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

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HIGHLIGHTS

- ISSM strategies are promising in rice agriculture for food security & GHG mitigation.
- ISSM-N2 is best with maximum NUE, increased yield & SOC with similar net GWP and GHGI.
- ISSM-N1 is good with increased yield, NUE, SOC with lower net GWP and GHGI.
- ISSM-N3 increased CH_4 and N_2O with higher N input though increased yield, NUE, SOC.

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ABSTRACT

The impact of integrated soil–crop system management (ISSM) on net global warming potential (GWP) and greenhouse gas intensity (GHGI) is poorly documented though crucial for food security and nitrogen fertilizer use efficiency (NUE). Using local farming practices (FP) and no nitrogen (NN) as the controls, three ISSM practices at different N rates were established in 2009 in a double rice system in Hunan Province, China. Soil organic carbon sequestration rates (SOCSR) were estimated by changes in SOC between 2009 and 2014. Field measurements of methane (CH_4) and nitrous oxide (N_2O) fluxes, grain yield and NUE of early and late rice were measured from April 2011 through April 2014. The net GWP of the annual CH_4 and N_2O emissions and SOCSR and the GHGI over the three years in the FP was 15.35 t CO_2 eq ha^{-1} $year^{-1}$ and 1.00 kg CO_2 eq kg^{-1} grain. The ISSM (N2) treatment increased annual rice yield by 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 CH_4 and N_2O emissions. Our findings show that the ISSM strategies are promising and feasible in sustainable rice agriculture for food security and GHGs mitigation.

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;

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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 (Chen 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 (Chen 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 CH_4 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 m × 8 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 CH_4 and N_2O fluxes

The CH_4 and N_2O 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 0.36 m^2 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