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Integration of urea deep placement and organic addition for improving yield and soil properties and decreasing N loss in paddy field

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ABSTRACT

Few studies have examined nitrogen (N) loss and crop yield under urea deep placement combined with organic addition in highly fertilized paddy field. Therefore, a three-year paddy field trial was conducted in Taihu Lake region of China to gain insight into yields, NH_3 volatilization and N leaching. Six treatments were used: control (CK, zero N application), conventional (CT, broadcasting of 300 kg ha^{-1} N), recommended N (RT, broadcasting of 225 kg ha^{-1} N), organic addition (RTM, broadcasting of 225 kg ha^{-1} N and organic N), N deep placement (RTD, deep placement of 225 kg ha^{-1} N) and organic addition combined with N deep placement (RTDM, organic N combined with deep placement of 225 kg ha^{-1} N). Compared to the CK treatment, the RTM and RTDM treatments increased soil organic matter by 8%–11% and TN by 9%–14%. NH_3 loss was dominated by floodwater NH_4^+-N concentration and increased with the increase of chemical N use. The RTM treatment had obviously higher floodwater NH_4^+-N concentration and NH_3 loss than the RT treatment. By contrast, NH_3 loss in the RTD and RTDM treatment was 84%–89% less than in the RT treatment, only accounting for 0.2%–1% of the total N application. Compared to NH_3 volatilization, N leaching was low; and NO_3^--N in the percolation water prevailed over NH_4^+-N and was linearly correlated with floodwater NO_3^--N concentration. NO_3^--N and TN leaching between the CT and RTDM treatments differed little ($p > 0.05$). N loss (NH_3 loss and N leaching) induced by fertilizer was linearly correlated with N surplus. By comparison with the CT treatment, the RTDM treatment decreased N surplus by 73.1%, and increased grain yield by 18.3% and N recovery efficiency by 63.8%. The RTD treatment also had higher rice yield than the CT treatment, whereas unfavorable delayed senescence occurred in it in 2016 and led to a marked decrease of grain yield. The RTD treatment significantly increased plant N uptake (PNU) by rice straw compared to chemical N treatment and had the lowest N harvest index (NHI) and N physiological efficiency (NPE) among the fertilizer treatments. In short, urea deep placement combined with organic addition was superior to N deep placement or organic addition combined with N broadcasting to decrease N loss and increase grain yield, representing an effective and promising practice to achieve food and environmental security.

1. Introduction

Rice is the staple food for more than half of the world's population and the main crop in Asia (Patel et al., 2010). China, which is one of the largest rice producers in the world, plays a major role in global food security (FAO, 2013). To increase crop yield and feed the large population, chemical fertilizer applied to farmland has increased since 1980s. About 27 Tg of fertilizer N was annually applied for crop production during 2001–2010 in China (Yan et al., 2014); and more than 15% of the total fertilizer N was used for rice production (Heffer, 2013). In Taihu Lake region, one of the most densely populated and intensively cropped areas in China, the average N input for a single paddy field is as high as 300 kg N ha^{-1} (Zhao et al., 2012). However, recent studies show that the rate of rice yield has slowed markedly and even stagnated in many areas of China despite of the increased rate of N application (Zhao et al., 2015). And the excessive N input without corresponding increase of crop yield led to the low N use efficiency and resulted in fertilizer N loss to the environment through ammonia, leaching, runoff and N_2O emission, causing a series of environmental issues (Qin et al., 2007; Chen et al., 2010; Yang et al., 2013).

Ammonia volatilization which is the main pathway of N loss in rice fields may have significant environmental effects, including effects on

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the local, regional and global nitrogen cycles (Zhang et al., 2011; Cao et al., 2013). The sinking of NH_3 can directly or indirectly cause soil acidification, eutrophication of water bodies and loss of biodiversity (Qin et al., 2007; Shang et al., 2014). As an alkaline gas in atmosphere, ammonia also plays an important role in the formation of sulfate, nitrate and ammonium which are important constituents of urban aerosol particle and accounts for 30%-70% of $PM_{2.5}$ (Wei et al., 2014). Agricultural activities, such as fertilizer input and livestock production, are demonstrated to be the largest global emission source of NH_3 (Huang et al., 2016). In China, the total NH_3 emission from synthetic N was estimated to be 2.8–3.55 Tg yr^{-1}, with a value of 0.3-0.65 Tg yr^{-1} in paddy fields (Zhang et al., 2011; Huang et al., 2012; Cui et al., 2014; Kang et al., 2016). Thus, an effort should be made to decrease NH_3 loss from agricultural fields to reduce environmental pollution. Many improved N management practices were conducted to reduce NH_3 loss, such as site-specific nutrient, controlled-release fertilizer, urease inhibitors, and split N application (Hu et al., 2007; Peng et al., 2012; Yang et al., 2012). However, the development of these practices was restricted by the related knowledge requirements, higher prices or extra labour inputs. Urea deep placement for one time was recommended in many studies (Savant and Stangel, 1990; Liu et al., 2015). Compared to broadcasting, urea deep placement (at depths of 5–15 cm) in paddy fields was showed to evidently decrease floodwater NH_4^+-N concentration; and a 15%–45% reduction of ammonia loss was found in the previous studies (Kapoor et al., 2008; Liu et al., 2015; Huda et al., 2016).

To meet the crucial challenges (resource shortage, increased food demand and environmental pollution) in the future, China needs to not only prevent environmental degradation but also increase crop production. As the populations rises, China will need to produce about 20% more rice yield by 2030 to meet the domestic demands (Peng et al., 2009; Grassini et al., 2013). Compared to broadcasting, deep placement of N was demonstrated to be an effective way in improving crop yields (Mohanty et al., 1998; Kapoor et al., 2008). In previous researches, urea deep placement increased the absorption of N by crop, promoted the root growth, and improved the rice production (Savant and Stangel, 1990; Liu et al., 2015). However, the positive effects of N deep placement on crop yield and N loss in the previous studies were mainly at low N application rates which were lower than 120 kg N ha^{-1} (Savant and Stangel, 1990; Mohanty et al., 1998; Kapoor et al., 2008). In Chinese paddy fields, which are over fertilized, the effect of N deep placement on rice yield and N loss might be different. N deep placement at high rate for one time lead to excessive N in the deep rhizosphere, and might result in the lavish N absorption by crop (high N absorption by crop straw) and unfavorable-delayed senescence (plants remain green at harvest), which went against the increase of crop yield. Exposing paddy field to sun during the late tillering period to control the inefficient tiller could be an effective method to avoid the unfavorable condition (Yang et al., 2001). Moreover, some studies showed that increasing the potassium fertilizer rate could promote crop to ripen (Zhou and Sun, 2010; Chen, 2014). Organic addition, which brings extra potassium input, might be a useful practice to retard the occurrence of unfavorably-delayed senescence.

Organic fertilizer combined with chemical N was demonstrated to decrease NH_3 loss and increase crop yield, whereas the results depended on the fertilizer types, quantity and the application method (Banerjee et al., 2002; Zhang et al., 2013; Xue et al., 2014). The effect of organic addition combined with N deep placement on NH_3 loss and rice yield was rarely studied. N leaching, which may cause underground water pollution and threaten public health, is another important way of N loss in paddy field (Tian et al., 2007; Cao et al., 2014). However, the effect of N deep placement on N leaching was different in the former studies and still needs further study (Vlek et al., 1980; Mohanty et al., 1998; Bautista et al., 2001). Therefore, we conducted a field trial during 2014–2016 in Taihu Lake region with three N levels (0, 225, and 300), aiming to study the effect of organic fertilizer addition combined with deep placement on NH_3 volatilization, N leaching and crop yield.

2. Materials and methods

2.1. Experimental site

The field plot experiment was performed at the Changshu Agroecosystem Experimental Station (31°15′15″N, 120°57′43″E), Chinese Academy of Sciences, in the Taihu Lake region, China. The dominant cropping pattern in this region is summer rice and winter wheat rotation. The climate is classified as humid subtropical monsoon, with an annual average air temperature of 15.5 °C, mean annual precipitation of 1038 mm, and a frost-free period of 224 days. The soil is classified as Hydragric Anthrosols, a waterlogged soil developed from lacustrine deposits with the following characteristics (0–20 cm): pH (H_2O), 7.35; organic matter, 35 g kg^{-1}; total N, 2.09 g kg^{-1}; total P, 0.93 g kg^{-1}; available K 121.3 mg kg^{-1}; and cation exchange capacity (CEC), 17.7 cmol kg^{-1}.

2.2. Field plot experiment

Field experiments were conducted for three consecutive rice seasons (*Oryza sativa L., cv. Changyou 5*) of a summer rice-winter wheat rotation system, from Jun 24 to Nov 5, 2014, from Jun 22 to Nov 9, 2015, and from Jun 22 to Nov 3, 2016. There were six treatments, namely, control (CK, local practice with no N-fertilizer), conventional treatment (CT, local practice with farmers' N management), recommended treatment (RT, local practice with recommended N application rate), organic fertilizer addition combined with recommended N treatment (RTM), deep placement of recommended N treatment (RTD) and organic fertilizer addition combined with deep placement of recommended N treatment (RTDM). They were performed with four replicates in a completely randomized plot with an area of 40 m^2 for each (limited by the labour, the area of RTD and RTDM is 4 m^2). The fertilizers included synthetic and organic forms. The synthetic fertilizers were urea (N, 46%), superphosphate (P_2O_5, 12%), potassium chloride (K_2O, 60%). The organic form referred to decaying rapeseed cake fertilizer (a month of anaerobic digestion for rapeseed cake mixed with water) which was applied 1 day before basic fertilizer, and it contained TN 18.22 g kg^{-1}, TP 2.64 g kg^{-1}, TK 3.82 g kg^{-1} and organic C 340 g kg^{-1}. Fertilizers were homogeneously broadcasted manually onto the surface water for all the treatments except the RTD and RTDM treatments, in which urea was applied once into 10 cm deep holes positioned 5 cm from the rice root as basal fertilizer. The rate and timing of fertilizers for the six treatments are shown in Table 1.

For all the treatments, rice seedlings (30 days old) were transplanted with a spacing of 20 cm × 20 cm and 3–5 cm of floodwater was maintained except during mid-season aeration (from July 23 to August 1, 2014, from July 20 to August 3, 2015 and from July 21 to August 4, 2016) and final drainage which was performed approximately 1 week before harvesting. Earthen banks covered with plastic film were constructed between each plot to prevent lateral water movement. Pesticide and herbicide application were kept the same for the six treatments.

2.3. Sampling and analysis

2.3.1. NH_3 volatilization and N leaching measurements

The NH_3 volatilization was measured by a dynamic chamber method. The system consisted of a vacuum pump, a dynamic chamber, and an acid trap to capture NH_3. The dynamic chamber was cylindrical, with an inner diameter of 20 cm and a height of 15 cm. Ambient air was taken at a height of 2.5 m above the surface water using the vacuum pump. When volatilized NH_3 was collected from the paddy field, the chamber was inserted into the surface water and soil to a depth of 7–8 cm. NH_3 in the downstream air was trapped using an acid trap