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Effect of continuous reduction of nitrogen application to a rice-wheat rotation system in the middle-lower Yangtze River region (2013–2015)

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ABSTRACT

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) are two stable food crops that play a vital role in national food security. Summer rice-winter wheat double-cropping rotation is the dominant crop rotation practice used in the middle-lower Yangtze River region of China. However, excessive application of nitrogen (N) fertilizer in this region has led to low nitrogen use efficiency (NUE). To our knowledge, no studies have investigated the effects of reducing N fertilizer applications during both the rice and wheat seasons on crop yield, NUE, and soil fertility. In this study, we conducted a two-year field experiment using N fertilizer rates of 180, 240, and 300 kg N ha^{-1} during the rice growing season and 135, 180, and 225 kg N ha^{-1} during the wheat growing season. No differences in yield were observed among the treatments during the rice growing season; however, reduced N fertilizer application significantly affected yield during the wheat growing season. Reducing the amount of N fertilizer applied during the previous season and current season and the interactions between these seasons (R × W) had no effect on rice yield but did affect wheat yield. In addition, the N application rates significantly influenced N uptake and NUE. During the rice growing season, the N agronomic efficiency (NAE), N physiological efficiency (NPE), N partial factor productivity (NPF), and N recovery efficiency (NRE) increased by 20.6–42.5%, 11.1–15.8%, 23.9–40.2%, and 4.8–28.2%, respectively. During the wheat growing season, the NAE, NPE, NPF, and NRE increased by 20.4–54.9%, 8.2–16.5%, 21.8–58.3%, and 11.6–24.4%, respectively. We applied ^{15}N-labelled urea in the remainder of the soil N fertilization treatments, which indicated that the addition of ^{15}N fertilizer resulted in no difference in the 0–60 cm soil profile after rice harvest. Collectively, reducing N fertilizer application rates can effectively improve NUE and decrease N losses, and short-term reductions in N fertilizer application do not affect soil fertility.

1. Introduction

Rice and wheat production have greatly increased in the past several decades owing to the Green Revolution; however, this increase in grain yield has required substantial increases in fertilizer nutrient inputs (Sun et al., 2014; Tilman et al., 2002; Khush, 2005). Rice-wheat rotation systems are one of the world's largest agricultural production systems (Gupta et al., 2003). An estimated area of 26 Mha of land is cultivated using rice-wheat rotation, and rice-wheat rotation is practiced in South and East Asia in subtropical to warm-temperate climatic zones (Timsina and Connor, 2001; Zhang et al., 2013a,b). In China, rice–wheat rotation is the dominant practice in the middle-lower Yangtze River Basin, where rice and wheat have been grown in sequence for many years (Wang and Guo, 1994).

The use of fertilizers is a unique approach for producing sufficient food to meet the needs of the current human population (Lawlor et al., 2001), with N as the most limiting nutrient for crop production. However, in most tropical soils, N is also insufficient for satisfactory crop yields. Hence, high inputs of chemical N have been used globally to increase crop yields. In China, N consumption has accounted for more than 30% of total N consumption worldwide, but yields appear to have reached a ceiling; for instance, the con-

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sumption of N increased by 50% from 1990 to 2008 while crop yields only increased by approximately 10% (Duan et al., 2014; National Bureau of Statistics of China, 2009). Under these conditions, it was revealed that farmers often apply more N fertilizer than recommended. Unfortunately, these increases in N fertilizer application have resulted in well-documented deleterious impacts on the environment, such as greenhouse gas emissions, eutrophication, and acidification (Guo et al., 2010; Zhu and Chen, 2002).

Underuse of fertilizer is not a problem in China because farmers generally feel that chemical fertilizer application rates are not sufficient in many parts of the country (Huang et al., 2008). Particularly, typical rice–wheat cropping systems are generally used in farmlands in the Taihu Lake region, and N inputs in this region have significantly increased in the past two decades, ranging from 550 to 650 kg N ha^{-1} (Zhu and Chen, 2002). Excessive N input quickly decreases N use efficiency (NUE), an index used widely for assessing fertilizer management (Peng et al., 2006). However, NUE has been defined in several ways in the literature and has been classified as N agronomic efficiency (NAE), N physiological efficiency (NPE), N partial factor productivity (NPF), the apparent crop N recovery efficiency (NRE), and the N harvest index (NHI) (Ladha et al., 1998). In the high yielding area of Taihu Lake, the average N application rate is 300 kg ha^{-1}, which is 67% higher than the N application rate used in single rice-cropping systems in China. The average agronomic NUE (increase in grain yield per kg N applied) is only 12 kg kg^{-1} N, which is less than half the NUE reported in developed countries (Zhang et al., 2013b; Xue et al., 2013; Ju et al., 2015).The NRE is only 30–35%, which is 15–20% less than the NREs reported in other major rice growing countries (Zhang et al., 2010; Fan et al., 2012). Dobermann (2007) combined research from Europe, Asia, and the USA and proposed the following NUE values for good management: AEN (25–30 kg kg^{-1}), IEN (55–65 kg kg^{-1}), PFPN (60–80 kg kg^{-1}), REN (0.5–0.8 kg kg^{-1}), and PEN (50–60 kg kg^{-1}).

Fortunately, several studies have indicated that better N balance can significantly reduce environmental risks without sacrificing crop yield by adopting optimum N fertilization techniques and decreasing N losses and greenhouse gas emissions (Chen et al., 2014; Ju et al., 2009). Scientists from the International Rice Research Institute developed site-specific N management and showed that N fertilizer can be reduced by 32% and rice grain yield can be increased by 5% compared with the current N use practices of farmers (Peng et al., 2010). The knowledge-based optimum N management techniques used in rice-wheat systems in southern China and wheat/maize systems in northern China during the last decade indicate that more efficient use of N fertilizer could reduce N application rates by 30–60% (Ju et al., 2009). Results from integrated soil–crop system management have shown that the use of N fertilizer for these three crops (rice, wheat, and maize) could be reduced by 33% (Chen et al., 2014). Based on an experimental study of site-specific nutrient management for rice production in China and a unique household dataset captured over seven years, excessive N use can be reduced without adversely affecting crop yield over short and long periods (Huang et al., 2015).

Paddy soil is considered the most important soil resource in China for food security (Li et al., 2009). Thus, it is essential that soils perform continuously regarding their nutrient stocks and nutrient-supplying capacities to sustain food production in rice-wheat cropping systems (Ladha et al., 2003). The effects of inorganic N fertilizer on soil fertility are highly debated (Roberston et al., 2013; Brown et al., 2014). N fertilization has been widely used as a common management practice to maintain crop yields, but long-term inappropriate fertilization has resulted in severe soil degradation (Chen et al., 2009). Previous studies have indicated that the concentrations of available soil nutrients (e.g., organic C, N, P, and K) are good indicators of soil quality and productivity because

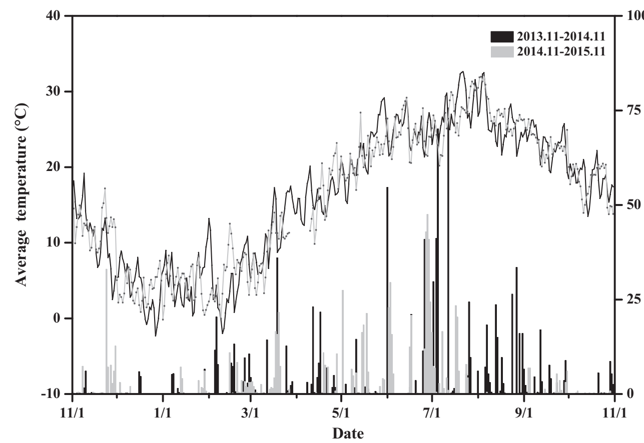

Fig. 1. The precipitation and average temperature of the rice and wheat in 2013 and 2015. Black and gray lines indicate average temperatures in 2013.11–2014.11 and 2014.11–2015.11, respectively. Black and gray bars indicate precipitation events during 2013.11–2014.11 and 2014.11–2015.11, respectively.

these nutrients can be absorbed directly by plants and contribute greatly to soil fertility (Dong et al., 2012).

However, although these studies found that reductions in N-fertilizer did not diminish rice yields, they did not consider that fertilizer reductions in the current crop may impact the next crop in an intensive agricultural system (the wheat-maize system or rice-wheat system) or that interactions may exist between the current crop and the crop of the next season in terms of fertilizer reductions. Here, we carried out a two-year field experiment using rice-wheat rotation, which is the most intensive agricultural system used worldwide and is widely practiced in Asian countries. We focused on reducing fertilizer addition for both rice and wheat and considered a series of fertilizer application rates to investigate whether the current crop influences the succeeding crop regarding the crop yield, NUE, and soil fertility.

2. Materials and methods

2.1. Experimental sites

Field experiments were conducted at the Danyang test base at Nanjing Agricultural University (longitude 119°10′, latitude 34°36′) in 2013 and were repeated in 2014 and 2015. The farm field chosen for this study was previously managed as a summer-rice/winter-wheat double-cropping system. Seasonal changes in the daily average temperature and precipitation are shown in Fig. 1. The average annual precipitation was 1243.3 mm, with most of the rainfall occurring during the rice growing season, and the average daily temperature was 16.5 °C. The soil was classified as yellow loam soil, and the main physicochemical properties were as follows: pH of 5.7, organic matter content of 17.15 g kg^{-1}, total N content of 0.97 g kg^{-1}, available phosphorus content of 13.6 mg kg^{-1}, and potassium content of 93.5 mg kg^{-1}.

2.2. Experimental design

2.2.1. Field experiment

The experiment was conducted in a completely randomized block, with each plot covering an area of 3 × 6 m. The rice variety was wuyunjing 24#, and rice was sown on May 26 and transplanted on June 21 in 2014 and sown on May 28 and transplanted on June 23 in 2015. During both years, the average spacing was 13.3 × 30 cm, with three seedlings per hole. The wheat variety was Yangmai 20# and was sown on November 8, 2013, and