Global warming potential and greenhouse gas intensity in rice agriculture driven by high yields and nitrogen use efficiency

Xiaoxu Zhang[a], Xin Xu[a], Yinglie Liu[a], Jinyang Wang[a,b], Zhengqin Xiong[a,]*

[a] Jiangsu Key Laboratory of Low Carbon Agriculture and GHGs Mitigation, College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing, 210095, China

[b] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China

*Corresponding author (Z. Xiong):
Tel: +86-25-84395148,
Fax: +86-25-84395210,
E-mail: zqxiong@njau.edu.cn

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 field experiment was conducted in China to evaluate the effects of integrated soil-crop system management (ISSM) 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). The ISSM was mainly consisted of different nitrogen (N) fertilization rates and split, manure, Zn and Na_2SiO_3 fertilization and planting density 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, 35 and 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 and 39%, 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 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 a limited agricultural land area, the intensive agricultural regions of China are facing serious environmental problems due to large inputs of chemical fertilizer 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 and application ratios, crop densities and advanced water management regimes, 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).

Carbon dioxide, methane (CH_4) and nitrous oxide (N_2O) are the most important greenhouse gases (GHGs) that contribute to global warming (IPCC, 2013). The concept of global warming potential (GWP) has been applied to agricultural lands by taking into 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). 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 on 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 3 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 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 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 Fig. 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, 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 rate which included chemical N fertilizer and N supplied from 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 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) were applied as basal fertilizers for both crops and rapeseed cake manure was applied for the 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.

2.3 Gas sampling and measurements

We measured the CH_4 and N_2O emissions 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. 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 were calculated using a linear increase in the two gas concentrations over time as 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):

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

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 as the following equations (Myhre et al., 2013):

$$\text{GWP (kg CO}_2\text{ eq. ha}^{-1}\text{ yr}^{-1}) = 28 \times CH_4 + 265 \times N_2O + Ei + Eo - 44/12 \times SOCSR \quad (2)$$

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

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 28 and 265 kg CO_2 equivalents respectively (without inclusion of climate-carbon feedbacks), based on 100-yr time scale (Myhre et al., 2013). 12 and 44 refers to 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), 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} N (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 threshing) were recorded and also estimated by coefficients provided by Lal (2004) since no specific coefficients were available for local conditions. 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 fertilizer was hand broadcasted for each fertilization event. Detailed information of each Ei and Eo component for rice and wheat crop seasons are presented in Table 2.

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 practices, years and their interaction at $P < 0.05$. One-way analysis of variance was conducted to compare the cumulative fluxes of CH_4 and N_2O, and grain yield among the different treatments. Tukey's HSD test was used to determine whether significant differences occurred between the treatments at a 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 (Table 3). 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. 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 4).

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 N^{-1}, respectively (Fig. 2). 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. As expected, the rice agronomic NUE significantly increased by 75, 67, 35 and 40% for the ISSM-N1, ISSM-N2, ISSM-N3 and ISSM-N4 scenarios, respectively, compared with the FP (Fig. 2). For the wheat crop, the agronomic NUE increased by 12 and 14% in the ISSM-N1 and ISSM-N2 scenarios, respectively, and slightly decreased 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. 3). 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}. The seasonal CH_4 emissions varied significantly among the treatments during the rice-growing season (Table 4, Fig. 3). No significant difference was found between the FP, ISSM-N1 and ISSM-N2 plots. Temporal variation was significant during the three cycles (Table 4, $P < 0.001$). 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 3, $P < 0.05$). 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 N_2O emissions occurring during the wheat-growing season after fertilization events, and several small emission peaks during the rice-growing season (Fig. 4). 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 3). The ISSM-N4 scenario significantly increased the cumulative N_2O emissions by 46% ($P < 0.05$) because this system 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 Ei and Eo are presented in Table 5. The CO_2 equivalents rates from N fertilizer dominated not only the chemical input section (67–75% of Ei) but also the total CO_2 equivalents from agricultural management (45–50% of the sum of the Ei and Eo). 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 8425 to 22711 kg CO_2 eq. ha^{-1} yr^{-1} for the NN and the ISSM-N4 plots, respectively (Table 6). 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 these cropping systems. Of the main field GHGs that were directly emitted, CH_4 accounted for 59–78% of the GWP in all plots. An increase in the annual SOC content led to a significant decrease in the GWP (contributed 5–9% decrease of the GWP except in the NN plot). The CO_2 equivalents from agricultural management practices, emissions associated with Ei (2493–4300 CO_2 eq. ha^{-1} yr^{-1}) were higher than those associated with Eo (1296–1708 CO_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 6). 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 55 and 84%, 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 712 to 1245 kg CO_2 eq. t^{-1} grain (Table 6). The significant difference in the 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 4, $P < 0.001$), which is in agreement with previous results (Chen et al., 2011; Zhang et al., 2011). Compared with the FP, rice yields increased significantly by all four ISSM scenarios (Table 3). 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). 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 3). This 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 fertilizer 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), the rice yield in these ISSM-N3 and ISSM-N4 plots 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.

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 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, 35 and 40% under the ISSM-N1, ISSM-N2, ISSM-N3 and ISSM-N4 scenarios, respectively (Fig. 2). The higher rice agronomic NUE in our study over the experimental period could be due to 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 3), 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 paterns and years on CH_4 emissions were found during the rice-wheat rotations (Table 4, $P < 0.001$). The CH_4 emissions were not significantly affected by the cycles but affected by crop season (Table 6, Fig. 3). 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, respectively (Table 6), 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, additional 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 more CH_4 emissions (Yan et al., 2005).

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 the soil N_2O emissions and resulted in negligible N_2O emissions when the rice field was flooded (Fig. 4), 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. 4), 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 in earlier studies (Wang et al., 2012; Xiong et al., 2007; Zou et al., 2005). The seasonal and annual rates of N_2O emissions were significantly affected by the cultivation practices and years (Table 4). Compared with the FP plot, the ISSM-N2 scenario significantly decreased the seasonal N_2O emissions in this study, which may have resulted from a reduction in the N fertilizer rate (Table 1, Table 3). 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 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 (10871–22711 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 machinery/equipment 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 to that of a double-rice cropping system (13407–26066 kg CO_2 eq. ha^{-1}) (Shang et al., 2011).The GHGIs, which ranged from 0.71 to 1.25 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 6). The ISSM-N1 and ISSM-N2 scenarios with optimized ISSM strategies led to a lower GWP than the FP by a certain extent, but there were not significant differences among the FP, ISSM-N1 and ISSM-N2 plots (Table 6). Compared with the FP, the ISSM-N1 and ISSM-N2 scenarios significantly 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 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 kg CO_2 eq. $ha^{-1}yr^{-1}$) and GHGI (0.87 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 6).

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 may be due to the incorporation of rapeseed cake and enhanced below-ground 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 6). Of the two crops, 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 (Table 2). 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 6). 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 and at the same time reducing the substantial environmental impact 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 kg grain kg N^{-1} (an increment of 43%) 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 three-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 by 23%. 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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References

Akiyama, H., Yagi, K. and Yan, X. Y.: Direct N_2O emissions from rice paddy fields: summary of available data, Global Biogeochem. Cy., 19, GB002378, doi:10.1029/2004GB002378, 2005.

Banger, K., Tian, H. and Lu, C.: Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields?, Glob. Change Biol., 18, 3259-3267, 2013.

Barrett, C. B.: Measuring food insecurity, Science, 327 (5967), 825-828, 2010.

Burney, J. A., Davis, S. J. and Lobell, D. B.: Greenhouse gas mitigation by agricultural intensification, Proc. Natl. Acad. Sci. U.S.A., 107, 12052-12057, 2010.

Chen, X., Cui, Z., Vitousek, P. M., Cassman, K. G., Matson, P. A., Bai, J., Meng, Q., Hou, P., Yue, S. and Römheld, V.: Integrated soil-crop system management for food security, P. Natl. Acad. Sci. USA., 108, 6399-6404, 2011.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X. and Yang, J.: Producing more grain with lower environmental costs, Nature, 514, 486-489, 2014.

Deng, J., Zhou, Z., Zheng, X., Liu, C., Yao, Z., Xie, B., Cui, F., Han, S. and Zhu, J.: Annual emissions of nitrous oxide and nitric oxide from rice-wheat rotation and vegetable fields: a case study in the Tai-Lake region, China, Plant Soil, http://dx.doi.org/10.1007/s11104-012-1223-6, 2012.

Food and Agriculture Organization Statistical Data (FAOSTAT), Available online at: http://www.fao.org/docrep/003/x6905e/x6905e04.htm, Rome, Italy, 2010.

Frolking, S., Qiu, J., Boles, S., Xiao, X., Liu, J., Zhuang, Y., Li, C. and Qin, X.: Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China, Global Biogeochem. Cy., doi:16, 10.1029/2001GB001425, 2002.

Gao, B., Ju, X., Meng, Q., Cui, Z., Christie, P., Chen, X. and Zhang, F.: The impact of alternative cropping systems on global warming potential, grain yield and groundwater use, Agr. Ecosyst. Environ., 203, 46-54, 2015.

Hossain, M. A., Jahiruddin, M., Islam, M. R., and Mian, M. H.: The requirement of zinc for improvement of crop yield and mineral nutrition in the maize-mungbean-rice system. Plant and soil, 306, 13-22, 2008.

Hu, X., Su, F., Ju, X., Gao, B., Oenema, O., Christie, P., Huang, B., Jiang, R. and Zhang, F.: Greenhouse gas emissions from a wheat-maize double cropping system with different nitrogen fertilization regimes, Environ. Pollut., 176, 198-207, 2013.

Huang, J., Chen, Y., Sui, P. and Gao, W.: Estimation of net greenhouse gas balance using crop-and soil-based approaches: Two case studies, Sci. Total Environ., 456, 299-306, 2013a.

Huang, T., Gao, B., Christie, P. and Ju, X.: Net global warming potential and greenhouse gas intensity in a double-cropping cereal rotation as affected by nitrogen and straw management, Biogeosciences, 10 , 7897-7911, 2013b.

Huang, Y. and Sun, W.: Changes in topsoil organic carbon of croplands in mainland China over the last two decades, Chinese Sci Bull., 51, 1785-1803, 2006.

Huang, Y., Zhang, W., Zheng, X. H., Li, J. and Yu, Y. Q.: Modeling methane emission from rice paddies with various agricultural practices, J. Geophys. Res. Atmos., 109, D08, doi:10.1029/2003JD004401, 2004.

IPCC.: Climate Change 2013: The Physical Science Basis: working group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Stockholm, 2013.

Jia, J. X., Ma, Y. C. and Xiong, Z. Q.: Net ecosystem carbon budget, net global warming potential and greenhouse gas intensity in intensive vegetable ecosystems in China, Agr. Ecosyst. Environ.,150, 27-37, 2012.

Ju, X., Xing, G., Chen, X., Zhang, S., Zhang, L., Liu, X., Cui, Z., Yin, B., Christie, P. and Zhu, Z.: Reducing environmental risk by improving N management in intensive Chinese agricultural systems, P. Natl. Acad. Sci. USA, 106, 3041-3046, 2009.

Ju, X., Lu, X., Gao, Z., Chen, X., Su, F., Kogge, M., Römheld, V., Christie, P. and Zhang, F.: Processes and factors controlling N_2O production in an intensively managed low carbon calcareous soil under sub-humid monsoon conditions, Environ. Pollut., 159, 1007-1016, 2011.

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

Lal, R.: Carbon emission from farm operations, Environ. Int., 30, 981-990, 2004.

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

Li, C. S., Salas, W., DeAngelo, B. and Rose, S.: Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in China over the next twenty years, J. Environ. Qual., 35, 1554-1565, 2006.

Liu, L., Xue Y., Sun, X., Wang, Z. and Yang, J.: Effects of water management methods on grain yield and fertilizer-nitrogen use efficiency in rice, Chin J Rice Sci., 23, 282-288, 2009.

Liu, Y. L., Zhou, Z., Zhang, X., Xu, X., Chen, H. and Xiong, Z.: Net global warming potential and greenhouse gas intensity from the double rice system with integrated soil-crop system management: A three-year field study, Atmos. Environ., 116, 92-101, 2015.

Ma, J., Ma, E., Xu, H., Yagi, K. and Cai, Z.: Wheat straw management affects CH_4 and N_2O emissions from rice fields, Soil Biol. Biochem., 41, 1022-1028, 2009.

Ma, Y., Kong, X., Yang, B., Zhang, X., Yan, X., Yang, J. and Xiong, Z.: Net global warming potential and greenhouse gas intensity of annual rice-wheat rotations with integrated soil-crop system management, Agr. Ecosyst. Environ., 164, 209-219, 2013.

Makino, A.: Photosynthesis, grain yield, and nitrogen utilization in rice and wheat, Plant physiol., 155, 125-129, 2011.

Mosier, A. R., Halvorson, A. D., Reule, C. A. and Liu, X. J.: Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado, J. Environ. Qual., 35, 1584-1598, 2006.

Murdiyarso, D., Hergoualc'h, K. and Verchot, L. V.: Opportunities for reducing greenhouse gas emissions in tropical peatlands, P. Natl. Acad. Sci. USA, 107, 19655-19660, 2010.

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. and Zhang, H.: 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. (Eds.), 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, New York, NY, USA, 659-740, 2013.

Paul, J.W., Beauchamp, E.G. and Zhang, X.: Nitrous and nitric oxide emissions during nitrification and denitrification from manure-amended soil in the laboratory, Can. J. Soil. Sci., 73, 539-553, 1993.

Peng, S., Buresh, R. J., Huang, J., Yang, J., Zou, Y., Zhong, X., Wang, G. and Zhang, F.: Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China, Field Crop. Res., 96, 37-47, 2006.

Qin, Y. M., Liu, S.W., Guo, Y. Q., Liu, Q. and Zou, J. W.: Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China, Biol. Fertil. Soils., 46, 825-834, 2010.

Robertson, G. P. and Grace, P. R.: Greenhouse gas fluxes in tropical and temperate agriculture: The need for a full-cost accounting of global warming potentials, Environment Development and Sustainability, 6, 51-63, 2004.

Rudaz, A. O., Wälti, E., Kyburz, G., Lehmann, P. and Fuhrer, J.: Temporal variation in N_2O and N_2 fluxes from a permanent pasture in Switzerland in relation to management, soil water content and soil temperature, Agr. Ecosyst. Environ., 73, 83-91, 1999.

Sainju, U. M., Stevens, W. B., Caesar-TonThat, T., Liebig, M. A. and Wang, J.: Net global warming potential and greenhouse gas intensity influenced by irrigation, tillage, crop rotation, and nitrogen fertilization, J. Environ. Qual., 43, 777-788, 2014.

Schlesinger, W. H.: On fertilizer-induced soil carbon sequestration in China's croplands, Glob. Change Biol., 16, 849-850, 2010.

Shang, Q., Yang, X., Gao, C., Wu, P., Liu, J., Xu, Y., Shen, Q., Zou, J. and Guo, S.: Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments, Glob. Change Biol., 17, 2196-2210, 2011.

Six, J., Ogle, S. M., Conant, R. T., Mosier, A. R. and Paustian, K.: The potential to mitigate global warming with no-tillage management is only realized when practised in the long term, Glob. Change Biol., 10, 155-160, 2004.

Slaton, N. A., Norman, R. J. and Wilson, C. E.: Effect of zinc source and application time on zinc uptake and grain yield of flood-irrigated rice, Agron. J., 97, 272-278, 2005.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F. and Rice, C.: Greenhouse gas mitigation in agriculture, Philos. T. R. Soc. B., 363, 789-813, 2008.

Snyder, C., Bruulsema, T., Jensen, T. and Fixen, P.: Review of greenhouse gas emissions from crop production systems and fertilizer management effects, Agr. Ecosyst. Environ., 133, 247-266, 2009.

Thangarajan, R., Bolan, N. S., Tian, G., Naidu, R. and Kunhikrishnan, A.: Role of organic amendment application on greenhouse gas emission from soil, Sci. Total Environ., 465, 72-96, 2013.

Tilman, D., Balzer, C., Hill, J., Befort, B. L. and Affiliations, A.: Global food demand and the sustainable intensification of agriculture, P. Natl. Acad. Sci. USA, 108, 20260-20264, 2011.

Wang, J., Zhang, X., Xiong, **Z.**, Khalil, M.A.K., Zhao, X., Xie, Y. and Xing, G.: Methane emissions from a rice agroecosystem in South China: Effects of water regime, straw incorporation and nitrogen fertilizer, Nutr. Cycl. Agroecosyt., 93,103-112, 2012.

Wang, L.J., Nie, Q., Li, M., Zhang, F.S., Zhuang, J.Q., Yang, W.S., Li, T.J. and Wang, Y.H.: Biosilicified structures for cooling plant leaves: a mechanism of highly efficient midinfrared thermal emission, Appl. Phys. Lett., 87, 194105, doi:10.1063/1.2126115, 2005.

West, T. O. and Marland, G.: A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States, Agr. Ecosyst. Environ., 91, 217-232, 2002.

Wu, C., Ye, D., Lin, H., Ni, R., Lai L. and Lin, H.: Effects of transplanting density on rice yield and its quality, Chinese Agricultural Science Bulletin, 21, 190-205, 2005.

Xie, Y., Zhang, J., Jiang, H., Yang, J., Deng, S., Li, X., Guo, J., Li, L., Liu, X. and Zhou, G.: Effects of different fertilization practices on greenhouse gas emissions from paddy soil, Journal of Agro-Environment Science, 3, 578-584, 2015.

Xiong, Z. Q., Xing, G. X. and Zhu, Z. L.: Nitrous oxide and methane emissions as affected by water, soil and nitrogen, Pedosphere, 17, 146-155, 2007.

Yan, X. Y., Yagi, K., Akiyama, H. and Akimoto, H.: Statistical analysis of the major variables controlling methane emission from rice fields, Glob. Change Biol., 11, 1131-1141, 2005.

Yang, B., Xiong, Z., Wang, J., Xu, X., Huang, Q. and Shen, Q.: Mitigating net global warming potential and greenhouse gas intensities by substituting chemical nitrogen fertilizers with organic fertilization strategies in rice-wheat annual rotation systems in China: A 3-year field experiment, Ecol. Eng., 81, 289-297, 2015.

Zhang, F., Cui, Z., Fan, M., Zhang, W., Chen, X. and Jiang, R.: Integrated soil-crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China, J. Environ Qual., 40, 1051-1057, 2011.

Zhang, W., Dou, Z., He, P., Ju, X., Powlson, D., Chadwick, D., Norse, D., Lu, Y., Zhang, Y. and Wu, L.: New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China, P. Natl. Acad. Sci. USA, 110, 8375-8380, 2013.

Zhang, X., Fan, C., Ma, Y., Liu, Y., Li, L., Zhou, Q. and Xiong, Z.: Two approaches for net ecosystem carbon budgets and soil carbon sequestration in a rice-wheat rotation system in China, Nutr. Cycl. Agroecosys., 100, 301-313, 2014.

Zhao, M., Tian, Y., Ma, Y., Zhang, M., Yao, Y., Xiong, Z., Yin, B. and Zhu, Z.: Mitigating gaseous nitrogen emissions intensity from a Chinese rice cropping system through an improved management practice aimed to close the yield gap, Agr. Ecosyst. Environ., 203, 36-45, 2015.

Zhu, Z.: Fate and management of fertilizer nitrogen in agro-ecosystems. Nitrogen in Soils of China, Springer Netherlands, 239-279, 1997.

Zou, J. W., Huang, Y., Jiang, J. Y., Zheng, X. H. and Sass, R.L.: A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application, Global Biogeochem. Cy., 19, GB002401, doi:10.1029/2004GB002401, 2005.

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

Agricultural management practices for chemical inputs and farm operations in the rice and wheat cropping seasons.

	Rice season													
	Chemical inputs (kg ha^{-1})[a]								Farm operations[b]					
Treatment	N	P	K	Si	Zn	Herbicide	Insecticide	Fungicide	Irrigation (cm)	Tillage (kg diesel ha^{-1})	Crop planting (event)	Farm manure (kg ha^{-1})	Crop harvest (kg diesel ha^{-1})	Threshing[c] (kw▪h ha^{-1})
NN	0	90	120	0	0	1	13	2	78	20	1	0	6	74
FP	300	90	120	0	0	1	13	2.4	78	20	1	0	6	80
ISSM-N1	225	90	120	0	0	1	13	2.4	57	20	1	0	6	74
ISSM-N2	270	90	120	0	0	1	13	2.4	57	20	1	0	6	100
ISSM-N3	300	108	144	225	15	1	17	3.5	57	20	1	2250	6	100
ISSM-N4	375	126	180	225	15	1	26	5	57	20	1	2250	6	175
	Wheat season													
NN	0	90	180	0	0	1	5	2	0	17	1	0	5	61
FP	180	90	180	0	0	1	7	2	0	17	1	0	5	67
ISSM-N1	135	90	180	0	0	1	7	2	0	17	1	0	5	65
ISSM-N2	162	90	180	0	0	1	7	2	0	17	1	0	5	77
ISSM-N3	180	108	216	0	0	1	10	2.5	0	17	1	0	5	77
ISSM-N4	225	126	270	0	0	1	15	4	0	17	1	0	5	100

[a] There was no machinery used for fertilizer application.

[b] Tillage and crop harvest, crop planting, and threshing were calculated by diesel fuel (kg ha^{-1}), event and electricity (kw▪h ha^{-1}), respectively.

[c] Electricity energy is calculated according to the power and working hours. The power of thresher is 15 kilowatt in this experiment.

Table 3

Seasonal CH$_4$ and N$_2$O emissions, and yields during rice and wheat cropping seasons in the three cycles of 2011–2014.

	Rice season			Wheat season		
Treatment	CH$_4$ (kg C ha^{-1})	N$_2$O (kg N ha^{-1})	Yield (t ha^{-1})	CH$_4$ (kg C ha^{-1})	N$_2$O (kg N ha^{-1})	Yield (t ha^{-1})
2011						
NN	153±10.8c	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 4

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 5

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[c]							
	N	P	K	Si	Zn	Herbicide	Insecticide	Fungicide	Irrigation (cm)[b]			Tillage and raking	Crop planting	Farm manure	Crop harvest	Threshing
									2011	2012	2013	(kg diesel ha^{-1})	(event)	(kg ha^{-1})	(kg diesel ha^{-1})	(kw▪h ha^{-1})
NN[d]	0	180	300	0	0	2	18	4	75	80	80	37	2	0	11	135
FP	480	180	300	0	0	2	20	4.4	75	80	80	37	2	0	11	147
ISSM-N1	360	180	300	0	0	2	20	4.4	50	65	55	37	2	0	11	139
ISSM-N2	432	180	300	0	0	2	20	4.4	50	65	55	37	2	0	11	177
ISSM-N3	480	216	360	225	15	2	27	6	50	65	55	37	2	2250	11	177
ISSM-N4	600	252	450	225	15	2	41	9	50	65	55	37	2	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	338	53	1419	1514	1514	127	23	0	37	36
FP	2288	132	165	0	0	46	375	59	1419	1514	1514	127	23	0	37	39
ISSM-N1	1716	132	165	0	0	46	375	59	946	1230	1041	127	23	0	37	37
ISSM-N2	2059	132	165	0	0	46	375	59	946	1230	1041	127	23	0	37	47
ISSM-N3	2288	158	198	58	6	46	506	79	946	1230	1041	127	23	62	37	47
ISSM-N4	2860	185	248	58	6	46	768	129	946	1230	1041	127	23	62	37	73

[a] The carbon emission coefficients were 1.3,0.2,0.15, 6.3, 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 C cost (kg C eq. kg^{-1} diesel) for tillage, raking and harvesting, 3.2 C cost (kg C eq. event^{-1}) for crop planting, 0.0075 C cost (kg C eq. kg^{-1}) for farm manure application and 0.0725 C cost (kg C eq. (kw▪h)$^{-1}$) for threshing, as referred to in Lal (2004).

[d] See Table 1 for treatment codes.

Table 6

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. $ha^{-1}yr^{-1}$) = $28 \times CH_4 + 265 \times N_2O + Ei + Eo - 44/12 \times SOCSR$, 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 Daily mean air temperature and precipitation during the rice-wheat rotation in 2011–2014 in Changshu, China.

Fig 2 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 3 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 4 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.

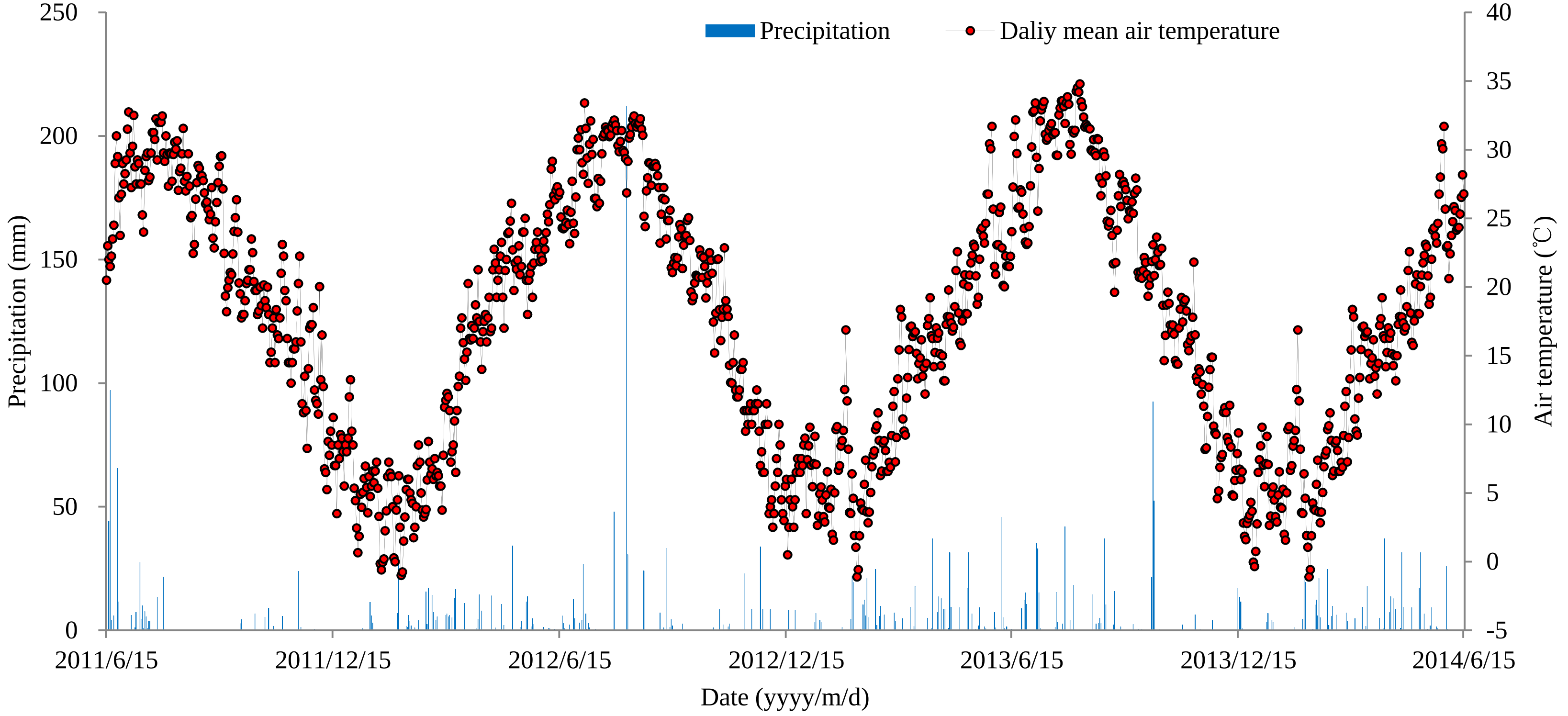
Precipitation
Daliy mean air temperature
Precipitation (mm)
250
200
150
100
50
0
Air temperature (℃)
40
35
30
25
20
15
10
5
0
-5
2011/6/15
2011/12/15
2012/6/15
2012/12/15
2013/6/15
2013/12/15
2014/6/15
Date (yyyy/m/d)

Fig.1

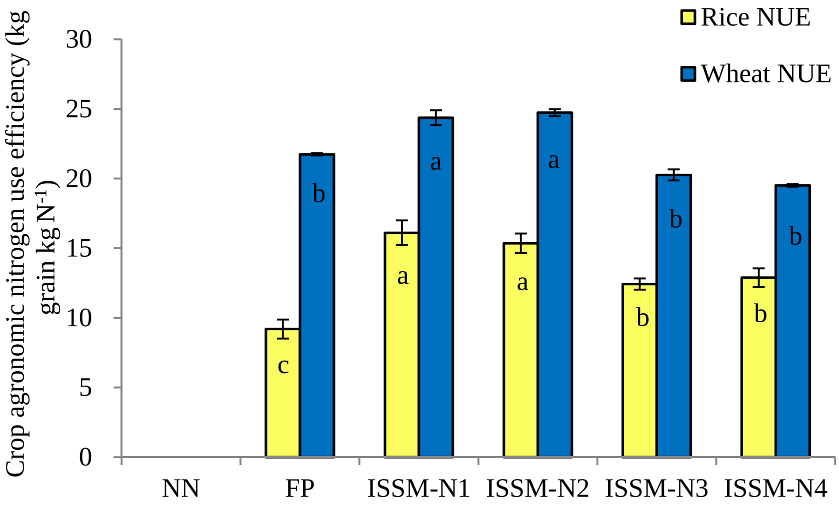
Rice NUE
Wheat NUE
Crop agronomic nitrogen use efficiency (kg grain kg N^{-1})
30
25
20
15
10
5
0
NN
FP
ISSM-N1
ISSM-N2
ISSM-N3
ISSM-N4
c
b
a
a
a
a
b
b
b
b

Fig. 2

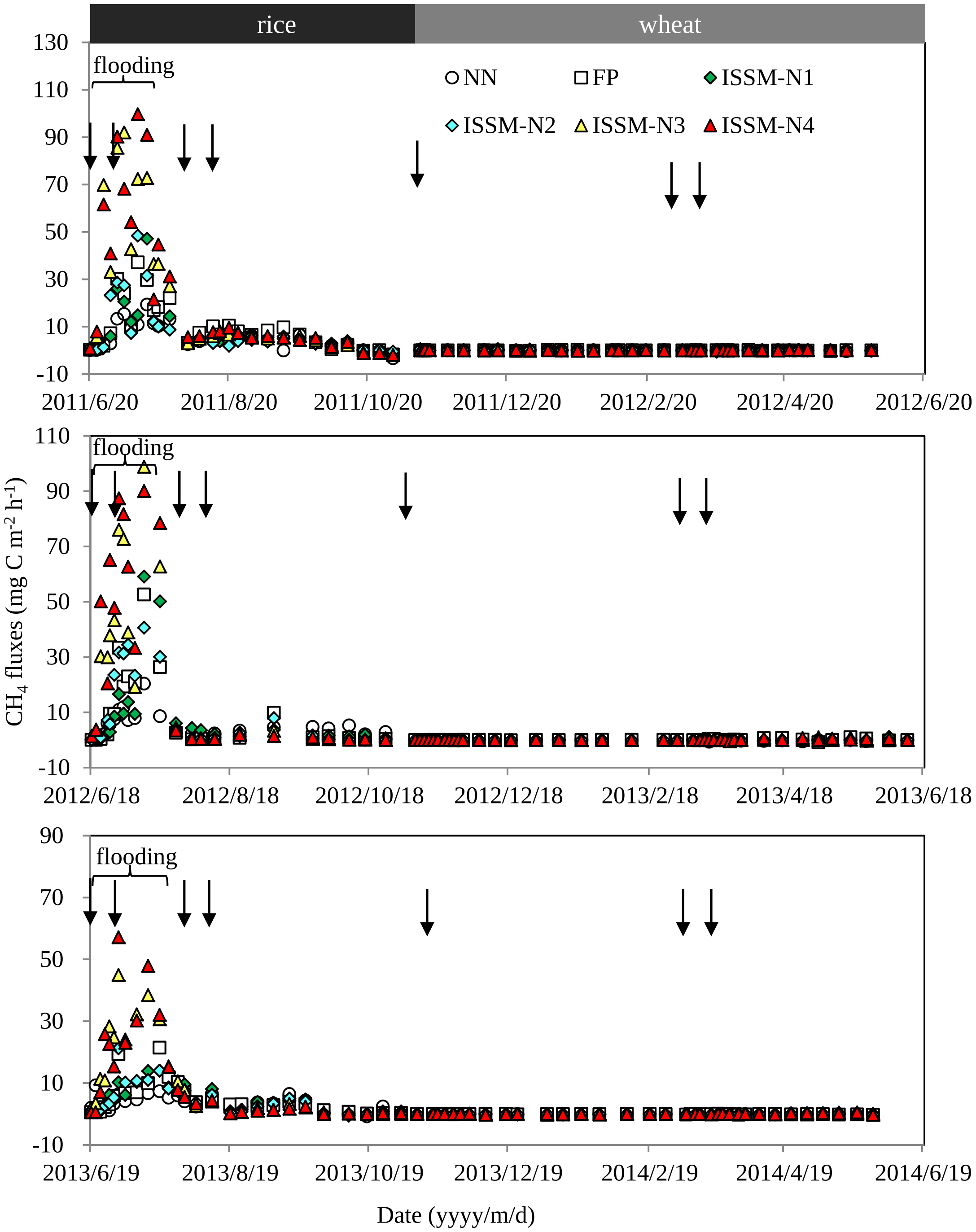
rice
wheat
flooding
○ NN
□ FP
◆ ISSM-N1
◇ ISSM-N2
△ ISSM-N3
▲ ISSM-N4
130
110
90
70
50
30
10
-10
2011/6/20
2011/8/20
2011/10/20
2011/12/20
2012/2/20
2012/4/20
2012/6/20
flooding
110
90
70
50
30
10
-10
2012/6/18
2012/8/18
2012/10/18
2012/12/18
2013/2/18
2013/4/18
2013/6/18
flooding
90
70
50
30
10
-10
2013/6/19
2013/8/19
2013/10/19
2013/12/19
2014/2/19
2014/4/19
2014/6/19
CH$_4$ fluxes (mg C m^{-2} h^{-1})
Date (yyyy/m/d)

Fig. 3

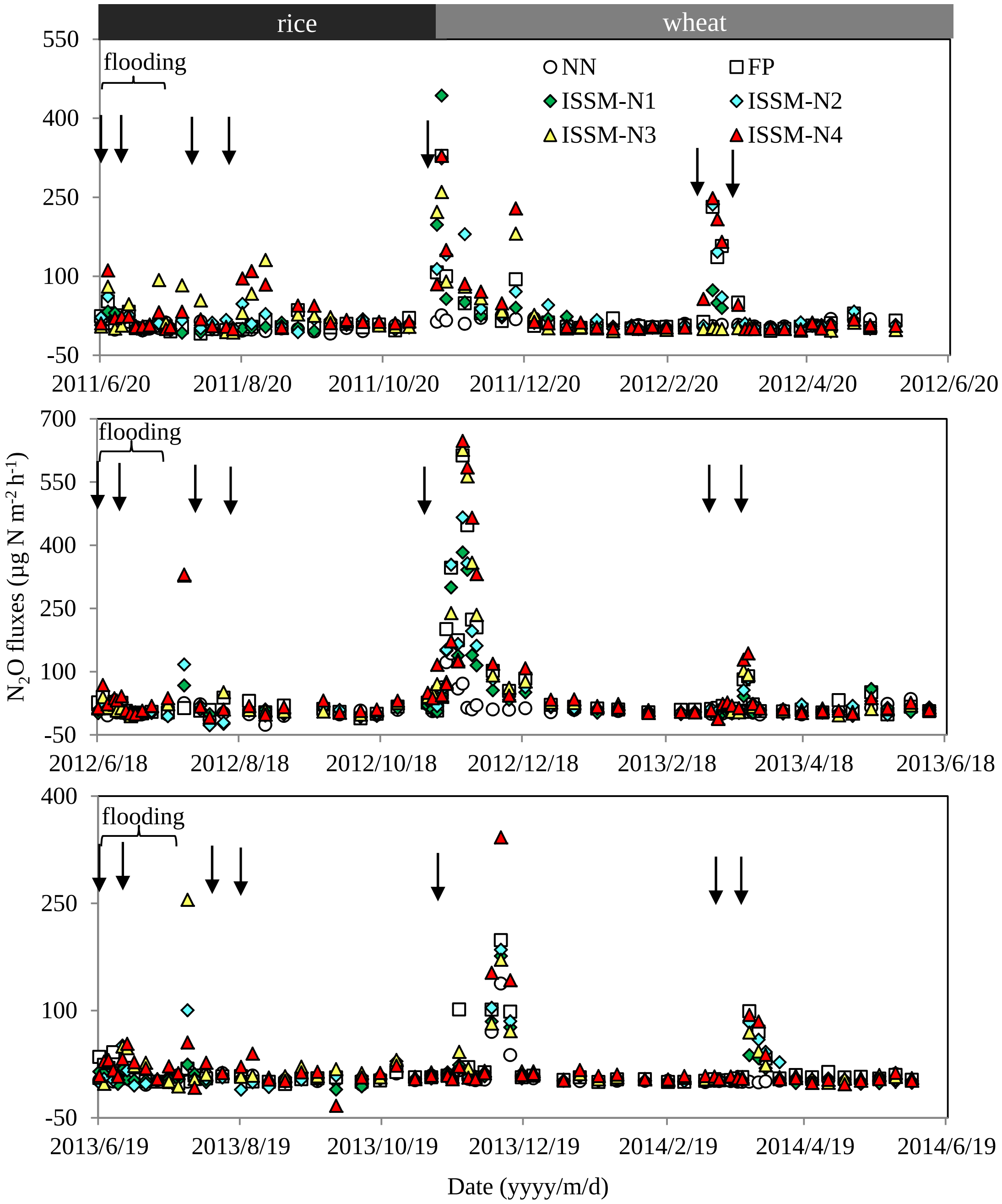
rice
wheat
550
400
250
100
-50
flooding
○ NN
□ FP
◆ ISSM-N1
◇ ISSM-N2
△ ISSM-N3
▲ ISSM-N4
2011/6/20
2011/8/20
2011/10/20
2011/12/20
2012/2/20
2012/4/20
2012/6/20
700
550
400
250
100
-50
flooding
2012/6/18
2012/8/18
2012/10/18
2012/12/18
2013/2/18
2013/4/18
2013/6/18
400
250
100
-50
flooding
2013/6/19
2013/8/19
2013/10/19
2013/12/19
2014/2/19
2014/4/19
2014/6/19
N_2O fluxes (μg N m^{-2} h^{-1})
Date (yyyy/m/d)

Fig. 4