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Mitigating gaseous nitrogen emissions intensity from a Chinese rice cropping system through an improved management practice aimed to close the yield gap

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ABSTRACT

A major challenge in cereal production is achieving the dual goal of closing yield gaps without further undermining environmental benefits by increasing gaseous nitrogen (N) emissions. To address this challenge, we conducted a two-rotation field experiment with four different management practices in the Taihu Lake region to gain insight into crop yields, N use efficiency (NUE), and the emission fluxes of nitrous oxide (N_2O), nitric oxide (NO), and ammonia (NH_3) from the rice cropping system. The four practices were a control (CK, local practice with zero N-fertilizer), the current traditional practice (CT, local practice with farmers' N management), an improved practice (IP, which closed the yield gap with a reduced N dose of 25%), and a high-yield practice (HY, which maximized the attainable yield with more nutrient inputs). The HY attained the yield potential that was higher by 40% than current yield from the CT. The IP closed the yield gap, achieving 80% of the yield potential, and increased the NUE by 31% and reduced the N surplus by 57% compared with the CT. The lower N surplus of the IP resulted in a decrease in the N_2O and NH_3 emissions intensity (the N_2O or NH_3 emission per unit crop yield) of 40% and 65%, respectively relative to the CT. Low NO emissions concomitant with yield increases incurred the marginal NO emission intensity. Thus, the IP should be a promising strategy to increase yield while simultaneously mitigating the gaseous N emissions intensity. Linear or nonlinear responses of gaseous N emissions (N_2O, NO and NH_3) by N fertilizer to incremental N surplus suggested that reducing the N surplus by both increasing the crop uptake and optimizing N management should be effective in reducing projected gaseous N emissions.

1. Introduction

The Green Revolution helped to create the world's "Miracle in China," with less than 9% of the world's arable land feeding more than 22% of the world's population (Zhang et al., 2011). However, Chinese food success has been at the cost of excessive consumption of resources and ongoing environmental degradation since the 1980s (Tilman et al., 2011). In the past 10–20 years (1996–2011), the agricultural input of chemical fertilizers, such as nitrogen (N) and phosphorus (P), has continued to increase, whereas the rate of gain in cereal yields has slowed markedly and even stagnated in many areas (Grassini et al., 2013; Chen et al., 2014). That large increase in input without a correspondingly large increase in yield further lowered the already-low ratio of grain harvested to fertilizer applied in China. For example, often twice as much fertilizer N is applied than is recovered in crops, which, in turn, results in a nutrient surplus and drives environmental damage mainly by reactive N (Nr) losses (Chen et al., 2011). In the coming decades, Chinese agriculture will face a crucial challenge from multiple pressures stemming from resource exhaustion, environmental pollution and food demand as a result of population growth and an increasing consumption of calorie- and meat-intensive diets.

An effort should be made to ensure food security without further undermining the integrity of the Earth's environmental systems in spite of these pressures. Many studies demonstrate that

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current crop cultivars or hybrids that have gained low rates of yield increase despite a high nutrient input may not reach their yield ceiling or absolute biophysical 'yield potential', owing to deficiencies in the crop growth environment that are not addressed by agricultural management practices (Mueller et al., 2012; Chen et al., 2014). For example, a recent study in the North China Plain demonstrated that an advanced 'Integrated Soil–Crop Management System' practice achieved a mean maize yield of 13.0 t ha^{-1} on 66-farm experimental plots—nearly twice the yield of current practices—with no increase in N fertilizer use (Chen et al., 2011). Fan et al. (2009) conducted field experiments in the southwest of China showing that combing a triangular transplanting pattern with split N fertilizer application increased the rice yield by 20%, saved the N fertilizer input by 18%, and reduced N losses by 44% compared with traditional practices. Several other studies suggested the improving crop cultivation, water and nutrient management practices could significantly increase crop yield (Li et al., 2012; Xue et al., 2013; Cui et al., 2014).

Increased crop yield requires increased crop biomass and a high harvest index (HI) in addition to the best-adapted cultivars or hybrids (Donmez et al., 2001; Ciampitti and Vyn, 2012). An increase of crop biomass requires crop canopies to be designed to make maximum use of solar and heat resources according to local conditions (Cui et al., 2013). Moreover, it is crucial to increase crop biomass during the critical growing period of crop. Several earlier studies generally assumed that N accumulation in major cereals occurs primarily during the pre-anthesis stage and that grain yields are largely dependent on the translocation of pre-anthesis assimilates and N uptake (Papakosta and Gagianas, 1991). However, it is now commonly believed that more N is accumulated in the middle-late growing stage of plants (Meng et al., 2013; Chen et al., 2014). For instance, rice biomass primarily increases during both tillering to anthesis and after anthesis (Li et al., 2012). Topdressing of N fertilizer during tillering, as well as heading, is thus important to regulate the population of the rice canopy and to increase the biomass. In addition, water regime of moderate alternating dry–wet irrigation can help stimulate an increase of the grain-filling rate and enhance root growth (Zhang et al., 2010), which further improves the HI (Yang et al., 2007). An approach that integrates these improved management practices may be able to close the yield gap (defined as the difference between the yield potential or the attainable yield and the observed yield in a given region) and approach the attainable yield.

Nitrogen fertilizer input to achieve synchronization between the nutrient supply and crop demand can maintain nutrient uptake for a crop yield increase. However, an N surplus (the N input minus the N removal from harvest), which occurs when the N addition exceeds the crop requirement, can result in environment pollution via gaseous emissions, leaching and runoff (Xing and Zhu, 2000). Recent studies suggested that Nr losses increased linearly or exponentially with an increasing N application rate (Cui et al., 2013; Shcherbak et al., 2014; Zhao et al., 2015). Therefore, reducing the N surplus caused by N fertilizer overuse might reduce potential Nr losses.

Paddy cultivation is conducted in approximately 33% of the cereal arable land in China (National Bureau of Statistics of the People's Republic of China, 2012). The Taihu Lake region is a major agricultural intensification region for rice cultivation in China with a typical paddy-upland rotation system. Currently, yields in this region have already stagnated or plateaued, and the N use efficiency (NUE) has been low (<30%) due to poor agricultural practices (Ju et al., 2009; Zhao et al., 2009). For example, most farmers usually apply most of the N in two split dressings (as basal and topdressings) within the first two weeks (before tillering) of the rice growing season (Fan et al., 2009). To save labor costs, farmers often allow a sparse transplanting density, which results in a low spikelet ratio of rice (Xue et al., 2011). The prevalence of the submerged irrigation practice inhibits the tillering number and the root growth of rice and increases the potential for the occurrence of plant diseases and insect pests (Zhang et al., 2008). In addition, an input of as much as 300 kg N ha^{-1} yr^{-1} N fertilizer in paddy fields exceeds the crop demand and has caused high proportion of N losses to the environment (Ju et al., 2009; Huang and Tang, 2010). Recently, a high concentration of aerosol particles (PM 2.5) and enhanced N deposition from the atmosphere could be partly attributed to comprehensive effects of gaseous N emissions such as nitrous oxide (N_2O), nitric oxides ($NO + NO_2$) and ammonia (NH_3) arising from local agricultural activity.

Improved management practices (previously mentioned) in the Taihu Lake region could increase yield and improve the NUE. However, these management practices might have different effects on gaseous N emissions. Reducing the N input seems to decrease available substrates for nitrification or denitrification and retard N_2O or NO production. Nevertheless, N_2O- or NO-producing microbes simultaneously compete with plants for soil N after an N input to soil. Optimal conditions for microbes could allow better competition for soil N than that by plants. Split N application might offer more opportunities for microbes and plants to compete for soil N. The water regime is also one of the most important agricultural activities directly affecting N_2O or NO emissions in rice paddies (Zou et al., 2007). In contrast to continuous flooding and midseason drainage irrigation, alternating dry–wet irrigation often triggers substantial N_2O emissions from rice paddies (Zheng et al., 2000 Zou et al., 2007). Whether this improved management practice significantly increases yield while simultaneously reducing gaseous N emissions must be further addressed.

Therefore, we established a two-rotation field experiment with four different management practices to assess their effects on crop yield, NUEs; and the emission fluxes of N_2O, NO and NH_3 from the rice fields in a rice–wheat rotation system in the Taihu Lake region of China. The objectives of this study were to quantify the effectiveness of the improved management practices in closing the yield gap while simultaneously reducing gaseous N emissions from the paddy field.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at the Changshu Agro-ecological Experimental Station (31°32′45″N, 120°41′57″E), Chinese Academy of Sciences. The station is located in the Taihu Lake region of China. Paddy-upland rotation (rice–wheat or rice–rape) is the general cropping system in this region. The area is 1.3 m above sea level and has a humid subtropical monsoon climate. The soil is a gleyed paddy soil developed from lacustrine sediments, classified as a Gleyi-stagnic Anthrosol. The topsoil (0–20 cm) has a pH of 7.6, containing 35.0 g kg^{-1} of organic matter, 2.12 g kg^{-1} of total N, and 0.93 g kg^{-1} of total P. The daily mean air temperature and precipitation during the experiment were recorded by an automatic weather station in the experimental station.

2.2. Field treatments

The experimental campaign covered two rice seasons of a summer rice (*Oryza sativa* L.)–winter wheat (*Triticum aestivum* L. cv) rotation system, from June 1 to November 1, 2009, and from June 1 to November 1, 2010. Four treatments were assigned to the field: a control (CK, local practice with no N-fertilizer); the current traditional practice (CT, local practice with farmers' N management); an improved practice (IP, which closed the yield gap with a reduced N dose of 25%); and a high-yield practice (HY, which