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EFFECTS OF WATER AND NITROGEN LIMITED SUPPLY ON STEREOTYPIC CHARACTERISTICS OF HIGH-YIELDING WHEAT

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Abstract

Water and nitrogen fertilizer are important factors affecting wheat yield and quality. In this study, canopy morphogenesis and yield formation of winter wheat were studied by optimizing field water and nitrogen input. The specific treatments included Jimai 22 and Jimai 15 as materials, two irrigation methods (W1, 90 mm; W2165 mm) and three nitrogen fertilizer amounts (Nb, 123 kg/hm^2; N1192 kg/hm^2; N2270 kg/hm^2). The results showed that W2N1 had the highest yield of 9954.61 kg/hm^2. Under the same irrigation level, the leaf area index of each leaf layer under N2 treatment was higher than that under N1 treatment, and the appropriate addition of nitrogen fertilizer could effectively improve the leaf area index. Accordingly, the dry matter accumulation of wheat reached the highest level at maturity, and the contribution of dry matter to grain yield before flowering of Jimai 22 and Shimai 15 was 33.7% and 18.6%, which showed that the effective accumulation and transportation of dry matter had a more obvious impact on the yield formation of Jimai 22. Therefore, proper water and nitrogen input can effectively improve the wheat canopy structure, and W2N1 treatment has the best effect. The above research provides technical and theoretical support for water-saving and efficient cultivation of winter wheat.

Key words: Wheat, Limited irrigation and nitrogen, Leaf and stem characteristics, Phenotypic traits.

Introduction

Wheat is the staple food for nearly one third of the world's population (Wen *et al*., 2022). As the main wheat producing regions, the serious lack of water resources and uneven distribution of rainfall have become the biggest obstacles to agricultural production about resource constrained regions in north China (Wang *et al*., 2017; Xiao *et al*., 2020). The main source of water for agriculture in this region is groundwater. In recent decades, traditional irrigation methods have led to overexploitation of groundwater level (Chen *et al*., 2019; Qiu *et al*., 2018). However, in order to ensure higher food yields, farmers generally consume too much water and nitrogen fertilizer in the process of wheat cultivation (Gao *et al.*, 2021; Li *et al*., 2019; Zhang *et al*., 2020; Zhang, 2022). Therefore, one of the most important problems at present is the rational input of water and nitrogen resources, so as to reduce environmental harm and protect environmental development under the condition of ensuring the formation of wheat yield and quality.

As a communal cultivar, the variation of wheat phenotype is directly related to the formation of yield. Therefore, the construction of efficient population phenotype can provide reference for water-saving and high-yield cultivation or variety breeding. Studies on phenotype, photosynthesis and yield of 80 greenhouse cultivated wheats showed that phenotype and yield were more closely formed (Sales *et al*., 2022). It is one of the best methods to provide reliable data for breeders to carry out field experiments under controlled conditions, supplemented by enhanced phenotypic analysis(Gérard *et al*., 2022). The results showed that under low nitrogen condition, the first leaf area of hydroponic wheat seedlings decreased significantly, while the second and third leaf area had no significant change (Li *et al*., 2013). Because the wheat canopy is vertically distributed, the vertical distribution characteristics of chlorophyll showed a significant downward trend from the top of canopy to the ground surface (Huang *et al*., 2011). As the leaf position of wheat canopy decreased, the upper leaves contributed the most to the canopy spectrum, while the lower leaves contributed less to the canopy spectrum (Xiao *et al*., 2011). The researches have shown that nitrogen application significantly affects the changing of leaf length, single leaf area and SPAD value of different wheat varieties(Vos *et al*., 2005), and more nitrogen application will increase plant growth and internodes (Laghari *et al*., 2010). Nitrogen reduction increases the lower canopy light transmittance ratio and improves the light transmittance after anthesis (Guo *et al*., 2014). Whereas nitrogen increasing, the plant height, leaf area index and photosynthetically active radiation of canopy increased (Peng *et al*., 2021). Lower nitrogen supply will change the crop phenotype by promoting the transfer of dry matter among leaves and nodes, while remaining nodes of wheat plants to the grain and so benefit to increase the grain yield (Nozaka *et al*., 2008). When the nitrogen supply increase to 225 kg/ha, the thicknesses from lower second and third internodes of wheat cultivars were greater than other nitrogen treatments(Sharifi *et al*., 2017).

Water and nitrogen fertilizer directly affect the growth and yield of wheat (Gu *et al*., 2018; Mon *et al*., 2016; Peng *et al*., 2021). Research shows that proper irrigation combined with nitrogen supply can promote wheat growth and improve yield (Agami *et al*., 2018). Within a certain range of nitrogen application rate, winter wheat yield increases with the increase of nitrogen application rate, but decreases with the excessive application (Duan *et al*., 2019;

Rampino *et al*., 2006). Under the condition of quantitative irrigation, with the increase of nitrogen application, the wheat grain yield shows an increasing trend, and reaches the maximum at 240 kg/hm^2 nitrogen application rate. The nitrogen application rate continues to increase, and the grain yield has no significant change (Liu *et al*., 2018). Proper water supply can improve wheat yield by improving nitrogen assimilation and distribution (Wang *et al*., 2015). Although the wheat yield increases with the input of nitrogen fertilizer, excessive application of nitrogen fertilizer will also lead to a decrease in yield (Hartmann *et al*., 2015). Proper nitrogen application can increase post anthesis material production, while excessive nitrogen application may have adverse effects on post anthesis material accumulation and storage transport (Reza & Narges, 2008). Therefore, under resource constraints, the matching of nitrogen fertilizer and irrigation amount is crucial to improve the yield and quality of winter wheat and improve resource utilization efficiency. In conclusion, although a large number of studies have been conducted on water and nitrogen input during wheat cultivation, few studies have focused on vertical morphological changes of wheat canopy under the condition of reduced water and nitrogen supply. Based on this, combined with the current situation of water resources utilization in North China, this study clarified the changes of various canopy structures of high-yield wheat through the limited input of nitrogen fertilizer and water in the field, so as to provide scientific basis and technical guidance for the construction of water-saving, high-yield and efficient canopy structure of winter wheat. It can be seen from the above analysis that although a large number of studies have been conducted on the water and nitrogen input in wheat cultivation, few studies have focused on the vertical morphological changes of wheat canopy under the condition of reduced water and nitrogen supply. Based on this, combined with the current situation of water resources utilization in North China, this study clarified the changes of various canopy structures of high-yield wheat through the limited input of nitrogen fertilizer and water in the field, so as to provide scientific basis and technical guidance for the construction of water-saving, high-yield and efficient canopy structure of winter wheat.

Material and Methods

Research site and environmental conditions: In the time, 2009-2011, all researches were finished at Wuqiao experimental station of China Agricultural University. Wuqiao experimental station is located in Wuqiao county, which is in the middle of the Heilongjiang Basin of the Haihe Plain around warm temperate monsoon climate. Global positioning was 116°37′23″E and 37°41′02″N. The average annual sunshine duration and temperature were 2767.1 hours and 12.5°C. The average annual rainfall was 676.9 mm. Meanwhile they were 116.3 mm from 2009 to 2010 and 62.4 mm from 2010 to 2011 (Fig. 1).

Before the cultivation of winter wheat, the field was planted silage summer maize and was loamy bottom clay aquic soil. The interannual cultivation pattern is the same, the previous crop is maize, and the high-yield field management. (Table 1) shows the basic soil fertility of the 0-20 cm soil layer.

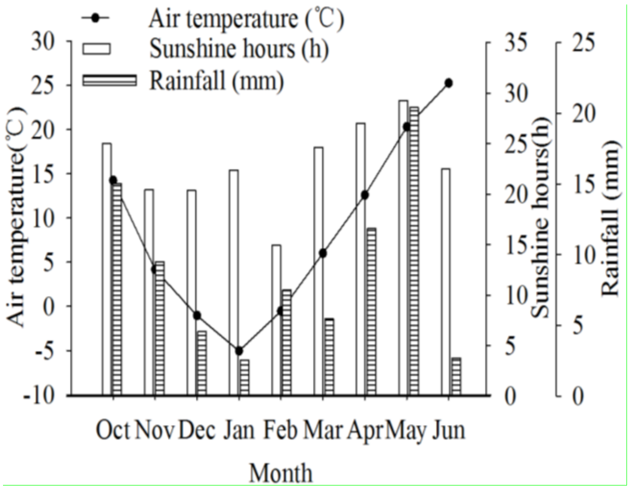

Fig. 1. Meteorological conditions during the winter wheat growing period from 2009 to 2011.

Table 1. Agro-chemical characteristics of the tested soil.

Year	O.M. (g/kg)	Total N (g/kg)	Available N (mg/kg)	Available P (mg/kg)	Available K (mg/kg)
2009~2010	11.0	1.1	68.6	49.1	123.7
2010~2011	12.0	1.1	72.6	44.2	132.3

Experimental design: From 2009 to 2010, winter wheat varieties with large promotion area in North China were used in this study: high-yield winter wheat variety Jimai 22, water-saving and drought resistant winter wheat variety Shimai 15. The growth stages are divided into seedling stage, jointing stage, flowering stage, filling stage and maturity stage. The researches had been designed to two water-efficient irrigation modes (W1, W2) and two nitrogen levels (N1, N2). Before the study began, soil moisture was suitable and two water-saving irrigation modes were set in the experiment: W1 (spring irrigation at jointing stage, 90 mm) and W2 (spring irrigation at jointing and anthesis stages, 90 mm+75 mm); two nitrogen fertilizer treatments: N1 (base fertilizer: 123 kg/ha + topdressing 69 kg/ha at the jointing stage) and N2 (base fertilizer: 123 kg/ha + topdressing 147 kg/ha at the jointing stage). The combinations were W1N1, W1N2, W2N1 and W2N2. Each plot area was 54 m^2 of three replicates and the distance of plots was 0.6 m. Sowing at October 16, 2009 and basic seedling density was 510×10^4 plants/ha and a row spacing of 16 cm.

Before sowing, corn stalks are crushed and returned to the field. Organic fertilizer (50% chicken manure+50% soil manure) was applied in different treatments, 15m^3/ha; Urea, 150 kg/ha; Diammonium phosphate, 300 kg/ha (including P_2O_5 138 kg/ha), and 225 kg/ha (including K_2O 112.5 kg/ha) of potassium sulfate. The test was arranged in random blocks and each treatment was repeated three times. At jointing stage, the above treatment is combined with irrigation and nitrogen fertilizer topdressing. The irrigation and nitrogen fertilizer topdressing involved in the above treatment were completed before the jointing stage. Water consumption measurement and other field management measures refer to water-saving and high-yield cultivation techniques. The wheat was harvested on June 15, 2010, while the (Table 3) shows specific treatments.

From 2010 to 2011, the wheat variety tested in this year was Shimai 15. Through setting nitrogen application level in the previous year, it was found that no significant differences between the two nitrogen application levels. Therefore, 123 kg·hm^{-2} of bottom applied pure nitrogen was added in this year's test on the basis of the previous year's test. Each test treatment combination is: W1Nb, W1N1, W1N2, W2Nb, W2N1, W2N2. Other field management is the same as 2009~2010.

Determination of leaf shape, stem node morphology: On May 19, 2010 and May 19, 2011, during the anthesis period, the LI-3000 leaf area meter was used to measure leaf area (10 wheat plants) and calculate LAI (Li *et al*., 2019).

The height, ear length, node length and stem thickness were measured with a ruler and a vernier caliper respectively to reflect the morphological changes of wheat. Both tested varieties have five internodes. The lower internode is divided into the first internode, followed by the second internode, the third internode, and the fourth internode. The lower internode is the inverted fifth internode.

Dry matter accumulation: At anthesis stage (May 19, 2010 and May 19, 2011) and maturity stage (June 15, 2010 and June 15, 2011), two rows of 50 cm wheat plants from representative sample sections were selected for sampling in each test plot. All samples were blanched at 105℃ for 15 min and dried at 80℃ to constant weight. The calculation method of plant dry matter transport and contribution is as follows:

$$\text{Dry matter remobilization amount} = \text{Dry weight at flowering stage} - \text{Dry weight at maturity}$$

$$\text{Contribution of dry matter remobilization to dry matter of grain} = \frac{\text{Dry matter remobilization amount}}{\text{Grain dry weight at maturity}} \times 100$$

Grain yield: At the maturity stage, 4 m^2 sampling points were selected from each plot, harvested manually alone, and then air dried after threshing for yield calculation. The grain moisture content was 13%. Each treatment was repeated four times. At the same time, 1 m double row sample section was taken from each plot to investigate the number of spikes, grains per spike and 1000 grain weight.

Data analyses

SPSS19.0 (ANOVA) and GraphPad Prism 5.0 were used for data analysis (p<0.05).

Results and analysis

Yield composition: Table 2 shows that there is no significant difference between the grain yield N1 of Jimai 22 and the N2 treatment at the W1 level from 2009 to 2010. On the contrary, the N2 treatment of Shimai 15 is significantly higher than that of N2. At the W2 level, the grain yield of the two kinds of wheat treated with N1 was significantly higher than that of N2. When the nitrogen application level is the same, the grain yield of the two kinds of wheat under W2 treatment is generally higher than that under W1 treatment. The yield of W2N1 treatments (Jimai 22 and Shimai 15) were 9557.48 kg/hm^2 and 9349.04 kg/hm^2, so Jimai 22 was higher. Difference yields were mainly caused by the decrease of grain number per spike and 1000 grain weight. From 2010 to 2011, at same nitrogen application level, W2 grain yield was higher than W1. Under W1 level, grain yield of Shimai 15 in N2 treatment was significantly higher than that in other treatments; Under W2 level, grain yield of Shimai 15 in N1 treatment was significantly higher than that in other treatments. Two years of research data showed consistent results, indicating that higher grain yield could be obtained under W2N1 treatment.

Table 2. Grain yield and its components of winter wheat under different irrigation and nitrogen treatments.

Year	Variety	Treatment	Spike number (×10^4/hm^2)	Grain number Per spike (Grain/Spike)	1000-grain Weight (g)	Grain yield (kg/hm^2)
2009–2010	Jimai 22	W1N1	732.9 ± 12.2a	35.4 ± 0.2a	47.3 ± 0.8b	8459.3 ± 211.5 b
		W1N2	748.3 ± 37.3a	34.7 ± 0.2a	47.6 ± 0.7b	8762.2 ± 285.4 b
		W2N1	756.5 ± 32.3a	36.4 ± 0.5a	48.7 ± 0.1a	9557.5 ± 144.1a
		W2N2	760.5 ± 30.7a	35.5 ± 0.2a	49.5 ± 0.5a	9152.8 ± 172.5ab
	Shimai 15	W1N1	740.2 ± 14.1a	34.8 ± 0.8b	44.0 ± 0.4b	8367.6 ± 114.8b
		W1N2	750.9 ± 18.6a	34.1 ± 1.1b	42.4 ± 0.2c	7943.7 ± 179.8c
		W2N1	760.5 ± 42.9a	36.7 ± 0.4a	46.1 ± 0.2a	9349.0 ± 245.5a
		W2N2	768.7 ± 45.9a	34.7 ± 0.5b	45.7 ± 0.3a	8596.8 ± 99.7b
2010–2011	Shimai 15	W1Nb	779.2 ± 43.9a	29.5 ± 3.2a	33.2 ± 0.5e	7174.2 ± 729.5c
		W1N1	783.3 ± 50.5a	28.7 ± 2.1a	34.0 ± 0.6d	7441.9 ± 491.4c
		W1N2	791.7 ± 59.1a	27.2 ± 2.0a	35.2 ± 0.1c	7573.0 ± 249.6c
		W2Nb	795.8 ± 125.2a	30.9 ± 4.1a	43.9 ± 0.1b	9353.3 ± 748.9b
		W2N1	825.0 ± 12.5a	29.8 ± 0.4a	45.2 ± 0.3a	9954.6 ± 272.9a
		W2N2	833.3 ± 56.4a	30.0 ± 0.3a	44.0 ± 0.1b	9613.5 ± 551.1a

Note: Different letters indicate a significant difference among different irrigation methods at p<0.05 level. All the data are shown as the mean ± standard error

Leaf area index (LAI): It can be seen from Table 3 that the LAI of each leaf layer in 2010 – 2011 was significantly higher than that in 2009 – 2010. From 2009 to 2010, the leaf area index of different leaf layers of the two kinds of wheat showed a downward trend from top to bottom, with the middle and upper layers being larger. Under the condition of limited water irrigation, the single-layer leaf area index of two kinds of wheat treated with N2 was higher than that treated with N1. Compared with different varieties, the single-layer leaf area index of Jimai 22 is also higher than Shimai 15, so it is speculated that the leaf area stability of Jimai 22 is strong. In addition, from 2010 to 2011, under the condition of limited water irrigation, the leaf area index of increased nitrogen application treatment showed an upward trend. Through two years of experiments, the research shows that the vertical leaf area index distribution of wheat canopy with large leaf area index in the upper middle layer and small leaf area index in the lower layer is not only conducive to the transmission of light from the upper layer to the lower layer, but also conducive to the increase of light interception in the lower layer.

Plant height and internode length: The internode length of wheat directly affects the height changing, while the length increases from bottom to top. As shown in (Table 4) there was no significant difference in plant height and internode length between different treatments in two years. Under limited irrigation conditions, the length of the first three nodes of flowering stage accounts for about 70% of plant height. The plant height and spike length of two kinds of wheat treated with N2 were higher than those of other treatments, and the internode length decreased from top to bottom with the decrease of node layer. The plant height of the two kinds of wheat is basically similar, and the length of the last five internodes of Jimai 22 is lower than that of Shimai 15. Therefore, it is speculated that compared with Shimai 15, Jimai 22 has strong lodging resistance. From the above analysis, it can be seen that proper nitrogen application at jointing stage can effectively prevent wheat lodging and is conducive to improving yield.

Stem diameter: During the formation of wheat grain, it will absorb substances stored in the stem, resulting in changes in the size of the pulp cavity between the stem nodes. As shown in (Table 5) as the height of the node layer decreases, the stem diameter of the two wheat varieties reaches the maximum in the last three nodes. Under the same water-limited irrigation condition, except for the diameter of the last five stems, the diameter of each internode of the two kinds of wheat under N2 treatment was higher than that of other treatments. The stem diameter of Jimai 22 is larger than that of Shimai 15, indicating that the lodging resistance of Jimai 22 is higher than that of Shimai 15.

Dry matter accumulation and transport: As shown in (Table 6) the two-year data show that the peak of dry matter accumulation occurs in the mature period. Firstly, from 2009 to 2010, under the same irrigation level, the dry matter accumulation of two kinds of wheat N2 treatment was higher than that of N1 treatment. However, when the amount of nitrogen fertilizer is the same, W2 treatment is significantly higher than W1 treatment. The comparative analysis of different varieties showed that the dry matter accumulation of Shimai 15 was higher than that of Jimai 22 at W1 level; At the W2 level, the dry matter accumulation of Jimai 22 was higher than that of Shimai 15. The above results show that Jimai 22 is sensitive to water. In addition, from 2010 to 2011, when the irrigation level was the same, the dry matter accumulation of Shimai 15 was the highest in N2 treatment, and when the nitrogen fertilizer level was the same, the dry matter accumulation of Shimai 15 W2 treatment was significantly higher than that of W1 treatment.

Secondly, during the period from 2009 to 2010, when the irrigation level is the same, before the flowering stage, the dry matter contribution of N2 treatment is higher than that of N1 treatment, and on the contrary, the dry matter contribution of N1 treatment is higher than that of N2 treatment after the flowering stage. Similarly, when the amount of nitrogen fertilizer is the same, the contribution of dry matter to grains before flowering in W1 treatment is higher than that in W2 treatment, and vice versa. In addition, before flowering, the contribution of dry matter of Jimai 22 to grain yield was significantly higher than that of Shimai 15, and the contribution to grain yield of Jimai 22 and Shimai 15 was 33.7% and 18.6% respectively. The above results showed that the effective accumulation and transportation of dry matter had a more significant impact on the yield formation of Jimai 22. From 2010 to 2011, when the irrigation level is the same, before flowering, the dry matter transport of N1 treatment contributed more to the formation of Shimai 15 grain, on the contrary, the dry matter transport of Nb treatment contributed more to the grain formation after flowering; When the amount of nitrogen fertilizer is the same, W1 treatment and W2 treatment have different effects on the contribution of dry matter accumulation to grains before and after flowering of Shimai 15.

Table 3. Distribution of leaf area index at anthesis under limited irrigation and nitrogen supply.

Year	Variety	Treatment	Flag leaf	2nd from flag	3rd from flag	4th from flag
2009–2010	Jimai 22	W1N1	1.08	1.25	1.07	0.84
		W1N2	1.19	1.34	1.12	0.87
	Shimai 15	W1N1	1.03	1.11	0.91	0.67
		W1N2	1.18	1.26	1.09	0.75
2010–2011	Shimai 15	W1Nb	1.56b	1.91b	1.41b	0.86a
		W1N1	1.91ab	2.27ab	1.72a	0.94a
		W1N2	2.20a	2.38a	1.74a	0.97a

Note: Different letters indicate a significant difference among different irrigation methods at $p<0.05$ level. All the data are shown as the mean ± standard error

Table 4. Distribution of plant height and internode length at anthesis under limited irrigation and nitrogen supply.

Year	Variety	Treatment	Height (cm)	Ear length (cm)	Internode length (cm)				
					L_1	L_2	L_3	L_4	L_5
2009–2010	Jimai 22	W1N1	73.8	8.3	22.8	16.9	11.8	9.2	4.8
		W1N2	74.0	8.4	23.3	17.2	11.2	8.8	5.0
	Shimai 15	W1N1	72.3	7.7	19.5	18.3	12.0	9.5	5.2
		W1N2	73.3	7.9	20.5	18.4	11.8	9.2	5.3
2010–2011	Shimai 15	W1Nb	72.2b	7.6a	20.3b	18.4b	12.3b	9.8b	3.8b
		W1N1	76.1ab	7.7a	21.3a	18.8ab	12.5b	10.5a	5.3a
		W1N2	77.8a	7.9a	21.5a	19.2a	13.0a	10.8a	5.4a

Note: Different letters indicate a significant difference among different irrigation methods at $p<0.05$ level. All the data are shown as the mean ± standard error

Table 5. Characteristics of stem diameter at anthesis under limited irrigation and nitrogen supply.

Year	Variety	Treatment	1st stem diameter (cm)	2nd stem diameter (cm)	3rd stem diameter (cm)	4th stem diameter (cm)	5th stem diameter (cm)
2009–2010	Jimai 22	W1N1	0.478	0.490	0.499	0.489	0.430
		W1N2	0.486	0.494	0.505	0.491	0.424
	Shimai 15	W1N1	0.385	0.456	0.478	0.465	0.417
		W1N2	0.407	0.467	0.483	0.476	0.390
2010–2011	Shimai 15	W1Nb	0.423a	0.451a	0.454a	0.450b	0.431b
		W1N1	0.425a	0.453a	0.459a	0.457ab	0.446a
		W1N2	0.427a	0.461a	0.463a	0.461a	0.431b

Note: Different letters indicate a significant difference among different irrigation methods at $p<0.05$ level. All the data are shown as the mean ± standard error

Table 6. Effects of different irrigation methods and nitrogen treatments on dry matter accumulation, translocation of winter wheat.

Year	Variety	Treatment	DMA (kg/hm^2)	DMM (kg/hm^2)	DMR (%)	DMPR (%)
2009–2010	Jimai 22	W1N1	12419.23	17693.4 ± 289.4b	38.1 ± 4.7a	61.9 ± 4.7a
		W1N2	12989.65	18204.4 ± 186.9b	41.0 ± 3.0a	59.0 ± 3.0a
		W2N1	12419.23	19769.5 ± 291.5a	25.5 ± 4.3b	74.5 ± 4.3b
		W2N2	12989.65	20211.4 ± 236.7a	30.1 ± 4.6b	69.9 ± 4.6b
	Shimai 15	W1N1	11231.76	18753.6 ± 126.2b	16.0 ± 4.2b	84.0 ± 4.2b
		W1N2	12107.68	18951.8 ± 141.6b	25.8 ± 3.6a	74.2 ± 3.6a
		W2N1	11231.76	19675.6 ± 267.8a	14.5 ± 3.1b	85.5 ± 3.1b
		W2N2	12107.68	19928.1 ± 199.4a	18.0 ± 2.8b	82.0 ± 2.8b
2010–2011	Shimai 15	W1Nb	12328.4 ± 108.1b	18520.4 ± 276.3b	21.1 ± 1.6ab	78.9 ± 1.6ab
		W1N1	13023.6 ± 286.0a	18846.3 ± 211.4b	25.5 ± 1.4a	74.5 ± 1.4a
		W1N2	13164.9 ± 294.1a	19615.1 ± 232.9b	21.7 ± 1.8ab	78.3 ± 1.8ab
		W2Nb	12328.4 ± 108.1b	21496.4 ± 257.1a	8.1 ± 3.4c	91.9 ± 3.4c
		W2N1	13023.6 ± 226.4a	21555.3 ± 115.5a	15.2 ± 5.1b	84.8 ± 5.1b
		W2N2	13164.9 ± 294.1a	22444.7 ± 271.8a	11.0 ± 1.1b	89.0 ± 1.1b

Note: DMA, dry matter accumulation at anthesis; DMM, dry matter accumulation at maturity; DMR, contribution of dry matter pre-anthesis translocation to grain yield; DMPR, contribution of dry matter post-anthesis accumulation to grain yield

Discussion

Leaf morphological characteristics are mainly based on the leaf length, leaf width and leaf area, which are among the important factors that affect the light distribution and interception in the canopy. Leaf area is an important part of the canopy structure, and nitrogen indirectly affects the formation of high-yield canopy by affecting the accumulation and transport of nitrogen in crops (Wang *et al.*, 2015; Zhang *et al.*, 2011). Proper application of nitrogen fertilizer can promote the increase of leaf area index, which can optimize the light receiving attitude of wheat (Yao *et al.*, 2011). Some studies have pointed out that the optimal application of nitrogen fertilizer can inhibit the increase of the upper three leaves of wheat, reduce the leaf area index of the upper leaves, and improve the absorption and interception of light by the middle and lower leaves (Kong *et al.*, 2008). Many researchers also pointed out that the flag leaf should be in the shape of a tower, and the length of the first two leaves at the top should be about 20 cm, so as to build a good light transmittance of the canopy. In this study, with the decrease of leaf position, the leaf area and leaf area index of Shimai 15 decreased, while under the same limited irrigation conditions, the leaf length, leaf width and leaf area of Shimai 15 treated with N2 were higher than those of N1, and the leaf area index increased with the appropriate increase of nitrogen application, which is consistent with previous research results (Li *et al.*, 2010). To sum up, in this study, increasing nitrogen fertilizer significantly increased the length and width of the upper three leaves of Shimai 15, and then the leaf area index.

The length and thickness of wheat stem nodes are the main characteristics of its morphology, and the reasonable length and thickness directly affect the formation of wheat yield (Ehdaie *et al*., 2006; Guo *et al*., 2010; Pheloung & Siddique, 1991). The basal internodes of lodging resistant wheat are mostly coarse and short, and the dry matter content of each wheat internode is high, which improves its lodging resistance (Lei *et al*., 2009; Wang *et al*., 2016; Wang *et al*., 2010). The ratio of basal internode to plant height of wheat is within a reasonable threshold, which will not reduce the lodging resistance of the stem (Yong, 1995). However, in the process of nitrogen fertilizer application, the increase of topdressing proportion led to the thinning of wheat basal internodes, which led to the reduction of stem strength (Zhang *et al*., 2014). In this study, the internode length of Shimai 15 decreased from the top to the bottom, and its thickness reached the maximum value in the third internode. Under the same limited irrigation conditions, except for five internode lengths and five stem diameters, the length of the upper three nodes accounted for about 70% of the plant height at flowering, and the length of each internode and stem thickness of Shimai 15 in N2 area were higher than those of N1 treatment. Proper application of nitrogen fertilizer promoted the increase of plant height, internode length and stem diameter. Therefore, proper irrigation and application of nitrogen fertilizer can improve the lodging resistance of wheat, which is conducive to obtaining high yield.

Photosynthetic products of green organs after anthesis and storage materials of vegetative organs before anthesis are important sources of grain yield formation, and their contribution to yield is affected by varieties and environmental factors. The soil water content during grain filling has a significant impact on the dry matter accumulation and transportation of plants (Reza *et al*., 2008), and waterlogging and drought after flowering significantly reduce the dry matter accumulation and transportation of plants (Ercoli *et al*., 2008). The formation of grains is significantly correlated with the photosynthetic efficiency at the filling stage and the redistribution of assimilates stored in the vegetative organs before flowering (Meng *et al*., 2017). This study showed that under the same irrigation level from 2009 to 2010, the dry matter accumulation of N2 treatment and the contribution of dry matter before flowering to the grains of two wheat varieties were higher than that of N1; Under the same nitrogen application level, the dry matter accumulation of W2 treatment and the contribution of dry matter after flowering were higher than that of W1 treatment. The contribution of dry matter accumulated before flowering to the grain yield of Jimai 22 and Shimai 15 was 33.7% and 18.6%, respectively, which showed that the effective accumulation and transportation of dry matter played a more prominent role in the yield formation of Jimai 22.

Conclusion

In summary, optimizing the level and period of nitrogen fertilizer application by moderately reducing the water supply can increase the upper leaf area index of wheat, improve the dry matter accumulation in the later stage, effectively improve the population filling performance, and ensure the stable and high yield of wheat.

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