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Assessing of an irrigation and fertilization practice for improving rice production in the Taihu Lake region (China)

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ABSTRACT

To address the global environmental and resource crisis, integrated, efficient, and sustainable agricultural practices need to be developed. We examined the effects of combining one of two irrigation methods (*i.e.*, controlled irrigation and conventional flooding irrigation) with one of four different levels of nitrogen fertilizer applications (N; 300 (N0), 270 (N1), 240 (N2), and 180 kg N ha^{-1} (N3)) on grain yield, water use efficiency, and N production efficiency in rice. Additionally, we analyzed nitrogen leaching at different soil depths (20 cm and 80 cm) using lysimeters and N_2O emission using a polyvinyl chloride chamber for each of the combinations examined. We found that the irrigation regime and level of N application significantly affected rice yield, and the rice yield in the controlled irrigation treatment was higher than that in the conventional flooding irrigation treatment by 2.12%–12.30%. Of all the treatments, combining controlled irrigation with the N1 fertilizer application resulted in the greatest grain yield. Loss of N was mainly caused by nitrate leaching. Controlled irrigation and reducing the amount of N fertilizer applied in the soil reduced N leaching, and increased the N production efficiency, while increasing N_2O emission. Furthermore, water use efficiency was increased under controlled irrigation conditions, but reduced when less N fertilizer was applied. Thus, an agricultural regime that uses less water and lower amounts of N fertilizer than are currently being used in standard practices would likely increase yield and N production efficiency in soils, while reducing potential N leaching; however, the N_2O emissions would also increase.

1. Introduction

China has a population of over 1.37 billion people and the population is growing at an annual rate of 4.96‰. To meet the population's demands, food production must be increased by 50% by 2050 (Huang et al., 2014). This poses an enormous challenge for agricultural production in China, especially considering the continued decrease of land that is available for agriculture due to processes of agricultural restructuring, rural urbanization, industrialization, and economic reform (Cao and Yin, 2015). The required increase in food production can therefore only be met by increasing grain production per unit area.

China's grain production has already more than tripled in the past 50 years, due to the use of fertilizers, specifically synthetic nitrogen (N) fertilizer (Guo et al., 2010). For instance, in the Taihu Lake region, where rice (*Oryza sativa* L.) is the main crop, N fertilizer is widely used to improve crop yields. In this densely populated and intensively farmed region, paddy fields are fertilized with an average annual application of 350 kg N ha^{-1}, with 40% of paddy fields being fertilized with more than 360 kg N ha^{-1}. These levels are much higher than the mean N fertilizer input (300 kg N ha^{-1}) for rice monoculture, and N fertilizer use efficiency ranges from 25% to 35% (Zhao et al., 2012). This excessive application of N fertilizer causes substantial N losses through surface runoff, leaching, and gaseous emission, and results in nonpoint source pollution responsible for 59% of the N contributing to the eutrophication of Taihu Lake (Piirainen et al., 2013).

Water, in addition to N, is another important factor that determines crop yield, especially for rice, which requires more water than any other crop. Under traditional flood-irrigated conditions, water consumption in paddy fields accounts for approximately 50% of all diverted freshwater in China (Ye et al., 2013). The increased water demands of cities and industries, coupled with a limited water supply highlight the need to reduce water usage. Moreover, N leaching in the

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Taihu Lake region, where submerged irrigation practices are combined with excessive N fertilization of paddy fields, is a major cause of serious pollution of both groundwater and surface water. Indeed, the Taihu Lake is transitioning from eutrophication to heavy eutrophication (Wu et al., 2011; Peng et al., 2015).

Nitrous oxide (N_2O), a long-lived greenhouse gas (GHG), is mostly derived from agricultural practices and activities, with about 4.5 Tg N being produced worldwide per year (Wuebbles, 2009). Rice paddies covered with standing water, creating the anaerobic conditions that facilitated the denitrification, were considered to be an important source of N_2O emissions (Das and Adhya, 2014; Pandey et al., 2014). Furthermore, N_2O emissions increased significantly with an increase in the nitrogen application rate (Zou et al., 2005; Tariq et al., 2017). Therefore, water and nutrient management are important factors determining N_2O emissions from rice paddies (Pandey et al., 2014). As N_2O emissions are GHGs with high warming potentials (IPCC, 2007), there is an urgent need to reduce N_2O emissions from agricultural ecosystems, to improve N agronomic efficiency, to minimize the environmental impacts of N fertilizers.

Several techniques have been used to monitor drainage of water and N losses, such as methods involving coring, suction cups, and lysimeters. Lysimeters have been shown to be the best method for analyzing the total water flow and N movement in soil, specifically in the field (Basso and Ritchie, 2005; Gu et al., 2016). Many studies of N in the soil have focused on the upper layer of soil horizon (0–0.2m); however, significant denitrification activity was found in anaerobic deeper layers, which could be an important mechanism for the removal of excess NO_3^- before it is leached to groundwater or discharged to the surface aquifer (Sotomayor and Rice, 1996; Fenton et al., 2009; Bernard-Jannin et al., 2017). Therefore, monitoring the water flow and N losses in the deep soil was necessary.

To address the impending environmental crisis and the increasing scarcity of water resources, integrated, environmentally-friendly, and high-efficiency sustainable agricultural practices need to be developed. Many studies have shown that certain water-saving irrigation regimes can reduce the total N loss from the paddy fields when compared with traditional flood irrigation, although the NH_4^+-N and NO_3^--N concentrations in the percolation water increased (Peng et al., 2011; Tan et al., 2013; Peng et al., 2015). Furthermore, the overuse of N fertilizer can reduce grain yield. Lowering the use of N fertilizer to the optimal nitrogen fertilizer rate (200 kg N ha^{-1} for the rice growing season in the Taihu Lake region), especially during the early growth phases, could minimize the risk of N leaching, without compromising grain yields (Ju et al., 2009; Deng et al., 2012; Qiao et al., 2013). Irrigation regimes and proper N fertilizer application rates have been shown to act synergistically to improve crop yield, water use efficiency, and nitrogen use efficiency (Wang et al., 2016). However, N loss (through leaching and emission) and grain yields under various irrigation and fertilizer regimens have not been systematically assessed. An improved understanding of the relationship between N input and irrigation volumes would pave the way for minimizing N leaching and optimizing rice yields in the Taihu Lake region.

In this study, we developed an integrated, high-efficiency agricultural practice for reducing water and N use in rice paddies. In addition, we compared the effects of this integrated practice on grain yield and N losses through leaching (measured using lysimeters) or N_2O emissions (measured using a polyvinyl chloride chamber) with data obtained here using traditional submersion irrigation and N fertilizer application methods.

2. Materials and methods

2.1. Experimental site

The experiments were conducted at Xingeng Village, Suzhou City, Jiangsu Province (31°26′44″N, 120°28′48″E), in the lower part of the Taihu Lake Basin. The study area has a subtropical monsoon climate with an average annual temperature of 16.6 °C, and an annual precipitation of 1312 mm. The top 15 cm layer of the soil in the experimental field contained 30.35 g kg^{-1} organic matter, 1.73 g kg^{-1} total N, 141.83 mg kg^{-1} available N, 14.58 mg kg^{-1} available phosphate, and 92.80 mg kg^{-1} available potassium, and had a pH (H_2O) of 7.4. The texture of the soil was sandy clay loam, with 22.6% of clay, 68.2% of silt, 9.2% of sand.

2.2. Experimental design

The experiments were conducted during the rice growing season from 2010 to 2013. One of two irrigation treatments, *i.e.*, controlled irrigation (CI) and conventional flooding irrigation (CF), were combined with fertilization with one of four different levels of nitrogen fertilizer applications, *i.e.*, conventional level of nitrogen fertilizer application (N0, 300 kg N·ha^{-1}), 90% of the conventional level of nitrogen fertilizer application (N1, 270 kg N·ha^{-1}), 80% of the conventional level of nitrogen fertilizer application (N2, 240 kg N·ha^{-1}), and 60% of the conventional level of nitrogen fertilizer application (N3, 180 kg N·ha^{-1}). The eight treatments that combined each irrigation method with each level of nitrogen fertilizer application are listed in Table 1. A randomized complete block design was established for all treatments and three replications were performed in twenty-four experimental field plots (5.0 m × 4.0 m). Each plot was isolated using field ridges (40 cm at the base and 40 cm high) that were covered with plastic foil to prevent lateral water movement.

The variety of rice (*Oryza sativa* L.) planted in this area was Nanjing 46, a systematic breeding line from the Jiangsu Academy of Agricultural Sciences. In 2012 and 2013, the rice seedlings were transplanted on June 28. Three to four plants were transplanted in every hill and were harvested on December 5. Local fertilization practices for rice cultivation were followed. Urea (46% N), superphosphate (6% P), and potassium chloride (54% K) were applied. Urea was supplied in three applications, with 45 kg N·ha^{-1} as a basal application before planting and 30% of the total N supplied at panicle formation, and the rest supplied at the tillering period. Phosphorus and K were applied as basal fertilizers at the same level as basal application of N (Wang et al., 2014).

Conventional flooding irrigation was the traditional irrigation method used in this region (Peng et al., 2015); 30–40 mm of standing water was constantly maintained after transplanting, until the late tillering and ripening phases. For the controlled irrigation, 10–20 mm of standing water was maintained only during the re-greening stage, with limited subsequent irrigation to keep the soil moist.

Table 1
Summary of fertilization and irrigation treatments used in this study.

Treatment	Fertilization	Irrigation
CIN0	Conventional level of nitrogen fertilizer application (300 kg N·ha^{-1})	Controlled irrigation
CIN1	90% of the conventional level of nitrogen fertilizer application (270 kg N·ha^{-1})	Controlled irrigation
CIN2	80% of the conventional level of nitrogen fertilizer application (240 kg N·ha^{-1})	Controlled irrigation
CIN3	60% of the conventional level of nitrogen fertilizer application (180 kg N·ha^{-1})	Controlled irrigation
CFN0	Conventional level of nitrogen fertilizer application (300 kg N·ha^{-1})	Conventional Flooding irrigation
CFN1	90% of the conventional level of nitrogen fertilizer application (270 kg N·ha^{-1})	Conventional Flooding irrigation
CFN2	80% of the conventional level of nitrogen fertilizer application (240 kg N·ha^{-1})	Conventional Flooding irrigation
CFN3	60% of the conventional level of nitrogen fertilizer application (180 kg N·ha^{-1})	Conventional Flooding irrigation