Wide space sowing achieved high productivity and effective nitrogen use of irrigated wheat in South Shanxi, China

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Wheat (*Triticum aestivum* L.) is a staple crop worldwide and yield improvement since the green revolution was attributed to chemical nitrogen (N) fertilizer application. N dose, however, would decrease N use efficiency (NUE, the ratio of grain dry matter yield to N supply from soil and fertilizer). Various practices were conducted to maintain high crop yield and improve NUE. Nowadays, the enhanced sowing method, i.e., wide space sowing (WS), was beneficial to the wheat crop for high productivity. However, it is not known precisely how the sowing method and N rate affect N use and yield productivity. Field experiments with treatments of two sowing methods (WS, and drill sowing, DS) and four N rates (0, 180, 240, and 300 kg ha^{-1}, represented as N0, N180, N240, and N300, respectively) were conducted from 2017 to 2019. The results showed that grain yield under WS was 13.57%–16.38% higher than that under DS. The yield advantage under WS was attributed to increased ear number . Both the higher stems and productive stem percentage accounted for the increased ear number under WS. Higher total N quantity and larger leaf area index at anthesis under WS contributed to higher dry matter production, causing higher grain yield. Higher dry matter production was due to pre-anthesis dry weight and post-anthesis dry weight. The wheat crop under WS had a significant advantage in NUE of 12.44%–15.00% over that under DS. The increased NUE under WS was attributed to higher N uptake efficiency (the ratio of total N quantity at maturity to N supply from soil and fertilizer), which was the result of the greater total N quantity. The higher total N quantity under WS was due to both higher pre-anthesis N uptake and post-anthesis N uptake. It was remarkable that, compared with DS with 240 kg N ha^{-1}, WS with 180 kg N ha^{-1} had almost equal grain yield, dry matter, and total N quantity. Therefore, the wheat crop under WS could achieve both high NUE and grain yield simultaneously only with moderate N fertilizer in south Shanxi, China.

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ABSTRACT

Wheat (*Triticum aestivum* L.) is a staple crop worldwide and yield improvement since the green revolution was attributed to chemical nitrogen (N) fertilizer application. N dose, however, would decrease N use efficiency (NUE, the ratio of grain dry matter yield to N supply from soil and fertilizer). Various practices were conducted to maintain high crop yield and improve NUE. Nowadays, the enhanced sowing method, i.e., wide space sowing (WS), was beneficial to the wheat crop for high productivity. However, it is not known precisely how the sowing method and N rate affect N use and yield productivity. Field experiments with treatments of two sowing methods (WS, and drill sowing, DS) and four N rates (0, 180, 240, and 300 kg ha^{-1}, represented as N0, N180, N240, and N300, respectively) were conducted from 2017 to 2019. The results showed that grain yield under WS was 13.57%–16.38% higher than that under DS. The yield advantage under WS was attributed to increased ear number. Both the higher stems and productive stem percentage accounted for the increased ear number under WS. Higher total N quantity and larger leaf area index at anthesis under WS contributed to higher dry matter production, causing higher grain yield. Higher dry matter production was due to pre-anthesis dry weight and post-anthesis dry weight. The wheat crop under WS had a significant advantage in NUE of 12.44%–15.00% over that under DS. The increased NUE under WS was attributed to higher N uptake efficiency (the ratio of total N quantity at maturity to N supply from soil and fertilizer), which was the result of the greater total N quantity. The higher total N quantity under WS was due to both higher pre-anthesis N uptake and post-anthesis N uptake. It was remarkable that, compared with DS with 240 kg N ha^{-1}, WS with 180 kg N ha^{-1} had almost equal grain

yield, dry matter, and total N quantity. Therefore, the wheat crop under WS could achieve both high NUE and grain yield simultaneously only with moderate N fertilizer in south Shanxi, China.

Subjects: Agricultural Science, Ecology, Plant Science,

Keywords: wheat; grain yield; N use efficiency; sowing method; N rate.

INTRODUCTION

With the current growth rate, the global population will reach about 10 billion in 2050 (*UN, 2017*). Increasing crop yield to maintain food security while reducing environmental impacts of agriculture is the dual challenges for humans in the future (*Manschadi & Soltani*, *2021*). Wheat (*Triticum aestivum* L.) is the global staple food feeding about 30% of the world population (*Fahad et al., 2018*). China is the largest producer of wheat. The North China Plain (NCP) is one of the most vital cereal production regions in China, with 25% of the of national food production (*Duan et al*., *2019*; *Fan et al., 2019*). Thus, the future productivity of wheat will have more influence on China and global food security.

Nitrogen (N) is a major driver for crop production, as it directly influences dry matter production of crop plants by influencing the leaf area, radiation interception, photosynthetic efficiency (*Duan et al*., *2019; Manschadi & Soltani*, *2021; Li et al*., *2022*). Crop yield and quality considerably depend on N application (*Zhang et al., 2016*). In many parts of the world, a large increase in N fertilizer input was required to increase crop yield (*Manschadi & Soltani*, *2021*). However, the increase in the crop yield has not matched the increase in N fertilizer input. For example, from 1980 (9.3 Mt) to 2012 (24 Mt), the increase in N fertilizer input was 158%, which was associated with a 70% increase in China's crop yield (321–547 Mt) (*Yang et al., 2017*). In addition, excessive N input significantly reduces crop yield and N use efficiency (NUE, the ratio of grain dry matter yield to N supply, N supply is the sum of N from soil and fertilizer) (*Nehe et al., 2020; Manschadi & Soltani*, *2021*). Furthermore, excessive N input also leads to N fertilizer residue, which causes many environmental problems, such as soil acidification, N_2O emissions, decreased soil microbial activity (*Zhang et al., 2015; Duan et al*., *2019*). Therefore, it is widely recognized that improving NUE to alleviate hazards to the environment of crop production systems and improve their economic and environmental performance (*Yang et al., 2017*).

NUE can be defined as the grain dry matter yield (kg ha^{-1}) divided by the supply of available N supply from soil and fertilizer (kg N ha^{-1}; *Moll et al*., *1982*). NUE is calculated as the product of two subcomponents: (i) N uptake efficiency (total N at maturity / N supply from soil and fertilizer; NUpE). (ii) N utilization efficiency (grain dry matter yield / total N at maturity; NUtE). Besides NUE and its components, agronomic N use efficiency (AE_N), N recovery efficiency (RE_N), and partial factor productivity of applied N (PFP_N) were also usually used to evaluate efficiency of N use. AE_N is defined as the difference of grain yield in N treatment minus grain yield in blank N treatment divided by the N supply from N fertilizer, which indicates the grain yield produced per unit of supplied N fertilizer (*Zhang et al*., *2015*). RE_N is defined as the difference of total N in N treatment minus total N in blank N treatment divided by the N supply from N fertilizer. which indicates the percentage of fertilizer N absorbed by plants (*Yang et al*., *2017*). PFP_N is the ratio of grain yield to the supplied fertilizer N, which indicates the grain yield produced per unit of fertilizer applied (*Cox et al*., *1986*). According to the current situation of agricultural production, N fertilizer input is a common management strategy to achieve high crop yield (*Duan et al., 2019; Li et al*., *2022*). Increasing N fertilizer application can significantly improve crop yield but inevitably reduce NUE according to the above definition of N use related efficiencies (*Chen et al., 2016: Yang et al*., *2017*). It may seem impossible to achieve both high yield and NUE at the same time. Therefore, how to solve these scientific problems becomes very important.

An important factor to improve wheat yield is the sowing method, which influences the spatial distribution of plants as well as their growth (*Fan et al., 2019; Liu et al., 2020*). Compared with the traditional sowing method, drill sowing (DS), the wide space sowing (WS) alters the former sowing width from 2–3 cm to 5–8 cm, in addition to changing the seed distribution by separating single grains from each other instead of planting all the seeds in a line, while using the same seeding rate (*Zhao et al., 2013*). It was reported that an extreme winter grain yield, 12.4 t ha^{-1}, was achieved under WS in north China (*Liu et al., 2020*). WS has been proven useful in improving crop productivity in China (*Fan et al*., *2019*; *He, 2020*). Liu *et al.* (*2017*) showed that ear number under WS was significantly higher than that under DS, accounting for increased grain yield under WS than that under DS. It was reported that the increased ear number was attributed to the stems number rather than productive stem percentage (*Chu et al*., *2018*). It was reported that WS had higher NUE than that under DS (*Chu et al., 2018; Liu et al., 2021a*). However, whether WS can achieve both high yield and NUE at the same time remains unclear.

South Shanxi is located in the NCP, which supplies more than 50% of the winter wheat produced in China. However, excessive N application is common in this region, causing decreased NUE. Considering the demand for achieving high yield, high NUE and environmental protection is urgent in this region. Thus, we conducted a two-year field experiment to examine the effect of sowing method and N application on winter wheat production and NUE. The main objectives of this study were to (1) clarify the effects of N rate under WS on population development and yield formation; and (2) determine whether WS could help improve both yield and NUE simultaneously.

MATERIALS AND METHODS

Site description

Field experiments were conducted in a farmer's field at Shangyuan Village, Hougong Township, Wenxi County, Shanxi Province, China (35°24′N, 111°26′E) in 2017-2018 and repeated in the nearby field in 2018–2019. This site has a typical semiarid warm temperature and continental monsoon climate (Köppen classification) with average daily temperature of 8.6°C, average precipitation of 190.5 mm, and 3015.6 MJ m^{-2} of total solar radiation during wheat growing season (from middle October to early June) from 2005 to 2015. Soil samples from the upper 20 cm layer were randomly collected with five replicates for soil analysis before the wheat was sowed in 2017 and 2018. The soil type was classified as calcareous cinnamon soil according to Chinese soil taxonomy with a pH of 8.47–8.61, organic matter of 13.61–14.31 g kg^{-1}, total N of 1.01–1.05 g kg^{-1}, alkaline N of 40.05–44.07 mg kg^{-1}, Olsen P of 10.71–11.25 mg kg^{-1}, and available K of 188.87–200.24 mg kg^{-1} in 2017–2018 and 2018–2019 (Table 1). The cropping pattern of the experiment site is winter wheat-summer maize double-cropping system. The climate parameter in 2017–2018 and 2018–2019 was collected from a weather station (Watchdog 2000 Series, Spectrum Technologies Inc, Aurora, USA) about 200–metres distance from the experimental field.

Experimental design and crop management

The experiment was arranged in a split-plot design with sowing method as the main plots and N rate as subplots with three replications. Two sowing methods (Figure 1), wide space sowing (WS, sowing and row width were 8 and 25 cm, respectively) and drill sowing (DS, sowing and row width were 3 and 20 cm, respectively), and four N rates, 0 kg ha^{-1}, 180 kg ha^{-1}, 240 kg ha^{-1}, and 300 kg ha^{-1} (represented as N0, N180, N240, and N300, respectively) were applied in this research. DS was accomplished with drill sowing machine (2BXF-12, Nonghaha mechanical Co. Ltd. Hebei, China), WS was accomplished with wide space sowing machine (2BMYF-10/5, Yuncheng Gongli Co. Ltd. Shandong, China).

Each subplot size was 8 m in length and 4 m in width. A widely planted wheat cultivar Liangxing99 was planted on October 25 and October 11 in 2017 and 2018, respectively. The expected plant density was about 300 plant m^{-2} for both sowing methods. The plant density at three-leaves stage (Zadoks code 13) were 295 and 312 plant m^{-2} in 2017 and 2018, respectively, and there was no significant difference between WS and DS.

The fertilizer N was applied as urea (46.0% N), 60% of the fertilizer N was applied before sowing, and 40% of the fertilizer N was applied as topdressing fertilizer at jointing (Zadoks code 32). 150 kg P_2O_5 kg ha^{-1} in the form of calcium super-phosphate (16% P_2O_5) and 90 kg K_2O ha^{-1} in the form of potassium chloride (52% K_2O) were applied before sowing. Each plot was irrigated triple, with 60 mm (1.92 m^3/plot) water at the wintering (Zadoks code 26), jointing (Zadoks code 32), and anthesis (Zadoks code 65), the irrigation water was supplied by a movable sprinkler system, and the amount of water applied was measured a flow meter. The field was kept free from diseases, pests, insects and using pesticides as needed. Weeds were well controlled with herbicides 2-3 times in each experimental year.

2.3 Sampling and measurements

Stems number (the sum of main stems and tillers) of the wheat plant was counted in a typical and central row of 1-metre length at jointing, at which the wheat plants had the maximum stems number (*Lu et al*., *2021*). Then the productive stem percentage was calculated as the ratio of ear number to maximum stems number. During each growing season, the wheat plants were sampled in a row of 0.5 m length at anthesis and maturity (Zadoks code 91). At anthesis, all green leaves were separated and measured at anthesis using a leaf area meter (LI–3100C, LI–COR, Lincoln, NE, USA) for calculating the leaf area index. Then all samples were divided into ear and vegetative parts (stem, sheath plus leaves). At maturity, after counting the ear number, the samples were divided into grain and straw (stem, sheath, leaves, chaff plus rachis). All the separated samples were oven at 105°C for 30 min and weighed after further drying at 70°C to a constant weight. Grain number per ear and 1000-grain weight were calculated by using the grain sample above. Yield was determined from a 10 m^2 area at maturity in the center of each plot and adjusted to the standard moisture content of 0.125 g H_2O g^{-1} fresh weight. Grain moisture content was measured with a digital moisture tester (PM8188A, Kett Electric Laboratory, Tokyo, Japan).

After the dry matter of all separated samples plants at anthesis and maturity were weighed, then they were shredded by applying plant ball mill pulverizer (Jxfstprp-11, Jingxin Co Ltd, Shanghai, China) for N concentration measurement. N concentration of the samples was determined by using the standard indophenol-blue colorimetric method (*Novamsky et al*., *1974*).

The soil samples were collected from 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil depth in each plot , which were analyzed for total mineral N content (NO_3^--N and NH_4^+-N) using the method described *Wagner, (1974)* and *Benesch & Mangelsdorf, (1972)*.

Statistical analysis and calculations

Experimental data was statistically analyzed using Microsoft Excel 2016 and Statistix 8.0 (Analytical Software, Tallahassee, FL, USA), and the figure was generated using Origin Lab pro 2021b (OriginLab Corporation, Northampton, MA, USA). All data are means of three replicates (n = 3). Comparisons among multiple groups were performed using Tukey's honestly significant difference (HSD) test. Probability values $p < 0.05$ were considered statistically significant. Statistix 8.0 software was used for variance analysis.

The accumulation, partitioning, and translocation of dry matter and N were calculated using the following equations (*Laza et al*., *2003*; *Cox et al*., *1986*).

Post-anthesis dry matter production (DM_{post}, t ha^{-1}) = Total dry weight at maturity – TDW_{as} (1)

Harvest index (%) = Grain dry weight /Total dry weight at maturity (2)

Post-anthesis accumulated N (N_{post}, kg ha^{-1}) = TN – TN_{as} (3)

N harvest index (NHI, %) = GN / TN (4)

Where TDW_{as} (t ha^{-1}) is total dry weight at anthesis. TN (kg ha^{-1}) and TN_{as} (kg ha^{-1}) are total N quantity at maturity and anthesis, respectively. GN (kg ha^{-1}) is grain N content.

N use related traits was calculated by the following Equations (*Moll et al*., *1982*; *Foulkes et al*., *2009*).

N uptake efficiency (NUpE, %) = TN / soil N (pre-sowing soil mineral N + N_f) (5)

N utilization efficiency (NUtE, kg kg^{-1}) = Grain dry weight / TN ×1000 (6)

N use efficiency (NUE, kg kg^{-1}) = NUpE × NUtE (7)

Agronomic N use efficiency (AE_N, kg kg^{-1}) = $(Y_N - Y_0) / N_f \times 1000$ (8)

N recovery efficiency (RE_N, %) = $(TN_N - TN_0) / N_f$ (9)

Partial factor productivity of applied N (PFPN, kg kg^{-1}) = Yield / $N_f \times 1000$ (10)

Where, Y_N and Y_0 are yield (t ha^{-1}) in N fertilization and N0 treatment, respectively. TN_N and TN_0 are total N quantity at maturity (kg ha^{-1}) in N fertilization and N0 treatment, respectively. N_f is the total input of fertilizer N (kg ha^{-1}).

RESULTS

Weather conditions and crop growth duration

Seasonal precipitation in 2017–2018 was 51.2 mm greater than that in 2017–2018, due to the more rainfall from jointing to booting and from anthesis to maturity in the former growing season (Table 2). However, there were higher mean temperature, more accumulated temperature, and greater incident solar radiation during all growing periods in 2018–2019 than those in 2017–2018, especially from jointing to booting and from anthesis to maturity.

The growing durations in each period (sowing to jointing, jointing to booting, and anthesis to maturity) were longer in 2018–2019 than those in 2017–2018, thus total growing durations was longer in 2018–2019 (Table 3). It should be noted that the wheat crop was sowed late (about 10 days) in 2017–2018 due to the continuous raining weather before sowing.

Yield and yield related attributes

The sowing method and N rate significantly affected the grain yield (Table 4). The wheat crop under WS produced higher grain yield by 16.38% and 13.57% averaged across N rates than that under DS in 2017–2018 and 2018–2019, respectively. There were significant increases in yield when the N rate increased from 0 to 180 kg ha^{-1} and then to 240 kg ha^{-1} under both sowing methods in two growing seasons. The sowing method and N rate had a significantly interactive effect on grain yield. Grain yield slightly improved with the further increasing N rate (from 240 to 300 kg ha^{-1}) under WS in both growing seasons, whereas significant yield reductions (11.78% in 2017–2018 and 7.21% in 2018–2019) were observed under DS. In addition, the wheat crop under WS with N application of 180 kg ha^{-1} produced the commensurate yield compared with that under DS with 240 kg N ha^{-1} applied in both growing seasons.

The positive effect of WS on grain yield was mainly due to the increased ear number per ha (Table 4). Averaged across N rates, the wheat crop under WS showed higher ear number per ha by 20.36% and 18.95% than that under DS in 2017–2018 and 2018–2019, respectively. There was little or no difference in the grain number per ear and 1000-grain weight between sowing methods. Under both sowing methods, although it was observed that the higher N rate, the more ear. The rates of ear number increase under WS with improved N rate (from 180 to 240 kg ha^{-1} and from 240 to 300 kg ha^{-1}) was significantly larger than those under DS (8.91%–13.81% vs. 4.62%–8.81%). However, with the increase in N rate, a decreasing trend in grain number per ear and 1000-grain weight was recorded in both sowing methods and two growing seasons.

Although the maximum stems number and productive stem percentage under WS were both significantly higher than those under DS (Fig.2 and3). The improvement in maximum stems number (14.52%–16.09%), rather than productive stem percentage (3.24%–3.85%), mainly accounted for that the wheat crop under WS produced more ears per ha. With the increase in N rate, the maximum stems number of winter wheat significantly and continuously increased. A decreasing trend, however, was recorded in productive stem percentage in both sowing methods and two growing seasons.

Leaf area index at anthesis under WS was significantly higher by 6.70% and 7.97% averaged across N rates than that under DS in 2017–2018 and 2018–2019, respectively (Fig.4). With the increase in N rate, leaf area index at anthesis significantly increased in both sowing methods and two growing seasons.

Total dry weight at maturity under WS was significantly higher by 13.62% and 15.26% averaged across N rates than that under DS in 2017–2018 and 2018–2019, respectively, whereas no significant difference was observed in harvest index between sowing methods (Table 5). Total dry weight at maturity significantly increased when the N rate increased from 0 to 180 kg ha^{-1} and then to 240 kg ha^{-1} under both sowing methods in two growing seasons. Given further increasing N rate (from 240 to 300 kg ha^{-1}), total dry weight at maturity under WS slightly improved in both growing seasons, but significant reductions of 6.49% and 7.65% were observed under DS in 2017–2018 and 2018–2019, respectively. The harvest indices with N fertilizer applied were significantly lower than those without N applied. There was no significant difference in the harvest index among treatments with N applied except that N rate of 300 kg ha^{-1} demonstrated significantly lower value than N rates of 180 and 240 kg ha^{-1} under DS in 2017–2018.

Total dry weight at anthesis and post-anthesis dry matter production were both significantly higher under WS than those under DS in two growing seasons, which account for the advantage in total dry weight of the wheat crop under WS over DS (Table 5). Pre-anthesis dry matter production and post-anthesis dry matter production significantly increased when the N rate increased from 0 to 180 kg ha^{-1} and then to 240 kg ha^{-1} under both sowing methods in two growing seasons. When N rate further increased (from 240 to 300 kg ha^{-1}), pre-anthesis dry matter production and post-anthesis dry matter production under WS demonstrated an increasing or unchanging trend in both growing seasons, but significant reductions of 5.35%-6.34% and 8.76%-10.10% were recorded under DS in 2017–2018 and 2018–2019, respectively.

N uptake, utilization, and related efficiencies

There was no significant difference in grain N concentration between sowing methods averaged across N rates in two growing seasons (Table 6). Among the treatments with N applied, there was no significant difference in grain N concentration under DS except that significant improvements (5.02%–5.98%) were recorded at 300 kg N ha^{-1} under WS in two growing seasons. The grain N content under WS was significantly higher than that under DS by 18.67% and 15.24% in 2017–2018 and 2018–2019, respectively. The grain N content significantly increased when the N rate increased from 0 to 180 kg ha^{-1} and then to 240 kg ha^{-1} under both sowing methods in two growing seasons. When the wheat crop received more N fertilizer (300 kg ha^{-1}), the grain N content under WS significantly and continuously improved in both growing seasons, but significant reductions of 9.78% and 6.22% were observed under DS in 2017–2018 and 2018–2019, respectively.

The wheat crop under WS had higher total N quantity at maturity and N harvest index averaged across N rates than those under DS in both growing seasons (Table 6). With the increase in N rate, total N quantity at maturity significantly and consistently increased in both sowing methods and two growing seasons, whereas N harvest index showed a decreasing trend. Pre-anthesis N uptake and post-anthesis N uptake were both significantly higher under WS than those under DS in two growing seasons, which account for the advantage in total N quantity at maturity under WS over DS. With the increase in N rate, both pre-anthesis N uptake and post-anthesis N uptake significantly and continuously increased in both sowing methods and two growing seasons. In addition, there were commensurate values in total N (including pre-anthesis N uptake and post-anthesis N uptake, and total N quantity at maturity) between DS with 240 kg N ha^{-1} applied and WS with 180 kg N ha^{-1} applied.

The wheat crop under WS showed higher NUE by 15.00% and 12.44% averaged across N rates than that under DS in 2017–2018 and 2018–2019, respectively (Table 7). The more N fertilizer applied, the significantly lower NUE was recorded. NUpE under WS was significantly higher by 11.98% and 10.15% averaged across N rates than that under DS in 2017–2018 and 2018–2019, respectively, whereas there was no significant difference in NUtE between two sowing methods in two growing seasons. The higher NUE under WS largely resulted from the advantage in NUpE over DS.

AE_N under WS was significantly higher by 16.51% and 21.05% averaged across N rates than that under DS in 2017–2018 and 2018–2019, respectively (Table 7). AE_N significantly decreased when the N rate increased from 180 kg ha^{-1} to 240 kg ha^{-1} and then to 300 kg ha^{-1} under both sowing methods in two growing seasons except that there was no significant difference between 180 kg ha^{-1} and 240 kg ha^{-1} under WS in 2017–2018.

Higher RE_N under WS was observed than that under DS by 11.55% and 9.75% averaged across N rates in 2017–2018 and 2018–2019, respectively (Table 7). When the N rate increased from 180 to 240 kg ha^{-1} and then to 300 kg ha^{-1}, RE_N under DS significantly and continuously decreased except for that under WS in 2017–2018 and 2018–2019, respectively.

The wheat crop showed significantly higher PFP_N under WS by 15.11% and 13.51%

averaged across N rates than that under DS in 2017–2018 and 2018–2019, respectively (Table 7). With the increase in N rate, PFP_N significantly and continuously decreased in both sowing methods and two growing seasons.

DISCUSSION

The wheat crop under wide space sowing produced higher grain yield than that under drill sowing in our present study. The yield advantage under wide space sowing over drill sowing was attributed to increased ear number. Similar effects of wide space sowing on grain yield were reported in previous studies (*Zhao et al*., *2013; Fan et al*., *2019*). The individual wheat plant under wide space sowing had more distance with each other than that under drill sowing (*Zhao et al*., *2013*), which reduced intraspecific competition for resources and growing space and resulted in more stems produced (*Liu et al., 2017*; *Liu et al*., *2020*). Additionally, it was observed that wide space sowing had a significantly positive effect on improving productive stem percentage. It could be reasonably assumed that the wheat crop under wide space sowing could uptake more N and water from soil, and then manufacture greater carbohydrates by canopy for maintaining the growth and differentiation of the huge population of stems. It was reported that wide space sowing could optimize root distribution and enhance root absorptive capacity of wheat than that under drill sowing (*He, 2020*). Our result also showed that the wheat crop uptake more N under wide space sowing than that under drill sowing at the same N rate.

The N input of 240 kg N ha^{-1} was a locally recommended rate which could produce high yield with acceptable N use efficiency (*Chen et al*., *2016*; *Zhang et al*.,*2016*; *Duan et al*., *2019*). It is worth noting that the wheat crop under wide space sowing received N application of 180 kg ha^{-1} produced the commensurate yield compared with that under drill sowing with 240 kg N ha^{-1} applied. This result indicted that an effective sowing method could compensate the yield loss due to a reduction of 25% in N input.

This study also found that, compared with the locally recommended N rate (240 kg ha^{-1}), even though there was no significant increase in grain yield due to the higher N application (300 kg ha^{-1}) under wide space sowing, an obvious enhance of about 6% in grain N concentration was recorded. Whereas, the significant yield reduction and no significant increase in grain N concentration were observed under drill sowing with 300 kg N ha^{-1} applied due to stem lodging occurring during grain filling. It was reported that the wheat crop under drill sowing with high N rate had the lower bending resistance of stem and the higher lodging possibility of wheat due to the contradiction between population and individual plants (*Liu et al*., *2021b*; *Li et al*., *2022*), which caused a decline in grain yield and quality (*Foulkes et al*., *2011*). These results indicated that, even though great amount N fertilizer was applied, the enhanced sowing method, wide space sowing, could not only maintain the high yield level but also improved the grain nutrient quality.

Crop yield was determined by dry matter production and harvest index (*Yoshida et al*., *1972*). Thus, crop yield can be enhanced by increasing dry matter accumulation, harvest index or both (*Carolina et al*., *2019*). In the present study, higher total dry weight at maturity under wide space sowing was achieved than that under drill sowing, whereas no significant difference in harvest index was recorded between two sowing methods. This result suggested that the wheat crop under wide space sowing over drill sowing produced greater total dry weight instead of higher biomass partitioning efficiency. Additionally, pre-anthesis dry matter production and post-anthesis dry matter production were both significantly higher under wide space sowing than those under drill sowing. Similar results were also reported in previous studies (*Liu et al*., *2017*).

Dry matter production largely depended on canopy photosynthetic area, leaf area index (*Man et al.*, *2017*; *Fan et al.*, *2019*), meanwhile leaf area growth was affected by N supply and uptake (*Peng & Ismail*, *2004*). In the present study, the wheat crop under wide space sowing uptake greater N before anthesis than that under drill sowing, which attributed to higher leaf area index at anthesis than that under drill sowing. It was also reported that wide space sowing could increase photosynthetic rate and delay senescence of flag leaves, and promoted carbohydrates accumulation after anthesis (*Fan et al*., *2019*). Our results also showed that the wheat crop under wide space sowing received 180 kg N ha^{-1} could produce statistically equal amounts of dry matter (including pre-anthesis dry matter production and post-anthesis dry matter production, and total dry weight at maturity) compared with those under drill sowing received 240 kg N ha^{-1}, which accounted for the same yield under the above-mentioned treatments.

In the present study, total N quantity at maturity and N harvest index under wide space sowing was significantly higher than those under drill sowing, which resulted in the higher grain N content under wide space sowing. The main sources determining total N at maturity were the amount of N absorbed before and after anthesis (*Dupont & Altenbach, 2003*). Our study showed that the wheat crop under wide space sowing had both higher pre-anthesis N uptake and post-anthesis N uptake than those under drill sowing. In addition, the values of pre-anthesis accumulated N and post-anthesis accumulated N, and total N quantity at maturity under wide space sowing with N rate of 180 kg ha^{-1} were statistically equal to those under drill sowing with 240 kg N ha^{-1}. These results suggested that the wheat crop could uptake adequate N without high N Fertilizer input but with enhanced sowing method.

The ability to enhance N uptake is the first step to increasing NUE (*Du et al*., *2020*). Our results showed that NUE under wide space sowing was significantly higher than that under drill sowing, and the higher NUE was the result of improvement in NUpE instead of NUtE. Previous studies also suggested that the variation in NUE under wide space sowing was more closely associated with NUpE, rather than NUtE (*Chu et a*l., *2018*; *Liu et al*., *2021a*). The higher AE_N and RE_N in crop plant indicated that crop plant had an efficient use of fertilizer N, which decreased the loss of N fertilizer (*Yang et al*., *2017*). This present study also showed that AE_N and RE_N under wide space sowing were significantly higher than those under drill sowing. These results indicated that the enhanced sowing method, wide space sowing, could not only produce high grain yield but also decrease the risk of N leaching, ammonia emission, and ground runoff which could cause environmental pollution. It is widely recognized that N use related efficiencies (e.g., NUE, NUpE, NUtE, RE_N, AE_N, PFP_N) will decrease when N fertilizer rate is improved (*Yang et al*., *2017; Duan et al*., *2019; Manschadi & soltani*, *2021*). It was a remarkable fact that all the above-mentioned efficiencies under wide space sowing with N rate of 240 kg ha^{-1} were comparable to those under drill sowing with 180 kg N ha^{-1} applied. These results indicated that enhancement in sowing method provided an opportunity to not only maintain high N use efficiencies but also output high grain yield under moderate N fertilizer input.

CONCLUSION

Compared with DS, WS had higher grain yield which was mainly attributed to ear number. The increased grain yield under WS depended on improved total dry weight. Higher total N quantity under WS was attributed to NUpE, which led to greater NUE. The wheat crop under WS received N application of 180 kg ha^{-1} produced the commensurate yield, total dry weight, and total N quantity compared with those under DS with 240 kg N ha^{-1}. Thus, WS with moderate N fertilizer input can help to maintain high N use efficiencies and output high grain yield.

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Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Qiang Wang performed the experiments, analyzed the data, prepared figures and/or tables, and approved the final draft.
- Hafeez Noor conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.
- Min Sun performed the experiments, analyzed the data, prepared figures and/or tables, and approved the final draft.

- Aixia Ren conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.
- Yu Feng performed the experiments, prepared figures and/or tables, and approved the final draft.
- Peng Qiao performed the experiments, prepared figures and/or tables, and approved the final draft.
- Jingjing Zhang conceived and designed the experiments, performed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.
- Zhiqiang Gao conceived and designed the experiments, authored or reviewed drafts of the paper, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The raw data are available in the Supplemental Files.

Supplemental Information

Supplemental information for this article can be found online at

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Figure 1

Figure 1 The sketch maps of drill sowing (A) and wide space sowing (B) used in this study.

Figure 1

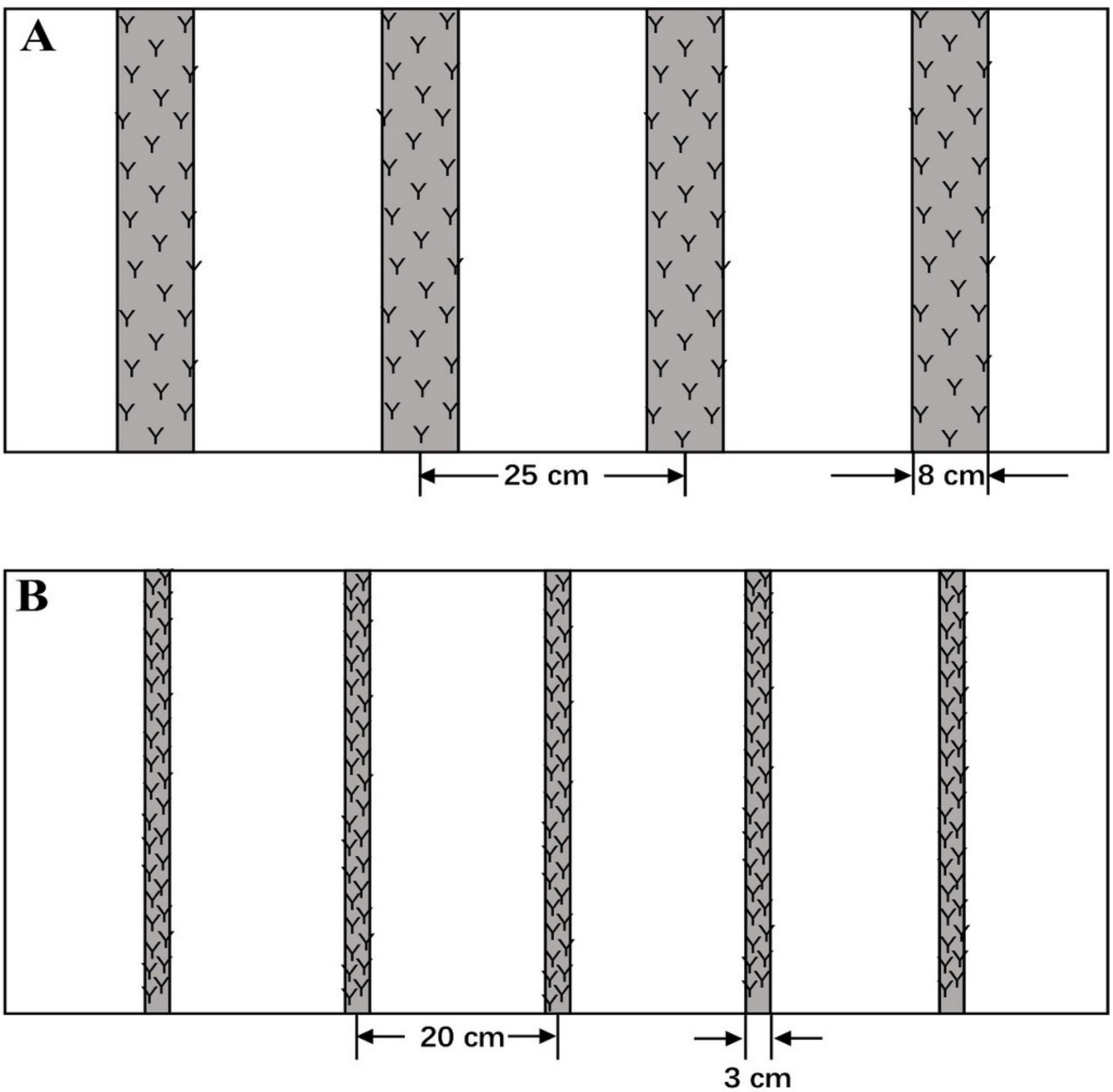


Figure 2

Figure 2

Figure 2 Maximum stems number of winter wheat under different sowing method and N rate in 2017-2018 and 2018-2019. DS, drill sowing; WS, wide space sowing. Within each growing season, bars with different upper-case letters are significantly different according to Tukey's HSD test ($\alpha=0.05$) between two sowing methods. Within each growing season for sowing method, bars with different lower-case letters are significantly different according to Tukey's HSD test ($\alpha=0.05$) among four N treatments.

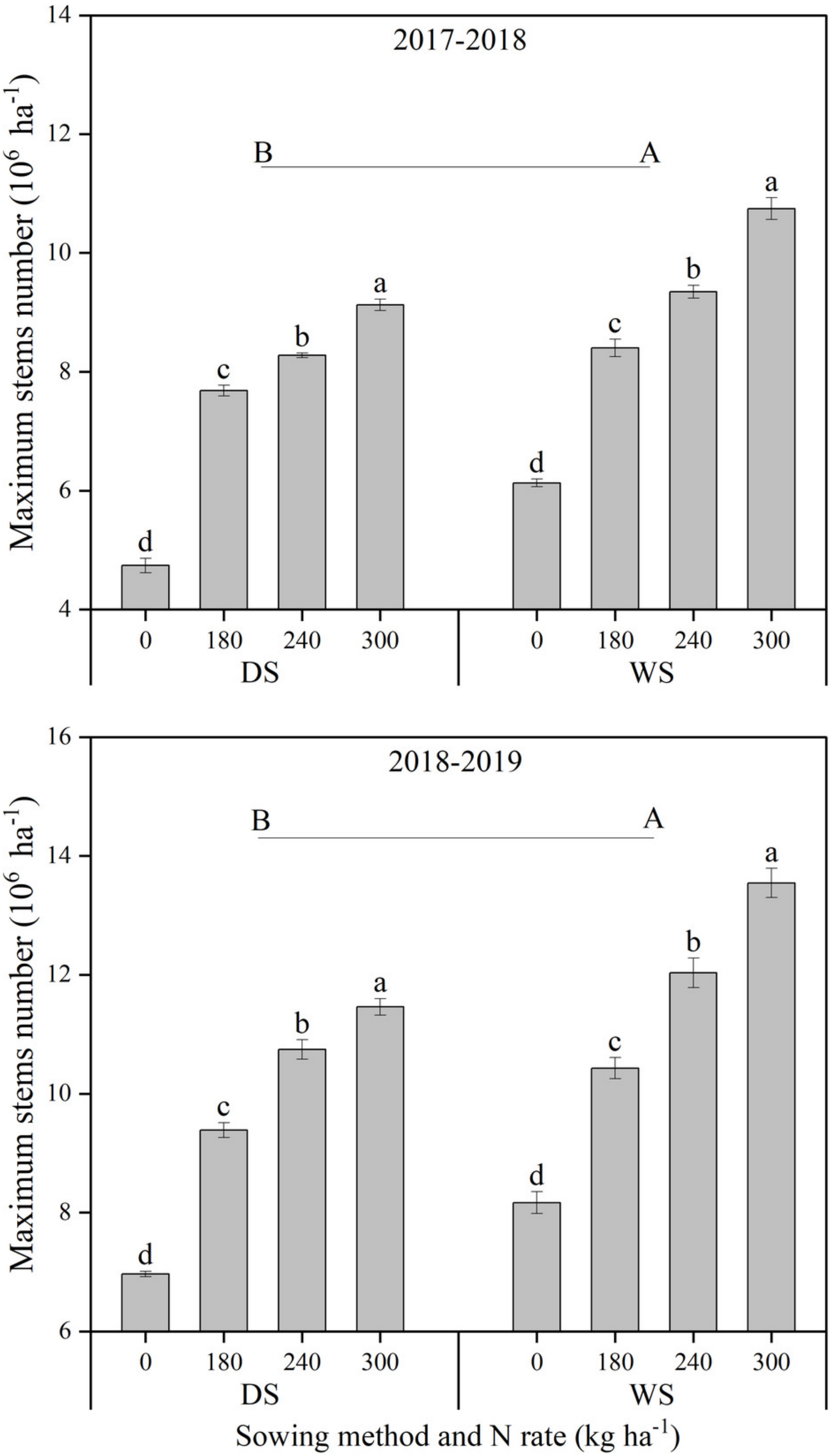
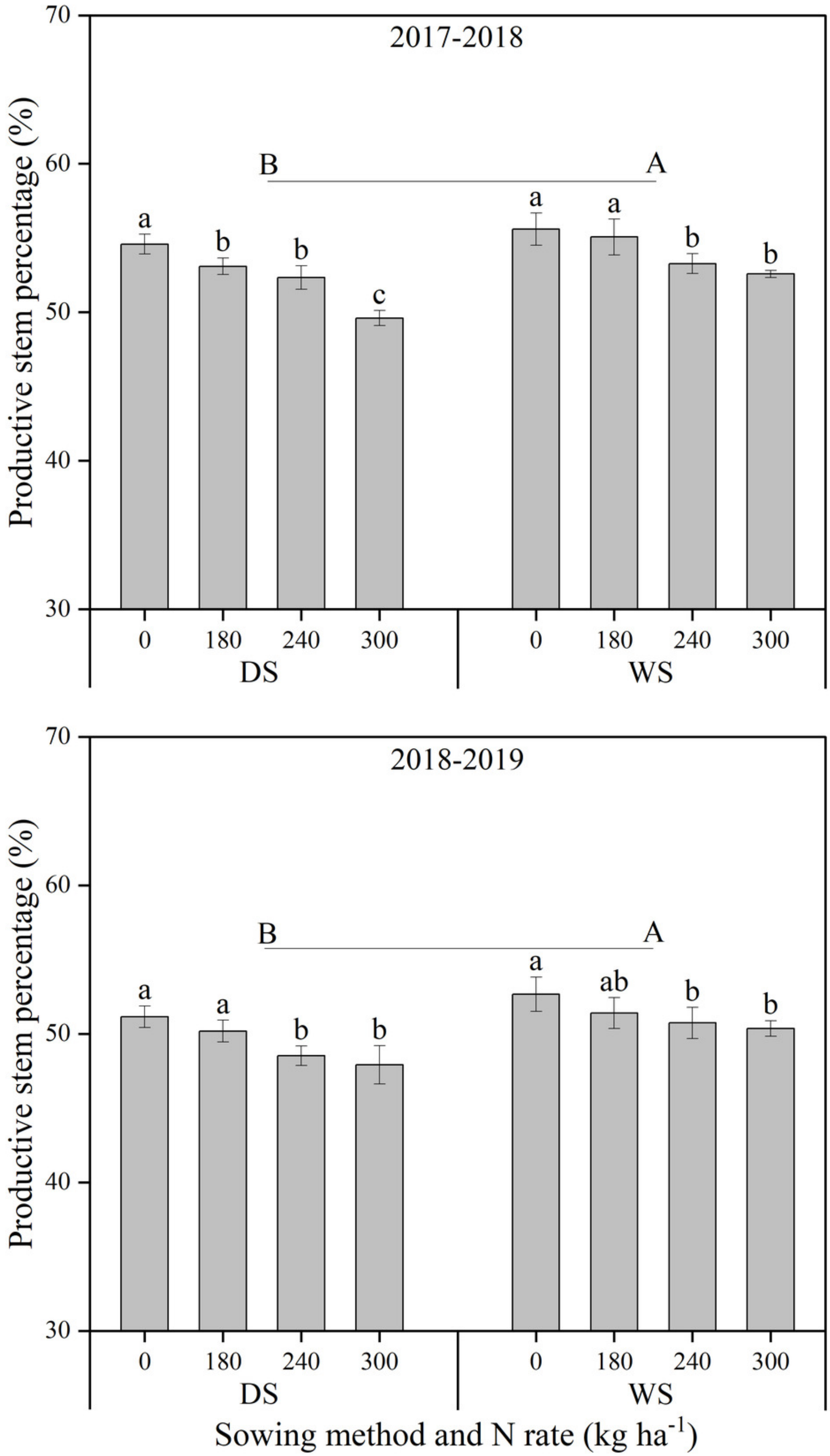

2017-2018
Maximum stems number (10^6 ha^-1)
14
12
10
8
6
4
B
A
a
b
c
d
0
180
240
300
DS
WS
2018-2019
16
14
12
10
8
6
Sowing method and N rate (kg ha^-1)

Figure 3

Figure 3

Figure 3. Productive stem percentage of winter wheat under different sowing method and N rate in 2017-2018 and 2018-2019. DS, drill sowing; WS, wide space sowing. Within each growing season, bars with different upper-case letters are significantly different according to Tukey's HSD test (*α=0.05*) between two sowing methods. Within each growing season for sowing method, bars with different lower-case letters are significantly different according to Tukey's HSD test (*α=0.05*) among four N treatments.



2017-2018
Productive stem percentage (%)
70
60
50
40
30
B
A
a
b
b
c
a
a
b
b
0
180
240
300
0
180
240
300
DS
WS
2018-2019
Productive stem percentage (%)
B
A
a
a
b
b
a
ab
b
b
DS
WS
Sowing method and N rate (kg ha-1)

Figure 4

Figure 4.

Figure 4. Leaf area index at anthesis of winter wheat under different sowing method and N rate in 2017-2018 and 2018-2019. DS, drill sowing; WS, wide space sowing. Within each growing season, bars with different upper-case letters are significantly different according to Tukey's HSD test (*α=0.05*) between two sowing methods. Within each growing season for sowing method, bars with different lower-case letters are significantly different according to Tukey's HSD test (*α=0.05*) among four N treatments.

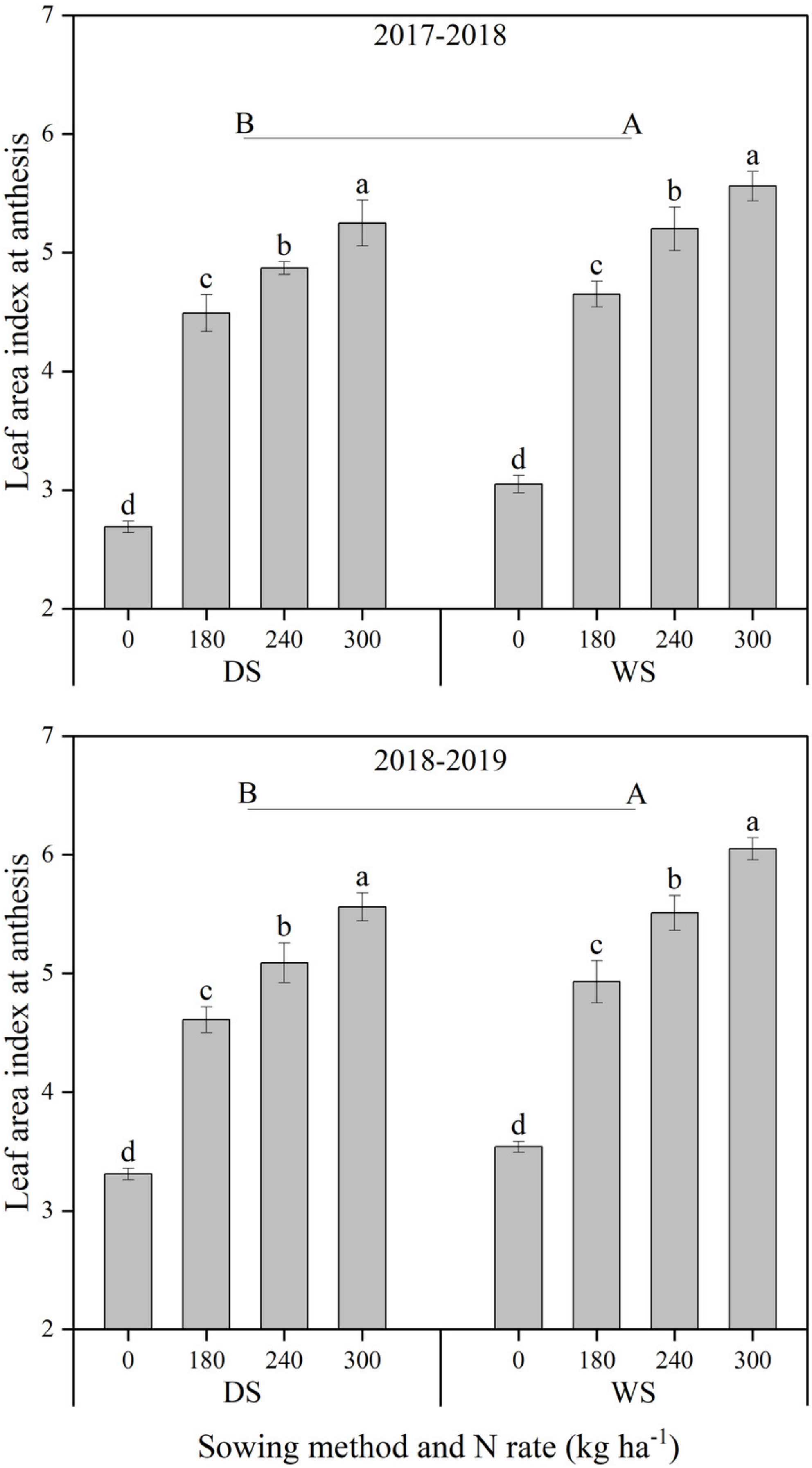

2017-2018
2018-2019
Leaf area index at anthesis
B
A
a
b
c
d
0
180
240
300
DS
WS
2
3
4
5
6
7
Sowing method and N rate (kg ha-1)

Table 1(on next page)

Table1.

Table 1 Soil basic fertility before sowing at the experimental site in 2017-2018 and 2018-2019

Table 1 Soil basic fertility before sowing at the experimental site in 2017-2018 and 2018-2019.

Year	pH	Organic matter ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Alkaline N ($mg\ kg^{-1}$)	Olsen P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)
2017-2018	8.61	13.61	1.06	44.07	10.71	188.87
2018-2019	8.47	14.31	1.01	40.05	11.25	200.24

Table 2(on next page)

Table 2.

Table 2 The climate parameters in 2017-2018 and 2018-2019.

1 Table 2 The climate parameters in 2017-2018 and 2018-2019.

Year	Period	Precipitation	Daily mean temperature	Total accumulated temperature	Incident radiation
		mm	°C	°C d	MJ m^{-2}
2017-2018	S-J	35.3	3.2	654.7	1395.1
	J-B	47.5	11.9	226.1	303.9
	B-A	27.1	18.1	344.7	360.8
	A-M	44.3	20.9	753.1	708.1
	Whole season	**154.2**	**7.9**	**1978.6**	**2767.9**
2018-2019	S-J	48.9	3.7	732.8	1588.0
	J-B	20.7	13.2	304.5	338.1
	B-A	22.7	18.6	371.4	370.0
	A-M	10.7	21.8	871.6	738.5
	Whole season	**103.0**	**8.7**	**2280.3**	**3034.5**

2 S-J, from sowing to jointing; J-B, from jointing to booting; B-A, from booting to anthesis; A-M, from anthesis to maturity.

3

Table 3(on next page)

Table 3

Table 3 Growth durations in wheat growing season in 2017-2018 and 2018-2019

Table 3 Growth durations in wheat growing season in 2017-2018 and 2018-2019.

Year	S-J	J-B	B-A	A-M	Whole season (d)
2017-2018	155	19	19	36	229
2018-2019	162	23	20	40	245

S-J, from sowing to jointing; J-B, from jointing to booting; B-A, from booting to anthesis; A-M, from anthesis to maturity.

Table 4(on next page)

Table 4

Table 4 Grain yield and yield components of winter wheat under different sowing method and N treatment in 2017-2018 and 2018-2019.

Table 4 Grain yield and yield components of winter wheat under different sowing method and N treatment in 2017-2018 and 2018-2019.

Year	Sowing method	N treatment	Yield (t ha^{-1})	Ear number (10^6 ha^{-1})	Grain number per ear	1000-grain weight (g)
2017-2018	DS	N0	3.88 d	2.59 d	28.5 c	44.1 a
		N180	6.31 b	4.08 c	33.3 a	41.2 b
		N240	6.79 a	4.33 b	33.2 a	40.9 b
		N300	5.99 c #	4.53 a	30.4 b	38.2 c
		Mean	**5.74 B**	**3.88 B**	**31.3 A**	**41.1 A**
	WS	N0	4.43 c	3.41 d	25.8 c	43.0 a
		N180	6.86 b	4.60 c	32.9 a	40.1 b
		N240	7.64 a	5.01 b	32.7 a	40.0 b
		N300	7.79 a	5.65 a	29.9 b	39.1 c
		Mean	**6.68 A**	**4.67 A**	**30.3 B**	**40.6 A**
2018-2019	DS	N0	5.02 c	3.56 d	27.0 c	44.6 a
		N180	7.47 b	4.77 c	32.8 a	42.0 b
		N240	8.04 a	5.19 b	32.8 a	41.9 b
		N300	7.46 b #	5.49 a	29.4 b	40.2 c
		Mean	**7.00 B**	**4.75 B**	**30.5 A**	**42.2 A**
	WS	N0	5.51 c	4.30 d	24.8 c	44.3 a
		N180	8.23 b	5.36 c	31.7 a	42.3 b
		N240	8.95 a	6.10 b	30.8 a	41.9 b
		N300	9.12 a	6.82 a	28.9 b	40.4 c
		Mean	**7.95 A**	**5.65 A**	**29.0 B**	**42.2 A**
ANOVA						
Year (Y)		**	**	**	**	**
Sowing (S)		**	**	**	**	ns
N rate (N)		**	**	**	**	**
Y×S		ns	ns	ns	ns	ns
Y×N		ns	ns	ns	ns	ns
S×N		**	**	**	**	**
Y×S×N		**	**	**	**	**

DS, drill sowing; WS, wide space sowing. #, lodging happened during grain filling. Within a column for each growing season, means followed by different upper-case letters are significantly different according to Tukey's HSD test (*α=0.05*) between two sowing methods. Within a column for sowing method, means followed by different lower-case letters are significantly different according to Tukey's HSD test (*α=0.05*) among four N treatments. * and **. significant at 0.05 and 0.01 probability levels, respectively; ns, not significant at 0.05 probability level.

Table 5(on next page)

Table 5

Table 5 Total dry weight, harvest index, total dry weight at anthesis, post-anthesis dry matter production of winter wheat under different sowing method and N treatment in 2017-2018 and 2018-2019.

Table 5 Total dry weight, harvest index, total dry weight at anthesis, post-anthesis dry matter production of winter wheat under different sowing method and N treatment in 2017-2018 and 2018-2019.

Year	Sowing method	N treatment	Total dry weight (t ha^{-1})	Harvest index (%)	Total dry weight at anthesis (t ha^{-1})	Post-anthesis dry matter production (t ha^{-1})
2017-2018	DS	N0	6.34 c	51.2 a	4.12 c	2.22 c
		N180	12.09 b	46.3 b	8.05 b	4.04 b
		N240	12.94 a	45.8 b	8.60 a	4.34 a
		N300	12.10 b	43.4 c	8.14 b	3.96 b
		Mean	**10.87 B**	**46.7 A**	**7.23 B**	**3.64 B**
	WS	N0	7.61 c	49.7 a	4.90 d	2.71 c
		N180	12.98 b	46.6 b	8.26 c	4.72 b
		N240	14.20 a	46.0 b	9.01 b	5.19 a
		N300	14.63 a	45.1 b	9.40 a	5.23 a
		Mean	**12.35 A**	**46.9 A**	**7.89 A**	**4.46 A**
2018-2019	DS	N0	9.27 c	46.3 a	6.09 c	3.18 c
		N180	14.90 b	43.7 b	9.77 b	5.13 b
		N240	16.46 a	43.5 b	10.72 a	5.74 a
		N300	15.20 b	42.7 b	10.04 b	5.16 b
		Mean	**13.96 B**	**44.1 A**	**9.16 B**	**4.80 B**
	WS	N0	10.19 c	46.3 a	6.53 c	3.66 c
		N180	16.90 b	42.5 b	10.91 b	5.99 b
		N240	18.53 a	42.5 b	11.83 a	6.70 a
		N300	18.75 a	42.4 b	12.06 a	6.69 a
		Mean	**16.09 A**	**43.4 A**	**10.33 A**	**5.76 A**
ANOVA						
Year (Y)			**	**	**	**
Sowing (S)			**	ns	**	**
N rate (N)			**	**	**	**
Y×S			ns	ns	ns	ns
Y×N			ns	ns	ns	ns
S×N			**	**	**	**
Y×S×N			**	**	**	**

DS, drill sowing; WS, wide space sowing. Within a column for each growing season, means followed by different upper-case letters are significantly different according to Tukey's HSD test (*α=0.05*) between two sowing methods. Within a column for sowing method, means followed by different lower-case letters are significantly different according to Tukey's HSD test (*α=0.05*) among four N treatments. * and **. significant at 0.05 and 0.01 probability levels, respectively; ns, not significant at 0.05 probability level.

Table 6 (on next page)

Table 6

Table 6 Grain N concentration and content (GNC% and GN) at maturity, total N quantity at maturity (TN), N harvest index (NHI), total N quantity at anthesis (TN_{as}), post-anthesis accumulated N (N_{post}) of winter wheat under different sowing method and N treatment in 2017-2018 and 2018-2019.

Table 6 Grain N concentration and content (GNC% and GN) at maturity, total N quantity at maturity (TN), N harvest index (NHI), total N quantity at anthesis (TN_{as}), post-anthesis accumulated N (N_{post}) of winter wheat under different sowing method and N treatment in 2017-2018 and 2018-2019.

Year	Sowing method	N treatment	GNC% (%)	GN (kg ha^{-1})	TN (kg ha^{-1})	NHI (%)	TN_{as} (kg ha^{-1})	N_{post} (kg ha^{-1})
2017-2018	DS	N0	2.19 b	71.3 c	99.1 d	71.9 a	70.2 d	28.9 d
		N180	2.46 a	137.6 b	198.8 c	69.2 b	149.6 c	49.2 c
		N240	2.52 a	149.3 a	218.6 b	68.3 b	161.1 b	57.5 b
		N300	2.57 a	134.7 b	235.6 a	57.2 c	168.6 a	67.0 a
		Mean	**2.43 A**	**123.2 B**	**188.0 B**	**66.6 B**	**137.4 B**	**50.6 B**
	WS	N0	2.19 c	82.6 d	111.1 d	74.4 a	79.2 d	31.9 d
		N180	2.54 b	153.6 c	218.1 c	70.4 b	157.0 c	61.2 c
		N240	2.59 b	169.0 b	244.5 b	69.1 b	172.3 b	72.2 b
		N300	2.72 a	179.5 a	269.8 a	66.5 c	189.6 a	80.2 a
		Mean	**2.51 A**	**146.2 A**	**210.9 A**	**70.1 A**	**149.5 A**	**61.4 A**
2018-2019	DS	N0	2.12 b	90.9 c	123.6 d	73.6 a	91.6 d	32.0 d
		N180	2.30 a	150.0 b	222.9 c	67.3 b	156.3 c	66.6 c
		N240	2.31 a	165.6 a	247.5 b	66.9 b	172.6 b	74.9 b
		N300	2.39 a	155.3 b	264.2 a	58.8 c	179.6 a	84.6 a
		Mean	**2.28 A**	**140.4 B**	**214.6 B**	**66.6 B**	**150.0 B**	**64.5 B**
	WS	N0	2.12 c	100.0 d	136.0 d	73.5 a	99.0 d	37.0 d
		N180	2.31 b	165.7 c	241.4 c	68.7 b	169.8 c	71.5 c
		N240	2.34 b	184.1 b	270.3 b	68.1 b	185.1 b	85.1 b
		N300	2.48 a	197.3 a	299.5 a	65.9 c	201.6 a	97.9 a
		Mean	**2.31 A**	**161.8 A**	**236.8 A**	**69.0 A**	**163.9 A**	**72.9 A**
ANOVA								
Year (Y)			**	**	**	**	**	**
Sowing (S)			ns	**	**	**	**	**
N rate (N)			**	**	**	**	**	**
Y×S			ns	ns	ns	ns	ns	ns
Y×N			ns	ns	ns	ns	ns	ns
S×N			**	**	**	**	**	**
Y×S×N			**	**	**	**	**	**

DS, drill sowing; WS, wide space sowing. Within a column for each growing season, means followed by different upper-case letters are significantly different according to Tukey's HSD test (*α=0.05*) between two sowing methods. Within a column for sowing method, means followed by different lower-case letters are significantly different according to Tukey's HSD test (*α=0.05*) among four N treatments. * and **. significant at 0.05 and 0.01 probability levels, respectively; ns, not significant at 0.05 probability level.

Table 7(on next page)

Table 7

Table 7 N use efficiency (NUE), N uptake efficiency (NUpE), N utilization efficiency (NUtE), agronomic N use efficiency (AE_N), N recovery efficiency(RE_N), partial factor productivity of applied N (PFP_N) of winter wheat under different sowing method and N treatment in 2017-2018 and 2018-2019.

Table 7 N use efficiency (NUE), N uptake efficiency (NUpE), N utilization efficiency (NUtE), agronomic N use efficiency (AE_N), N recovery efficiency(RE_N), partial factor productivity of applied N (PFP_N) of winter wheat under different sowing method and N treatment in 2017-2018 and 2018-2019.

Year	Sowing method	N treatment	NUE (kg kg^{-1})	NUpE (%)	NUtE (kg kg^{-1})	AE_N (kg kg^{-1})	RE_N (%)	PFPN (kg kg^{-1})
2017-2018	DS	N0	21.0 a	63.9 a	32.8 a	-	-	-
		N180	16.7 b	59.3 b	28.1 b	13.5 a	55.4 a	35.0 a
		N240	15.0 c	55.4 c	27.1 b	12.1 b	49.8 b	28.3 b
		N300	11.5 d	51.8 d	22.3 c	7.0 c	45.5 c	20.0 c
		Mean	**16.0 B**	**57.6 B**	**27.6 A**	**10.9 B**	**50.2 B**	**27.8 B**
	WS	N0	24.4 a	71.7 a	34.0 a	-	-	-
		N180	18.1 b	65.1 b	27.7 b	13.5 a	59.5 a	38.1 a
		N240	16.5 c	61.9 c	26.7 b	13.4 a	55.6 b	31.8 b
		N300	14.5 d	59.3 d	24.5 c	11.2 b	52.9 b	26.0 c
		Mean	**18.4 A**	**64.5 A**	**28.2 A**	**12.7 A**	**56.0 A**	**32.0 A**
2018-2019	DS	N0	26.4a	76.1 a	34.7 a	-	-	-
		N180	19.0 b	65.1 b	29.2 b	13.6 a	55.2 a	41.5 a
		N240	17.8 c	61.5 c	29.0 b	12.6 b	51.6 b	33.5 b
		N300	14.0 d	57.2 d	24.6 c	8.1 c	46.9 c	24.9 c
		Mean	**19.3 B**	**65.0 B**	**29.4 A**	**11.4 B**	**51.3 B**	**33.3 B**
	WS	N0	29.1 a	83.8 a	34.7 a	-	-	-
		N180	21.0 b	70.5 b	29.7 b	15.1 a	58.5 a	45.7 a
		N240	19.5 c	67.2 c	29.1 b	14.4 b	55.9 b	37.3 b
		N300	17.2 d	64.8 d	26.6 c	12.1 c	54.5 b	30. 4 c
		Mean	**21.7 A**	**71.6 A**	**30.0 A**	**13.8 A**	**56.3 A**	**37.8 A**
ANOVA								
Year (Y)			**	**	**	**	**	**
Sowing (S)			**	**	ns	**	**	**
N rate (N)			**	**	**	**	**	**
Y×S			ns	ns	ns	ns	ns	ns
Y×N			ns	ns	ns	ns	ns	ns
S×N			**	**	**	**	**	**
Y×S×N			**	**	**	**	**	**

DS, drill sowing; WS, wide space sowing. Within a column for each growing season, means followed by different upper-case letters are significantly different according to Tukey's HSD test (*α=0.05*) between two sowing methods. Within a column for sowing method, means followed by different lower-case letters are significantly different according to Tukey's HSD test (*α=0.05*) among four N treatments. * and **. significant at 0.05 and 0.01 probability levels, respectively; ns, not significant at 0.05 probability level.