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RESEARCH ARTICLE

Integrated management strategy for improving the grain yield and nitrogen-use efficiency of winter wheat

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Abstract

Understanding of how combinations of agronomic options can be used to improve the grain yield and nitrogen use efficiency (NUE) of winter wheat is limited. A three-year experiment involving four integrated management strategies was conducted from 2013 to 2015 in Tai'an, Shandong Province, China, to evaluate changes in grain yield and NUE. The integrated management treatments were as follows: current practice (T1); improvement of current practice (T2); high-yield management (T3), which aimed to maximize grain yield regardless of the cost of resource inputs; and integrated soil and crop system management (T4) with a higher seeding rate, delayed sowing date, and optimized nutrient management. Seeding rates increased by 75 seeds m^{-2} with each treatment from T1 (225 seeds m^{-2}) to T4 (450 seeds m^{-2}). The sowing dates were delayed from T1 (5th Oct.) to T2 and T3 (8th Oct.), and to T4 treatment (12th Oct.). T1, T2, T3, and T4 received 315, 210, 315, and 240 kg N ha^{-1}, 120, 90, 210 and 120 kg P_2O_5 ha^{-1}, 30, 75, 90, and 45 kg K_2O ha^{-1}, respectively. The ratio of basal application to topdressing for T1, T2, T3, and T4 was 6:4, 5:5, 4:6, and 4:6, respectively, with the N topdressing applied at regreening for T1 and at jointing stage for T2, T3, and T4. The P fertilizers in all treatments were applied as basal fertilizer. The K fertilizer for T1 and T2 was applied as basal fertilizer while the ratio of basal application to topdressing (at jointing stage) of K fertilizer for both T3 and T4 was 6:4. T1, T2, T3, and T4 were irrigated five, four, four and three times, respectively. Treatment T3 produced the highest grain yield among all treatments over three years and the average yield was 9 277.96 kg ha^{-1}. Grain yield averaged across three years with the T4 treatment (8 892.93 kg ha^{-1}) was 95.85% of that with T3 and was 21.72 and 6.10% higher than that with T1 (7 305.95 kg ha^{-1}) and T2 (8 381.41 kg ha^{-1}), respectively. Treatment T2 produced the highest NUE of all the integrated treatments. The NUE with T4 was 95.36% of that with T2 and was 51.91 and 25.62% higher than that with T1 and T3, respectively. The N uptake efficiency (UPE) averaged across three years with T4 was 50.75 and 16.62% higher than that with T1

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and T3, respectively. The N utilization efficiency (UTE) averaged across three years with T4 was 7.74% higher than that with T3. The increased UPE with T4 compared with T3 could be attributed mostly to the lower available N in T4, while the increased UTE with T4 was mainly due to the highest N harvest index and low grain N concentration, which consequently led to improved NUE. The net profit for T4 was the highest among four treatments and was 174.94, 22.27, and 28.10% higher than that for T1, T2, and T3, respectively. Therefore, the T4 treatment should be a recommendable management strategy to obtain high grain yield, high NUE, and high economic benefits in the target region, although further improvements of NUE are required.

Keywords: integrated management strategy, grain yield, winter wheat, nitrogen use efficiency, nitrogen uptake efficiency, nitrogen utilization efficiency

1. Introduction

Over the decades, the exponential increase in population and gradual decrease in arable land has imposed tremendous pressure on researchers to increase wheat (*Triticum aestivum* L.) productivity. High application rates of chemical fertilizers, especially nitrogen (N) fertilizers, are commonly used to increase wheat yield, and China is the largest consumer of N fertilizers globally. In 2010, 32.6 million tons of N fertilizers, approximately 31.3% of the global N consumption, were applied in China, and approximately 13.8% of this N consumption was used for wheat production (Heffer 2013). However, these high N inputs have not enhanced grain yield, but instead have had negative environmental impacts through nitrate leaching and nitrous oxide emissions (Sylvester-Bradley and Kindred 2009; Hawkesford 2014). Consequently, agricultural N use efficiency (NUE) in China is extremely low (Zhang *et al*. 2008). Therefore, over-application of fertilizers could be one of the main reasons that China's grain production has not increased proportionally with the increase in chemical fertilizer consumption in the last decades (Jiao *et al*. 2016).

The wheat production area in China is divided into a spring wheat production zone, a winter wheat production zone, and a spring-winter wheat mixed production zone. The spring wheat production zone includes the northeastern, northern, and northwestern regions. The winter wheat production zone includes the northern, Huang-Huai, the middle and lower reaches of the Changjiang River, southwestern, and southern China regions. The Xinjiang and Qinghai-Tibet regions are included in the spring-winter wheat mixed production zone. The Huang-Huai region is the most important wheat production zone, and accounts for approximately 45 and 48% of the national planting area and output, respectively. There is a pressing demand for synergetic improvement of the grain yield and NUE of wheat in the Huang-Huai winter wheat production zone.

The demand for crop production security and the demands of resource and environmental management require crops with both high yields and high N efficiency (Peng *et al*. 2006). Breeding of N efficient wheat cultivars is one method to reduce the application rate of N fertilizers while maintaining acceptable yields (Foulkes *et al*. 2009). However, wheat yield and N efficiency have been shown to be directly affected by agronomic practices, such as seeding rate (Berry *et al*. 2000; Dai *et al*. 2013), N management (Fageria and Baligar 2005; Shi *et al*. 2012), and sowing date (Sun *et al*. 2007; Gao *et al*. 2012).

NUE was defined as the grain dry matter yield per unit of available N (from both soil and fertilizer) and can be divided into two components: N uptake efficiency (UPE) and N utilization efficiency (UTE; Moll *et al*. 1982). UPE depends mainly on the aboveground N uptake (AGN) and available N. UTE can be calculated by dividing the N harvest index (NHI) by the grain N concentration (GNC; Zhang *et al*. 2016). Thus, agronomic management can be used to improve NUE by recovering more N from both soil and fertilizer (better UPE) and/or utilizing the absorbed N to produce more grain (better UTE).

Appropriately increasing the seeding rate is considered the basis for achieving greater grain yield (Hiltbrunner*et al*. 2007) and N accumulation (Arduini*et al*. 2006; Dai *et al*. 2014) in winter wheat. Dai *et al*. (2013) concluded that proper management of the seeding rate can lead to both higher grain yield and NUE through increasing the UPE and AGN. A positive quadratic relationship was observed between wheat grain yield and N application rate (Hawkesford 2014), whereas NUE, UPE, UTE, and NHI were found to decrease with an increased N application rate (Abril *et al*. 2007; Pask *et al*. 2012; Zhang *et al*. 2016). Both high seeding rates and high N levels have also been shown to increase the risk of lodging because stems tend to be weaker under high-input conditions (Berry *et al*. 2000; Loyce *et al*. 2008). In addition, Zhang *et al*. (2015) have suggested that decreasing the N application rate and increasing the seeding rate allows efficient absorption of N at deep soil depths and could lead to high grain yield, NUE, UPE, and UTE in winter wheat. An improper N application