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Delayed sowing can increase lodging resistance while maintaining grain yield and nitrogen use efficiency in winter wheat☆

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ABSTRACT

Lodging resistance of winter wheat (*Triticum aestivum* L.) can be increased by late sowing. However, whether grain yield and nitrogen use efficiency (NUE) can be maintained with delayed sowing remains unknown. During the 2013–2014 and 2014–2015 growing seasons, two winter wheat cultivars were sown on three dates (early sowing on October 1, normal sowing on October 8, and late sowing on October 15) to investigate the responses of lodging resistance, grain yield, and NUE to sowing date. No significant differences in lodging resistance, grain yield, or NUE between early and normal sowing were observed. Averaging over the two cultivars and years, postponing the sowing date significantly increased lodging resistance by 53.6% and 49.6% compared with that following early and normal sowing, respectively. Lodging resistance was improved mainly through a reduction in the culm height at the center of gravity and an increase in the tensile strength of the base internode. Late sowing resulted in similar grain yield as well as kernel weight and number of kernels per square meter, compared to early and normal sowing. Averaging over the two cultivars and years, delayed sowing resulted in a reduction in nitrogen uptake efficiency (UPE) by 11.0% and 9.9% compared to early and normal sowing, respectively, owing to reduced root length density and dry matter accumulation before anthesis. An average increase in nitrogen utilization efficiency (UTE) of 12.9% and 11.2% compared to early and normal sowing, respectively, was observed with late sowing owing to a reduction in the grain nitrogen concentration. The increase in UTE offset the reduction in UPE, resulting in equal NUEs among all sowing dates. Thus, sowing later than normal could increase lodging resistance while maintaining grain yield and NUE.

Abbreviations: AGN, aboveground nitrogen uptake at maturity; CHCG, culm height at the center of gravity; CLRI, culm lodging resistance index; GNC, grain nitrogen concentration; NHI, nitrogen harvest index; NUE, nitrogen use efficiency; RLD, root length density; TFS, tensile failure strength; UPE, nitrogen uptake efficiency; UTE, nitrogen utilization efficiency

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1. Introduction

Lodging [1,2] and decreased nitrogen (N) use efficiency (NUE) [3] are two major limitations in winter wheat (*Triticum aestivum* L.) production. Lodging, the permanent displacement of stems from the vertical position [1], is responsible for large reductions in grain yield and quality [2,4,5], increases harvesting costs [6], and provides a favorable environment for foliar disease [1], causing potential health risks for humans resulting from increased risk of fungal infection and subsequent development of mycotoxins [7]. Worldwide, excessive N input is responsible for reduced N fertilizer recovery and NUE [3,8]. The loss of N results in both higher production costs and a greater risk of environmental hazards [9,10].

Lodging occurs as a result of the buckling or bending of the culm at the basal stem internodes [1,11], especially at the second base internode [12,13]. Cultural practices (e.g., sowing date, seeding rate), environmental conditions (e.g., occurrence and quantity of rainfall and wind), and plant growth regulators are the main factors that affect lodging in winter wheat [6,11,12,14,15]. The strength of the stem is based on its diameter, wall thickness, and material strength of the stem wall [2].

Seeding rate, sowing date, and their interaction have large effects on grain yield, NUE, and lodging resistance. N uptake is highest with the optimum seeding rate in common wheat [16] or durum wheat (*Triticum durum* Desf.) [17]. Grain yield and NUE of winter wheat can be simultaneously improved by managing the seeding rate [18,19]. However, increasing the seeding rate makes wheat plants more susceptible to lodging [5,12,20]. Managing the seeding rate and sowing date to improve or maintain lodging resistance without reductions in grain yield and NUE is a major goal of management strategies for wheat research.

Because temperatures are increasing worldwide [21], delaying the sowing date may be feasible for wheat. The increased cumulative degree days above 0 °C before wintering [22] may provide a foundation for delaying the current sowing date. Late sowing has been reported to be effective in reducing lodging [20,23,24], and appropriately delaying the sowing date can result in similar grain yields [25–27]. Additionally, late sowing in winter wheat production can allow a timely late harvest of summer maize (*Zea mays* L.), increasing its yield [28], which is important to total cereal production and food security in China and provides the potential to improve the annual use efficiency of solar radiation, temperature, and moisture [29].

Widdowson et al. [30] reported that late sowing weakened N uptake. Unaffected or increased grain nitrogen concentration (GNC) was reported with late sowing [31–34]. However, few studies have focused on the effects of sowing date with optimum seeding rate on NUE and its two components: nitrogen uptake efficiency (UPE) and nitrogen uptake efficiency (UTE) [3].

The primary objectives of the present study were to determine whether the lodging resistance of winter wheat could be increased and the grain yield and NUE maintained by delaying sowing date. Additionally, changes in morphological and physiological traits associated with lodging resistance and NUE were investigated to explain difference in lodging resistance and NUE variation with different sowing dates.

2. Materials and methods

2.1. Site and growing conditions

Field experiments were performed in 2013–2014 and 2014–2015 at the experimental station of Dongwu village, in Dawenkou town, Daiyue district, Tai'an, Shandong, China. Rainfall and temperature data were obtained from a meteorological station located <500 m from the experimental field (Fig. 1). The soil was characterized as sandy loam with a pH of 8.24 [35], and contained 14.51 g kg^{-1} organic matter (Walkley and Black method) [36], 1.09 g kg^{-1} total N (semi-micro Kjeldahl method; 8200 Auto Distillation Unit; Kjeltec, Hillerød, Denmark) [37,38], 24.09 mg kg^{-1} available phosphorus (P; Olsen method) [39], and 40.17 mg kg^{-1} available potassium (K; Dirks–Sheffer method) [40].

2.2. Experimental design and treatments

Two widely planted cultivars, Tainong 18 (a cultivar with large ears and low tillering capacity) and Shannong 15 (a cultivar with middle-sized ears and high tillering capacity), henceforth referred to as T18 and S15, respectively, were selected as the experimental plants. Early, normal, and late sowing were performed on October 1, 8, and 15, respectively. The cumulative degree days above 0 °C before wintering were 100.8 and 124.4 (°C d) higher with early sowing than for the normal sowing date for 2014 and 2015, respectively, and were reduced by 103.9 and 111.7 (°C d) for late sowing in 2014 and 2015, respectively. Taking into consideration the tillering capacity, grain yield, and NUE potential for each cultivar [18], the cultivars T18 and S15 were sown at densities of 405 and 172.5 plants m^{-2}, respectively. Accordingly, the experiments for each cultivar were established separately, in a completely randomized design with three replicates. The size of each subplot was 25.0 m × 3.0 m (12 rows spaced 25 cm apart).

The previous crop in the planting areas was summer maize, and all straw and leaves were returned to the soil before tillage in both years. Basal fertilization of each subplot included N as urea, P as calcium superphosphate, and K as potassium chloride at rates of 120 kg ha^{-1} N, 90 kg ha^{-1} P_2O_5, and 90 kg ha^{-1} K_2O, respectively. An additional 120 kg ha^{-1} N as urea was applied at the beginning of jointing.

2.3. Crop measurement

Plant material samples were taken before wintering, jointing, booting, anthesis, and maturity by manually cutting all plants in a quadrat of 50 cm × 6 rows at ground level and mixing them. Before wintering, jointing, and booting, 30 plants were sampled. At anthesis and maturity, 50 single stems were sampled. Plant samples were separated into sheaths and stems, leaves, glumes, and spike rachis and grains. All separated samples were oven-dried at 70 °C to a constant weight to estimate dry matter accumulation. Oven-dried samples were milled and analyzed for N concentration (semi-micro Kjeldahl method) [37,38], and N accumulation was calculated by multiplying the element concentration by dry weight.

Quadrats of 2.0 m (parallel to rows) and 1.5 m (perpendicular to rows) were established in both years, and all spikes

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