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Optimized Planting Density Maintains High Wheat Yield Under Limiting Irrigation in North China Plain

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Abstract

Regulating plant density is an important practice to improve winter wheat productivity under limited irrigation in North China Plain. Field experiments were carried out over two seasons (2014–15 and 2015–16) under three plant densities (D_h: 480–570, D_m: 360–390, D_l: 240–270 10^4 plants hm^{-2}) and three irrigation levels (W0: no irrigation; W1: irrigated 80.0 mm only at the jointing stage, which also means limited irrigation; W2: irrigated 60.0 mm each at the jointing and the flowering stages). Results showed that higher numbers of spikes and higher yield were obtained at high density than that at low density under limited irrigation. Under the same irrigation, wheat culms at ripening stage and the proportion of main stem spikes increased with plant density increasing, along with the increasing of transportation amount, transportation rate, and contribution rate of pre-anthesis storage material to grain. But accumulation amount and contribution rate of post-anthesis dry matter, which was influenced by irrigation level, showed a declining trend with increasing plant density under W2 and W1. Therefore, (1) under limited water condition, yield loss could be compensated by increasing contribution rate of pre-anthesis storage material to grain with increasing plant density. (2) Meantime, under the same limited water condition, higher plant densities could promote nitrogen accumulation in grain and plant of wheat, which was significantly correlation to wheat yield. (3) Considering water and nitrogen use efficiency, medium plant density (D_m) is recommended in wet years, high plant density (D_h) may be considered to increase wheat yield in dry years.

Keywords Plant density · Water use efficiency · Yield components · Nitrogen use efficiency

Introduction

The Huang–Huai–Hai Plain is known as wheat silos of China. In this region, the annual rainfall is about 150–180 mm, which could only meet 20–30% water requirement of wheat growth (Liu et al. 2011; Yuan et al. 2015). In order to obtain high wheat grain yield, it is very common for producers to flood-irrigate with more than 300 mm of underground water that result in over-exploit water resources and serious ecological crisis (Xu et al. 2005; Sun et al. 2011;

Aeschbach-Hertig and Gleeson 2012; Li et al. 2012). Since 2015, the irrigation water supply volume for wheat planting has been reduced by 30% in Hebei, which aims to ease ground water shortage. Under such situation, it is inevitable the wheat yield, nitrogen and water use efficiency may be decreased with reducing irrigation (Zhao et al. 2015). There has been a continuing effort to balance stably high wheat yield and use of limited irrigation water in order to develop better crops potential productivity and water management practices.

Reductions in grain yield due to restricted water availability depend on the degree, duration and timing of the imposed soil-moisture deficit. The most sensitive stage can exhibit variations from one region to another (Singh et al. 1991; Gooding et al. 2003; Mohammadi et al. 2012). Higher yield can be compensated by increasing seeding rate under-water deficit conditions (Blue et al. 1990; Lloveras et al. 2004). Increasing plant density from 350 to 450 plants per m^2 improved yield and yield components by regulating leaf area index, growth rate and nitrogen application rate under

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water deficit (Ai 2012). Dry matter remobilization from vegetative organs at pre-flowering and the photosynthesis at post flowering both have contributed to wheat grain filling (Hu et al. 2007). Post-anthesis water deficit increased contribution of remobilized dry matter to a grain (Bahrani et al. 2011). Dry matter remobilization to grain from vegetative organs at pre-flowering would be promoted by increasing seeding density (Qu et al. 2009). Yield response to seeding rate also depends on rainfall. Higher seeding densities for winter wheat in average-rainfall years can ensure greater water availability at grain filling stage (Fang et al. 2015). However, under the same irrigation treatment, actual photochemical efficiency of PSII (Φ PSII), dry matter accumulation amount after anthesis and dry matter translocation amount to grains at 150 plants per m^2 were significantly higher than those at 225 plants per m^2 (Luo et al. 2011). These contrasting results could be related to different water conditions. Under normal water conditions, photosynthesis supplies the materials required for grain filling, but under drought stress, remobilization of dry matter in spike and stem during the grain filling period could help the plant recover its grain yield (Golabadi et al. 2015). Wheat plants allocate relatively higher assimilates to roots under drought during stem elongation and post-anthesis stages, but remobilize them to grains under drought during stem elongation and re-watering at post-anthesis stage (Tatar et al. 2016).

Although suitable planting density is the determinative factor for high yield, yield may be decreased because of the mutual competition for nutrition among individuals when planting density is excessively large (Hiltbrunner et al. 2007). Under high plant density, lower yield potential lines react more conservatively producing a reduced number of grains per plant and lower yields (Sukumaran et al. 2015). The optimum seeding density should not be consistent for different varieties, rainfall, soil types and so on (Geleta et al. 2002; Fang et al. 2010; Dai et al. 2013). Additionally, water use efficiency on yield level is often limited by environmental (e.g., seasonal distribution of rainfall) and management factors (Zhang et al. 2013). In North China Plain, with increasingly erratic rainfall patterns particularly in irrigation-limited wheat production systems, there is a need to optimize planting density and to keep stable wheat yield with increased water use efficiency (WUE) under limited irrigation.

Materials and Methods

Experimental Site

Field experiments were conducted at Gaocheng station (37° 79′N, 115° 31′E) of Hebei Agricultural University, Shijiazhuang, Hebei during 2013−16. The experiment was a

two-factor split zone design arranged in randomized blocks with three replications. The main plots were irrigation times, including three different irrigation regimes: no irrigation at any time during the winter wheat growing season (W0), irrigated 80.0 mm only at the jointing stage (W1)-limited irrigation, and irrigated 60.0 mm each at the jointing and the flowering stages (W2). Irrigation water amount was measured by a flow meter analyzer. Subplots consisted of three planting densities: D240−270 (D_L), D360−390 (D_M), and D480−570 (D_H) plants m^{-2} in 2014−15 and in 2015−16. The actual sowing rate was regulated by feed level of wheat precision drill. Wheat cultivar was Shimai18, a semi-winterness variety, is cultivated by Shijiazhuang Academy of Agricultural and Forestry Sciences. This variety with strong tillering ability is one of main extending varieties in Hebei province. At the time of sowing, 15.0 g m^{-2} of P_2O_5 and 9.0 g m^{-2} of K_2O were applied to the soil. For W0 treatment, 21.2 g m^{-2} pure nitrogen fertilizer was applied to the soil at sowing time. But for W1 and W2, half of pure nitrogen (10.6 g m^{-2}) was applied at sowing, another half of pure nitrogen was applied at the jointing stage. It should be noted that preceding maize was irrigated during grain filling period, which not only relive drought stress on maize at latter stage, but also ensure seeding emergency of next-stubble wheat. Each experimental plot was 7.0 m × 10.0 m in size with brown-loamy soil and concrete slabs were placed around the plots to prevent the lateral flow of soil water. The levels of rapidly available nitrogen, phosphorus, and potassium in the 0–20 cm soil layer were 103.8, 21.9, and 133.3 mg kg^{-1}, respectively. The organic matter and total nitrogen content were 21.3 and 1.1 g kg^{-1}, respectively. The soil bulk density was 1.4 g cm^{-3}. The monthly precipitations and temperatures during the experimental years were shown in Fig. 1.

The preceding crop summer maize was crushed three times after being harvested, and returned into the field. The line spacing was 15 cm. The winter wheat was planted on October 7, 2015 and 2016, respectively. During the jointing stage, irrigation was conducted on 23 March and on 4 April in 2015 and 2016, respectively. The second irrigation was conducted on 9 May, 2016 and was postponed on 23 May, 2015 due to heavy rainfall at the flowering stage.

Traits Measurements

Dry matter measurement: 30 representative plants were selected at the erecting, flowering and mature stage, respectively. Plants were separated into leaf, stem + leaf sheath, spike at the flowering stage and into leaf, stem sheath, glume + spike stalk at the mature stage. Plant samples were killed at 105 °C for 30 min, and dried in an oven at 75 °C to constant weight. The dry weight of all organs were then recorded (Masoni et al. 2007; Fang et al. 2015).
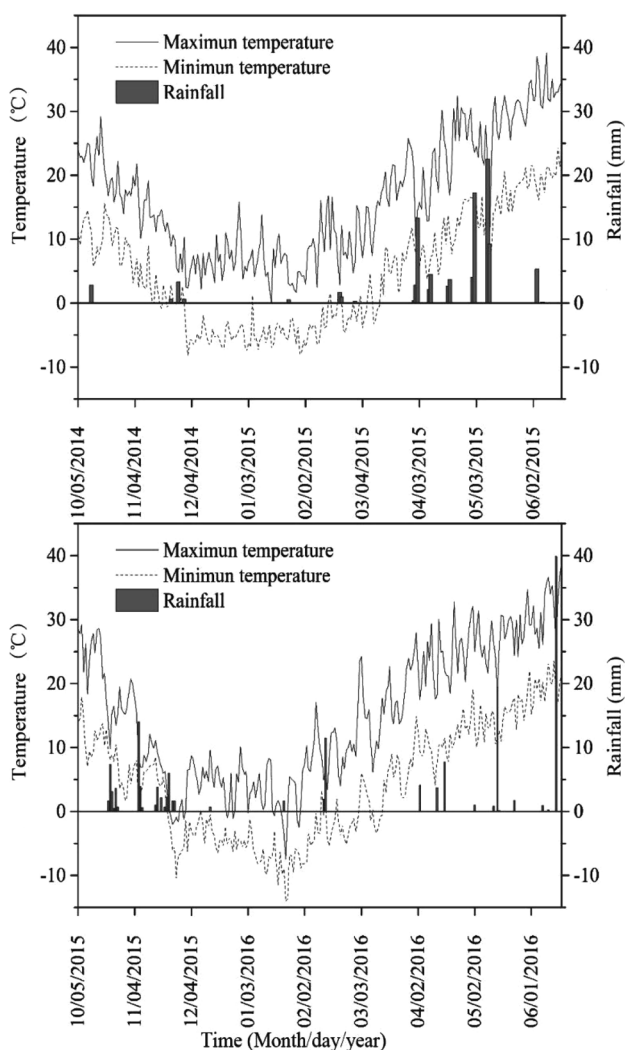
Fig. 1 Monthly temperature and precipitation in experimental years (2014–2016)

$$DMR = DMA \text{ at the anthesis stage} - DMA \text{ at the mature stage} \quad (1)$$

$$TCDMR = DMR/DMA \text{ at the anthesis stage} \times 100 \quad (2)$$

$$CDMR = DMR/\text{dry matter in grain at the mature stage} \times 100 \quad (3)$$

$$ADM = \text{dry matter accumulation at the mature stage} \\ - \text{dry matter accumulation at the anthesis stage} \quad (4)$$

$$ACDM = ADM/\text{dry matter in grain at the mature stage} \quad (5)$$

where DMR (kg hm^{-2}) is the amount of dry matter transferred in the vegetative organ, DMA is the dry matter accumulation in the vegetative organ, TCDMR (%) is the dry matter transfer rate of the vegetative organs, CDMR (%) is

the contribution rate of dry matter in the vegetative nutrient organs to grains before flowering, ADM (kg hm^{-2}) is the amount of dry matter accumulated after flowering, ACDM (%) is the contribution rate of dry matter accumulated after flowering to grain.

Soil Water Measurements Soil water content was measured by oven drying method (Qiao et al. 2010).

$$GWC = (SFW - SDW)/SDW \times 100\% \quad (6)$$

where GWC is gravimetric water content of soil, SFW is fresh weight of soil samples in each 20 cm depth for the 0−200 cm underground, and SDW is dry weight of soil samples was dried in an oven at 105 °C to constant weight.

Soil water storage was calculated as follows (Xu et al. 2016):

$$\text{Soil water storage (SWS, mm)} = 10 \times GWC \times \gamma \times H \quad (7)$$

where GWC is the gravimetric water content of soil (g g^{-1}), γ (g cm^{-3}) is the soil bulk density, and H (cm) is the soil depth.

Field water consumption was calculated by a water balance method (Liu et al. 2004).

$$\text{Field water consumption (ET, mm)} = I + P - R - D + \Delta SWS \quad (8)$$

where ΔSWS is variable quantity of soil water storage during wheat growth stage (mm), I was irrigation amount (mm), P is precipitation (mm), R is surface runoff (mm), D is supply amount of ground water(mm). D and R were treated as zero in this study because of the absence of R in the North China Plain.

Water Use Efficacy Water use efficiency was calculated as follows (Li et al. 2007):

$$WUE = Y/ET \quad (9)$$

$$WUE_I = Y/I \quad (10)$$

where WUE is water use efficiency (kg hm^{-2} mm^{-1}), Y is grain yield (kg hm^{-2}), ET is the actual water consumption during wheat growth stage (mm), WUE_I is irrigation water use efficiency (kg hm^{-2} mm^{-1}), and I is the irrigation amount (mm).

Grain Yield Ripe wheat was harvested from the harvest area (3 m^2) in the ten middle rows of each subplot. The grain weight was corrected to 12.5% moisture content to determine the actual yield.

Nitrogen use efficiency was calculated as follows:

$$\text{Nitrogen partial factor productivity} \left(NPFP, \text{kg kg}^{-1}\right) = \frac{Y_N}{A_N} \quad (11)$$

$$\text{Nitrogen uptake efficiency} \left(NUpE, \text{kg kg}^{-1}\right) = \frac{U_N}{A_N} \quad (12)$$

Nitrogen physiological efficiency $\left(\text{NPE, kg kg}^{-1}\right) = \dfrac{Y_N}{U_N}$

$$(13)$$

Y_N(kg grain hm^{-2}) is the grain yield under different nitrogen treatments. A_N (kg N hm^{-2}) is the nitrogen amount, U_N(kg N hm^{-2})is the nitrogen accumulation.

Date Analysis

Experimental data were performed with Microsoft Excel 2016 (Microsoft Corporation, Redmond, USA) and SPSS Statistics 19.0 (SPSS, IBM, New York, USA). The significant differences among means followed by a different letter within a column of each table are significantly different at $p \leq 0.05$ by Tukey's HSD (honest significant difference) test. Because the interaction effect of irrigation and nitrogen level on all measuring items was not significant at the 0.05 probability level, the experiment results with two factors were only evaluated using the main effect analysis.

Results

Effect of Planting Density on Yield and Yield Components Under Limited Irrigation

Mixed Effect Model was used to analyze total effect of irrigation amount and plant density on wheat grain yield in 2 years (Table 1). Results showed that the effect of irrigation amount on wheat grain yield was significant. However, interaction effect of plant density and irrigation on wheat yield was insignificant.

Table 2 showed that wheat yield significantly decreased with decreasing irrigation frequency. For W2 treatment, plant density did not affect grain yield in these 2 years. For W1, wheat yield decreased with increasing plant density in 2014−15, however, the trend was reverse in 2015−16. For W0 treatment, there were no significant differences in yield among these three planting densities in 2014−15, however, yield increased with increasing plant density in 2015−16.

These differences were possibly caused by different rainfalls in the wheat growing seasons. In 2014−15, rainfall occurred twice reaching 53.1 mm on first ten-days of May. This means all wheats obtained irrigation during flowering stage, which relieved water stress on wheat under W0 to some extent. The differences among all density treatments were not significant. This was a disadvantage to yield at high plant density under the W1. In contrast, there was small rainfall on first 10-days of May, 2016. Drought stress affected wheat growth plant densities after flowering under W0 and W1. Higher yield with more spikes was obtained from high density wheat plant than that from low density.

Yield range varied obviously for wheat under low density treatment. Grain yield from D_L in 2014−15 was 9270.6 kg hm^{-2}, and that from D_L in 2015−16 was 8000.1 kg hm^{-2}, which was 1270.5 kg hm^{-2} higher than the former. However, the yield gap was only 485.3 kg hm^{-2} from D_M between 2 years, showing that high plant density was advantageous to stable grain yield.

Spike number and grains per spike under different irrigation and plant density treatments both showed a similar changing trend between the 2 years. Under the same irrigation, spikes per ha increased but grains per spike decreased with increasing plant density. In 2014−15, although spikes per ha of D_H under W1 increased significantly, the 1000−grain weight and the grain yield decreased significantly. This suggested that the 1000−grain weight was the main factor causing yield loss under the W1 condition. Spikes per ha could compensate yield loss caused by reduced irrigation. In 2015−16, spikes per ha of D_M increased more significantly than that of D_L under W1, and also yield increased correspondingly. Under W0, spikes per ha and yield increased with increasing plant density in the two growth seasons.

Tiller Population Dynamics

Table 3 showed interannual differences in tillers. The culms (spikes) of wheat population at the erecting and mature stages in 2014−15 were both higher than that in 2015−16. This may be attributed to different climatic factors. Over−wintering period began on December 1, 2014, when the average temperature decreased below 0 °C. During the

Table 1 The effects of planting density and irrigation amount on grain yield of winter wheat

Variable	Value	S.E.	DF	t value	p value	Sign.
Intercept *a*	6598.599	517.496	13	12.751	0.000	***
Irrigation water *W*	19.524	4.995	13	3.909	0.002	**
Plant density *D*	2.356	1.286	13	1.832	0.090	ns
W × *D*	− 0.021	0.012	13	− 1.726	0.108	ns

S.E. standard error, *DF* degree of freedom

, * and ns refer to significant treatment effects in ANOVA at $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively

Table 2 Effects of irrigation amount and planting density on grain yield and its components of wheat (2014–2016)

Irrigation	Density (10^4 hm^{-2})	Spikes (10^4 hm^{-2})	Grains per spike	1000 grain weight (g)	Grain yield (kg hm^{-2})
2014–2015					
W2	D_L	708.3b	37.6a	39.72b	9302.0a
	D_M	721.7b	36.0a	39.15bc	9261.7a
	D_H	776.7a	34.4ab	39.70b	9098.1ab
W1	D_L	756.7b	37.5a	38.11de	9270.6a
	D_M	760.0b	35.4a	38.56cd	9046.9ab
	D_H	783.3a	35.3a	37.66ef	8406.2b
W0	D_L	640.0d	31.6bc	37.29f	7096.5c
	D_M	717.5c	31.9b	39.27b	7560.5c
	D_H	768.3b	28.7c	40.46a	7338.9c
2015–2016					
W2	D_L	604.4cd	36.9a	40.63ab	9156.4a
	D_M	680.0b	35.1a	39.91b	9162.1a
	D_H	765.6a	34.5a	39.23bc	9129.7a
W1	D_L	614.4c	37.1a	36.57d	8000.1c
	D_M	694.4b	35.2a	38.05cd	8561.6b
	D_H	770.2a	34.6a	37.35d	8613.3b
W0	D_L	541.1e	33.9a	37.18d	6635.6d
	D_M	558.9de	35.8a	39.81b	7672.3c
	D_H	655.6bc	30.8b	41.92a	7999.0c

Means followed by a different letter within a column are significantly different at $P \leq 0.05$ by Tukey's HSD (honest significant difference) test

LSD least significant difference

growth season in 2014−15, the accumulated temperature (> 0 °C) before winter was 573.6 °C, and the rainfall was 7.5 mm. In 2015, over−wintering period began on November 22, the accumulated temperature (> 0 °C) before winter was 506.5 °C, and the rainfall was 54.4 mm (Fig. 1). Because of lower accumulated temperature, the culms at the erecting stage in 2015−16 was lower than that in 2014−15, with D_M at erecting the highest under W2 and W1. In 2015−16, the culms with three irrigation treatments increased with increasing plant density at the erecting and mature stage. Under the same irrigation, spikes formation rate, proportion of tiller spikes and ear−bearing tiller rate decreased, but the proportion of main stem spikes increased with increasing plant density.

Dry Matter Accumulation and Transfer

Dry matter accumulation of wheat at flowering stage increased with increasing plant density under the same irrigation in the two growth seasons (Table 4). But at the mature stage, dry matter accumulation of D_L was significantly higher than that of D_M and D_H under W2 and W1 in 2014−15. This result suggested that high density population had more water consumed at early growth stage, which aggravated soil drought at later stage and decreased dry

matter accumulation. In 2015−16, dry matter accumulation of wheat at the mature stage increased with increasing plant density under all three irrigation treatments.

The transportation amount, transportation rate, contribution rate of pre-anthesis storage material to grain showed an ascending changing trend with increasing plant density under all three irrigation treatments. However, the effect of plant density and irrigation on post-anthesis dry matter accumulation was different. In 2014−15, the accumulation amount and contribution rate of post-anthesis dry matter showed a descending trend with increasing plant density under W2 and W1. In 2015−16, post-anthesis dry matter accumulation amount at D_L was significantly higher than that of D_H under W2. In contrast, its value at D_L was significantly lower than that of D_H under W0. There was no significant difference between two densities under W1.

Water Consumption and Water Use Efficiency

The water use efficiency of was the highest at D_L and decreased with increasing plant density under W2 and W1 in 2014−15 (Table 5). This value was significantly higher at D_M than that at D_H under W0. No significant differences were observed between other treatments. In 2015−16, under the W2 treatment, the water use efficiency was the highest

Table 3 Population of spikes and spike formation rate of wheat with different irrigation amount and planting densities

Irrigation	Density (10^4 hm^{-2})	Erecting stage	Ripening stage	Spikes formation rate (%)	Proportion of main stem spikes (%)	Proportion of tiller spikes (%)	Ear-bearing tiller rate (%)
2014–2015							
W2	D_L	2226.7cd	758.3b	34.22ab	31.65f	68.35a	26.25a
	D_M	2566.7ab	771.7b	30.18bc	46.65d	53.35c	18.75bc
	D_H	2287.8bcd	826.7a	36.27a	58.13b	41.87e	19.22bc
W1	D_L	2113.3d	756.7b	36.10a	31.72f	68.28a	27.87a
	D_M	2625.6a	760.0b	28.95c	47.40d	52.60c	17.65bc
	D_H	2487.8abc	833.3a	33.57ab	57.63b	42.36e	17.64bc
W0	D_L	2193.3cd	640.0d	29.33c	37.51e	62.49b	20.60b
	D_M	2288.9bcd	717.5c	31.37bc	50.21c	49.79d	18.53bc
	D_H	2288.9bcd	768.3b	33.58ab	62.47a	37.53f	15.95c
2015–2016							
W2	D_L	1000.0c	604.4cd	60.48ab	44.68e	55.32a	45.85a
	D_M	1403.3b	680.0b	48.52cd	57.51c	42.49c	28.56c
	D_H	1833.3a	765.6a	42.28d	74.54b	25.46d	15.92d
W1	D_L	987.8c	614.4c	62.24a	44.02e	55.98a	48.04a
	D_M	1326.7b	694.4b	52.38c	56.16c	43.84c	32.55bc
	D_H	1800.0a	770.0a	43.46d	74.10b	25.90d	16.71d
W0	D_L	993.3c	541.1e	54.70bc	49.94d	50.06b	37.80b
	D_M	1295.6b	558.9de	43.29d	69.90b	30.10d	18.79d
	D_H	1902.2a	655.6bc	34.46e	87.10a	12.90e	6.34e

Means followed by a different letter within a column are significantly different at $P \leq 0.05$ by Tukey's HSD (honest significant difference) test

LSD least significant difference

at D_L and decreased with increasing plant density, but there were no significant differences among all three densities treatments. Under W0, water use efficiency increased with increasing plant density, significantly higher at D_H than that at D_L. Considering the resources of water consumption, soil water consumption and evapotranspiration increased with reduced irrigation and increasing plant density, respectively.

Nitrogen Accumulation Amount and Nitrogen Use Efficiency

Different irrigation and plant density treatments also influenced nitrogen accumulation amount and nitrogen use efficiency (Table 6). Nitrogen accumulation in grain and plant at maturity decreased with reduced irrigation. In 2014−15, nitrogen accumulation in grain of D_L was the highest and it was significantly higher than that of D_H under W2. The nitrogen accumulation in grain and plant changed insignificantly among all three density treatments under W0. In 2015−16, nitrogen accumulation in grain and plant increased significantly with increasing plant density under W1 and W0. No significant differences were observed in this value among all densities under W2.

Nitrogen partial factor productivity (NPFP), nitrogen uptake efficiency (NUpE) and nitrogen physiological

efficiency (NPE) of D_L were significantly higher than that of D_H, which was not significantly different from that of D_M in 2014−15. There was no significant difference in NPFP among all plant density treatments under W2 and W0. In 2015−16, NPFP and NUpE of D_H were significantly higher than that of D_L under W1 and W0. NPE of D_H was significantly higher than that of D_L under W0 and W2. But this result was reversed under W1.

Correlations Between Nitrogen Uptake Efficiency and Grain Yield

Positive correlations were observed between grain yield and nitrogen uptake efficiency (Fig. 2). But the correlations between grain yield and nitrogen physiological efficiency was insignificant. Hence, it was an effective way to promote nitrogen accumulation in grain in order to increase wheat yield by increasing nitrogen uptake efficiency.

Discussion

Irrigation is a significant limited factor in wheat grain yield. Wheat yield decreased as irrigation amount decreased (Zhao et al. 2015). Early research have shown that yield reduction

Table 4 The transportation of pre-anthesis storage of assimilates in vegetative organs and post-anthesis accumulation and their contribution to grains of wheat with different densities and irrigation treatments (2014–2016)

Irrigation	Density (10^4 hm^{-2})	Dry matter amount (kg hm^{-2})		Pre-anthesis storage of assimilates			Post-anthesis accumulation	
		Anthesis	Maturity	Transportation amount DMR (kg hm^{-2})	Transportation rate TCDMR (%)	Contribution rate CDMR (%)	Amount ADM (kg hm^{-2})	Contribution rate ACDM (%)
2014–2015								
W2	D_L	10921.3b	19098.0a	1125.3c	10.29c	12.09c	8176.7a	87.91a
	D_M	10317.6cd	18442.9ab	1136.4c	10.99c	12.30c	8125.3a	87.70a
	D_H	11740.8a	18336.3ab	2172.8ab	18.50b	24.71b	6925.3b	76.11b
W1	D_L	10921.3b	18884.2a	1307.7c	11.93c	14.05c	7962.9a	85.95a
	D_M	10317.6cd	17906.1b	1458.4c	14.15c	16.17c	7588.5ab	83.83a
	D_H	11740.8a	17701.1b	2445.8ab	20.82ab	29.13ab	5960.3c	70.87bc
W0	D_L	9735.8e	14858.1c	1974.2b	20.22ab	27.78b	5122.4d	72.22b
	D_M	10004.4de	15334.1c	2230.8ab	22.21ab	29.48ab	5329.7cd	70.52bc
	D_H	10829.1bc	15648.6c	2519.3a	23.20a	34.29a	4819.6d	65.71c
2015–2016								
W2	D_L	10034.4cd	18014.2b	1176.6d	11.64e	12.86d	7979.8a	87.14a
	D_M	10836.8bc	18502.2b	1496.7cd	13.90de	16.33d	7665.4ab	83.67a
	D_H	12427.9a	19397.3a	2160.3b	17.38cd	23.66c	6969.4b	76.34b
W1	D_L	10034.4cd	16026.9d	2007.6bc	20.03bc	25.10c	5992.5c	74.90b
	D_M	10836.8bc	16940.5c	2457.8ab	22.66ab	28.68bc	6103.7c	71.32bc
	D_H	12427.9a	18188.5b	2852.6a	22.95ab	33.16ab	5760.6cd	66.84cd
W0	D_L	9859.5d	14021.0e	2474.1ab	24.99ab	37.46a	4161.5f	62.54d
	D_M	9758.7d	14856.1e	2574.9ab	26.30a	33.54ab	5097.5de	66.46cd
	D_H	11068.7b	16052.5d	3015.3a	27.15a	37.67a	4983.7e	62.33d

Means followed by a different letter within a column are significantly different at $P \leq 0.05$ by Tukey's HSD (honest significant difference) test

LSD least significant difference

can be compensated by increasing plant population under water deficit conditions (Blue et al. 1990; Lloveras et al. 2004). Recently, limited irrigation has been reported an effective measure on ensuring wheat production and saving water resource in different rainfall years (Zhang et al. 2016; Wang et al. 2018). In current research, spikes per ha and wheat yield both decreased under no irrigation (W0), but increased with increasing plant density in the two growth seasons. These results were consistent with former researches (Dong et al. 2011; Ai 2012). Some study reported seedling rate should decrease to avoid over vegetative growth before winter under rain-fed condition (David 2011). In our research, seeding rate of wheat under no irrigation treatment could still utilize irrigation water of preceding maize during filling stage. Additionally, the optimum seeding density was not the highest density and it was related to rainfall, temperature, etc. (Dai et al. 2013; Sukumaran et al. 2015). In current study, wheat yield decreased with increasing plant density under limited irrigation treatment (W1, 80 mm) in 2014−15, however, opposite trend was noticed in 2015−16. Explanations may go with different rainfalls in the two wheat

growing seasons. In 2014−15, rainfall occurred twice reaching 53.1 mm on first ten−days of May, which relieved water stress on wheat under W0 to some extent. In contrast, there was only small rainfall at the same time period in 2016. Previous research has also referred that increasing plant densities could compensate partly wheat yield under low sowing soil water content in dry year (Zhang et al. 2011). But when the sowing soil water content was sufficient, the yield-improving effect was weak by increasing plant density.

Compared with a rainfed control, supplemental irrigation increased the yield by improving the survival rate of the tillers and increasing the assimilate accumulation and the 1000-grain weight (Lin et al. 2016). In the current study, we found that the culms at the mature stage under W1 and W2 increased comparing with that under W0 (no irrigation). Under the same irrigation, culms increased with increasing plant density, spike formation rate, proportion of tiller spike and ear-bearing tiller rate decreased, but the proportion of main stem spike increased with increasing plant density. This was also supported by recent research that increased planting density could

Table 5 Effects of planting density and irrigation on the resources of water consumption and water use efficiency (WUE) (2014–2016)

Irrigation	Density (10^4 hm^{-2})	ΔSWC (mm)	Irrigation amount (mm)	Rainfall (mm)	ET (mm)	WUE (kg hm^{-2} mm^{-1})
2014–2015						
W2	D_L	105.3f	160	99.3	364.6d	25.52ab
	D_M	131.6e	160	99.3	390.9c	23.73bc
	D_H	139.3e	160	99.3	398.6bc	22.83cd
W1	D_L	163.6d	80	99.3	342.9e	27.03a
	D_M	235.3c	80	99.3	414.6b	21.82cde
	D_H	278.9a	80	99.3	458.2a	18.35g
W0	D_L	248.9bc	0	99.3	348.9de	20.37ef
	D_M	260.1b	0	99.3	359.4de	21.02de
	D_H	295.4a	0	99.3	394.7c	18.64fg
2015–2016						
W2	D_L	120.5e	160	109.8	390.3bc	23.46a
	D_M	134.9de	160	109.8	404.7b	22.72ab
	D_H	159.1c	160	109.8	428.9a	21.29abc
W1	D_L	156.9cd	80	109.8	346.7de	23.08a
	D_M	174.5c	80	109.8	364.3d	23.50a
	D_H	181.2c	80	109.8	371.0cd	23.24a
W0	D_L	229.4b	0	109.8	339.2e	19.54c
	D_M	248.3ab	0	109.8	358.1de	20.44bc
	D_H	255.9a	0	109.8	365.7d	22.06ab

Means followed by different letter within a column are significantly different at $P \leq 0.05$ by Tukey's HSD (honest significant difference) test

ΔSWC soil water consumption, *ET* evapotranspiration, *WUE* water use efficiency, *LSD* least significant difference

regulate tiller number and increase the number of superior tillers with enhanced yield (Yang et al. 2019). As known, re-transportation of dry matter in vegetative organ to grain at pre-anthesis was an important material source during wheat grain filling (Xue et al. 2006). Mild water deficit could promote dry matter in the vegetative organ to grain, resulting in increased wheat rain yield and water use efficiency (Zhang et al. 2008). However, under severe water stress, this transferred amount of dry matter could not off-set yield loss (Ma et al. 2014). This research showed that the transportation amount, transportation rate, contribution rate of pre-anthesis storage material to grain increased with reduced irrigation. This result was consistent with previous findings that remobilized dry matter accumulation to the grains was promoted under progressive drought condition at the premise of wheat plant survival (Tatar et al. 2016). Additionally, contribution rate of pre-anthesis storage material to grain showed an ascending trend with increasing plant density under all three irrigation treatments (Arduini et al. 2006). However, accumulation amount and contribution rate of post-anthesis dry matter varied with different irrigation levels and rainfall. Continuous drought easily reduced the redistribution of the post-anthesis assimilate from the vegetative organs to the grain and the wheat yield at maturity (Lin et al. 2016). This

suggested that wheat yield loss could be compensated by increasing contribution rate of pre-anthesis storage material to grain with increasing plant density.

Early research showed that the grain yield was not the highest and WUE was relatively low in the highest irrigation (450 mm) treatment, appropriately limited irrigation (300 mm) could improve the grain yield and WUE on the Loess Plateau of China (Kang et al. 2003). Recent studies demonstrated that micro-sprinkling irrigation (150 mm) could also obtain higher grain yield, water and nitrogen use efficiency than that of traditional irrigation (Zhang et al. 2016). Although reducing irrigation could decrease wheat yield, it is still an efficient means to improve water use efficiency and maintain crop production sustainability on the North China Plain (Wang et al. 2018). In the current research, soil water consumption and evapotranspiration increased, water use efficiency decreased with increasing plant density under W1 and W2 in 2014−15. Ma et al. (2018) speculated that higher seeding rate can consume more soil water before jointing stage. Also, our research showed the effect of plant density on wheat WUE was influenced by climate change. Under W0, medium plant density had shown higher water use efficiency in the first year, increased with increasing plant density in the second year. Firstly, the effective accumulative temperature before

Table 6 Effects of planting density and irrigation on nitrogen accumulation and nitrogen use efficiency at maturity of wheat (2014–2016)

Irrigation	Density (10^4 hm^{-2})	GNA (kg hm^{-2})	TNA (kg hm^{-2})	NPFP (kg kg^{-1})	NUpE (kg kg^{-1})	NPE (kg kg^{-1})
2014–2015						
W2	D_L	210.5a	273.8a	44.30a	1.30a	33.97f
	D_M	198.4ab	265.0ab	44.10a	1.26ab	34.95e
	D_H	194.1bc	258.4ab	43.32ab	1.23ab	35.18e
W1	D_L	191.7bcd	249.5bc	44.15a	1.19bc	37.16c
	D_M	193.0bc	240.3cd	43.08ab	1.14cd	37.65c
	D_H	180.1c	232.2d	40.03b	1.11d	36.19d
W0	D_L	155.4d	191.3e	33.79b	0.91e	37.08c
	D_M	152.3d	185.8e	36.00b	0.88e	40.68a
	D_H	157.3d	190.9e	34.95b	0.91e	38.42b
2015–2016						
W2	D_L	207.2a	253.8a	43.60a	1.21a	36.08d
	D_M	196.3ab	246.9a	43.63a	1.18a	37.12c
	D_H	194.7abc	245.3a	43.47a	1.17a	37.22c
W1	D_L	165.4ef	203.7c	28.10bc	0.97c	39.28b
	D_M	182.7cd	218.5b	40.77ab	1.04b	39.19b
	D_H	184.5bc	226.3b	41.02a	1.08b	38.06c
W0	D_L	145.3g	176.5d	31.60d	0.84d	37.56c
	D_M	154.6fg	182.8d	36.53c	0.87d	41.98a
	D_H	171.5de	201.0c	38.09bc	0.96c	39.80b

Means followed by a different letter within a column are significantly different at $P \leq 0.05$ by Tukey's HSD (honest significant difference) test

GNA grain nitrogen accumulation, *TNA* total nitrogen accumulation in plant, *NPFP* nitrogen partial factor productivity, *NPE* nitrogen physiological efficiency, *LSD* least significant difference

Fig. 2 Relationship between grain yield and nitrogen uptake efficiency as well as nitrogen physiological efficiency (2014-2016)
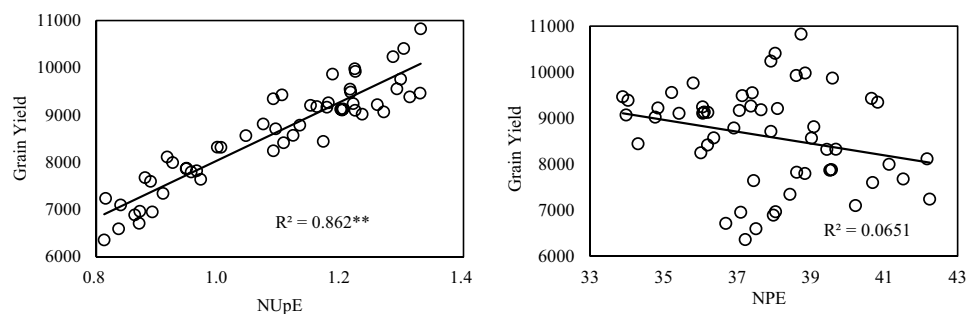
winter reduced from 573.6 °C in 2014–2015 to 506.5 °C in 2015-16. Meantime, the rainfall increased from 7.5 mm to 54.4 mm. Thus, lower effective accumulative temperature and more cloudy days before winter result in lower total tiller by 50% at double ridge stage in 2015–16 than in 2014–15. So high plant density produced higher spikes per unit area, and increased grain yield and WUE. This suggested that adjusting plant density was an effective way to improve water use efficiency in different years with rainfall based on the actual irrigation condition. Also, recent study showed that wheat yield was remarkably insensitive to planting density within 80−400 plants m^{-2}. Very low plant densities could be possible to achieve high yield when opening up for optimum planting date, row spacing,

cultivars, intercepted photosynthetic radiation, tiller survival, etc. (Fischer et al. 2019).

Not only wheat yield but also nitrogen uptake was significantly higher at high density than that at low density (Gao et al. 2009). Effect of nitrogen on plant growth depended on soil water conditions (Wang et al. 2014). The grain yield was significantly and positively correlated with the uptakes and harvest indexes of nitrogen (Liu et al. 2018). In this research, under the same nitrogen treatment, nitrogen accumulation in grain and plant decreased with reduced irrigation times, but increased significantly with increasing plant density under W1 and W0 in 2015−16. NPFP and NUpE of D_H were significantly higher than that of D_L under W1 and W0. NPE of D_H was also significantly higher than that of D_L under

W0 and W2. However, early research referred that excessive seeding number would not be beneficial to nitrogen accumulation and reduce the yield and nitrogen agronomical use efficiency (Yu et al. 2006). Nitrogen accumulation and transportation to grain with different plant densities was possibly influenced by soil water condition and annual rainfall, and thus influence the final yield of crop (Li et al. 2018). Additionally, Soil water increased the availability of nitrogen, while counteracting water use efficiency (Qiu et al. 2008). The underlying mechanism for nitrogen accumulation and utilization under limited irrigation would be worthwhile to have more attention in the future.

Conclusions

It is prerequisite to choose a reasonable irrigation schedule that optimizes grain yield, water and nitrogen use efficiency for a given level of water supply. Under limited irrigation, higher yield were also obtained at high density than that at low density by increasing contribution rate of pre-anthesis storage and promoting nitrogen accumulation in grain and plant of wheat, which was significantly correlated to wheat yield. As for the limited irrigation availability in North China Plain, medium plant density (D360−D390) with irrigation in wet years is recommended. However, in dry years, it is necessary to consider increasing plant density (D480−D570) so as to obtain high wheat yield with both higher water and nitrogen use efficiency.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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