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

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Abstract: Our understanding of how global warming potential (GWP) and greenhouse gas intensity (GHGI) is affected by management practices aimed at food security with respect to rice agriculture remains limited. In the present study, a 5-year field experiment was conducted in China to evaluate the effects of integrated soil-crop system management (ISSM) mainly consisting of different nitrogen (N) fertilization rates and split, manure, Zn and Na$_2$SiO$_3$ fertilization and planting density on GWP and GHGI after accounting for carbon dioxide (CO$_2$) equivalent emissions from all sources including methane (CH$_4$) and nitrous oxide (N$_2$O) emissions, agrochemical inputs and farm operations and sinks (i.e., soil organic carbon sequestration). For the improvement of rice yield and agronomic nitrogen use efficiency (NUE), four ISSM scenarios consisting of different N rates relative to the local farmers’ practice (FP) rate were carried out, namely, N1 (25% reduction), N2 (10% reduction), N3 (FP rate) and N4 (25% increase). The results showed that compared with the FP, the four ISSM scenarios significantly increased the rice yields by 10, 16, 28 and 41% and the agronomic NUE by 75, 67, 74 and 73%, respectively. In addition, compared with the FP, the N1 and N2 scenarios significantly reduced the GHGI by 14 and 18%, respectively, despite similar GWPs. The N3 and N4 scenarios remarkably increased the GWP and GHGI by an average of 67 and 37%, respectively. In conclusion, the ISSM strategies are promising for both food security and environmental protection, and the ISSM scenario of N2 is the optimal strategy to realize high yields and high NUE together with low environmental impacts for this agricultural rice field.
Introduction

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

CO₂, methane (CH₄) and nitrous oxide (N₂O) are the most important greenhouse gases (GHGs) that greatly contribute to global warming (IPCC, 2013). The concept of global warming potential (GWP) was proposed based on the radiative properties of all the GHG emissions and soil organic carbon (SOC) fixation, expressed as CO₂ eq. ha⁻¹ yr⁻¹ (Robertson and Grace, 2004; Mosier et al., 2006). Although agriculture releases significant amounts of CH₄ and N₂O into the atmosphere, the net emission of CO₂ 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 CH₄ and N₂O (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 CO₂ eq. yr⁻¹ by 2030 (Smith et al., 2008). However, the release of CO₂ during the manufacturing and application of N fertilizer to crops and from fuel used in machines for farm operations can counteract these mitigation efforts (West and Marland, 2002). This indicates that agricultural ecosystems are not only a very important source of GHG emissions
but also present substantial opportunities for mitigation. Therefore, when determining the
GWP of GHG (CO₂, CH₄ and N₂O) emissions from agroecosystems, there is a need to
account for all sources including GHGs emissions, agrochemical inputs (Ei) and farm
operations (Eo) and sinks, e.g. soil organic carbon (SOC) sequestration of CO₂ equivalents
(Sainju et al., 2014).

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

2 Materials and Methods

2.1 Experimental site

A 5-year field experiment was conducted at the Changshu agro-ecological experimental
station (31°32’93″N, 120°41’88″E) in Jiangsu Province, China. This is a typical, intensively
managed agricultural area where the cropping regime is dominated by a flooding rice (Oryza
sativa L.)-drained wheat (Triticum aestivum L.) rotation system. The site is characterized by a
subtropical humid monsoon climate with a mean annual air temperature of 15.6, 15.2 and
15.8 °C and precipitation of 878, 1163 and 984 mm for three years, respectively. The soil of
the field is classified as an Anthrosol with a sandy loam texture of 6% sand (1–0.05 mm), 80%
silt (0.05–0.001 mm), and 14% clay (<0.001 mm), which developed from lacustrine sediment.
The major properties of the soil at 0–20 cm can be described as follows: bulk density, 1.11 g
cm⁻³; pH, 7.35; organic matter content, 35.0 g kg⁻¹; and total N, 2.1 g kg⁻¹. The daily mean air
temperatures and precipitation during the study period from June 15, 2011, to June 15, 2014,
are given in the supplementary resource 1.

2.2 Experimental design and management

A completely randomized 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 N application rates relative to the local FP rate, namely N1 (25% reduction), N2 (10% reduction), N3 (FP rate) and N4 (25% increase). The designed ISSM (only for rice but not wheat production) including a redesign of a split N fertilizer application, a balanced fertilizer application (rapeseed cake in additional 112.5 kg N ha\(^{-1}\), C/N=8), additional phosphorus and potassium application, and transplanting density, used as the main techniques for improving rice yield and agronomic NUE (calculated as the difference in grain yield between the plots that received N application and the NN plot, divided by the N fertilizer rate). The details of the fertilizer applications, irrigation, and field management practices of the six different treatments are presented in Table 1. Further detailed information was described previously (Zhang et al., 2014). Each plot was 6 m × 7 min size with an independent drainage/irrigation system.

One midseason drainage (about one week) and final drainage before harvest were used during the rice-growing season, whereas the plots only received precipitation during the wheat-growing season. The N fertilizer was split into a 6:2:0:2 or 5:1:2:2 ratio of basal fertilizer and topdressings for the rice crop and a 6:1:3 ratio for the wheat crop. All of phosphorous (P), silicon (Si), zinc (Zn) and rapeseed cake manure were applied as basal fertilizers for both crops. 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 and panicle stages of the rice crop and at the seedling establishment and elongation stages of the wheat crop. Harvests included crop grains as well as the rice and wheat straws were removed out of the field for all the treatments in this study.

2.3 Gas sampling and measurements

We measured the CH\(_4\) emissions and N\(_2\)O fluxes in 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.

The gas samples were analyzed for CH\textsubscript{4} and N\textsubscript{2}O concentrations using a gas chromatograph (Agilent 7890A, Shanghai, China) equipped with two detectors. CH\textsubscript{4} was detected using a hydrogen flame ionization detector (FID), and N\textsubscript{2}O was detected using an electron capture detector (ECD). Argon-methane (5%) and N\textsubscript{2} were used as the carrier gas at a flow rate of 40 ml min\textsuperscript{-1} for N\textsubscript{2}O and CH\textsubscript{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.

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):

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

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

2.5 GWP and GHGI measurements

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

\[
\text{GWP (kg CO}_2\text{eq. ha}^{-1} \text{yr}^{-1}) = 25 \times \text{CH}_4 + 298 \times \text{N}_2\text{O} + E_i + E_o - 44/12 \times \text{SOCSR} (2)
\]

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

In Eq. (2), E\textsubscript{i}, E\textsubscript{o} and SOCSR represent CO\textsubscript{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 N\(_2\)O are equivalent to 25 and 298 kg CO\(_2\) based on 100-year time scale, respectively (IPCC, 2013). The 12 and 44 are the molecular weight 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. In addition to the CH\(_4\) emissions and N\(_2\)O fluxes, we considered the ‘hidden’ CO\(_2\) equivalent emissions, including agrochemical inputs (Ei), such as the manufacture and transportation of the N, P and K fertilizers (Snyder et al., 2009), and farm operations (Eo), such as the water used for irrigation (Zhang et al., 2013) and diesel fuel (Huang et al., 2013a). The CO\(_2\) equivalent emissions of N fertilizer were calculated as the mean value of the C emissions of 1.3 kg C equivalent kg\(^{-1}\) (Lal, 2004). Similarly, the CO\(_2\) equivalent for irrigation was calculated from the total amount of water used during the rice-growing season; the coefficient for the C cost was 5.16 (kg C eq. cm\(^{-1}\) ha\(^{-1}\)) (Lal, 2004). The CO\(_2\) equivalents of other Ei (P and K fertilization, manure, herbicide, pesticide and fungicide applications) and Eo (tillage, planting, harvest, and farm machinery production) were recorded and estimated according to the methods provided by Lal (2004). We collected data specific to China’s fertilizer manufacture and consumption, and then estimated C emissions coefficients were 0.07 and 0.1 C cost (kg C eq. kg\(^{-1}\) active ingredient) per applied Si and Zn fertilizer, respectively.

2.6 Statistical analysis

Repeated-measures multivariate analysis of variance (MANOVA) and linear relationships were determined using JMP 7.0, ver. 7.0 (SAS Institute, USA, 2007). The F-test was applied to determine whether there were significant effects of the practices, years and their interaction at \(P < 0.05\). One-way analysis of variance was conducted to determine the emissions of CH\(_4\) and N\(_2\)O, and the grain yield among the different treatments. Tukey’s HSD test was used to determine whether significant differences occurred between the treatments at a significance level of \(P < 0.05\). 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 these cultivation patterns; these results are shown in Table 2. The grain yields ranged from 5.83 to 12.11 t ha$^{-1}$ for rice and 1.75 to 6.14 t ha$^{-1}$ for wheat (Table 2). On average over the three cycles, the annual rice yield of the FP was significantly lower than that of the ISSM scenarios of N1, N2, N3 and N4. Compared with the FP, rice grain yields increased by 10% and 16% for the N1 and N2 scenarios, respectively, i.e., with the lower N input, by 28% for the N3 scenario with the same N input and by 41% for the N4 scenario with the highest N input. However, we did not observe any significant increases in the wheat-grain yields compared with the FP except for the N4 scenario. Statistical analysis indicated that rice and wheat yields from the three years were not significantly influenced by the interaction of cultivation patterns and cropping year (Table 3).

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

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

All plots showed similar CH$_4$ emission patterns, being a source in the rice season and negligible in the wheat season. During the three annual rice-wheat rotations from 2011 to 2014, the CH$_4$ fluxes ranged from −3.89 to 99.67 mg C m$^{-2}$ h$^{-1}$ (Fig. 2). The seasonal CH$_4$ emissions varied significantly among the treatments during the rice-growing season (Table 3, Fig. 2). No significant difference was found between the FP, N1 and N2 plots. Temporal variation was significant during the three cycles (Table 3, $P < 0.001$). Averaged across years, the CH$_4$ emission was greater in the N3 and N4 plots than in the NN, FP, N1 and N2 plots (Table 2, $P < 0.05$). However, compared with the NN plots, the FP, N1 and N2 plots with inorganic fertilizer application resulted in increased CH$_4$ emission rates of 59.9, 41.9 and 43.0%, respectively, averaged over the rice-growing seasons. The CH$_4$ emission rates were
further enhanced by 198.5% in the N3 plots and by 246.7% in the N4 plots.

The annual N\textsubscript{2}O fluxes varied from \(-33.1\) to \(647.5\) µg N\textsubscript{2}O-N m\textsuperscript{-2} h\textsuperscript{-1}, most of the N\textsubscript{2}O was emitted during the wheat-growing season after fertilization events, and there were several small emission peaks during the rice-growing season (Fig. 3). With respect to the N application effect, the annual cumulative N\textsubscript{2}O emissions for all four ISSM scenarios were significantly higher than in NN (\(P < 0.05\)). Relative to the FP plot, the N1 and N2 scenarios decreased the annual N\textsubscript{2}O emissions by an average of 41% and 22%, respectively (Table 2).

The N4 scenario significantly increased it by 46% (\(P < 0.05\)) because they received additional N via manure application compared to the FP practice, although there was no significant difference between the 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 (E\textsubscript{i} and E\textsubscript{o}), and SOC sequestration was expressed as kg CO\textsubscript{2} eq. ha\textsuperscript{-1} yr\textsuperscript{-1}. The emission of CO\textsubscript{2} equivalents for E\textsubscript{i} and E\textsubscript{o} are classified in Table 4. While irrigation was a large proportion of farm operations, these were much less significant than chemical inputs. The CO\textsubscript{2} equivalents rates from N fertilizer dominated not only the chemical input section (67–76% of E\textsubscript{i}) but also the total CO\textsubscript{2} equivalents from agricultural management (46–51% of the sum of the E\textsubscript{i} and E\textsubscript{o}). The GWP ranged from 7871 to 20911 kg CO\textsubscript{2} eq. ha\textsuperscript{-1} yr\textsuperscript{-1} for the NN and the N4 plots, respectively (Table 5). Although fertilized treatments increased the annual CH\textsubscript{4} and N\textsubscript{2}O emissions, it also increased the SOC sequestration in this cropping system. Of the main field GHGs that were directly emitted, CH\textsubscript{4} accounted for 56–75% of the GWP in all plots. An increase in the annual SOC content led to a significant decrease in the GWP (contributed to 5–10% of the GWP except in the NN plot). The CO\textsubscript{2} equivalents from agricultural management practices for E\textsubscript{i} (2449–4256 CO\textsubscript{2} eq. ha\textsuperscript{-1} yr\textsuperscript{-1}) were higher than those for E\textsubscript{o} (1285–1697 CO\textsubscript{2} eq. ha\textsuperscript{-1} yr\textsuperscript{-1}) in the fertilized plots. There was no significant difference in the annual GWP observed between the FP, N1 and N2 plots (Table 5). Across the three years, N1 and N2 slightly reduced the GWP by 12 and 10%, respectively; however, N3 and N4 significantly increased the GWP by an average of 52 and 81%, respectively, in comparison with the FP.

The GHGI was used to express the relationship between GWP and grain yield. The
GHGIs in this study ranged from 664 to 1145 kg CO$_2$ eq. t$^{-1}$ (Table 5). The significant difference in the annual GHGI was found between the FP and the ISSM strategies. Compared with the FP, N1 and N2 significantly reduced the GHGI by 14 and 18%, respectively, mainly due to the increased grain yield and SOC sequestration as well as reduced GHG emissions for the ISSM strategies. Although N fertilizer or organic/inorganic combination fertilizer application reduced the SOC losses caused by crop cultivation and increased the grain yields, the GHGIs were generally higher for the N3 and N4 scenarios than the N1 and N2 scenarios due to further increases in CH$_4$ and N$_2$O emissions.

4 Discussion

4.1 Grain yield and agronomic NUE as affected by ISSM strategies

Grain yields are directly related to fertilizer management. The MANOVA results indicated that the rice and wheat grain yields were significantly affected by the cultivation strategies (Table 3, $P < 0.001$), which is in agreement with previous results (Chen et al., 2011; Zhang et al., 2011). Compared with the FP plot, the rice yields were remarkably increased by all four ISSM scenarios (Table 2). However, the wheat grain yield decreased significantly when the N fertilizer rate was reduced by 25% (N1 scenario). It has been reported in previous studies that ISSM strategies can effectively improve the rice grain yield (Ma et al., 2013; Liu et al., 2015).

First, the adjusted transplanting density for the N1, N2, and N3 scenarios would produce a positive effect on rice yield by influencing rice colony structure, which agreed with Wu et al. (2005). Second, reasonable N split for the N1, N2, N3 and N4 scenarios would significantly increase rice yield and agronomic NUE which had been confirmed by Liu et al. (2009). In the present study, N1 and N2 significantly increased annual rice production by 10 and 16%, respectively, in comparison with the FP (Table 2). The finding is consistent with the result of Peng et al. (2006), who reported that a 30% reduction in the total N rate during the early vegetative stage did not reduce the yield but slightly increased it when combined with the modified farmers’ fertilizer practice. Third, integrated management of three macronutrients: N, P and K as well as the two micronutrients: Si and Zn were considered as essential for sustainable high crop yields. Additional Si and Zn fertilizers for the N3 and N4 scenarios would support better seedling establishment and reduce both biotic and abiotic stress, thus
produce higher yields (Wang et al., 2005; Slaton et al., 2005; Kabata-Pendias and Mukherjee, 2007; Hossain et al., 2008). As expected, when the total N rate was at the FP rate and increased by 25% and applied with rapeseed cake manure, the rice yield in these N3 and N4 plots remarkably increased by 28 and 41%, respectively. Based on a long-term fertilizer experiment, Shang et al. (2011) reported that organic fertilizer incorporation significantly increased the early rice grain yield. This may have resulted from the organic fertilizer applied in combination with adequate nutrients, which improved the rice yield.

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

4.2 CH4 and N2O emissions as affected by ISSM strategies

During the three years, the annual cumulative CH4 emissions, on average, varied from 133 to 469 kg C ha−1 yr−1 (Table 2), and these values fell within the range of 4.1 to 1015.6 kg CH4 ha−1 observed previously in a rice field (Huang et al., 2004). The MANOVA results indicated that obvious effects of cultivation patterns and years on CH4 emissions were found during the rice-wheat rotations (Table 3, P < 0.001). The CH4 emissions were not significantly affected by the cycles but affected by crop season (Table 5, Fig. 2). In this study, no significant difference in CH4 emission was observed between the FP, N1 and N2 plots. However, compared with the FP plot, the N3 and N4 scenarios emitted 87 and 118% more CH4 emissions, respectively (Table 5), which is probably due to the incorporation of the organic
rapeseed cake manure. Previous reports support the observations that CH$_4$ emissions were significantly increased with the application of organic amendments (Ma et al., 2009; Thangarajan et al., 2013; Zou et al., 2005). Additional application of Si and Zn fertilizers had no significant effect on CH$_4$ and N$_2$O fluxes, which was consistent with the result of Xie et al. (2015). Moreover, rice growth was found to be significantly increased under the N3 and N4 scenarios. In this case, the organic matter inputs such as root litter and rhizodeposits in the N3 and 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 the more CH$_4$ emissions (Yan et al., 2005). The results obtained in the present study revealed that both inorganic and organic fertilizer application significantly increased the CH$_4$ emissions in the rice season (Table 2), which was probably associated with the increase in the SOC content and crop biomass (Ma et al., 2013).

Denitrification and nitrification are the main processes that produce N$_2$O in the soil (Paul et al., 1993). Changes in the soil water content strongly affected the soil N$_2$O emissions and resulted in negligible N$_2$O emissions when the rice field was flooded (Fig. 3), which is consistent with previous reports (Akiyama et al., 2005; Murdiyarso et al., 2010). A relatively high N$_2$O peak was observed in the first two weeks of the wheat-growing season (Fig. 3), possibly because soil changes from flooded to drained condition may have enhanced N$_2$O release (Deng et al., 2012). Alternation of drainage and flooding may induce large amounts of N$_2$O emissions, particularly in fertilized systems; this has commonly been proved in earlier studies (Wang et al., 2013; Xiong et al., 2007; Zou et al., 2005). The seasonal and annual rates of N$_2$O emission were significantly affected by the cultivation practice patterns and years (Table 3). Compared with the FP plot, the N2 scenario greatly decreased the seasonal N$_2$O emissions in this study, which may have resulted from a reduction in the N fertilizer rate (Table 1, Table 2). The total N$_2$O 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$_2$O was
emitted (Mosier et al., 2006) as a result of the additional N made available to the soil microbes through N fertilizer application, which probably increased the CH₄ 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).

4.3 GWP and GHGI as affected by ISSM strategies

The GWP in our study (10104–20911 kg CO₂ eq. ha⁻¹) with the ISSM strategies was higher than that in a double-cropping cereal rotation (1346–4684 kg CO₂ eq. ha⁻¹) and a rice-wheat annual rotation (290–4580 kg CO₂ eq. ha⁻¹) reported by Huang et al. (2013b) and Yang et al. (2015), respectively. Dominant CH₄ emissions as well as additional CO₂ emitted by the machinery/equipment used for irrigation and farm operations under the ISSM strategies may increase the GWP more than in other cropping systems. However, the current GWP was still much lower than that of a double-rice cropping system (13407–26066 kg CO₂ eq. ha⁻¹) (Shang et al., 2011). The GHGIs, which ranged from 0.66 to 1.15 kg CO₂ eq. kg⁻¹ grain in this study, were slightly higher than previous estimates of 0.24–0.74 kg CO₂ 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 CO₂ eq. kg⁻¹ grain) (Li et al., 2006). Differences in GWP or GHGI were found in the cultivation patterns over the three rice-wheat rotations (Table 5). Although there were not significant differences among the FP, N1 and N2 plots, the N1 and N2 scenarios with optimized ISSM strategies led to a lower GWP than the FP (Table 5). Compared with the FP, the N1 and N2 scenarios dramatically reduced the GHGI, which was mainly due to higher yields. In spite of the similar GWP compared with the FP plot, the lowest GHGI (0.66 kg CO₂ eq. kg⁻¹ grain) was obtained under the 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 CH₄ emissions dominate the GWP in rice paddies (Ma et al., 2013; Shang et al., 2011). In comparison to the GWP (11545 kg CO₂ eq. ha⁻¹yr⁻¹) and GHGI (0.81 kg CO₂ eq. kg⁻¹ grain) of the FP, the N3 and N4 scenarios increased both the GWP and GHGI, mainly because these scenarios notably increased the CH₄ emissions compared with the FP, which resulted in relatively higher GWP (Table 5).

Agricultural management practices that change one type of GWP source/sink may also
impact other sources/sinks and therefore change the GWP and GHGI (Mosier et al., 2006; Shang et al., 2011). Although the N-fertilizer plots, especially those with the incorporation of organic fertilizer, increased the annual CH$_4$ and N$_2$O emissions, they increased the SOC sequestration in this cropping system, which is agreement with previous reports (Huang and Sun, 2006). This was mainly due to the enhanced incorporation of rapeseed cake and crop residue associated with higher crop productivity (Ma et al., 2013). In the present study, the N2 scenario with ISSM decreased the CH$_4$ and N$_2$O emissions as well as the energy consumption related to irrigation and the manufacture and transport of N fertilizer (depending on coal combustion), ultimately leading to a decrease in the GWP relative to the FP plot. Moreover, despite the lower N fertilizer input, the grain yield did not decline and the GHGI of the N2 scenario was thus lower than of the FP plot, indicating less consumption of CO$_2$ equivalents per unit of grain produced. We demonstrate that high yield and agronomic NUE, together with low GWP, are not conflicting goals by optimizing ISSM strategies.

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

Determining the main components of the GWP and GHGI in specific cropping systems is very important for mitigating GHG emissions in the future because the benefits of C sequestration would be negated by CH$_4$ and N$_2$O 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$_2$O emissions (Table 5). CH$_4$ emissions, the most important component of GWP in this typical rice-wheat rotation system, could be further mitigated by some other strategies, such as reasonable irrigation (Zou et al., 2005; Wang et al., 2012).

Although N fertilizer application increased SOC sequestration when it was applied with rapeseed cake manure, this benefit was consistently overshadowed, on a CO$_2$ equivalent basis, by the increases in CH$_4$ and N$_2$O emissions (Table 5). Similar results have been reported, i.e., GHG emissions substantially offset SOC increases (Six et al., 2004). It is possible that the realization of reducing the GWP and GHGI in China should focus on
increasing the SOC and simultaneously decreasing the CO$_2$ equivalents from CH$_4$ emissions and N fertilizer inputs. Several studies reported possible methods for these types of mitigation strategies, such as optimizing the chemical fertilizer application amount and rate (Ju et al., 2011), the amount of water used for irrigation (Gao et al., 2015), and the timing and rate of N using the in-season N management approach, as well as improving the N fertilizer manufacturing technologies (Zhang et al., 2013), and using nitrification inhibitors or polymer-coated controlled-release fertilizers (Hu et al., 2013).

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

5 Conclusions

Reasonable agricultural management practices are the key to reducing GHG emissions from agricultural ecosystems. This study provided an insight into the complete GHG emission accounting of the GWP and GHGI affected by different ISSM scenarios. After a five-year field experiment, we found that the CH$_4$ emissions, production of N fertilizer, irrigation, SOC sequestration and N$_2$O fluxes were the main components of the GWP in a typical rice-wheat rotation system. In contrast with the FP, N1 and N2 significantly reduced the GHGI, though they resulted in similar GWPs, and N3 and N4 remarkably increased the GWP and GHGI. By
adopting the ISSM strategy, the conventional N application rate was reduced by 10% while the rice yield was significantly increased by 16%, the NUE was improved by 67% and the GHGI was lowered. ISSM scenarios could be adopted for both food security and environmental protection with specific targets. We propose that the ISSM-N2 scenario is the most appropriate management strategy (10% reduction of N input, no rapeseed manure and higher plant density) for realizing higher yields and NUE, together with some potential to reduce GHGI by integrated soil-crop management. For simultaneously mitigating GHG emissions, further research on integrated soil-crop system managements is required particularly for mitigating CH₄ emissions in sustainable rice agriculture.

Acknowledgments We sincerely appreciate two anonymous reviewers for their critical and valuable comments to help improve this manuscript. This work was jointly supported by the National Science Foundation of China (41171238, 41471192), the Special Fund for Agro-Scientific Research in the Public Interest (201503106) and the Ministry of Science and Technology (2013BAD11B01).
References


and factors controlling N\textsubscript{2}O production in an intensively managed low carbon calcareous soil under sub-humid monsoon conditions, Environ. Pollut., 159, 1007-1016, 2011.


Table 1

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NN&lt;sup&gt;a&lt;/sup&gt;</th>
<th>FP</th>
<th>ISSM-N1</th>
<th>ISSM-N2</th>
<th>ISSM-N3</th>
<th>ISSM-N4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed cake manure (t ha&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>Water regime</td>
<td>F-D-F-M&lt;sup&gt;b&lt;/sup&gt;</td>
<td>F-D-F-M</td>
<td>F-D-F-M</td>
<td>F-D-F-M</td>
<td>F-D-F-M</td>
<td>F-D-F-M</td>
</tr>
<tr>
<td>Planting density (cm)</td>
<td>20×20</td>
<td>20×20</td>
<td>20×15</td>
<td>20×15</td>
<td>20×15</td>
<td>20×20</td>
</tr>
</tbody>
</table>

Rice-growing season

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NN&lt;sup&gt;a&lt;/sup&gt;</th>
<th>FP</th>
<th>ISSM-N1</th>
<th>ISSM-N2</th>
<th>ISSM-N3</th>
<th>ISSM-N4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed sowing density (kg ha&lt;sup&gt;−1&lt;/sup&gt;)</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
</tbody>
</table>

<sup>a</sup>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<sup>−1</sup> for the rice crop and 180 kg N ha<sup>−1</sup> for the wheat crop, namely, N1 (25% reduction), N2 (10% reduction), N3 (FP rate) and N4 (25% increase). Urea, calcium biphosphate and potassium chloride were used as N, P and K fertilizer respectively.

<sup>b</sup>F-D-F-M, flooding-midseason drainage-re-flooding-moist irrigation.
Table 2
Seasonal CH$_4$ and N$_2$O emissions, and yields during rice and wheat cropping seasons in the three cycles of 2011–2014.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice season</th>
<th>Wheat season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH$_4$ (kg C ha$^{-1}$)</td>
<td>N$_2$O (kg N ha$^{-1}$)</td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NN</td>
<td>153±10.8c</td>
<td>0.03±0.05c</td>
</tr>
<tr>
<td>FP</td>
<td>266±25.3b</td>
<td>0.11±0.08c</td>
</tr>
<tr>
<td>ISSM-N1</td>
<td>212±30.3bc</td>
<td>0.08±0.03c</td>
</tr>
<tr>
<td>ISSM-N2</td>
<td>220±32.5bc</td>
<td>0.17±0.11bc</td>
</tr>
<tr>
<td>ISSM-N3</td>
<td>518±58.9a</td>
<td>0.38±0.15ab</td>
</tr>
<tr>
<td>ISSM-N4</td>
<td>561±50.9a</td>
<td>0.37±0.07a</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NN</td>
<td>149±25.8d</td>
<td>0.13±0.10c</td>
</tr>
<tr>
<td>FP</td>
<td>239±34.5c</td>
<td>0.33±0.11bc</td>
</tr>
<tr>
<td>ISSM-N1</td>
<td>226±30.4cd</td>
<td>0.27±0.07bc</td>
</tr>
<tr>
<td>ISSM-N2</td>
<td>228±32.6cd</td>
<td>0.38±0.29bc</td>
</tr>
<tr>
<td>ISSM-N3</td>
<td>431±26.8b</td>
<td>0.52±0.16ab</td>
</tr>
<tr>
<td>ISSM-N4</td>
<td>536±58.7a</td>
<td>0.78±0.13a</td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NN$^b$</td>
<td>135±19.6d</td>
<td>0.11±0.05c</td>
</tr>
<tr>
<td>FP$^b$</td>
<td>215±19.9c</td>
<td>0.29±0.13bc</td>
</tr>
<tr>
<td>ISSM-N1$^b$</td>
<td>191±19.2c</td>
<td>0.18±0.06c</td>
</tr>
<tr>
<td>ISSM-N2$^b$</td>
<td>192±11.6c</td>
<td>0.27±0.12bc</td>
</tr>
<tr>
<td>ISSM-N3$^b$</td>
<td>402±23.8b</td>
<td>0.50±0.16ab</td>
</tr>
<tr>
<td>ISSM-N4$^b$</td>
<td>467±39.2a</td>
<td>0.68±0.15a</td>
</tr>
</tbody>
</table>

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

$^b$See Table 1 for treatment codes.
Table 3

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

<table>
<thead>
<tr>
<th>Crop season</th>
<th>Source</th>
<th>df</th>
<th>CH₄ (kg C ha⁻¹)</th>
<th>N₂O (kg N ha⁻¹)</th>
<th>Yield (t ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>Between subjects</td>
<td>5</td>
<td>35.3***</td>
<td>3.71***</td>
<td>123***</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>5</td>
<td>35.3***</td>
<td>3.71***</td>
<td>123***</td>
</tr>
<tr>
<td></td>
<td>Within subjects</td>
<td>2</td>
<td>20.7***</td>
<td>0.88**</td>
<td>1.15**</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>2</td>
<td>20.7***</td>
<td>0.88**</td>
<td>1.15**</td>
</tr>
<tr>
<td></td>
<td>P×Y</td>
<td>10</td>
<td>6.73***</td>
<td>0.15</td>
<td>0.37</td>
</tr>
<tr>
<td>Wheat</td>
<td>Between subjects</td>
<td>5</td>
<td>0.26</td>
<td>14.8***</td>
<td>76.3***</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>5</td>
<td>0.26</td>
<td>14.8***</td>
<td>76.3***</td>
</tr>
<tr>
<td></td>
<td>Within subjects</td>
<td>2</td>
<td>0.55*</td>
<td>15.1***</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>2</td>
<td>0.55*</td>
<td>15.1***</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>P×Y</td>
<td>10</td>
<td>0.83</td>
<td>4.39***</td>
<td>0.05</td>
</tr>
<tr>
<td>Rice-Wheat</td>
<td>Between subjects</td>
<td>5</td>
<td>37.2***</td>
<td>24.2***</td>
<td>153***</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>5</td>
<td>37.2***</td>
<td>24.2***</td>
<td>153***</td>
</tr>
<tr>
<td></td>
<td>Within subjects</td>
<td>2</td>
<td>20.5***</td>
<td>5.83***</td>
<td>0.70*</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>2</td>
<td>20.5***</td>
<td>5.83***</td>
<td>0.70*</td>
</tr>
<tr>
<td></td>
<td>P×Y</td>
<td>10</td>
<td>6.50***</td>
<td>1.11</td>
<td>0.17</td>
</tr>
</tbody>
</table>

*df – degrees of freedom, * P < 0.05, ** P < 0.01, and *** P < 0.001 represent significant at the 0.05, 0.01 and 0.001 probability level, respectively.*
Table 4
Agricultural management practices for chemical inputs and farm operations and contributions to carbon dioxide equivalents (kg CO\textsubscript{2} eq. ha\textsuperscript{-1} yr\textsuperscript{-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).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Chemical inputs (kg ha\textsuperscript{-1})\textsuperscript{a}</th>
<th>Farm operations (kg ha\textsuperscript{-1})\textsuperscript{c}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>NN\textsuperscript{d}</td>
<td>0</td>
<td>180</td>
</tr>
<tr>
<td>FP</td>
<td>480</td>
<td>180</td>
</tr>
<tr>
<td>ISSM-N1</td>
<td>360</td>
<td>180</td>
</tr>
<tr>
<td>ISSM-N2</td>
<td>432</td>
<td>180</td>
</tr>
<tr>
<td>ISSM-N3</td>
<td>480</td>
<td>216</td>
</tr>
<tr>
<td>ISSM-N4</td>
<td>600</td>
<td>252</td>
</tr>
</tbody>
</table>

Chemical inputs (Ei)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Chemical inputs (kg ha\textsuperscript{-1})\textsuperscript{a}</th>
<th>Farm operations (kg ha\textsuperscript{-1})\textsuperscript{c}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>NN\textsuperscript{d}</td>
<td>0</td>
<td>132</td>
</tr>
<tr>
<td>FP</td>
<td>2288</td>
<td>132</td>
</tr>
<tr>
<td>ISSM-N1</td>
<td>1716</td>
<td>132</td>
</tr>
<tr>
<td>ISSM-N2</td>
<td>2059</td>
<td>132</td>
</tr>
<tr>
<td>ISSM-N3</td>
<td>2288</td>
<td>158</td>
</tr>
<tr>
<td>ISSM-N4</td>
<td>2860</td>
<td>185</td>
</tr>
</tbody>
</table>

\textsuperscript{a}The carbon emission coefficients were 1.3, 0.2, 0.15, 0.3, 5.1 and 3.9 C cost (kg C eq. kg\textsuperscript{-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\textsuperscript{-1} active ingredient) per applied Si and Zn fertilizer, respectively.

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

\textsuperscript{c}The carbon emission coefficients were 0.94, 3.2, 0.0075, 0.94 and 0.0725 C cost (kg C eq. kg\textsuperscript{-1} active ingredient) for tillage and raking, crop planting, per farm manure application, harvesting, spraying and threshing, respectively, as referred to in Lal (2004).

\textsuperscript{d}See Table 1 for treatment codes.
Table 5

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

<table>
<thead>
<tr>
<th>Treatment</th>
<th>CH₄</th>
<th>N₂O</th>
<th>Ei</th>
<th>Eo</th>
<th>SOCSR</th>
<th>GWP&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Grain yield</th>
<th>GHGI&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg CO₂ eq. ha&lt;sup&gt;−1&lt;/sup&gt; yr&lt;sup&gt;−1&lt;/sup&gt;</td>
<td></td>
<td>t ha&lt;sup&gt;−1&lt;/sup&gt; yr&lt;sup&gt;−1&lt;/sup&gt;</td>
<td></td>
<td>kg CO₂ eq. t&lt;sup&gt;−1&lt;/sup&gt; grain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NN&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4418±628d&lt;sup&gt;c&lt;/sup&gt;</td>
<td>276±29d&lt;sup&gt;c&lt;/sup&gt;</td>
<td>690</td>
<td>1694</td>
<td>~ 792±327c</td>
<td>7871±646d</td>
<td>7.58±0.04d</td>
<td>1038±85b</td>
</tr>
<tr>
<td>FP</td>
<td>7181±766c</td>
<td>816±55b</td>
<td>3021</td>
<td>1697</td>
<td>1170±396ab</td>
<td>11545±505c</td>
<td>14.26±0.36c</td>
<td>810±23c</td>
</tr>
<tr>
<td>ISSM-N1</td>
<td>6381±633c</td>
<td>479±62c</td>
<td>2449</td>
<td>1285</td>
<td>491±435b</td>
<td>10104±930c</td>
<td>14.50±0.14c</td>
<td>697±63d</td>
</tr>
<tr>
<td>ISSM-N2</td>
<td>6421±379c</td>
<td>633±97c</td>
<td>2792</td>
<td>1295</td>
<td>709±193ab</td>
<td>10433±516c</td>
<td>15.74±0.44b</td>
<td>664±49d</td>
</tr>
<tr>
<td>ISSM-N3</td>
<td>13418±744b</td>
<td>906±87b</td>
<td>3295</td>
<td>1357</td>
<td>1383±503a</td>
<td>17593±688b</td>
<td>16.36±0.18b</td>
<td>1075±33ab</td>
</tr>
<tr>
<td>ISSM-N4</td>
<td>15630±1246a</td>
<td>1188±65a</td>
<td>4256</td>
<td>1383</td>
<td>1545±348a</td>
<td>20911±1289a</td>
<td>18.26±0.46a</td>
<td>1145±84a</td>
</tr>
</tbody>
</table>

<sup>a</sup>GWP (kg CO₂ eq. ha<sup>−1</sup> yr<sup>−1</sup>) = 25 × CH₄ + 298 × N₂O + Ei + Eo − 44/12 × SOCSR, Ei (agrochemical inputs), Eo (farm operations), SOCSR (SOC sequestration rate)

<sup>b</sup>GHGI (kg CO₂ eq. t<sup>−1</sup> grain) = GWP/grain yields

<sup>c</sup>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.

<sup>d</sup>See Table 1 for treatment codes.
**Fig 1** Rice and wheat agronomic nitrogen use efficiency (NUE) in 2011–2014 in Changshu, China. Different letters indicate a significant difference between treatments ($p<0.05$). See Table 1 for treatment codes.

**Fig 2** Seasonal variation of methane (CH$_4$) fluxes from the rice-wheat rotation cropping systems from 2011 to 2014. The black and gray part in figure separates different grain growth periods. See Table 1 for treatment codes. The solid arrows indicate fertilization.

**Fig 3** Seasonal variation of nitrous oxide (N$_2$O) fluxes from rice-wheat rotation cropping systems in three annual cycles over the period 2011–2014. The black and gray part in the figure separates different growth periods. See Table 1 for treatment codes. The solid arrows indicate fertilization.

**Supplementary resource 1** Daily mean air temperature and precipitation during the rice-wheat rotation in 2011–2014 in Changshu, China.
Crop agronomic nitrogen use efficiency (kg grain kg\(^{-1}\) N)

**Rice NUE**

**Wheat NUE**