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Delayed sowing improves nitrogen utilization efficiency in winter wheat without impacting yield

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ABSTRACT

Increased economic costs and environmental concerns have heightened the desire to reduce crop nitrogen (N) input. Improvements in crop N use efficiency (NUE) are urgently needed for sustainable agriculture. It has been shown that sowing date exerts significant effects on N uptake and grain yield in wheat. However, there is little information regarding the influence of sowing date on crop N status assessed by N nutrition index (NNI), NUE, N uptake efficiency (UPE), and N utilization efficiency (UTE) in winter wheat. There have also been few studies on the effects of varying crop N status on NUE, UPE, and UTE in winter wheat. Here, we evaluated four sowing date treatments of 1 October (early sowing), 8 October (normal sowing), 15 October (late sowing), and 22 October (latest sowing) over two wheat growing seasons. We examined the effects of sowing date on the NNI, reserve N (RN) content at anthesis, tillering, floret differentiation, grain yield and components, NUE and components, and soil N budget. The wheat plants sown at the early and normal dates were in conditions of excess N, while those at the late and latest sowing dates were in near-optimum N conditions after N fertilizer application at jointing. In response to delayed sowing, aboveground N uptake (AGN), accumulation RN, UPE, and spikes per unit area decreased; storage RN, UTE, and grain number per spike increased; and grain yield and NUE remained unchanged. The final mineralized N in the 0–100-cm soil layer at harvest ($N_{f\text{-}min}$), and apparent N loss (N_{loss}) were higher in the late and latest sowing dates than in the early and normal sowing dates. The NNI was positively correlated with UPE, and negatively correlated with UTE, while no significant correlation between NNI and NUE was observed. Hence, wheat plants with delayed sowing can use N more efficiently by optimizing crop N status. There exists potential for improvement in NUE by combining delayed sowing and reduced N fertilizer rates that meet but do not exceed crop N requirements.

1. Introduction

Nitrogen (N) fertilizer is a costly component during wheat (*Triticum aestivum* L.) crop production, and excess N can lead to negative environmental repercussions, such as nitrate leaching and N_2O emissions (Foulkes et al., 2009; Maharjan et al., 2014). Improving N use efficiency (NUE) is one of the most effective means to increase crop productivity while decreasing environmental degradation and costs to farmers (Cassman et al., 2003; Davidson et al., 2015; Zhang et al., 2015).

NUE has been defined as grain yield per unit of N available (from the soil and/or fertilizer) and can be further divided into N uptake efficiency (crop N uptake/N available or UPE) and N utilization efficiency (grain yield/crop N uptake or UTE) (Moll et al., 1982). The UTE represents the crop N utilization efficiency measured as a function of the plant's grain yield (Foulkes et al., 2009). Improving UTE decreases N consumption and maintains or can even increase yield as well as potentially reduce excess N fertilizer input.

The N nutrition index (NNI), provides a basic tool for analyzing actual plant N status in crops, and can be used to quantify the level of both N deficiency and excess consumption of a given crop (Jeuffory and Bouchard, 1999; Lemaire and Gastal, 1997). Determination of the NNI at specific intervals during the vegetative growth period of crops could help to optimize the timing and rate of N fertilizer applications to adjust as precisely as possible N application to crop N demand corresponding to the target yield (Lemaire et al., 2008). In addition, determination of the NNI allows for the detection of any indirect effects of N induced by manipulation of other field conditions (Barro et al., 2012). Furthermore, a correlation was observed between seed number and crop NNI at

Abbreviations: N, nitrogen; NNI, nitrogen nutrition index; AGN, aboveground nitrogen uptake; NUE, nitrogen use efficiency; UPE, nitrogen uptake efficiency; UTE, nitrogen utilization efficiency; $N_{f\text{-}min}$, final mineralized N in the 0–100-cm soil layer at harvest; N_{loss}, apparent N loss

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Table 1
Organic matter content, total N, available phosphorus, and available potassium in top 20-cm soil before sowing.

Season	Organic matter (g kg^{-1})	Total N (g kg^{-1})	Available phosphorus (mg kg^{-1})	Available potassium (mg kg^{-1})
2014–2015	12.0	1.0	25.6	47.2
2015–2016	11.9	1.0	25.1	47.0

anthesis (Justes et al., 1997a,b; Plénet et al., 1997; Doré et al., 1998; Jeuffroy et al., 2003). A strong negative correlation was also observed between crop NNI and NUE and its components in linseed, potato, and barley (Bélanger et al., 2001; Dordas, 2011; Hu et al., 2014; Dordas, 2017).

Global warming over recent decades has provided extended growing periods prior to wheat wintering that encourage farmers to delay the winter wheat sowing date (Xiao et al., 2013, 2015). It is unclear how this delay in sowing could affect wheat yields. Studies have shown that it may increase, maintain or decrease the grain yield of winter wheat (Weiss et al., 2003; Sun et al., 2007; Jalota et al., 2013; Ding et al., 2016; Rasmussen and Thorup-Kristensen, 2016). Generally, late sowing reduces N uptake and accumulation in wheat crops (Widdowson et al., 1987; Ehdaie and Waines, 2001).

Previous research has indirectly suggested that delayed sowing of winter wheat may have advantages in crop productivity as a function of plant N usage. However, relatively few studies have investigated how delayed sowing affects crop N status, NUE, UPE, and UTE. The relationship between the NNI and NUE, UPE, and UTE as affected by delayed sowing date is also unclear. Increased knowledge regarding UTE variation-associated plant physiological processes will improve crop management and breeding strategies aimed at increasing productivity in low N environments. Hence, the objective of the present study was to evaluate the following: (i) the influence of delayed sowing on crop N status; (ii) the effects of varying crop N status, expressed as the NNI, on NUE, UPE, and UTE; and (iii) the potential for improvement in NUE by reducing N application under late and latest sowing without impacting grain yield.

2. Materials and methods

2.1. Plant material and growing conditions

A widely planted winter wheat cultivar, Tainong 18, was grown under field conditions at the experimental station of Shandong Agricultural University (38°39′ N, 104°04′ E), Taian, Shandong, China during the 2014–2015 and 2015–2016 growing seasons. The preceding crop in these fields was summer maize. The soil was a sandy loam with a pH of 8.1 (Typic Cambisols; FAO/EC/ISRIC, 2003). The organic matter content (Walkley and Black method), total N (semi-micro Kjeldahl method), available phosphorus (Olsen method), and available potassium (Dirks-Sheffer method) are listed in Table 1. Fresh soil samples were analyzed for mineralized N (N_{min}) in the soil, including NO_3-N and NH_4-N, and were taken prior to any fertilization before

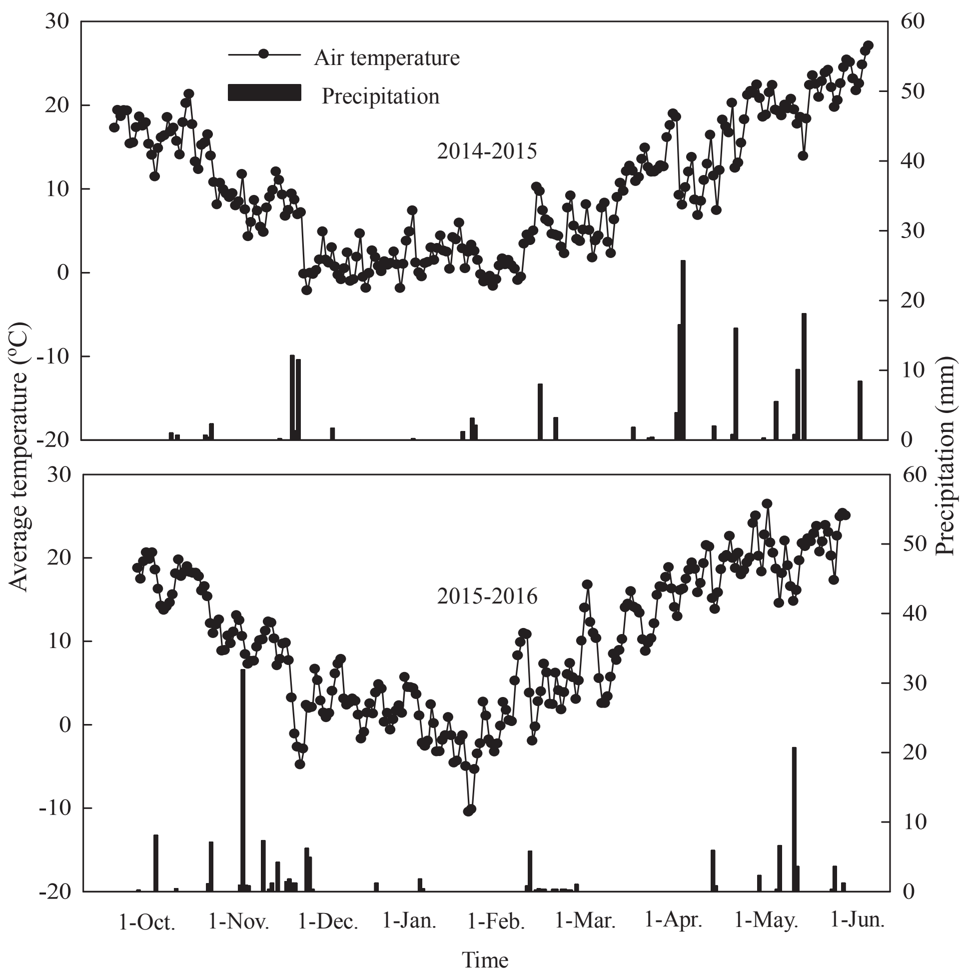

Fig. 1. Average air temperature and precipitation over two growing seasons. Top panel shows data from the 2014–2015 growing season, while the bottom panel shows data from the 2015–2016 growing season. Data were collected by the agricultural meteorological station located approximately 500 m from the study field.