Agriculture, Ecosystems and Environment xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Nitrogen management in a rice–wheat system in the Taihu Region: Recommendations based on field experiments and surveys

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ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form 25 March 2015
Accepted 27 March 2015
Available online xxx

Keywords:
Nitrogen fertilization
N use efficiency
N balances
Residual mineral N
N emissions
Agro-economic survey
Standard gross margin

ABSTRACT

Excessive use of mineral nitrogen (N) fertilizer has been a common practice in the high-yielding rice–wheat double-cropping system in the Taihu Region of southeastern China. As a consequence of high N balance surpluses and low N use efficiencies (NUEs), nitrogen losses to water bodies and to the atmosphere are high. Field experiments on five replicate farmers' field sites were conducted in southern Jiangsu Province over three consecutive rice–wheat double-crop rotations with three different N fertilization treatments ('conventional' (farmers' practice), 'reduced' (by 23% for rice and 32% for wheat) and zero N application). A parallel survey was carried out involving 43 farmers' households, in order to calculate standard gross margins (SGM) and to conduct an environmental assessment of the rice–wheat farming system in the Taihu Region. The results of the field experiment showed that a distinct reduction in fertilizer N application rates to summer rice and winter wheat crops is possible without significant decrease in mean grain yields. Mean grain yields for the entire double-crop rotation were 14.7 Mg ha^{-1} yr^{-1} under the conventional N fertilization practice and 14.1 Mg ha^{-1} yr^{-1} under reduced N fertilization. A significant increase in NUEs could be achieved in most years and crops under reduced N fertilization compared to farmers' practice, and N balance surpluses were significantly decreased from 142 kg N ha^{-1} to less than 60 kg N ha^{-1} yr^{-1} under the reduced N fertilization regime. The residual mineral N contents in the soil profiles after winter wheat harvest showed a decreasing tendency over time with a reduction of N fertilization. Mineral N contents in fertilized fields were significantly higher than on the zero N plots. Concentrations of NH_4^+-N in soil extracts from the puddled layer during the summer rice in 2010 showed significant differences between the two N fertilization treatments and the zero N plots. Results of the agro-economic survey showed that production of rice was 50% more profitable than that of wheat, and that fertilizer costs made up less than 20% in the rice season, but almost 50% of the total production costs during the wheat season. It can be concluded that N losses to the environment can be efficiently decreased by reducing the overall N fertilization rates without any risk of decline in grain yield and related income for farmers. Based on the field experiments and investigations, a reduction in N fertilizer application rates by 15–25% for summer rice and by 20–25% for winter wheat, compared to present levels is recommended.

1. Introduction

Agriculture in the Tai Lake (Taihu) Region in southeastern China has a long-standing history of rice (*Oryza sativa* L.) cultivation of about 7000 years (Smith, 1995). Irrigated summer rice has been grown in a double-cropping system with winter wheat (*Triticum aestivum* L.) since 1000 AD with rice as the main crop (Ellis and Wang, 1997). Traditional agricultural practices were characterized by complex crop rotations, also including mulberry cultivation and

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http://dx.doi.org/10.1016/j.agee.2015.03.032
0167-8809/

fish ponds, and an almost complete recycling of organic materials as fertilizers to the field. Soil fertility had been maintained for thousands of years and provided stable crop yields at a moderate level (Yang, 2006). However, due to a growing population in China, the introduction of new high-yielding varieties and mineral nitrogen (N) fertilizers since the late 1960s and the overall importance of food security, a rapid change in agricultural practices occurred. Over-application of N fertilizer became a common practice and, with the exception of open field vegetables, the application of organic fertilizers to field crops was almost completely abandoned (Zhu and Chen, 2002; Yang, 2006; Gao et al., 2006). In the part of the Taihu Region belonging to southern Jiangsu Province, mineral N inputs to summer rice were about 280 to 360 kg N ha^{-1} in the mid-late 1990s, those to winter wheat 185 to 285 kg N ha^{-1} (Richter and Roelcke, 2000; Roelcke et al., 2004). The resulting mean annual N balance surpluses for summer rice–winter wheat double-cropping systems at two different locations were very high, ranging from 217 to 335 kg N ha^{-1} yr^{-1} (Richter and Roelcke, 2000). Nitrogen inputs to summer rice in southern Jiangsu Province have decreased slightly since about 2001 to around 240 to 280 kg N ha^{-1} yr^{-1} in the late 2000s (Li et al., 2010; Qiao et al., 2012) and those to winter wheat have also begun decreasing in the early 2000s (Roelcke et al., 2004). Yet total annual mineral N fertilizer use currently still exceeds 500 kg N ha^{-1} yr^{-1} for one double-crop rotation. This high nutrient input in combination with improper timing of N application and a low recovery of fertilizer N by the plants have led to high N surpluses and high losses of reactive N to the environment. In a lysimeter study by Ju et al. (2009) at a research station in Changshu, southern Jiangsu Province, fertilizer N recovery efficiencies amounted to 29.6% for rice and 34.5% for wheat, and total N losses of up to 329 kg N ha^{-1} yr^{-1} were reported for one double-crop rotation under farmers' fertilization practices in the early 2000s. Consequently, the Taihu Region is faced with one of the largest net anthropogenic N inputs in China (Ti et al., 2012; Han et al., 2014). High losses of N from agricultural systems have led to eutrophication of Lake Taihu, growth of cyanobacterial blooms (Qin et al., 2007; Conley et al., 2009; Paerl et al., 2011), regularly exceeding the WHO threshold for N concentration in ground- and freshwater bodies (Chen et al., 2010), deterioration of drinking water quality (Qin et al., 2010) as well as increased atmospheric N depositions (Luo et al., 2007; Hayashi and Yan, 2010). An enhanced N deposition in terrestrial and aquatic ecosystems of currently about 21.1 kg N ha^{-1} yr^{-1}, as it was recently reported for China (Liu et al., 2013), has wide implications for human and ecosystem health, the greenhouse gas emissions and biological diversity (Matson et al., 2002; Townsend et al., 2003; Sutton et al., 2011; Bleeker et al., 2011). Moreover, recent studies have shown that the potential of greenhouse gas emissions associated with agricultural N addition in the lower reaches of the Yangtze River is among the highest in China (Tian et al., 2012) and that anthropogenic soil acidification driven by N fertilization has been significantly increased in the rice–wheat double-cropping system since the 1980s (Guo et al., 2010).

The main loss pathways of fertilizer N during the summer rice growing season are ammonia (NH_3) volatilization and denitrification. Direct measurements of NH_3 volatilization during the rice growth period in the Taihu Region under conventional fertilization practice ranged from 76 kg N ha^{-1} (Zhao et al., 2012b) and to 70 kg N ha^{-1} (Yang et al., 2013) to somewhat lower values found by Lin et al. (2007) reporting total NH_3 losses of 50 kg N ha^{-1} with a fertilizer N application rate of 300 kg N ha^{-1}, and by (Li et al., 2008) who measured NH_3 losses up to 32 kg N ha^{-1} in fields with a zero-drainage water management at an application rate of 270 kg N ha^{-1}. Ju et al. (2009) reported apparent denitrification losses of 36% of applied N to rice, while Zhao et al. (2012b) estimated mean denitrification losses of 79 kg N ha^{-1} or 22.3% of the applied N during the rice growing season (both calculated by difference-method). Denitrification is promoted by the flooding of the fields after the wheat harvest in preparation for the subsequent rice crop, by draining the fields for mid-season aeration, and before rice harvest (Fan et al., 2007; Zhao et al., 2009). In contrast, denitrification during the wheat growing season occurs mainly due to wet soil conditions, high temperatures during the spring vegetation period and relatively high carbon (C) contents of the soils in the Taihu Region, and account for 44% of applied N (Ju et al., 2009). Besides denitrification, nitrate (NO_3^--N) leaching and runoff is another major N loss pathway during the winter wheat growing season of Taihu Region. Zhao et al. (2012a) reported N losses through runoff and leaching from paddy soils of 50 kg N ha^{-1} during the wheat growth period. According to Tian et al. (2007) N losses through runoff and leaching for the whole rice–wheat double-crop rotation ranged from 14 to 48 kg N ha^{-1} yr^{-1}, while in a study by Ma (1997) they ranged between 10 and 34 kg N ha^{-1} yr^{-1} and Zhao et al. (2012a) showed that these losses can be as high as 70 kg N ha^{-1} yr^{-1}.

At present, N fertilization recommendations for the Taihu Region and Jiangsu Province are mostly based on exact field experiments on research stations or in well-managed farmers experimental field plots, subdivided into subplots that represent different fertilizer treatments. Summarizing results of exact field experiments on farmers field sites in the Taihu Region, Ju et al. (2009) found no increase in rice and wheat grain yields for N fertilization rates higher than the recommended 'optimum N fertilization', given as 200 kg N ha^{-1} for rice and 153 kg N ha^{-1} for wheat. Xia and Yan (2012) recommended N rates from 190 to 213 kg N ha^{-1} for summer rice in the Taihu Region as optimum rates from an economic and ecological point of view. The latter results were obtained using an economic evaluation model with data from several field experiments around Lake Taihu. Recommendations for N fertilizer application for winter wheat in the Taihu Region have been given by Liang et al. (2008). Based on their field trials on two research stations in the Taihu Region, the ecologically optimum N rate ranged from 120 to 180 kg N ha^{-1}.

Two similar three-year on-farm field studies were carried out in Jiangsu Province from 2008 to 2011, in southern (Taihu region), and northern Jiangsu, respectively. Only the Taihu Region study is presented here; results from N Jiangsu will be presented separately. The objectives of the present study are to (1) derive optimized N fertilization levels for a summer rice–winter wheat double-crop rotation in the Taihu Region in southern Jiangsu Province on farmers' field sites rather than in exact field experiments, based on farmers' current N application rates and using a newly-bred rice variety, and thus to (2) increase N use efficiencies, (3) quantify apparent N losses from the rice–wheat system by balance calculations on a plot level, (4) monitor mineral N contents under different N fertilization schemes and finally, to (5) assess the standard gross margin of the rice–wheat system as well as the economic consequences of a reduced N fertilization practice. Improved recommendations for N fertilization are derived on the basis of our results.

2. Materials and methods

2.1. Location

The experimental site was located in the eastern area of the Taihu basin in Dapu Township (31°17′N, 119°53′E), Yixing County, southern Jiangsu Province, China. This area is characterized by a subtropical climate with a mean annual temperature of 16.3 °C and an average annual rainfall of 1100–1200 mm, with nearly two thirds of precipitation concentrated during the summer rice growing season from July to October. The altitude was about 5 m above mean sea level, the depth of the groundwater table was 3 m.

Please cite this article in press as: M. Hofmeier, et al., Nitrogen management in a rice–wheat system in the Taihu Region: Recommendations based on field experiments and surveys, Agric. Ecosyst. Environ. (2015), http://dx.doi.org/10.1016/j.agee.2015.03.032