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Integrating agronomic practices to reduce greenhouse gas emissions while increasing the economic return in a rice-based cropping system

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ABSTRACT

The effective mitigation of greenhouse gas (GHG) emissions from crop cultivation requires an overall consideration, due to the trade-off relationship between GHGs and the mitigation measures sometimes undermining grain yields and economic returns. To explore the maximum potential of GHG mitigation without sacrificing economic returns, we investigated the GHG emissions, crop yields and economic returns over two years in three rice-cropping systems (rice–wheat, RW; rice–fava bean, RB; and rice–fallow, RF). Different N fertilization levels and straw incorporation methods were employed in each of the rice-cropping systems at the study site, in the Taihu Lake region (TLR) of China. Bean straw produced in the RB system was fermented aerobically before incorporation, while straws produced in the RW and RF systems were directly incorporated into the soils. Relative to the traditional RW system, methane emissions during the rice seasons were significantly reduced by 29–44% in the RB system; annual N inputs were reduced by 43%; annual nitrous oxide emissions for N fertilization treatments were decreased by 56–69%; and the average rice yield was increased by 5.2%. As a result, the GHG intensity (GHGI) was significantly reduced by 11–41%, and the annual net economic benefit (NEB) was increased by 22–94%. Compared with the RW system, the GHGI in the RF system was increased by 8–30% and the NEB was decreased by 3–33%. Considering the current rice/wheat production practices employed in the TLR, the GHGI could be reduced by 26% while the NEB could be improved by 23%, with an annual reduction in the N application rate (currently 525 kg N ha^{-1}) by 20% and the conversion of the RW systems into RB systems that use straw fermentation. The results of this study suggest that high economic return and GHG mitigation could be simultaneously achieved by the integrated adoption of reasonable reduction in N application rates, the use of appropriate rice-cropping systems and by employing eco-friendly straw management.

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1. Introduction

While rice is a staple food worldwide, rice paddies are important anthropogenic sources of greenhouse gas (GHG) emissions (Cai, 2012). It was estimated that about 7.4 Tg methane (CH_4) and 32 Gg N_2O-N nitrous oxide (N_2O) were emitted annually from rice cultivation in China (the largest rice producer in the world), contributing up to 22% of the total GHG emissions from cropland in the country (Yan et al., 2009; Zou et al., 2009). Increases in the soil organic carbon (SOC) of the topsoil in the rice paddies from the 1980s to 2000s only offset the annual emissions of CH_4 and N_2O by 5% (Yan et al., 2011); this highlights the need to reduce CH_4 and N_2O emissions and increase the SOC stocks of paddy soils. The emissions of CH_4 and N_2O from rice paddies, and the SOC stock, are strongly affected by agronomic practices, such as straw managements, N fertilization and cropping rotation practices (Zou et al., 2005; Khosa et al., 2010; Shang et al., 2011).

The Taihu Lake region (TLR), located in the center of the Yangtze River Delta, in southern China, is one of the most important rice production areas in China (Zhao et al., 2012). The dominant cropping system in the TLR comprises a summer rice (*Oryza sativa* L.) and winter wheat (*Triticum aestivum* L.) rotation. Rice and wheat straw are directly incorporated into the soils when the grains are gathered, due to a high degree of mechanization in the TLR (Xia et al., 2014). The direct incorporation of wheat straw before rice transplanting triggers substantial CH_4 emissions, by providing

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methanogens with abundant carbon sources (Ma et al., 2009; Shang et al., 2011). Straw incorporation is credited with promoting the accumulation of SOC stocks (Shang et al., 2011; Yan et al., 2011). In considering the balance of these, Xia et al. (2014) found that the global warming potential (GWP) of straw-induced CH_4 emission was 3–4 times that of straw-induced SOC sequestration rate (SOCSR), when wheat straw was directly incorporated before rice transplanting in the TLR. Their study highlights the need to develop an appropriate straw incorporation method.

Aside from substantial CH_4 emissions from the rice paddies, in the TLR, there are also high N_2O emissions that result from the overuse of N fertilizers (240–300 kg N ha^{-1} for rice and 200–250 kg N ha^{-1} for wheat) (Zhao et al., 2009). Low N recovery efficiencies (30–35%) demonstrate that the majority of N fertilizer applied is released as reactive N (Nr), which causes a cascade of damaging effects on environmental and human health (Galloway et al., 2008; Ju et al., 2009; Sutton et al., 2011). In addition to the direct CH_4 and N_2O emissions from the rice paddies, the indirect emissions of GHG that result from the production of various agricultural materials cannot be ignored, due to their high application rates in the TLR.

Efforts to reduce the GHG emissions from rice–wheat systems in the TLR have been effective, including the adoption of eco-friendly straw managements (e.g., applying straw during the off-rice season or fermenting straw aerobically before its incorporation) to reduce CH_4 emissions (Yan et al., 2009; Khosa et al., 2010); decreasing the N application rates, to reduce N_2O emissions (Zou et al., 2005; Ma et al., 2013); and cultivating rice with legume plants, to reduce the annual N fertilizer inputs, N_2O emissions and the GHG emissions associated with N fertilizer production (Zhao et al., 2015b). However, while each of these practices reduces one type of GHG emissions, they may produce favorable conditions for the emissions of other types of GHG; this is called the trade-off relationship between the GHGs (Huang et al., 2013). Moreover, the adoption of individual mitigation practice can sometimes reduce the crop yields and economic returns (Xia et al., 2016). Few studies have explored the combined effects of multiple mitigation measures on GHG emissions and economic returns, in rice-based cropping systems.

The main objective of this study was to evaluate the responses of GHG emissions, crop yields and economic returns in three rice-based cropping systems (rice–wheat, RW; rice–fava bean, RB; and rice–fallow, RF), to different N fertilization levels and straw incorporation methods. We considered that the maximum GHG mitigation levels, without reducing the economic returns, would result from the integrated adoption of appropriate reductions in N application rates, the adoption of a suitable rice-cropping system and the use of eco-friendly straw management practices. In the present study, the CH_4 and N_2O emissions, SOC changes and crop yields were simultaneously measured for two years (2013–2015) in the three rice-based cropping systems to achieve the above mentioned goal.

2. Materials and methods

2.1. Study site

The continuous experiment took place at the Changshu Agroecological Experimental Station (31°32′N, 120°41′E) of the Chinese Academy of Sciences in Jiangsu province, China. The station is located in the TLR, with the dominant cropping system of annual summer rice and winter wheat rotation. The soil in the experimental field had developed from lacustrine sediments, and was classified as Anthrosol. The basic properties of the topsoil (0–20 cm) were as follows: bulk density, 1.2 g cm^{-3}; pH (H_2O), 7.7; total N content, 2.0 g kg^{-1}; organic carbon content, 20.1 g kg^{-1}; available P content, 0.012 g kg^{-1}; and available K content, 0.126 g kg^{-1}.

2.2. Experimental design

The RB and RF system were compared with the traditional RW system due to their increasing implementation in the TLR. This is because social economic factors have affected the implementation of traditional RW cropping systems in the TLR. Some local farmers have started to substitute the winter wheat crop with fava bean, due to the lower yields and quality of wheat grains, and the higher market prices of fava beans (Zhao et al., 2015b). In addition, a large number of farmlands in the TLR now remain fallow during the winter season, because laborers leave the rural area for the city during that period. The winter crop area in Jiangsu province was reduced by 37% from 1999 to 2009 (Zhang et al., 2015).

The continuous field experiment, initiated in June 2012, was arranged in a randomized block design with three replicates of each treatment. The three rice-based cropping systems (RW, RB and RF rotation) were subdivided into different N fertilization treatments. Five treatments were applied to the RW system, RW0, RW120, RW180, RW240 and RW300, with 0/0, 120/90, 180/135, 240/180, and 300/225 kg N ha^{-1} applied for the rice/wheat cultivation period, respectively (Table S1). RW300 represents the local rice/wheat production pattern. The RB and RF cropping systems were each subdivided to four treatments (RB0, RB120, RB180 and RB240; and BF0, RF120, RF180 and RF240) which the N fertilization rates during rice cultivation were 0, 120, 180 and 240 kg N ha^{-1}; during the fava bean cultivation (RB) and fallow (RF) seasons, no N fertilizer was applied.

N fertilizer (urea) was applied at three stages during the rice (wheat)–growing seasons: 40% was applied as basal fertilizer, 30% as tiller fertilizer (elongation and booting fertilizer), and 30% was applied as panicle fertilizer. The application times of the N fertilizer were shown in Fig. 3. P (calcium superphosphate) and K (potassium chloride) fertilizers were applied as basal fertilizers at rates of 30 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1}, respectively, in each of the rice, wheat and bean seasons. The basal fertilizers, applied before crop transplanting or sowing, were incorporated into the soil by plowing; while top-dressings, were evenly broadcast over the soil surface.

Rice and wheat straw, as well as the weeds that grew during the fallow season of the RF system, were harvested and chopped in situ and plowed into the soils prior to the start of the next season. To reduce the content of labile carbon in the fava bean straw, which is easily used by methanogens, the straw was fermented aerobically in a metal fermenter before its incorporation. For this, fava bean straw was chopped and then mixed evenly with fermentative bacteria and sucrose before being put into the metal fermenter. The fermentative bacteria were screened by Peng et al. (2010), who demonstrated that it degraded the straw quickly under suitable conditions. The straw was continuously stirred to minimize the occurrence of anaerobic fermentation, once the metal fermenter was fully activated. A ventilating fan installed in the fermenter was activated every two hours during the fermentation, to release the gases produced and bring some fresh air into the fermenter simultaneously. After fermentation, the straw was applied to the soil evenly before rice transplanting.

2.3. Agricultural management practices

The field observation was started in June 2013, at the beginning of the rice season, and continued for two consecutive RW, RB and RF cycles. In 2013–2014, rice was transplanted on June 16–21 at a density of 2.5×10^4 plant ha^{-1} and harvested on October 25–November 3. Wheat was directly sown on November 8–13 at a rate

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