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Do high nitrogen use efficiency rice cultivars reduce nitrogen losses from paddy fields?

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ABSTRACT

Several high nitrogen use efficiency (high-NUE) rice cultivars have been developed to meet the increased food demand and urgent environmental concerns, but the effect of these cultivars on reducing N losses from paddy fields is not well documented. A two-year field experiment was conducted in the Taihu Lake region of China to evaluate the advantages of high-NUE rice on yields and N losses in 2011 and 2012. Two "high-NUE" rice cultivars and a conventional cultivar were compared at the same fertilizer N input of 200 kg N ha^{-1}. Ammonia (NH_3) volatilization, N_2O emission, N leaching and runoff losses were monitored during the entire rice growing season within a rice–wheat rotation. The high-NUE rice cultivars Wuyunjing 23 (W23) and Zhendao 11 (Z11) achieved higher grain yields, and took up more N with a higher NUE than the conventional cultivar Wuyujing 3 (W3). There was a trend toward smaller N losses with the high-NUE cultivars W23 and Z11 (N leaching, N_2O emissions and NH_3 volatilization decreased by 12–23%, 5–10% and 2–8%, respectively), but the total reductions for the growing season compared to W3 were not statistically significant. Even though the high-NUE cultivars did not significantly decrease the absolute losses of N from the field, they did show lower N losses expressed on a yield-scaled basis than the conventional cultivar due to higher grain yields. Cultivars W23 and Z11 produced 21–27% less NH_3 volatilization, 23–26% less N_2O emission, 23–33% less N leaching, and 13–24% less N in runoff per ton of rice grain harvested than those of W3. Another cultivar Aoyusi 386 (A386), known to have a higher N uptake at early growth stages than W23 and Z11 was also planted in 2012. This cultivar significantly reduced N losses compared with the conventional variety. It was concluded that improving N uptake rate of high-NUE cultivars in the early stages of growth would be most effective in decreasing N losses and that the main part of N fertilizer applications should be later in the growing season than is currently practiced in the region.

1. Introduction

China is one of the major rice producers globally. Approximately, 26% of its total cultivated land is utilized for growing rice (Zhao et al., 2009). However, with the expansion of infrastructure, industrialization, and urban encroachment, the area of arable lands has shrunk rapidly in recent years. Meanwhile, the population is steadily increasing and living standards are expected to improve further. Hence, the demand for food, feed and fiber is expected to continuously increase in the future (Zhu and Chen, 2002). Many farmers in China apply more chemical nitrogen (N) fertilizer than needed to ensure high grain yields. It has been reported that grain production and fertilizer N consumption reached 502 million and 32.6 million tons nationally in 2007, increases of 54 and 191%, respectively, as compared with 1980, when fertilizer N production was 12.3 million nationally (Zhu and Chen, 2002; Guo et al., 2010). Over-applying N fertilizer in some regions has resulted in decreased N use efficiency (NUE) (Zhang et al., 2009; Qiao et al., 2012; Sun et al., 2012) and increased N losses to water bodies through nitrate leaching and surface runoff and to the atmosphere

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through ammonia (NH_3) volatilization and nitrous oxide (N_2O) emission (Vlek and Byrnes, 1986; De Datta and Buresh, 1989; Min et al., 2011, 2012; Shang et al., 2013). Those losses will eventually contribute to air pollution, climate change, biodiversity loss, and eutrophication of water systems (Kronzucker et al., 2003; Shi et al., 2009; Shen et al., 2010; Liu and Zhang, 2011; Qiao et al., 2012). In recent years, environmental pollution related to N fertilizer applied to paddy fields has attracted great attention. As a result, many methods have been proposed to reduce N losses, including N application models, site-specific N management (SSNM), split application to match N needs of crops, and other water and nitrogen management improvements (Pampolino et al., 2007; Wang et al., 2007; Ju et al., 2009; Sun et al., 2012; Sun et al., 2013). However, some of these approaches are difficult for farmers to implement, especially in China where farm sizes are very small. Farmers have been following traditional farming practices, and have challenges in adapting modern agricultural techniques.

Technological developments in rice breeding have allowed breeders to develop rice cultivars classified as high-nitrogen use efficiency (high-NUE) because they produce higher grain yields than traditional varieties with the same rate of N application (Moll et al., 1982; De Macale and Velk, 2004; Zhang et al., 2009). Jiang et al. (2004) showed that high-NUE rice cultivar Liangyoupeijiu (hybrid rice) produced 10–27% higher grain yield than low-NUE rice cultivar Baguixiang (inbred rice) under the same N input level during a two-year field experiment. Gueye and Becker (2011) also indicated that high-NUE rice cultivar Farox 239-3-3-2 (conventional *Japonica*) had 38% greater yield than low-NUE IR 31851 (conventional *Japonica*) under the same N application rate. Other studies have also demonstrated high-NUE rice cultivars responded well to N fertilizers and generated higher yields compared to conventional low-NUE cultivars (Ladha et al., 1998; Wang et al., 2004; Li et al., 2012). The cultivation of high-NUE rice cultivars is believed to offer significant potential for alleviating N losses to water bodies and the atmosphere whilst concurrently addressing the increasing demand for food (Guindo et al., 1994; Wu and Tao, 1995; Raun and Johnson, 1999; Glass et al., 2002; Lian et al., 2006; Shi et al., 2010).

The characteristics of high-NUE rice cultivars have been studied in recent years. Zhang et al. (2009) suggested that high-NUE rice cultivars (conventional *Japonica*) accumulated more N and exhibited higher physiologically-based NUE than low-NUE rice cultivars (conventional *Japonica*). Fan et al. (2010) indicated that high-NUE conventional *Japonica* rice cultivars possessed greater roots length and surface area compared with low-NUE rice cultivars (conventional *Japonica*) and a higher roots exudation rate indicating stronger roots. Shi et al. (2010) found that high-NUE rice cultivars (conventional *Japonica*) almost invariably showed higher N uptake efficiency than low-NUE varieties at the seedling stage in conditions of low N, which was mainly attributed to 20–30% higher activities of the N metabolic enzymes (GS and NADH-GOGAT) in the roots of high-NUE cultivars. Chen et al. (2013) demonstrated that the high-NUE was partially attributed to higher tolerance to ammonium toxicity. It is proposed that these attributes enable high-NUE rice cultivars to alleviate the negative environmental impacts of using urea or ammonium-based N fertilizers in paddy fields. However, this remains to be validated in the field.

We conducted a two-year field experiment near Yixing City in the Taihu Lake region, a highly developed and densely populated region of southeast China. Nitrogen losses via NH_3 volatilization, N_2O emission and N losses through leaching and runoff from paddy fields cultivated with high- and low-NUE rice cultivars at the recommended N rate (200 kg N ha^{-1}), which was suggested by agronomists in view of balances between rice grain yield and environmental impacts in the Taihu Lake region (Zhu et al., 2010), were monitored. The objectives were to investigate whether high-NUE rice cultivars in the Taihu Lake region can play an effective role in alleviating N losses from paddy fields, and to identify the N loss pathways. The results of this study can provide useful information for understanding how high-NUE rice cultivars alleviate N losses in paddy fields and how to guide local farmers to implement best management practices.

2. Materials and methods

2.1. Experimental design

Field experiments were conducted in Yixing City, Jiangsu Province, China, in 2011 and 2012. Yixing is located in the Taihu Lake region (30°5′–32°8′N, 119°8′–121°5′E) and is within the northern subtropical humid climatic zone. Yixing has an average annual temperature of 16 °C and annual average rainfall of 1250 mm. The soil at the experimental site was a Gleyic-Stagnic Anthrosol developed on a lacustrine deposit. Summer rice and winter wheat double cropping is practiced in this region. Soil samples for site characterization were collected from the top 20 cm of the soil profile before rice cultivation and showed the following analysis: organic carbon, 13.2 g kg^{-1}; total N, 1.45 g kg^{-1}; alkali-hydrolyzable N, 148.9 mg kg^{-1}; Olsen P, 27.4 mg kg^{-1}; NH_4OAC-extractable K, 39.3 mg kg^{-1}; and pH (1:1 soil to water) 5.4.

The experiment was conducted with a split-plot design with three rice cultivars as the main plots and two N application rates, namely 0 (CK) and 200 (recommended input) kg N ha^{-1}, as subplots (in triplicate). Each main plot was 60 m^2 in area and the subplots were 20 m^2. Each cultivar in the subplot contained approximately 480 hills of rice plant transplanted by hand.

Urea was applied as N fertilizer in the following proportions: 40% as basal fertilizer prior to transplanting, 30% as top-dressing fertilizer before the tillering stage, and another 30% as the second top-dressing fertilizer before the ear differentiation stage. Superphosphate (75 kg P_2O_5 ha^{-1}) and potassium chloride (130 kg K_2O ha^{-1}) were broadcast and incorporated into the plow layer before planting. The two top-dress fertilizations were surface-applied without incorporation. Mid-season aeration (water drained for approximately one week) was used to inhibit ineffective tillering and improve rice root growth. Final drainage was practiced for maturing and harvesting of rice. The floodwater was maintained in the plot at a depth of 3-5 cm during the rice season except for the mid-season aeration or final drainage periods.

2.2. Rice cultivars and experimental treatments

Three rice cultivars (conventional *Japonica*), namely Wuyunjing 23 (W23), Zhendao 11 (Z11), and Wuyujing 3 (W3), were selected in the 2011 rice season based on grain yield level according to the China Rice Data Center (http://www.ricedata.cn/variety/), where W23, Z11 and W3 were approved in 2010, 2010 and 1992 by the Department of Agriculture Jiangsu Province with grain yields of 659 kg ha^{-1}, 660 kg ha^{-1} and 550 kg ha^{-1}, respectively. Cultivars W23 and Z11 achieved higher grain yields with the same fertilizer N input, hence, were classified as high-NUE cultivars. W3 had relatively lower grain yield, thus, was classified as a low-NUE cultivar. The selected rice cultivars were all developed in the Taihu Lake region. W3 was a traditional cultivar that had been cultivated widely for many years, while W23 and Z11 were newly developed and not yet adopted by farmers. In addition to the three rice cultivars described earlier, another rice cultivar (conventional *Japonica*), Aoyushi 386 (A386), was added in the 2012 rice season. A386 was chosen by an earlier hydroponic experiment. A386 accumulated 370 mg dry matter and 2.05 mg N in one plant after 25 days' hydroponic cultivation, which was obviously larger than 316 mg and 1.54 mg, respectively for W23 (unpublished).