Field Crops Research 227 (2018) 102–109

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Increasing yield and N use efficiency with organic fertilizer in Chinese intensive rice cropping systems

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ARTICLE INFO

Keywords:
Organic fertilizer
Ammonia volatilization
^{15}N recovery
Rice yield
Urease activity

ABSTRACT

In China, the current high reliance on chemical nitrogen (N) in agriculture has resulted in low N use efficiency and high N loss. Reducing N fertilizer input is necessary for environmental protection, but it has not been attractive to Chinese farmers because of insufficient increase in net income. Reduced use of N fertilizer might be attractive if reduced N combined with organic fertilizer could increase rice yield. Therefore, a three-year field trial and a ^{15}N micro-plot experiment were conducted to study the effect of organic fertilizer combined with chemical N on rice yield, NH_3 loss and the fate of ^{15}N in an intensive rice cropping system in Taihu Lake region. Six treatments were used: control (0 N, zero N application), organic N alone (OrgN, 41 kg N ha^{-1}), local farmers' N practice (FN, 300 kg N ha^{-1}), reduced N (RN, 225 kg N ha^{-1}), organic fertilizer combined with FN (FN + OrgN) and organic fertilizer combined with RN (RN + OrgN). Compared to chemical N, organic fertilizer markedly increased soil organic matter content, promoted grain N accumulation, and improved rice production. Organic fertilizer treatments showed 11%–13% higher yield and 4%–5% higher net economic benefit over FN for three years. Organic fertilizer produced high NH_4^+ in the floodwater and increased NH_3 loss. Although FN + OrgN had significantly higher ^{15}N-NH_3 loss than FN, it increased soil residual ^{15}N and decreased ^{15}N loss by 29%. There was no significant difference of yield and NEB between FN + OrgN and RN + OrgN, while RN + OrgN was superior to FN + OrgN because of the lower NH_3 loss and higher N recovery efficiency (NRE). Therefore, organic fertilizer is an economically attractive practice to increase NRE and rice yield without increasing chemical N input.

1. Introduction

Rice is the main staple food for more than half of the world's population and for approximately 60% of the Chinese population (Patel et al., 2010; Xiong et al., 2013). As the population increases, China will need to produce approximately 20% more rice by 2030 to meet the domestic needs if rice consumption per capita stays at the current level (Peng et al., 2009). Chinese farmers are accustomed to relying on high chemical nitrogen (N) use to increase crop yield, making China the largest N fertilizer consumer in the world. In 2013, the N fertilizer application amount in China was 33.6 Tg, accounting for 33% of the world's N fertilizer use (FAO, 2014). During thepast 10–20 years, however, the growth of rice yields has slowed markedly and even stagnated in many areas of China despite the high N input (Grassini et al., 2013; Zhao et al., 2015). The excessive N input without a corresponding increase in crop yield led to a low NRE (Ju et al., 2009). In the Taihu Lake region, which is one of the most densely populated and intensively rice cropped areas in China, the average N input for a single rice season is as high as 300 kg N ha^{-1}, but NRE ranged from 30%–35%, which is much lower than in developed countries (Yang et al., 2013). The low N use efficiency and high N input resulted in a large portion of N lost to the ambient environment, causing environmental pollution, such as air pollution, water eutrophication and soil degradation (Galloway et al., 2008; Chen et al., 2010; Zhang et al., 2017).

To enhance N use efficiency and decrease N loss, many improved N management practices were recommended, such as site-specific N management (Xu et al., 2012), optimum N application (Chen et al., 2006), controlled-release fertilizer (Yang et al., 2012), deep placement (Yao et al., 2017), and integrated management practices (Cao et al., 2013). However, the development of these practices was restricted by the related knowledge requirements, higher prices, extra labor inputs or

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https://doi.org/10.1016/j.fcr.2018.08.010
Received 1 April 2018; Received in revised form 13 August 2018; Accepted 14 August 2018
0378-4290/

the existing technology. In contrast, organic N combined with chemical N was shown to significantly increase N use efficiency, and it was easily implemented in paddy fields (Pan et al., 2009).

With the increase in human population, it is very important to increase rice yield in the remaining agricultural land to meet current and future food demand (Mueller et al., 2012; Xie et al., 2016). Previous studies have demonstrated that organic fertilizer was a key strategy to improve soil structure and nutrient contents and result in sustainable yield growth and high economic benefits (Pan et al., 2009; Ghosh et al., 2012; Mi et al., 2016). Generally, organic fertilizer was applied to replace a portion of chemical N, but it was shown that organic fertilizer, either as a full or partial substitution for inorganic N, did not significantly affect rice yields (Huang et al., 2016). Compared to studies substituting manure for fertilizer, some studies reported that organic N additions combined with full chemical N significantly increased crop yield (Ye et al., 2011). For instance, Hati et al. (2008) found evidence of a rise in crop yield under organic fertilizer compared to chemical N practice, but Yu et al. (2013) reported that organic fertilizer combined with high fertilizer N (> 210 kg N ha^{-1}) decreased the accumulated uptake of N and decreased rice yield. In the Taihu Lake region, which is over-fertilized, compared to conventional farming systems, whether organic fertilizer improve rice yield or not still needs further study. In 2015, the Ministry of Agriculture in China announced a 'Zero Increase Action Plan' for national fertilizer use by 2020 and aims to reduce fertilizer use and the environmental cost of the fertilizer that is used (Liu et al., 2016). There was no significant reduction in rice yield when N use was reduced from 300 kg ha^{-1} to 225 kg ha^{-1} in the Taihu Lake region (Wang et al., 2004), but the increase in net income from reduced use of N fertilizer was insufficient to be attractive to Chinese farmers. Reduced use of N fertilizer might be attractive to Chinese farmers if reduced N combined with organic fertilizer could increase rice yield.

In paddy fields, ammonia volatilization is the major pathway of N loss, accounting for 10–60% of the total N applied (Lin et al., 2007; Chen et al., 2014). It was demonstrated that agriculture is the main source of NH_3 emissions (through manure and synthetic fertilizers), contributing to 80–90% of the total emission (Zhang et al., 2010). The re-deposition of NH_3 can directly or indirectly contribute to soil acidification, eutrophication of water bodies and loss of biodiversity (Huang et al., 2012; Kang et al., 2016). There are a number of studies documenting the effect of organic fertilizer combined with chemical N on NH_3 loss, and substituting organic N for fertilizer N was demonstrated to decrease NH_3 loss (Banerjee et al., 2002; Xue et al., 2014). Nevertheless, organic fertilizer combined with the full chemical N amount, which supplied extra N input, might increase NH_3 loss. Sun et al. (2009) showed that organic fertilizer combined with chemical N significantly increased floodwater NH_4^+-N concentrations, and Shang et al. (2013) found a higher NH_3 loss under organic fertilizer treatments compared to chemical N treatments. It was speculated that the higher NH_3 loss under organic fertilizer was attributed to the release of extra N from organic fertilizer and the high soil urease activity, but there was no relevant substantial research. In previous researches, organic fertilizer was shown to enhance soil productivity and decrease N leaching (Luo et al., 2011; Xue et al., 2014). Thus, even if organic fertilizer combined with high N input increased NH_3 emissions, the effect of organic fertilizer on total N loss might be different. The ^{15}N isotope can be used to directly investigate the fate of fertilizer N applied to crops (Zhao et al., 2016). However, few studies have evaluated the effect of organic fertilizer on NH_3 volatilization, floodwater N dynamics and ^{15}N fate in a single experiment. Therefore, we conducted a three-year field trial with three N levels (0, 225 and 300) and a ^{15}N micro-plot experiment in the Taihu Lake region of China, to assess the effects of organic fertilizer on crop yield, economic benefits, NH_3 loss and ^{15}N fate.

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 a summer rice and winter wheat rotation. The climate is classified as a humid subtropical monsoon, with an average air temperature of 15.5 °C, mean annual precipitation of 1038 mm, and a frost-free period of 224 days. The soil is a gleyed paddy soil developed from lacustrine sediments, classified as a Gleyi-stagnic Anthrosol, based on the FAO soil taxonomy system. The topsoil (0–20 cm) has a pH of 7.35, 35 g kg^{-1} of organic matter (SOM), 2.09 g kg^{-1} of total N, 0.93 g kg^{-1} of total phosphorus (P) and 20.2 cmol kg^{-1} of cation exchange capacity.

2.2. Experimental design

The present study included a field trial and ^{15}N micro-plot experiment. A field experiment was conducted for three consecutive rice (*Oryza sativa* L., *cv. Changyou 5*) seasons in a summer rice-winter wheat rotation system. There were six treatments: no N fertilizer application (0 N), application of only organic fertilizer (OrgN), local farmers' N fertilizer practice (FN, 300 kg N ha^{-1}), reduced N fertilizer (RN, 225 kg N ha^{-1}), organic fertilizer combined with FN (FN + OrgN) and organic fertilizer combined with RN (RN + OrgN). The organic fertilizer referred to a fermented rapeseed cake fertilizer and was applied a day before basal fertilizer to OrgN, FN + OrgN and RN + OrgN plots, with 2250 kg fresh weight ha^{-1}. The water content of the organic fertilizer was 70%, and its total N, P_2O_5 and K_2O content were 6.1%, 2.0% and 1.5% (dry weight), respectively. Organic fertilizer supplied 41 kg N ha^{-1}, 13 kg P_2O_5 ha^{-1}, and 10 kg K_2O ha^{-1}. The synthetic fertilizers were urea (N, 46%), superphosphate (P_2O_5, 12%) and potassium chloride (K_2O, 60%). N fertilizer was applied in three splits, namely, basal (40%), first topdressing (20%) and second topdressing (40%). P_2O_5 and K_2O fertilizers were applied as a basal fertilizer at 60 and 120 kg ha^{-1}, respectively. Fertilizers were homogeneously broadcast manually into surface water for the six treatments. During the three rice seasons, the application dates for basal fertilizer, first topdressing and second topdressing were Jun 26, Jul 6, Aug 15 in 2014, Jun 24, Jul 7, Aug 14 in 2015 and Jun 24, Jul 7 and Aug 8 in 2016, respectively. All treatments were performed with four replicates in a randomized complete block design. The area of each plot was 40 m^2.

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 applications were kept the same for the six treatments. Rice was harvested on November 5, 2014, November 9, 2015 and November 3, 2016.

2.2.1. Experiment I: Measurements of volatilized NH_3, yield, crop N, net economic profit and soil properties in field experiment

In the field trial, NH_3 volatilization was measured by a dynamic chamber method during 2014 and 2015 (Zhou et al., 2011; Cao et al., 2013). The system consisted of a vacuum pump, a dynamic chamber, and an acid trap to capture NH_3. The dynamic chamber was cylindrical and was made from polymethyl methacrylate, with an inner diameter of 20 cm and a height of 15 cm. Ambient air was sampled at a height of 2.5 m above the surface water using the vacuum pump. When collecting volatilized NH_3, the chamber was inserted into the soil to a depth of 2–3 cm. Next, NH_3 in the downstream air was trapped using an acid trap containing 60 ml of 0.05 mol L^{-1} diluted sulfuric acid solution.