0	0	46~~2~~	375	59	1419	1514	1514	127	23~~12~~	0	37	39
ISSM-N1	1716	132	165	0	0	46~~2~~	375	59	946	1230	1041	127	23~~12~~	0	37	37
ISSM-N2	2059	132	165	0	0	46~~2~~	375	59	946	1230	1041	127	23~~12~~	0	37	47
ISSM-N3	2288	158	198	58	6	46~~2~~	506	79	946	1230	1041	127	23~~12~~	62	37	47
ISSM-N4	2860	185	248	58	6	46~~2~~	768	129	946	1230	1041	127	23~~12~~	62	37	73

[a]The carbon emission coefficients were 1.3,0.2,0.15, 6~~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 rice season, wheat season and 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
Rice season								
NN	5026±733d	44±20c	424	1601	-396±164c	7492±706d	5.83±0.04f	1285±123b
FP	8035±742c	121±53bc	1859	1603	585±198ab	11032±555c	8.59±0.25e	1285±68b
ISSM-N1	7132±716c	75±24c	1502	1191	246±218b	9654±800c	9.45±0.18d	1021±81c
ISSM-N2	7186±434c	112±49bc	1716	1198	355±97ab	9858±484c	9.98±0.25c	989±67c
ISSM-N3	15005±888b	208±66ab	2037	1260	691±252a	17818±786b	10.95±0.13b	1626±54a
ISSM-N4	17427±1463a	284±60a	2626	1280	773±174a	20844±1452a	12.11±0.28a	1720±108a
Wheat season								
NN	-78±71a	201±28d	310	104	-396±164c	934±214b	1.75±0.04d	533±125a
FP	8±148a	605±99b	1206	105	585±198ab	1339±129b	5.67±0.16b	236±21b
ISSM-N1	16±103a	351±32c	991	105	246±218b	1217±342b	5.04±0.08c	241±68b
ISSM-N2	6±22a	451±49c	1120	108	355±97ab	1329±109b	5.76±0.22ab	231±26b
ISSM-N3	23±131a	598±20b	1302	108	691±252a	1340±290b	5.40±0.16bc	247±48b
ISSM-N4	79±96a	772±66a	1674	114	773±174a	1867±175a	6.14±0.35a	305±33b
Rice-wheat rotation								
NN[d]	4948±704d[c]	246±26d	734	1705	-792±327c	8425±711d	7.58±0.04d	1111±94b
FP	8043±858c	725±49b	3065	1708	1170±396ab	12371±583c	14.26±0.36c	868±29c
ISSM-N1	7141±709c	426±55c	2493	1296	491±435b	10871±990c	14.50±0.14c	750±68d
ISSM-N2	7192±424c	563±86c	2836	1306	709±193ab	11187±552c	15.74±0.44b	712±52d
ISSM-N3	15028±833b	806±77b	3339	1368	1383±503a	19158±761b	16.36±0.18b	1171±37ab
ISSM-N4	17506±1396a	1056±58a	4300	1394	1545±348a	22711±1438a	18.26±0.46a	1245±93a

[a]GWP (kg CO_2 eq. $ha^{-1}yr^{-1}$) = 28~~5~~ × CH_4 +265~~98~~ × N_2O + Ei +Eo − 44/12 × SOCSR, Ei (agrochemical inputs), Eo (farm operations), SOCSR (SOC sequestration rate) is divided by 2 to roughly estimate the GWP from rice and wheat season, respectively. All other items were actually measured for each season.

[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.

Supplementary resource 2 The agricultural management practices for chemical inputs and farm operations in the rice and wheat cropping seasons.