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Ammonia volatilization losses from a rice paddy with different irrigation and nitrogen managements

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ABSTRACT

Ammonia volatilization (AV) is one of the main pathways of nitrogen (N) loss from a rice paddy, which results in low N use efficiency and many other environmental problems. To reveal AV losses from rice paddies with different combined irrigation and N managements, field experiments were conducted using site-specific nutrient management (SSNM), controlled released nitrogen management (CRN), and non-flooding controlled irrigation (NFI). The interactive effect of N management and irrigation management on AV losses is significant. N management is the dominant management factor of AV losses from a rice paddy. Weekly AV losses followed by fertilization comprise the majority of seasonal AV losses. Ammonium contents in surface water or top soil solutions determine the AV loss rate for both flooding irrigation (FI) and NFI paddies. Moreover, AV losses are less sensitive to surface ammonium nitrogen contents for the NFI paddy than that for the FI paddy. Shallower water condition in the NFI paddy immediately after fertilization may result in higher AV losses than that in the FI paddy in a short term during the first wet–dry cycle after fertilization. However, the following wet–dry cycles result in lower AV losses in most of the rice growth stages. Seasonal AV losses from the NFI paddy using farmers' fertilization practice (FFP), SSNM, and CRN treatments were 125.27, 37.63, and 23.73 kg N ha^{-1}, which account for 31.1%, 23.2%, and 13.2% of the seasonal N inputs, respectively. These results were reduced by 14.0%, −17.1%, and 28.7% compared with those from the FI paddy with the same N management. A combination of NFI and CRN is the optimal treatment, with the lowest AV losses and high potential in reducing nutrient leaching risks. Increasing the water depth and the duration of flooding for the first wet–dry cycle after fertilization is a promising measure to reduce AV losses and improve N use efficiency in an NFI paddy.

1. Introduction

Fertilizer nutrient input, especially nitrogen (N) fertilizer, plays an important role in increasing crop yields. To maximize grain yield, farmers often apply a much higher amount of nitrogen fertilizer than the crops needed. High N inputs always result in low N use efficiency and serious N losses (Wang et al., 2001; Peng et al., 2006), and consequently lead to serious pollutions of surface water, groundwater, and atmosphere (Liu and Diamond, 2005, 2008; Ju et al., 2009).

Paddy rice is one of the most important cereal crops in Monsoon Asia (Kyuma, 2004). N use efficiency is relatively low in irrigated rice because of rapid N losses through ammonia volatilization (AV), denitrification, surface runoff, and leaching (Zhu and Chen, 2002). China is the primary rice-producing country in the world. Its rice planting area and total production quantity are 29.88 million hectares and 196.68 million tons, respectively, accounting for about 18.88% of the rice planting area worldwide and 28.70% of the global rice production in 2009 (FAO, 2009). The rice high yields in China are also achieved through high chemical N application rates. Taking rice cultivation in the Tai-lake region as an example, an economically developed area of China confronted with the most serious problems of eutrophication resulting from agricultural non-point pollution, an average of 300 kg N ha^{-1} of chemical N fertilizer (some even reach 350 kg N ha^{-1}), is applied to the paddy soil (Lin et al., 2007). This is much higher than the optimal level of N fertilizer application ranging from 185 kg N ha^{-1} to 270 kg N ha^{-1} (Wang et al., 2004a; Huang et al., 2007; Xia and Yan, 2011) reported in China, and ranging from 26 kg N ha^{-1} to 190 kg N ha^{-1} reported in India (Alivelu et al., 2006). Such large amount of chemical N fertilizer application to the paddy soil in this region resulted in much lower N utilization efficiency and much higher N losses.

AV is one of the main pathways of N loss from soils. Previous measurements showed that N losses through AV were about 10–60% of N applications in paddy fields (Fillery and De Datta, 1986; Cai and Zhu, 1995; Cai, 1997; Tian et al., 2001; Song et al., 2004;

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Liang et al., 2007). Large amounts of volatilizing NH_3 result in high N loads to the environment through the atmospheric transportation and deposition processes. Continuous and excess N loads eutrophicate the environment, whereby ecosystems may suffer various impacts, such as acidification (Vitousek et al., 1997; Van der Eerden et al., 1998), eutrophication of surface water (Bobbink et al., 1992), and changes in biodiversity (Peoples et al., 2004; Stevens et al., 2004; Emmett, 2007). AV rate is induced by fertilizer application, weather conditions, and water management practices (Fenn and Hossner, 1985; Jayaweera and Mikkelsen, 1991; Sommera et al., 1991; Aneja et al., 2000; Fan et al., 2005; Hayashi et al., 2006; Li et al., 2008). The degree of AV losses differs with the N fertilizer types and N application methods in flooding paddy. Ammonium bicarbonate always resulted in a higher AV rate than urea (Cai et al., 1986). Puddling N fertilizers into the plowed layer always resulted in a lower AV rate than top dressing N fertilizers onto the paddy fields (Fillery et al., 1984; Cai et al., 1986; Obcemea et al., 1988; Zhu et al., 1989; Hayashi et al., 2008). High temperature, high wind velocity, and long sunshine duration always resulted in an increased AV rate compared with rainy or cloudy weather condition (Freney et al., 1981; Denmead et al., 1982).

In recent years, great efforts have been made to increase both the N and water use efficiency of irrigated rice. Real-time N management or fixed-time adjustable-dose N management is usually employed to dynamically adjust N application to accommodate field- and season-specific conditions, called site-specific nutrient management (SSNM). Moreover, controlled released nitrogen (CRN) fertilizers have been considered an important potential method for improving the efficiency of N fertilizer with reduced possibility of loss through leaching, volatilization, and surface runoff (Friedman and Mualem, 1994; Delgado and Mosier, 1996; Shoji et al., 2001; Javier et al., 2007; Pereira et al., 2009). In addition to N management, efficient irrigation techniques, such as non-flooding controlled irrigation (NFI) (Peng, 1992; Mao, 2001; Peng et al., 2011), saturated soil culture (Borell et al., 1997), dry–wet alternate irrigation (Li, 2001; Tabbal et al., 2002; Belder et al., 2004; Peng and Bouman, 2007), the system of rice intensification (Stoop et al., 2002; Uphoff et al., 2011), ground cover systems (Tao et al., 2006), and aerobic cultivation (Bouman and Tuong, 2001) have been tested to be feasible in high water use efficiency.

In the rice regions of China, especially in that of the Tai-lake region, efficient water use and N management practices for rice fields are widely implemented. However, much more attention has been paid on the rice yields and water as well as N use efficiency than on the quantity analysis of its environmental benefits. Wet–dry cycles and staged non-flooding condition result in a significant change in both surface ammonium content dynamics and soil properties (Mao, 2002; Yang et al., 2008), which will alternate the AV losses from rice paddies. A high floodwater level could prevent AV (Freney et al., 1988; Williams et al., 1990; Bhagat et al., 1996), and zero-drainage management during the first flooding–drying cycle after N application was effective in controlling AV from rice paddies (Li et al., 2008). However, Zhao et al. (2010) argued that the total AV loss increased by 23.6–46.7% using the system of rice intensification compared with traditional flooding. Scivittaro et al. (2010) indicated that moist soil result in higher AV losses than the muddy soil. Therefore, the behaviors of AV losses are expected to change under an efficient irrigation and combined water and N fertilizer managements. Recognizing the above concerns, based on the paddy field experiments in the Tai-lake region of China using the efficient nitrogen management (SSNM and CRN) and NFI, the current study attempted to quantify the AV losses from rice paddies with different irrigation and N managements and to reveal the influence of irrigation management, nitrogen management, and combined irrigation and N management on AV losses from rice paddies.

2. Materials and methods

2.1. Experiment site

The experiment was conducted in 2008 on rice fields at Kunshan irrigation and drainage experiment station (31°15′15″N, 120°57′43″E) in the Tai-lake region of China. The study area has a subtropical monsoon climate, with an average annual air temperature of 15.5 °C, a mean annual precipitation of 1097.1 mm, and a frost-free growing season of 234 days/year (from March to November). The soil type of the experimental field is dark-yellow hydromorphic paddy soil. The soil texture in the plowed layer is clay, with an organic matter of 30.3 g kg^{-1}, total nitrogen of 1.79 g kg^{-1}, total phosphorus of 1.4 g kg^{-1}, total potassium of 20.86 g kg^{-1}, and pH of 7.4 (soil/water, 1:2.5). The saturated soil water contents (vol/vol) for the layers of 0–20 cm (θ_{s1}), 0–30 cm (θ_{s2}), and 0–40 cm (θ_{s3}) are 54.4%, 49.7%, and 47.8%, respectively. The variety of rice is Japonica Rice Jia33, one of the prevailing varieties in this region (Li et al., 2007), which was transplanted with 16.7 cm × 26.7 cm hill spacing on June 25 and harvested on 25 October 2008.

2.2. Experiments design

Two irrigation treatments (flooding irrigation (FI) and NFI) have been designed for the experiment. Concurrently, there were three N fertilizer treatments for each irrigation treatment (i.e., farmers' fertilization practice (FFP), SSNM, and CRN). A randomized complete block design with all the six treatments and three replications, was established in 18 plots of 35 m^2 (5 m × 7 m). The ridges, 300 mm wide at the base and 200 mm high, were covered with a plastic membrane that was inserted into the soil plough layer to a depth of 300 mm at both sides of the ridges, to isolate the water within different plots and avoid hydraulic exchange between adjacent plots.

For the FI treatment, a depth of 3–5 cm standing water was always maintained after transplanting, except in the later tillering period and the yellow maturity period. For the NFI treatment, the ponded water depth was kept between 5 mm and 25 mm during the first 7 days or 8 days after transplanting (DAT) in the regreening period; then, irrigation was applied only to keep the soil moist. In addition, standing water depth was avoided in all the stages except during the pesticide and fertilizer applications periods or

Table 1
Soil moisture limits for irrigation in different stages of rice for non-flooding controlled irrigation (NFI).

Limits	Re-greening	Tillering			Jointing and booting	Heading and flowering	Milk maturity	Yellow maturity
		Initial	Middle	Late				
Upper limit[a]	25 mm	θ_{s1}	θ_{s1}	θ_{s1}	θ_{s2}	θ_{s3}	θ_{s3}	Naturally
Lower limit	5 mm	$0.7\theta_{s1}$	$0.65\theta_{s1}$	$0.6\theta_{s1}$	$0.75\theta_{s2}$	$0.8\theta_{s3}$	$0.7\theta_{s3}$	drying
Monitored root zone depth (cm)	–	0–20	0–20	0–20	0–30	0–40	0–40	–

[a] θ_{s1}, θ_{s2}, and θ_{s3} are saturated volumetric soil moisture for the layers of 0–20 cm, 0–30 cm and 0–40 cm respectively.