1 Net global warming potential and greenhouse gas intensity from the double rice
2 system with integrated soil-crop system management: A three-year field study
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13 **Abstract**

14 The impact of integrated soil-crop system management (ISSM) on net global warming
15 potential (GWP) and greenhouse gas intensity (GHGI) is poorly documented though crucial for
16 food security and nitrogen fertilizer use efficiency (NUE). Using local farming practices (FP)
17 and no nitrogen (NN) as the controls, three ISSM practices at different N rates were established
18 in 2009 in a double rice system in Hunan Province, China. Soil organic carbon sequestration
19 rates (SOCSR) were estimated by changes in SOC between 2009 and 2014. Field measurements
20 of methane (CH₄) and nitrous oxide (N₂O) fluxes, grain yield and NUE of early and late rice
21 were measured from April 2011 through April 2014. The net GWP of the annual CH₄ and N₂O
22 emissions and SOCSR and the GHGI over the three years in the FP was 15.35 t CO₂ eq ha⁻¹
23 year⁻¹ and 1.00 kg CO₂ eq kg⁻¹ grain. The ISSM (N2) treatment increased annual rice yield by
24 23%, NUE by 76% and SOCSR by 129%, with similar sizes of net GWP and GHGI under the

same N input relative to the FP. A second ISSM (N1) treatment in which annual fertilizer N input was decreased by 20% also showed the potential to lower net GWP and GHGI and increase SOCSR and significantly increased annual rice grain yield by 8.6% and NUE by 59%. The third ISSM (N3) in which fertilizer N input was 20% greater than in FP, significantly increased annual rice yield by 26%, NUE by 57% and SOCSR by 98% but notably increased the CH₄ and N₂O emissions. Our findings show that the ISSM strategies are promising and feasible in sustainable rice agriculture for food security and GHGs mitigation.

Keywords:

Methane (CH₄), Nitrous oxide (N₂O), Soil carbon sequestration, Global warming potential (GWP), Greenhouse gas intensity (GHGI), Integrated soil-crop system management (ISSM)

1. Introduction

An increase in global food production by 100% is the most appropriate way to sustain the increase in human population and consumption of animal protein (Tilman et al., 2011). Rice is the staple food for nearly 50% of the world's people, mainly in Asia. Harvested rice fields in China, averaging 30 M ha from 2010 to 2013 accounted for 18.7% of the world total (FAOSTAT). According to Cheng et al. (2007), rice production in China should increase 14% by 2030 (relative to 2010) to meet the rice requirement of the growing population. Increasing the use of nitrogen (N) fertilizer in rice production is essential, due partly to the limited cultivated area of rice paddies (Galloway et al., 2008). Since the early 1980s, Chinese agriculture has intensified greatly within a limited land area due to large inputs of chemical fertilizer (Ju et al., 2009; Miao et al., 2010). However, large input of N fertilizer and low nitrogen use efficiency (NUE) are causing serious environmental problems (Ju et al., 2009; Zhang et al., 2013), including soil and water pollution, loss of biodiversity and greenhouse gases (GHG) emissions (Chen et al., 2014).

Thus, the integrated soil-crop system management (ISSM) has been advocated and developed in China to increase crop production and reduce environmental risks (Chen et al., 2011; Zhang et al., 2011). The key points of the ISSM are (i) to take all soil quality improvement measures into consideration, (ii) to integrate the utilization of various nutrient sources and match nutrient supply to crop requirements, and (iii) to integrate soil and nutrient management with high-yielding cultivation systems (Zhang et al., 2011). The ISSM has been demonstrated to effectively increase yield of rice (Ma et al., 2013) and maize (Chen et al., 2011). Though the ISSM can potentially reduce GHG emissions, as indicated by an empirical model simulation

(Cheng et al., 2014), few field measurements have been conducted to investigate the effect of ISSM on GHG emissions (Ma et al., 2013). To our knowledge, no reports of ISSM practices on GHG emissions for double rice cropping systems have been published.

Global warming undoubtedly results from GHG emissions. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are three GHGs of major concern that are emitted from agricultural soils and the most potent long-lived GHG that contribute to global warming (Robertson et al., 2000). Globally, agriculture accounted for 50% and 60% of total anthropogenic CH_4 and N_2O emissions, respectively, in 2005. GHG emissions from agriculture contribute substantially to atmospheric pollution in China and elsewhere (Cheng et al., 2014). Rice fields have been identified as a major source of increasing atmospheric CH_4 , accounting for approximately 15–20% of global CH_4 emissions from all sources. N_2O is also produced from rice fields because of midseason drainage and moist irrigation (Wang et al., 2013). The total CH_4 emissions from Chinese rice paddies are estimated to be 7.41 Tg CH_4 year⁻¹, accounting for 29.9% of the world total (25.55 Tg CH_4 year⁻¹) (Yan et al., 2009). The direct N_2O emissions during the rice growing season, measured at a rate of 32.3 Gg N_2O -N, account for 8–11% of the total N_2O emissions from Chinese croplands (Zou et al., 2009).

The balance among the net exchange of CO_2 , N_2O and CH_4 constitutes the net GWP (Mosier et al., 2006). Paddy fields have a high capacity for soil carbon sequestration (Pan et al., 2004). The soil carbon sequestration, i.e., net exchanges of CO_2 , can be measured by soil organic carbon changes (Pan et al., 2004; Shang et al., 2011), and the CH_4 and N_2O flux can be measured by the opaque chamber method. Agricultural practices can be related to GWP by estimating the net GWP per ton of crop yield, referred to as the greenhouse gas intensity (GHGI)

(Wang et al., 2013). How to reduce net GWP or GHGI while realizing high yields in intensive cropping systems has become a major scientific question worldwide. To feed the growing population while protecting the environment, future sustainable agriculture should explore systems with low GWP and GHGI at high crop productivity (Ma et al., 2013). Some studies have shown promising results with high yields and small GHG emissions achieved simultaneously in intensive agricultural systems. Examples include irrigated cropping systems in northeastern Colorado with minimum tillage and proper fertilization (Mosier et al., 2006) and rice-wheat rotations in southeast China with improved N management under integrated soil-crop system management (Ma et al., 2013).

However, the overall impacts of different ISSM practices on the GHG emissions and GHGI are poorly understood in Chinese double rice system. Double rice system accounted for 56% of the harvested rice fields in China (Frolking et al., 2002). As a representative region planting double rice system, Hunan Province in central China produces more rice (National Bureau of Statistics of China, 2013) and emits more CH₄ than any other province in China. Here, a field experiment initiated in 2009 was employed to explore how ISSM practices affect the GHG emissions, net GWP, GHGI, NUE, SOCR and rice yield from the double rice system in Hunan Province, China.

2. Materials and Methods

2.1. Experimental site

A field experiment was initiated in 2009 in Liuyang County (28°09'N, 113°37'E) of Hunan Province, China. This region is characterized by a subtropical humid monsoon climate, with an annual average air temperature of 17.2 °C and precipitation of 1361 mm. The daily mean air

temperatures and precipitation during the experimental time were collected from a nearby weather station shown in Fig. 1. The paddy soil is classified as stagnic anthrosols developed from Quaternary red clay. Soil samples at a depth of 0–20 were collected in April 2009 (when the field experiment was initiated) for analysis of the physical-chemical characteristics. The soil at the experimental field has a bulk density of 1.14 g cm^{-3} , pH 6.3, organic C content of 18.4 g kg^{-1} , total N content of 1.09 g kg^{-1} , available P content of 7.81 mg kg^{-1} and available K content of 98.55 mg kg^{-1} .

2.2. Field plot treatment and management

Using local conventional farming practices (FP) as the control, three ISSM practices at different N application rates, designed to improve rice yield and agronomic NUE were established since 2009 and designated as ISSM-N1, ISSM-N2 and ISSM-N3. A zero-N control (NN) was included to calculate the agronomic NUE and N_2O emission factors. In total, five field experimental treatments with four replicated field plots ($5 \text{ m} \times 8 \text{ m}$) were established with a randomized block design. Blocks of the different treatments were completely separated by levees made with plastic covering. The ISSM strategies included an N fertilizer splitting application, a balanced fertilizer application, additional phosphorus and potassium and transplanting density as the main techniques to improve rice yield and NUE at different N levels of ISSM-N1, ISSM-N2 and ISSM-N3 with different yield targets. Details on each of the management practices of the five treatments are provided in Table 1. Urea, calcium superphosphate and potassium chloride fertilizer were applied to the field to meet the NPK requirement, and the dosages are shown in Table 1.

One midseason drainage (approximately one week) and final drainage before harvest were done during both the early and late rice seasons. Fertilizer P, Si, Zn and rapeseed cake manure were applied only as basal fertilizers for both the early and late rice. K was applied with two splits of 6:4 for the ISSM-N2 and ISSM-N3 plots and only as basal fertilizer for the other treatments. All basal fertilizers were broadcast at the time of rice transplanting, and additional top dressings were also broadcast.

2.3 Chamber measurements of CH₄ and N₂O fluxes

The CH₄ and N₂O fluxes were simultaneously measured over the three annual cycles (a cycle means a rice-rice-fallow system) from April 2011 through April 2014, using a static opaque chamber method in four replicate plots. Samples were generally collected once every 5 days during the rice-growing seasons and about 10-day interval during the fallow seasons. The chamber covered a field area 0.36m² and was placed on a fixed PVC frame on each plot. The chamber was 0.6 or 1.0 m high, having been adapted for crop growth and plant height. For each flux measurement, four gas samples were collected from 9:00 to 11:00 am by a 50-ml syringe at 0, 10, 20, and 30 min after the chambers were placed on the fixed frames. Sample sets were rejected unless they yielded a linear regression value of r^2 greater than 0.90. The average fluxes and standard deviations (SDs) of CH₄ and N₂O were calculated from four replicates. The seasonal amounts of CH₄ and N₂O were sequentially linearly determined from the emissions between every two adjacent intervals of the measurements.

The gas samples were analyzed for CH₄ and N₂O concentrations using a gas chromatograph (Agilent 7890A Shanghai, China), equipped with an electron capture detector (ECD) for N₂O

analysis and a hydrogen flame ionization detector (FID) for CH₄ analysis, after CO₂ was reduced by hydrogen to CH₄ in a nickel catalytic converter at 375°C. N₂O was separated by two stainless steel columns packed with 80–100 mesh Porapak Q. One column was 2 m long and had an inner diameter of 2 mm, whereas the other column was 3 m long and had an inner diameter of 2 mm. The carrier gas was argon-methane (5%) at a flow rate of 40 ml min⁻¹. The temperatures of the columns and the ECD detector were maintained at 40°C and 300°C, respectively. The oven and FID were operated at 50°C and 300°C, respectively.

2.4. Measurements of SOC change

Soil samples were collected when the field experiment was initiated in April 2009 and after five annual cycles of rice-rice-fallow in April 2014. A composite sample for each plot was obtained by randomly taking five or six soil cores at a depth of 20 cm (3 cm diameter) and mixing them thoroughly. Any visible roots, stones, or organic residues were removed manually after air-drying at room temperature. The samples were ground to pass a 2-mm sieve, and a portion was subsequently ground in a porcelain mortar to pass a 0.15 mm sieve for the SOC measurement. The total SOC was analyzed by wet digestion with H₂SO₄-K₂Cr₂O₇.

The soil organic carbon sequestration rate (SOCSR) was calculated as follows:

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

In Eq. (1), SOC_t and SOC₀ are the SOC contents measured before early rice transplanting in 2014 and 2009, respectively; γ and $\delta_{2\text{ mm}}$ are the average bulk density (in grams per cubic centimeters) and the gravel content (>2 mm) of the topsoil (0–20 cm),

respectively. The sand fractions of the paddy soils in China were mostly negligible. The number 20 represents the thickness of the topsoil.

2.5. Measurements for net GWP and GHGI

The net GWP of the cropland ecosystem equals the total CO₂ emission equivalents minus the SOC change in the cropland ecosystem; thus, the net GWP and GHGI were calculated as follows:

$$\text{net GWP} = 34 \times \text{CH}_4 \text{ (kg CH}_4 \text{ ha}^{-1}) + 298 \times \text{N}_2\text{O (kg N}_2\text{O ha}^{-1}) - 44/12 \times \text{SOC change (kg CO}_2 \text{ eq ha}^{-1}) \quad (2)$$

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

In Eq. (2), the numbers 34 and 298 represent the IPCC factors for the conversion of CH₄ and N₂O to CO₂ equivalent, respectively (IPCC 2013).

2.6. Statistical analysis

The differences in cumulative CH₄ and N₂O emissions and rice yield among the treatments were examined using Tukey's multiple range tests. The two-way analysis of variance (ANOVA) and linear relationships were determined using JMP 9.0. The F-test was applied to determine if there were significant differences among the practices, years or regression relationships at $P < 0.05$. The statistical analyses were carried out using JMP version 9.0 (SAS Institute Inc., Cary, USA). The average fluxes of CH₄ and N₂O from the four replicates are plotted without standard deviation bars for clarity. We define an emission peak as a peak that was significantly higher than the previous and following fluxes.

3. Results

3.1. Grain yield and agronomic nitrogen use efficiency

On average over the three cycles, the annual rice yield of the FP treatment, 15.46 t ha⁻¹yr⁻¹ was significantly lower than that from the ISSM strategies of ISSM-N1, N2 and N3 (Table 2). Both early and late rice yield significantly varied with the cycles and treatments (Table 3). With the highest N input, the ISSM-N3 treatment increased yield by 39% and 16% compared to the FP treatment for early and late rice, respectively. Compared with ISSM-N2, the additional N application (30 kg N ha⁻¹ for each rice season) in ISSM-N3 had no significant effect on late rice yield or annual rice production (Table 2, 3).

The agronomic NUE (kg grain yield increase per kg N applied) was calculated as the difference in grain yield between the treatments that received N application and the NN treatment, divided by the N fertilizer rate (Fig. 2). Compared with the FP plot (13.9 and 15.3 kg grain kg⁻¹ for early rice and late rice, respectively), the agronomic NUE across the three cycles significantly increased by 83%, 107% and 87% for ISSM-N1, ISSM-N2 and ISSM-N3, respectively, for early rice, and by 40%, 51% and 33%, respectively, for late rice. Compared with ISSM-N2, the additional N application in ISSM-N3 notably decreased the agronomic NUE by 9.8% and 12.0% for early rice and late rice, respectively (Fig. 2). Thus the ISSM-N2 treatment achieved the highest agronomic NUE among the treatments for both early rice and late rice (Fig. 2).

3.2. CH₄ emission

All treatments showed similar temporal patterns in the CH₄ fluxes from the double rice cropping system from April 2011 to April 2014 (Fig. 3). For the early rice growing seasons, CH₄ fluxes gradually increased in the early stage and stepped down in the late stage (Fig. 3). The rapeseed cake applications in the ISSM-N2 and ISSM-N3 plots induced one or two higher peaks while a slight peak was observed during the midseason in FP and ISSM-N1 with inorganic fertilizer application. The seasonal total of the CH₄ emissions significantly varied with the cycles and treatments during the early rice growing season (Table 3). No significant difference was found between the FP and ISSM-N1 treatments. Additional rapeseed cake manure application in early rice season for ISSM-N2 and ISSM-N3 significantly increased CH₄ emissions over the three-year cycles, averaging 38.2% and 40.7% greater for the ISSM-N2 and ISSM-N3 plots, respectively, as compared with the FP (Table 2).

The seasonal dynamic variations of the CH₄ flux rates from the late rice seasons are characterized by similar trends and emissions are concentrated around the early stage of late rice growth, but variations in the amplitudes of the fluxes among treatments were observed (Fig. 3). The CH₄ fluxes increased after transplantation and decreased dramatically during the midseason drainage. After reflooding, the CH₄ fluxes increased again to a low emission peak and then decreased gradually to a negligible amount toward harvest. It is worth noting that a large peak of CH₄ was observed approximately 1–2 weeks after late rice transplanting in ISSM-N2 and ISSM-N3 (Fig. 3). On average, substantial CH₄ emissions over the three cycles in the late rice growing season were observed to be 10.2–26.4% greater than those in the early rice season (Table 2). The total CH₄ emission in the late rice growing season depended greatly

on the cycles, while it did not significantly vary with the treatments and their interaction (Table 3).

In the fallow season, all treatments acted as small net sources of CH₄ to the atmosphere (Table 4). The CH₄ emissions during the fallow season varied significantly with the treatments and cycles but were not significantly affected by their interaction (Table 3). On average, the annual CH₄ emissions over the three cycles ranged from 380 kg CH₄ ha⁻¹ for NN to 645 kg CH₄ ha⁻¹ for ISSM-N3. Compared with FP, the annual CH₄ emissions were significantly increased by 31% and 34% in the ISSM-N2 and ISSM-N3 plots, respectively (Table 5). No significant differences were found between the FP and ISSM-N1 plots or between ISSM-N2 and ISSM-N3 (Table 5).

3.3. N₂O emission

As shown in Fig. 4, all treatments had a similar seasonal pattern of N₂O flux during the double rice growing seasons. The rice paddies served as small net sources of N₂O except for several pronounced fluxes due to fertilizer application and drainage (Fig. 4). Basic fertilizer application together with the first N topdressing produced a peak flux of N₂O in all the plots, whereas under flooded conditions, the N₂O emissions were negligible. Cumulative N₂O emissions ranged from 0.10 kg N ha⁻¹ to 0.24 kg N ha⁻¹ over the early rice growing season. The cumulative N₂O emissions were significantly affected by the treatments and cycles during the early rice season (Table 3). Relative to the early rice growing season, N₂O emissions were 43–168% greater in the late rice season. The average N₂O flux was 5.8–23.7 µg N m⁻²h⁻¹ over

the three late rice growing seasons amounting to 0.14–0.60 kg N₂O–N ha⁻¹ for the different treatments during the late rice growing season.

The N₂O flux peak was usually observed at the beginning of the fallow season after the harvest of late rice though no fertilizer was applied in the fallow season (Fig. 4, Table 4). The total N₂O emissions averaged 0.09–0.19 kg N ha⁻¹ over the three fallow seasons (Table 4). Relative to NN, the ISSM-N2 and ISSM-N3 plots significantly increased N₂O emissions (Table 4). Overall, the annual total N₂O emissions ranged from 0.34 kg N ha⁻¹ for NN to 1.03 kg N ha⁻¹ for ISSM-N3 averaged over the three annual rice-rice-fallow rotation cycles (Table 5). ISSM-N1 decreased the N₂O by 22%, while ISSM-2 and ISSM-N3 increased it by 25% and 39%, respectively, compared to FP (Table 5).

3.4 SOC change

The soil organic C content was 18.4 g kg⁻¹ when this field experiment was established in 2009. After five years of consecutive ISSM field managements, the soil organic C contents reached 18.7 g kg⁻¹, 19.2 g kg⁻¹, 19.6 g kg⁻¹, 20.3 g kg⁻¹ and 20.0 g kg⁻¹ in NN, FP, ISSM-N1, ISSM-N2 and ISSM-N3, respectively. Relative to NN, the SOC content was 8.6% and 7.2% greater for the ISSM-N2 and ISSM-N3 plots, respectively. The SOC increase rate ranged from 0.06 g C kg⁻¹ yr⁻¹ for NN to 0.38 g C kg⁻¹ yr⁻¹ for the ISSM-N2 plot over the period 2009–2014. We estimated topsoil SOC density based on topsoil SOC content and bulk density, and the results indicated that the SOC density was 42.6–46.3 t C ha⁻¹ in 2014, 1.6–10.3% greater than in 2009. The annual topsoil SOCSR was estimated to be 0.13 t C ha⁻¹ yr⁻¹ for NN and

0.38–0.86 t C ha⁻¹yr⁻¹ for the other treatments that received N fertilizers. The ISSM-N2 treatment significantly enhanced the SOCSR compared to the FP plot (Table 5).

3.5 annual net GWP and GHGI

No significant difference in annual net GWP was observed between FP and ISSM-N1 and ISSM-N2 strategies (Table 5). Compared with FP, ISSM-N1 slightly decreased the net annual GWP by 0.6%, while ISSM-N2 increased the net annual GWP by 22%. But the ISSM-N3 significantly increased the net GPW by 28% as relative to the FP. Similarly, no significant difference in annual GHGI was found between FP and the ISSM strategies, though the annual GHGI slightly decreased by 9.6% and 0.8% for ISSM-N1 and ISSM-N2, and increased by 0.8% for ISSM-N3, relative to the FP plot. It's worth noting that ISSM-N3 produced higher net GWP than ISSM-N1 and FP (Table 5). Thus, relative to FP, the ISSM-N1 and ISSM-N2 strategies produced similar sizes of annual net GWP and GHGI, with some potential to decrease them.

4. Discussion

4.1. Carbon sequestration as affected by ISSM strategies in double rice system

The topsoil (0–20 cm) SOC density was estimated to be 42.6–46.3 t C ha⁻¹ in April 2014, which is in good agreement with the values of 36.4–48.2 t C ha⁻¹ estimated by Shang et al. (2011) in the same region. This is also comparable to the values estimated by Pan et al. (2004), who reported that Chinese paddies have an area-weighted mean topsoil SOC density of 44 t C ha⁻¹. The SOCSR ranged from 0.13 t C ha⁻¹ yr⁻¹ for NN and 0.38–0.86 t C ha⁻¹ yr⁻¹ for the treatments receiving N fertilizers; these values fall within the SOCSR of 0.13–2.20 t C ha⁻¹

yr⁻¹ estimated by Pan et al. (2004) for paddy soils in China. Compared to the NN plot, integrated soil-crop system management significantly increased the SOCSR, and ISSM-N2 significantly enhanced the SOCSR (0.86 t C ha⁻¹ yr⁻¹) relative to the FP (0.38 t C ha⁻¹ yr⁻¹) plot. The difference was mainly due to the enhanced incorporation of rapeseed cake and crop residue associated with higher crop productivity (Ma et al., 2013). In this study, C inputs, including rapeseed cake application and C fixation in the rice roots and rhizodeposition were positively correlated with grain yield, which was supported by previous reports (Bolinder et al., 2007). Improved agronomic practices for increasing grain yields will generate higher inputs of carbon residues and thus lead to increased soil carbon storage.

4.2. Greenhouse gas emission as affected by ISSM strategies in double rice system

Double rice cropping systems emit more CH₄ than single rice cultivation due to the long period of flooding. Unfortunately, there are not many studies on the CH₄ emissions from double rice systems in South China (Shang et al., 2011; Yang et al., 2010). In this study, the annual CH₄ emissions, on average, varied between 380 and 645 kg CH₄ ha⁻¹yr⁻¹ over the three years (Table 5), which generally fall within the range (4.1 to 1015.6 kg CH₄ ha⁻¹) of estimates from 94 Chinese rice field observations (Huang et al., 2004). The CH₄ emissions were significantly affected by the cycles, mainly due to the different precipitation and temperature. In the fallow season, all treatments acted as small net sources of CH₄ to the atmosphere (Table 4) due to the relatively high precipitation and the residual effects.

Though ISSM-N1 had no effect on CH₄ emissions compared with FP, ISSM-N2 and ISSM-N3 significantly increased the annual CH₄ (Table 5). Significant positive linear

relationships between CH₄ emissions and the rice aboveground biomass were found for both early and late rice in this study (Fig. 5). Several reasons may be given to explain the greater CH₄ emissions in the ISSM-N2 and ISSM-N3 plots. First, the decomposition of organic rapeseed cake manure serves as an additional source of methanogenic substrates, particularly in early rice development (Zou et al., 2005). Second, ISSM-N2 and ISSM-N3 dramatically increased the rice biomass, and the growth of rice crop plants increases CH₄ emissions by providing C sources for methanogenic bacteria. Third, the rice plants served as a pathway for CH₄ emissions, and thus, the higher biomass of rice increased the CH₄ emissions by favoring CH₄ transport to the atmosphere (Yan et al., 2005).

N₂O is produced naturally in the soil through nitrification and denitrification (Robertson et al., 2000). Negligible N₂O was observed when the rice field was flooded (Fig. 4), which was consistent with previous studies (Akiyama et al., 2005). The occurrences of large amounts of N₂O emissions generally occurred with a shift in the soil aeration status (transient period), such as initial flooding and mid-season drainage (Fig. 4), which was identical to previous reports (Wang et al., 2013; Xiong et al., 2007). For both the early and late rice growing seasons, the highest N₂O was observed following basal fertilizer or N top-dressing (Fig. 4), which was proved by previous studies (Xiong et al., 2002; Yao et al., 2010). The application of mineral N to soil increases substrate availability for nitrification and denitrification, thus stimulating N₂O emissions. The relatively high N₂O peak observed at the first two weeks of the fallow season (Table 4) agreed well with our previous study (Xiong et al., 2002) since changes from flooded rice to winter season may enhance N₂O release after the soil was drained (Xiong et al., 2007).

The N₂O emission factor was estimated to be 0.05–0.08% and 0.10–0.25% during the early and late rice growing seasons, respectively, comparable to previous estimates in flooded rice paddies (Akiyama et al., 2005). Over the entire annual cycle, the emissions factors were, on average, estimated to be 0.13%, 0.09%, 0.19% and 0.18% for FP, ISSM-N1, ISSM-N2 and ISSM-N3, respectively. The application of rapeseed cake tends to increase N₂O emission factors, and greater N₂O emissions from organic relative to inorganic fertilizer treatments have also been reported (Kasier and Ruser, 2000; Wang et al., 2013). This was interpreted as a positive correlation between soil organic C content and the rate of nitrification and denitrification (Li et al., 2005). A regression analysis showed that the seasonal N₂O emissions were significantly exponentially and linearly correlated with the nitrogen application rate (Fig. 6). Previous studies have demonstrated that N₂O emissions increase with the amount of nitrogen fertilizer application in rice paddies (Xiong et al., 2002; Zou et al., 2005). N₂O was produced in the soil via the biogeochemical process of nitrification and denitrification, and thus, the more available N provided for the soil microbes through nitrogen fertilizer application will lead to higher N₂O (Wang et al., 2011).

4.3. Overall performance of integrated soil-crop system management (ISSM)

Strategies

The main objective of the ISSM strategies were to achieve high rice yield and agronomic N use efficiency while maintaining or decreasing greenhouse gases emission and GHGI. Compared with the FP plot, ISSM-N2 greatly increased rice yield (Table 5). Several reasons can be provided for the higher rice yields in ISSM-N2. First, balanced fertilization (Miao et al.,

2010) and the reduction of N during the early vegetative stage together with fixed-time adjustable-dose N management (Peng et al., 2006) can improve rice yields. Second, the addition of 5 kg Zn ha⁻¹ in ISSM-N2 would have contributed to better seedling establishment and vigor and thereby increased grain yield (Slaton et al., 2005). Additionally, the application of silicon to overcome both biotic and abiotic stress has been clearly investigated (Wang et al., 2005). Moreover, the NUE in the ISSM-N2 plots was greatly improved, which was mainly due to the higher rice yields. Compared with the FP plot, ISSM-N2 significantly increased the SOCSR, which offset the GWP induced by higher CH₄ emissions, and as a result, ISSM-N2 had no significant effect on the net GWP and the GHGI (Table 5). Similarly, Burney et al. (2010) showed that the net effect of higher yields has offset emissions by as much as 590 Gt CO₂ eq since 1961. Overall, ISSM-N2 is strongly recommended from our field measurements based on its overall performance of increased grain yields, NUE and SOCSR with similar size of net GWP and GHGI.

Compared with the FP plot, ISSM-N1 reduced N fertilizer by 30 kg ha⁻¹ for each rice season, significantly increased annual rice production by 8.6% (Table 5) and agronomic NUE by 83% and 40% for early rice and late rice season, respectively (Table 2, Fig. 2). Similarly, when the total N rate was reduced by 25%, the rice yield significantly increased by 8.2% in the Jiangsu Province (Ma et al., 2013). Peng et al. (2006) summarized that when using the modified farmers' fertilizer practice, a 30% reduction in the total N rate during the early vegetative stage did not reduce yield but slightly increased yield. The high input rate of fertilizer N and improper timing of N application (approximately 56% to 85% of the total N was applied in the first 10 days after transplanting) were two important factors that caused low

agronomic NUE of irrigated rice in China (Peng et al., 2006). Compared with the FP plot, the agronomic NUE was significantly increased by the ISSM-N1 treatments, primarily due to the reduction of N application at the early vegetative stage (Table 1), which increased N uptake during the flowering and maturity stage (Sui et al., 2013). Relative to the FP, ISSM-N1 had no significant effect on CH₄ and N₂O emissions and the SOC change and thus produced a comparable net GWP with significantly higher rice yield that further decreased the GHGI by 9.6%. All of these findings suggested that ISSM-N1 is an effective way to reduce N fertilizer for future sustainable rice agriculture in terms of grain yield, NUE, net GWP and GHGI in double rice system.

ISSM-N3 was set to exploit the rice yield with more N fertilizer by 30 kg N ha⁻¹ for each rice season. Compared with FP, the ISSM-N3 significantly increased the rice yield and agronomic NUE (Table 5, Fig. 2). Meanwhile, the ISSM-N3 notably increased the CH₄ and N₂O emissions relative to the FP, thus produced relative higher net GWP (Table 5). Moreover, compared with ISSM-N2, the rice yield was slightly increased by 4.0% and 1.5% (no significant difference) for the early and late rice season (Table 2), respectively, but the agronomic NUE was notably decreased by 9.8% and 12.0% for the early and late rice season, respectively, by the ISSM-N3. These results indicate that the N rate in ISSM-N2 (equal to FP) was enough to achieve satisfactory rice production in this region; more N application risk to decrease the agronomic NUE and emit more CH₄ and N₂O. Overall, the ISSM effectively improve rice yield and NUE with no significant effect on net GWP and GHGI in a double rice system, and these findings are consistent with the findings of Ma et al. (2013) in the rice-wheat

systems and Chen et al. (2011) and Zhang et al. (2011) on the major crop of maize in North China.

5. Conclusions

Our results show that the net GWP were mainly attributed to CH₄ emissions in the double rice system. ISSM-N2 is the most favorable management package for realizing maximum agronomic NUE and relatively high rice yield and SOCSR, together with some potential to reduce GHGI by integrated soil-crop management. Compared with FP, ISSM-N1 is also recommended since it reduced N input while significantly increasing rice yields and NUE with comparable net GWP, thus decreasing GHGI by 9.6%. However, the ISSM-N3 strategy requires further research because it notably increased the CH₄ and N₂O emissions and consumed more N though significantly increasing rice yield and NUE. Overall, the ISSM strategies are promising and feasible in rice agriculture, having the potential to decrease GHGI and significantly improve rice production and NUE in double rice system.

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531 **Figure legend**

532 **Fig. 1.** Daily mean air temperature (°C) and precipitation (mm) during three annual cycles from
533 April 2011 to April 2014 in the experimental field.

534 **Fig. 2.** Average rice grain yield and agronomic nitrogen use (NUE) for (a) early rice crop and (b)
535 late rice crop in three annual cycles of double rice systems. The different letters indicate
536 significant difference at $p < 0.05$ by Tukey's multiple range tests.

537 **Fig. 3.** Seasonal variation of CH₄ fluxes in three annual cycles of double rice systems from April
538 2011 to April 2014

539 **Fig. 4.** Seasonal variation of N₂O fluxes in three annual cycles of double rice systems from April
540 2011 to April 2014

541 **Fig. 5.** Correlation between seasonal CH₄ emissions and rice aboveground biomass during the
542 early and late rice seasons in 2011–2013

543 **Fig. 6.** Correlation between the N₂O emissions and the total N rate during the three cycles from
544 April 2011 to April 2014

545 Table 1. Integrated soil-crop system management (ISSM) practices established for early and late rice during three annual cycles from April 2011
546 to April 2014

Treatment	NN(zero-N)	FP(farmer's practices)	ISSM-N1 (N rate reduced by 30kg ha ⁻¹)	ISSM-N2 (N rate at FP rate)	ISSM-N3 (N rate increased by 30kg ha ⁻¹)
Early rice					
Total fertilizer (N:P ₂ O ₅ :K ₂ O:ZnSO ₄ :Na ₂ SiO ₃ ,kg ha ⁻¹)	0:45:90:0:0	150:30:60:0:0	120:45:90:5:0	150 ^a :50:100:5:50	180 ^a :50:100:5:50
N split(B:MT:PI:FI ^b)		8:2:0:0	5:2:3:0	5:2:3:0	5:2:2:1
K split(B:MT:PI:FI)	10:0:0:0	10:0:0:0	10:0:0:0	6:0:4:0	6:0:4:0
Water regime	F-M-D-M	F-M-D-M	F-M-D-M	F-M-D-M	F-M-D-M
Planting density (cm)	16.7×20	20×20	16.7×20	13.3×23.3	13.3×(16.7+33.7)
Late rice					
Total fertilizer (N:P ₂ O ₅ :K ₂ O:ZnSO ₄ :Na ₂ SiO ₃ ,kg ha ⁻¹)	0:45:90:0:0	165:30:60:0:0	135:45:90:5:0	165:50:100:5:50	195:50:100:5:50
N split(B:MT:PI:FI)		8:2:0:0	5:2:3:0	5:2:3:0	5:2:2:1
K split(B:MT:PI:FI)	10:0:0:0	10:0:0:0	10:0:0:0	6:0:4:0	6:0:4:0
Water regime	F-M-D-M ^c	F-M-D-M	F-M-D-M	F-M-D-M	F-M-D-M
Planting density (cm)	20×20	23.3×23.3	20×20	16.7×25	16.7×(16.7+33.7)

547 ^a 20 kg N ha⁻¹ in the form of rapeseed cake fertilizer was applied as basal fertilizer and included in the total N rate

548 ^b B, MT, PI, and FL indicate basal, maximum tillering, panicle initiation, and right before flowering stage, respectively

549 ^c F-D-F-M, flooding-midseason drainage-re-flooding-moist irrigation water regime

550 Table 2 Seasonal CH₄ and N₂O emissions and rice grain yield during the early and late rice growing seasons in 2011–2013

Year	Treatment	Early rice season			Late rice season		
		CH ₄ (kg ha ⁻¹)	N ₂ O (kg N ha ⁻¹)	Yield (t ha ⁻¹)	CH ₄ (kg ha ⁻¹)	N ₂ O (kg N ha ⁻¹)	Yield (t ha ⁻¹)
2011	NN	190.8±57.2	0.129±0.016	3.23±0.27	135.0±56.5	0.183±0.056	5.23±0.15
	FP	212.9±5.9	0.248±0.044	6.00±0.63	190.8±37.6	0.441±0.477	6.66±0.50
	ISSM-N1	211.9±28.8	0.212±0.082	6.97±0.28	202.4±97.2	0.339±0.160	7.66±0.14
	ISSM-N2	307.9±59.1	0.213±0.063	7.61±0.30	281.6±180.8	0.640±0.321	8.28±0.62
	ISSM-N3	316.6±87.0	0.301±0.089	8.64±0.42	266.9±151.3	0.672±0.387	9.29±0.54
2012	NN	118.6±40.3	0.076±0.023	5.59±0.07	141.1±39.8	0.161±0.103	7.59±0.29
	FP	144.3±19.5	0.144±0.037	7.29±0.35	236.5±38.3	0.442±0.330	9.94±0.68
	ISSM-N1	138.1±49.5	0.147±0.037	7.95±0.58	235.9±67.0	0.371±0.221	9.99±0.12
	ISSM-N2	223.4±46.7	0.187±0.030	9.54±0.24	330.2±30.8	0.625±0.199	11.60±0.45
	ISSM-N3	217.1±15.5	0.208±0.082	9.82±0.32	343.2±45.7	0.718±0.287	10.56±0.12
2013	NN	221.8±7.8	0.098±0.061	5.08±0.27	309.3±76.1	0.088±0.036	5.86±0.60
	FP	265.8±62.2	0.157±0.083	6.87±0.58	360.3±44.0	0.373±0.219	9.63±0.08
	ISSM-N1	302.8±63.9	0.168±0.038	8.16±0.31	372.0±48.1	0.136±0.073	9.67±0.34
	ISSM-N2	329.7±69.5	0.215±0.106	9.73±0.13	376.3±70.4	0.388±0.177	9.78±0.48
	ISSM-N3	342.9±62.9	0.220±0.028	9.48±0.18	394.6±63.6	0.400±0.148	10.67±0.56
Average over 2011–2013	NN	177.1±18.4b	0.101±0.020c	4.63±0.13e	195.1±56.8b	0.144±0.041c	6.22±0.18c
	FP	207.7±25.8b	0.183±0.043ab	6.72±0.38d	262.5±27.6ab	0.419±0.196ab	8.75±0.41b
	ISSM-N1	217.6±31.5b	0.175±0.040b	7.69±0.23c	270.1±67.5ab	0.282±0.036bc	9.11±0.11b
	ISSM-N2	287.0±32.5a	0.205±0.051ab	8.96±0.15b	329.4±66.0a	0.551±0.183a	10.02±0.28a
	ISSM-N3	292.2±18.8a	0.243±0.025a	9.31±0.01a	334.9±78.0a	0.597±0.110a	10.17±0.18a

551 *Mean±SD, different letters within the same column indicate significant differences among treatments by Tukey's multiple range tests ($P<0.05$).

552 Table 3 A two-way ANOVA for the effect of treatment (T) and cropping cycle (C) on CH₄ and N₂O emissions and grain yields in rice paddies

Season	Factors	df	CH ₄ (kg ha ⁻¹)			N ₂ O (kg N ha ⁻¹)			Yield (t ha ⁻¹)		
			SS	F	P	SS	F	P	SS	F	P
Early rice	T	4	58,720	4.89	<0.05	0.14	3.65	<0.05	55.05	74.50	<0.001
	C	2	123,484	20.57	<0.001	0.08	4.12	<0.05	23.24	62.91	<0.001
	T*C	8	214,413	0.89	0.53	0.05	0.64	0.74	3.85	2.60	<0.05
	Model	14	254,667	6.06	<0.001	0.41	3.01	<0.01	169.58	65.57	<0.001
	Error	45	117,065			0.38			7.20		
Late rice	T	4	57,755	1.94	0.12	1.14	2.00	0.11	32.59	27.17	<0.001
	C	2	190,530	12.83	<0.001	0.97	3.44	<0.05	51.66	86.10	<0.001
	T*C	8	29,749	0.50	0.85	0.42	0.37	0.95	8.15	3.40	<0.05
	Model	14	346,690	3.33	<0.05	5.26	2.65	<0.01	157.49	37.50	<0.001
	Error	45	289,620			5.52			11.70		
Fallow	T	4	357	3.05	<0.05	0.06	0.83	0.51			
	C	2	1,321	22.62	<0.001	0.12	3.11	0.06			
	T*C	8	159	0.68	0.70	0.18	1.23	0.31			
	Model	14	2,009	4.92	<0.001	0.49	1.89	0.06			
	Error	45	1,139			0.73					

553 Table 4 Seasonal CH₄ (kg CH₄ ha⁻¹) and N₂O (kg N ha⁻¹) emissions (Mean ± SD) during the fallow season from rice paddies

	2011/11/3–2012/4/13		2012/11/1–2013/3/27		2013/10/31–2014/3/31		Average over three fallow seasons	
Treatment	CH ₄	N ₂ O	CH ₄	N ₂ O	CH ₄	N ₂ O	CH ₄	N ₂ O
NN	9.73±1.35	0.097±0.057	11.81±2.02	0.088±0.035	3.19±0.74	0.090±0.048	8.24±0.83c	0.092±0.041c
FP	13.66±7.50	0.206±0.075	17.24±4.33	0.102±0.042	3.90±0.51	0.115±0.044	11.60±1.64bc	0.141±0.012abc
ISSM-N1	14.72±8.26	0.109±0.027	15.04±1.73	0.096±0.030	5.49±2.51	0.151±0.065	11.75±2.24bc	0.119±0.018bc
ISSM-N2	18.08±2.44	0.152±0.032	17.12±7.93	0.099±0.040	3.19±1.22	0.258±0.129	12.80±3.15b	0.170±0.030ab
ISSM-N3	23.29±5.15	0.166±0.033	22.77±3.12	0.100±0.056	6.91±4.03	0.303±0.218	17.65±3.48a	0.190±0.079a

554 Table 5 Mean annual CH₄ and N₂O emissions and soil organic carbon sequestration rates and their estimated global warming potentials (GWPs)
555 and greenhouse gas intensities (GHGIs) over three annual cycles from April 2011 to April 2014

Treatment	CH ₄ ^a (kg CH ₄ ha ⁻¹ yr ⁻¹)	N ₂ O-N (kg N ha ⁻¹ yr ⁻¹)	GWP ^b (kg CO ₂ ha ⁻¹ yr ⁻¹)	SOCSR ^c (t C ha ⁻¹ yr ⁻¹)	net GWP ^d (kg CO ₂ ha ⁻¹ yr ⁻¹)	Grain yield (t ha ⁻¹ yr ⁻¹)	GHGI ^e (kg CO ₂ -eq kg ⁻¹ grain)
NN	380±39b	0.34±0.10d	13093b	0.13±0.08c	12610c	10.86±0.06d	1.21±0.12a
FP	482±44b	0.74±0.23bc	16729b	0.38±0.05bc	15352bc	15.46±0.74c	1.00±0.11ab
ISSM-N1	499±96b	0.58±0.04cd	17252b	0.54±0.32ab	15261bc	16.80±0.14b	0.91±0.16b
ISSM-N2	629±79a	0.93±0.19ab	21824a	0.86±0.26a	18668ab	18.98±0.32a	0.99±0.19ab
ISSM-N3	645±87a	1.03±0.21a	22403a	0.74±0.21ab	19681a	19.49±0.19a	1.01±0.15ab

556 ^a Mean annual CH₄ and N₂O = early rice season + late rice season + fallow season

557 ^b GWP = CH₄ × 34 + N₂O-N × 44/28 × 298

558 ^c The SOCSR was estimated from April 2009 to April 2014

559 ^d net GWP = CH₄ × 34 + N₂O-N × 44/28 × 298 – SOCSR × 44/12

560 ^e GHGI (kg CO₂-equivalent kg⁻¹ grain yield) = net GWP/grain yield