The Impacts of Supplemental Irrigation Based on Soil Moisture Measurement and Nitrogen Use on Winter Wheat Yield and Nitrogen Absorption and Distribution

Xiukuan JIN[1,2], Maoting MA[2], Tongke ZHAO[2*], Lingling JIANG[1,2]

1. College of Resources and Environment Science, Hebei Agricultural University, Baoding 071000, China; 2. Institute of Plant Nutrition and Resources, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China

Abstract Based on split plot design method of field test, the impacts of supplemental irrigation based on soil moisture measurement and nitrogen use on winter wheat yield and nitrogen absorption and distribution were studied. Supplemental irrigation had three levels: 60% (W_1), 70% (W_2) and 80% (W_3) of the targeted relative water content at 0 – 40 cm of soil layer during jointing period of winter wheat. Nitrogen fertilization had three levels: not using nitrogen (N_0), using pure nitrogen of 195 kg/hm^2 (N_{195}) and 255 kg/hm^2 (N_{255}). Results showed that: (i) different supplemental irrigation and nitrogen fertilization significantly affected plant height and leaf area of winter wheat during key growth period. Under the same supplemental irrigation treatment, both plant height and leaf area of winter wheat showed as $N_{255} > N_{195} > N_0$ ($P < 0.05$). Plant height in N_{195} and N_{255} treatments was significantly higher than that in N_0 treatment, but there was not significant difference between N_{195} and N_{255} ($P > 0.05$). Under the same nitrogen fertilization, plant height in W_2 (569.4 m^3/hm^2) and W_3 (873.45 m^3/hm^2) treatments was significant higher than that in W_1 (265.2 m^3/ hm^2), but there was not significant difference between W_2 and W_3 ($P > 0.05$). It illustrated that excessive nitrogen fertilization and supplemental irrigation did not significantly affect plant height and leaf area of winter wheat. (ii) Under the same nitrogen fertilization level, yield increase effect of winter wheat by supplemental irrigation showed a declining trend with nitrogen application amount increased. It illustrated that nitrogen fertilization and supplemental irrigation had certain critical values on the yield of winter wheat. When surpassing the critical value, the yield declined. When nitrogen fertilization amount was 195 kg/hm^2, and supplemental irrigation amount was 70% of field moisture capacity (569.4 m^3/hm^2), the highest yield 8500 kg/hm^2 could be obtained. (iii) During mature period of winter wheat, nitrogen accumulation amount of plant treated by nitrogen was significantly higher than that not treated by nitrogen ($P < 0.05$). But under the treatments of W_2 and W_3, nitrogen accumulation amount in N_{255} significantly declined when compared with N_{195} ($P < 0.05$). Especially under W_3 (873.45 m^3/hm^2) level, nitrogen accumulation amount in N_{255} was even lower than N_0. Under the treatments of N_0 and N_{195}, nitrogen accumulation amount of plant significantly increased with supplemental irrigation increased ($P < 0.05$). But under N_{255} treatment, there was not significant difference ($P > 0.05$). It illustrated that moderate supplemental irrigation and nitrogen fertilization could improve nitrogen absorption ability of winter wheat, but excessive supplemental irrigation and nitrogen fertilization were not favorable for plant's nitrogen absorption. (iv) Although the increase of supplemental irrigation during jointing period improved nitrogen absorption ability of winter wheat and promoted winter wheat absorbing more nitrogen, it inhibited nitrogen transferring and distributing to seed. Comprehensively considering growth condition of winter wheat and nitrogen risk condition, it is suggested that nitrogen application amount was 195 kg/hm^2, and supplemental irrigation reached 70% of field moisture capacity (569.4 m^3/hm^2), which could be as the suitable water and fertilizer use amounts in the region.

Key words Winter wheat, Supplemental irrigation based on soil moisture measurement, Nitrogen application amount, Yield, Nitrogen absorption and distribution

1 Introduction

Water resource is short, and its temporal-spatial distribution is uneven. Adding unreasonable irrigation manner, it causes low farmland water use efficiency, and water resource waste is serious. Therefore, it is the practical problem of winter wheat production urgent needing to be solved to rationally irrigate, effectively use rainfall and soil water storage, and improve water use efficiency[1-2]. Meanwhile, to one-sided pursuit of high yield, farmers blindly and excessively use nitrogen fertilizer, which inevitably causes low use rate of nitrogen fertilizer, serious nitrogen fertilizer loss, leaching risk of soil nitrate nitrogen aggravating, environmental pollution[3]. The researches show that final yield of winter wheat and nitrogen use efficiency increase with irrigation amount increases, and excessive or insufficient irrigation could decline final yield of winter wheat and nitrogen use rate[4]. Huang Ling *et al.*[5-8] point out that crop's water demand is different at each growth stage, and irrigation at jointing and grouting stages could significantly improve final yield. When soil moisture content is too high or low after flowering period of winter wheat, grain number and thousand-grain weight decline, causing that yield of winter wheat declines. When soil moisture content after flowering is between 60% and 70%, the highest seed yield is 8160.9 kg/hm^2[9]. There are more researches on the impact of nitrogen use or irriga-

Received: July 10, 2017 Accepted: August 14, 2017
Supported by National Key Research Plan Project (2016YFD0801001, 2016YFD0200103, 2017YFD0800500).
* Corresponding author. E-mail: tkzhao@126.com

tion on the yield of winter wheat[10-12], and the researches on water-saving theory mainly use the method of quantitative irrigation[4,9], but irrigation effect has close relationship with soil moisture values and rainfall during growth period. Quantitative irrigation is blind, which wastes water resources. There are fewer reports on the impacts of supplemental irrigation based soil moisture measurement and nitrogen use on plant height, leaf area, yield of winter wheat and absorption, accumulation and distribution of nitrogen at different soil layers (0 – 40 cm). In the test, different nitrogen use treatments under different supplemental irrigation conditions were set. The water – nitrogen coordination effect under supplemental irrigation condition was studied to obtain the optimal combination of supplemental irrigation amount and nitrogen fertilization amount in the region, which could provide theoretical basis for rational, high-yield and high-efficiency water saving, irrigation and fertilization techniques of winter wheat.

2 Materials and methods

2.1 General situation of test site The test was conducted in Qianwangzhuang Village, Wangzhuang Town, Hua County, Anyang City of Henan Province (114°30′ E, 35°35′ N) during growth season of winter wheat from 2014 to 2015. Test soil was middle loamy alluvial soil, and farming system was winter wheat/summer corn rotation, and preceding crop was summer corn. Basic physical and chemical properties of soil at 0 – 20 cm of ploughing layer were as below: organic matter of 15.69 mg/kg, alkaline hydrolysis nitrogen of 76.67 mg/kg, available P of 16.22 mg/kg, available K of 91.2 mg/kg. Field moisture capacities at 0 – 20 and 20 – 40 cm of soil layers were respectively 18.75% and 22.41%, and its soil bulk densities were respectively 1.57 and 1.55 g/cm^3, and total rainfall during growth period of winter wheat was 193 mm.

2.2 Test design Test used split plot design, and supplemental irrigation was main region, while nitrogen fertilization was secondary region. Three relative soil moisture contents were set in main region: 60% (W_1), 70% (W_2) and 80% (W_3) of targeted relative soil moisture content at 0 – 40 cm of soil layer during jointing period of winter wheat. Three nitrogen fertilization levels were set in secondary region: not fertilizing nitrogen (N_0), fertilizing pure nitrogen 195 kg/hm^2 (N_{195}) and 255 kg/hm^2 (N_{255}), and there were 9 treatments in total. Each treatment had three repeats, and there were 27 field districts in total, and area of each district was 4 m × 6 m = 24 m^2. 3 m wide of isolation zone was set among different treatments. Nitrogen, phosphorus and potash fertilizers were respectively urea (N of 46.4%), calcium superphosphate (P_2O_5 of 16%) and potassium chloride (K_2O of 60%). Nitrogen fertilizer was used before sowing and jointing period, and basal-topdressing ratio was 6:4. Phosphorus and potash fertilizers were used as base fertilizer, and their application amounts were P_2O_5 of 120 kg/hm^2 and K_2O of 90 kg/hm^2. In whole growth period, only once irrigation was conducted before jointing based on test design, and irrigation capacity was controlled by pumping time of diving pump. In key growth period of winter wheat, irrigation was conducted based on test design, and irrigation capacity was controlled by water meter of submersible pump. PVC hose was used to irrigate in each district, and irrigation depth was between 0 and 40 cm. Based on soil moisture value and targeted moisture content, supplemental irrigation capacities of W_1, W_2 and W_3 were respectively 265.2, 569.4 and 873.45 m^3/hm^2. The tested variety was Aikang 58, and sowing quantity of winter wheat was 180 kg/hm^2. It was sown on October 12, 2014 and harvested on June 3, 2015. Except test treatment, other management measures were same as general field management.

2.3 Sample collection and measurement Plant height was from the base of winter wheat to top, which was measured by steel rule. By measuring the length and width of single leaf, leaf area was obtained based on the product of length and width. There were 20 repeats in each district, and mean was taken. The measurement of total nitrogen content of plant was as below. Dynamic investigation and sampling of colony were conducted before overwintering, jointing period, flowering period and mature period. To flowering and mature periods, 10 single stems were taken. According to the stem, leaf, sheath, spike stalk + glume, and seed, after fixed for 30 min at 105 ℃, they were dried to constant weight in 80 ℃ of oven, and the weight of dry matter was measured. Semi micro Kjeldahl method was used to determine nitrogen content of each organ. After maturity, 1 m of double rows was used to investigate ear traits in each district: total spike number, spike length, grain number and thousand-grain weight. Meanwhile, 4 m^2 of winter wheat was harvested in each district to count the yield.

2.4 Data processing and statistical analysis Mass water content of soil = (soil water mass / mass of dry soil) × 100; relative water content of soil = (mass water content of soil / field moisture capacity) × 100; irrigation capacity = [targeted moisture content of soil-soil moisture content before irrigation] × thickness of soil layer × bulk density of soil layer/10; nitrogen accumulation capacity of plant = dry matter weight of overground part of the plant × nitrogen content of overground part of the plant/100; nitrogen distribution proportion of each organ = nitrogen accumulation capacity of each organ/nitrogen accumulation capacity of single stem × 100. Excel 2003 and SPSS 19.0 were used for statistical analysis and significance test of test data, and the difference among each treatment used 5% of significant level (LSD method was used for the comparison of difference significance).

3 Results and analyses

3.1 The impacts of supplemental irrigation based on soil moisture measure and nitrogen fertilization on plant height of winter wheat Variance analysis showed that plant height of winter wheat at jointing, flowering and mature stages had significant difference among different supplemental irrigation treatments ($P < 0.05$). Plant height difference of winter wheat at jointing, flowering and mature stages among different nitrogen fertilization amounts reached extremely significant level ($P < 0.01$), and water-nitrogen interaction had insignificant effect on plant height of winter wheat ($P>0.05$). Seen from Table 1, under the same supplemental irrigation treatment, plant height of winter wheat at jointing, flowering and mature stages showed an upward trend with the nitrogen fertilization amount increased, showing as $N_{255}>N_{195}>N_0$. It illustrated that nitrogen fertilization had positive correlation with plant height of winter wheat. Plant height in N_{195} and N_{255} treatments was significantly higher than that in N_0 treatment, but there was not significant difference between N_{195} and N_{255} ($P>0.05$). It illustrated that there was not significant influence on plant height of winter wheat when exceeding certain nitrogen fertilization amount. Under the same nitrogen fertilization treatment, plant height of winter wheat showed slowly rising trend with supplemental irrigation amount increased. Under N_0 and N_{195} treatments, plant height of winter wheat at jointing, heading and mature stages showed a rising trend with supplemental irrigation amount increased. Plant height in W_2 (569.4 m^3/hm^2) and W_3 (873.45 m^3/hm^2) treatments was significantly higher than that in W_1 (265.2 m^3/hm^2), but there was not significant difference between W_2 and W_3 ($P>0.05$). Under N_{255} nitrogen fertilization treatment, supplemental irrigation amount increase did not have significant influence on plant height of winter wheat. It illustrated that there was not significant influence on plant height of winter wheat when supplemental irrigation amount increased to certain degree. Comprehensively considering water and fertilizer, the treatment combination of W_2N_{195} had the most significant influence on plant height.

Table 1 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization amount on plant height of winter wheat

(unit: cm/plant)

Main treatment (W)	Secondary treatment (N)	Jointing stage	Flowering stage	Mature stage
W_1	N_0	40.07 d	68.26 b	76.53 c
	N_{195}	43.22 bc	72.49 a	80.12 b
	N_{255}	44.11 ab	72.80 a	81.95 ab
W_2	N_0	38.06 e	71.63 ab	79.47 bc
	N_{195}	42.51 bc	75.35 a	81.27 bc
	N_{255}	43.10 bc	74.30 a	81.50 ab
W_3	N_0	41.16 cd	72.92 a	84.58 a
	N_{195}	43.15 bc	71.36 ab	80.38 bc
	N_{255}	45.28 a	73.54 a	82.30 ab
F-test	(W)	0.0298 *	0.0202 *	0.0078 *
	(N)	0.0000 **	0.0000 **	0.0004 **
	(W×N)	0.7136	0.5237	0.3984

Note: different lowercase letters in the same row showed that the difference among treatments reached $P<0.05$ of significant level. * and ** respectively showed that water, nitrogen or water-nitrogen interaction were significant at $P<0.05$ or $P<0.01$ level.

3.2 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization amount on leaf area of winter wheat Variance analysis showed that the leaf area difference of winter wheat by different supplemental irrigation treatments reached significant level ($P<0.05$), while leaf area difference of winter wheat among different nitrogen fertilization levels reached extremely significantly level ($P<0.01$), and the effect of water-nitrogen interaction on leaf area of winter wheat was insignificant ($P>0.05$). Seen from Table 2, leaf area of winter wheat at jointing and mature stages showed firstly increasing and then declining trend with nitrogen application amount increased under W_1 treatment. Leaf area in N_{195} and N_{255} treatments was significantly larger than that in N_0 treatment ($P<0.05$), but leaf area of winter wheat in N_{195} treatment was significantly larger than N_{255} treatment ($P>0.05$). It illustrated that there was negative effect on leaf area of winter wheat when exceeding certain nitrogen fertilization amount. At flowering stage of winter wheat, leaf area of winter wheat showed an increasing trend with nitrogen fertilization amount. Under W_2 and W_3 supplemental irrigation levels, leaf area at jointing, flowering and mature stages showed an obviously increasing trend with nitrogen fertilization amount increased. But at flowering and mature stages, leaf area of winter wheat under N_{195} and N_{255} treatments was significantly larger than that in N_0 treatment, but there was not significant difference between N_{195} and N_{255} ($P>0.05$). It illustrated that leaf area could be declined when exceeding certain nitrogen fertilization amount. Under the same nitrogen treatment, leaf area of winter wheat at jointing, flowering and mature stages showed the firstly declining and then rising trend with supplemental irrigation amount increased under N_0 level. Under N_{195} level, leaf area of winter wheat at jointing, flowering and mature stages showed a declining trend with supplemental irrigation amount increased. Under N_{255} treatment, leaf area of winter wheat showed firstly rising and then declining trend with supplemental irrigation amount increased. Leaf area in W_2 (569.4 m^3/hm^2) and W_3 (873.45 m^3/hm^2) treatments was significantly larger than that in W_1 (265.2 m^3/hm^2), but leaf area of winter wheat under W_2 treatment was significantly larger than that in W_3 treatment ($P>0.05$). It illustrated that there was not significant effect on leaf area of winter wheat when exceeding certain supplemental irrigation amount. The above results showed that 195 kg/hm^2 of nitrogen fertilization amount and supplemental irrigation amount to W_2 (569.4 m^3/hm^2) had significant influence on leaf area of winter wheat.

Table 2 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization amount on leaf area of winter wheat

(unit: cm^2/plant)

Main treatment (W)	Secondary treatment (N)	Jointing stage	Flowering stage	Mature stage
W_1	N_0	181.83 de	143.05 d	175.63 d
	N_{195}	253.21 bc	357.21 bc	344.02 a
	N_{255}	217.89 d	516.69 a	277.65 bc
W_2	N_0	152.27 e	357.26 bc	164.00 d
	N_{195}	246.17 c	525.51 a	185.99 d
	N_{255}	328.83 a	534.94 a	316.87 ab
W_3	N_0	183.11 de	217.96 cd	254.16 c
	N_{195}	241.82 c	410.91 ab	323.08 ab
	N_{255}	295.10 ab	333.04 bc	325.55 ab
F-test	(W)	0.0056 *	0.0203 *	0.0109 *
	(N)	0.0001 * *	0.0000 * *	0.0000 * *
	(W × N)	0.2039	0.3985	0.8549

Note: different lowercase letters in the same row showed that the difference among treatments reached $P<0.05$ of significant level. * and * * respectively showed that water, nitrogen or water-nitrogen interaction were significant at $P<0.05$ or $P<0.01$ level.

3.3 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization on yield and constitution of winter wheat Variance analysis showed that spike number per mu and yield of winter wheat reached extremely significant difference among different supplemental irrigation amounts ($P<0.01$). Grain number, spike length, spike number per mu, thousand-grain weight and yield among different nitrogen fertilization amounts reached extremely significant difference ($P<0.01$), and the difference of grain number, spike number per mu and yield of winter wheat reached extremely significant level by water – nitrogen interaction ($P<0.01$). Thousand-grain weight had insignificant difference by water – nitrogen interaction ($P>0.05$), which may be caused by large-area gibberellic disease in the year. Seen from Table 3, under the same supplemental irrigation treatment, increase effect of spike number per mu by nitrogen fertilization showed a declining trend with irrigation amount increased. Under W_1 level, the increase of spike number per mu reached significant level with nitrogen fertilization amount increased ($P<0.05$). Under W_2 level, spike number per mu showed firstly increasing and then declining trend with nitrogen fertilization amount increased. Spike number per mu in two nitrogen fertilization treatments was significantly higher than that in no nitrogen treatment ($P<0.05$), but there was not significant difference between N_{195} and N_{255} ($P>0.05$). Under W_3 level, spike number per mu declined with nitrogen fertilization amount increased, and there was not significant difference among different nitrogen fertilization levels ($P>0.05$). Spike number basically showed similar rule. Under the same supplemental irrigation treatment, thousand-grain weight of winter wheat declined somewhat with nitrogen fertilization amount increased. Thousand-grain weight in N_{195} and N_0 treatments was both higher than that in N_{255}, but there was not significant difference between N_{195} and N_0 ($P>0.05$). Under the same nitrogen fertilization treatment, spike number per mu increased with irrigation amount increased, while thousand-grain weight and grain number decreased somewhat, and the difference was significant between W_1 and W_2, W_3 treatments ($P<0.05$). There was not significant difference between W_2 and W_3 treatments ($P>0.05$). Under the same nitrogen fertilization treatment, irrigation amount increase could improve spike number per mu, but grain number and thousand-grain weight declined somewhat. Maybe it was caused by large-area gibberellic disease in the season. In water – nitrogen interaction treatments, spike number per mu reached the maximum under W_2N_{195} treatment, while thousand-grain weight was the maximum under W_2N_0 treatment, and grain number reached the maximum under W_3N_{195} treatment. Under the same supplemental irrigation treatment W_1, the yield of winter wheat showed a rising trend with nitrogen fertilization amount increased. Under W_2 and W_3 levels, the yield of winter wheat showed firstly rising and then declining trend with nitrogen fertilization amount increased. It illustrated that yield increase effect of winter wheat was insignificant when exceeding certain nitrogen fertilization amount under the same supplemental irrigation treatment. Under the same nitrogen fertilization treatment, yield increase effect of winter wheat by supplemental irrigation showed a declining trend with nitrogen fertilization amount increased. Under N_0 level, yield showed positive correlation with irrigation amount, and the difference reached extremely significant level ($P<0.01$). Under N_{195} level, the yield of winter wheat showed single-peak curve of firstly increasing and then declining, and there was not significant difference between W_2 and W_3 ($P>0.05$). Under N_{255} level, yield showed negative correlation with irrigation amount, and the difference among different supplemental irrigation treatments reached extremely significant level ($P<0.01$). It illustrated that moderate supplemental irrigation or nitrogen fertilization or their coupling could significantly improve the yield. But when exceeding certain critical value, yield increase effect was insignificant, and even there was negative effect. In the test, the yield reached the maximum 8500 kg/hm^2 under the nitrogen fertilization amount of 195 kg/hm^2 and W_2 (569.4 m^3/hm^2).

Table 3 The impact of water – nitrogen coupling on yield and yield structure (unit: kg/hm^2)

Main treatment (W)	Secondary treatment (N)	Grain number	Spike length	Spike number per mu	Thousand-grain weight	Yield
W_1	N_0	32 b	7.48 b	24.80 c	44.00 a	5180 c
	N_{195}	33 b	8.43 a	37.09 b	41.92 ab	7432 b
	N_{255}	34 a	8.14 ab	38.53 a	39.92 b	8092 a
W_2	N_0	29 b	7.28 b	35.00 b	43.99 a	6596 c
	N_{195}	34 a	8.50 a	40.24 a	41.33 ab	8500 a
	N_{255}	33 a	8.48 a	38.44 a	39.25 c	7550 b
W_3	N_0	31 b	7.95 b	39.33 a	43.50 a	7836 b
	N_{195}	35 a	8.36 a	38.80 a	40.83 a	8254 a
	N_{255}	30 b	8.18 ab	37.36 a	40.64 a	6832 c
F-test	(W)	0.116	0.246	0.000**	0.778	0.000**
	(N)	0.000**	0.000**	0.000**	0.000**	0.000**
	(W×N)	0.000**	0.002*	0.000**	0.552	0.000**

Note: the data was mean of three repeats; different lowercase letters in the same row showed that the difference among treatments reached $P<0.05$ of significant level. * and ** respectively showed that water, nitrogen or water-nitrogen interaction were significant at $P<0.05$ or $P<0.01$ level.

3.4 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization on nitrogen accumulation amount of plant Variance analysis showed that nitrogen accumulation amount of plant at key growth stage reached significant difference among different supplemental irrigation treatments($P<0.05$), while nitrogen accumulation difference of winter wheat among different nitrogen fertilization amounts reached significant level($P<0.05$), and the effect difference of water – nitrogen interaction on nitrogen accumulation at each growth stage reached significant ($P<0.05$) or extremely significant level ($P<0.01$). As shown in Table 4, under different treatment conditions, nitrogen accumulation amount of plant at key growth stage of winter wheat gradually increased with the growth period shifted and reached the maximum to mature period. Under the same supplemental irrigation treatment, nitrogen accumulation amount of plant increased with nitrogen fertilization amount increased at jointing and flowering stages, reaching significant difference ($P<0.05$), and nitrogen accumulation amount in N_{195} and N_{255} was significantly higher than that in N_0 ($P<0.05$). At mature stage of winter wheat, nitrogen accumulation amount of plant treated by nitrogen was significantly higher than that not treated by nitrogen ($P<0.05$). But under W_2 and W_3 treatments, nitrogen accumulation amount in N_{255} treatment showed significantly declining trend when compared with N_{195} treatment ($P<0.05$). Especially under W_3 level, nitrogen accumulation amount in N_{255} treatment was even lower than N_0 treatment. It illustrated that moderate supplemental irrigation could improve nitrogen absorption ability of winter wheat, but excessive supplemental irrigation was not favorable for nitrogen absorption and utilization by the plant. Under the same nitrogen fertilization treatment, nitrogen accumulation amount of plant at mature stage significantly increased with supplemental irrigation amount increased under N_0 and N_{195} ($P<0.05$). It showed that supplemental irrigation could promote nitrogen absorption by plant under low nitrogen fertilization condition. But under N_{255} treatment, nitrogen accumulation amount of plant between W_3 and W_1, W_2 did not have significant difference ($P>0.05$), and nitrogen accumulation amount in W_3 slightly declined than W_1. It showed that W_2N_{195} treatment combination could improve nitrogen accumulation amount of plant.

Table 4 Nitrogen accumulation amount of wheat plant at different growth stages (unit: kg/hm^2)

Main treatment (W)	Secondary treatment (N)	Nitrogen accumulation amount		
		Jointing stage	Flowering stage	Mature stage
W_1	N_0	124.37 c	258.39 c	277.94 c
	N_{195}	205.81 b	281.43 b	299.13 b
	N_{255}	241.48 a	296.88 a	332.05 a
W_2	N_0	145.19 b	274.40 c	296.70 c
	N_{195}	229.87 a	284.03 b	334.59 a
	N_{255}	235.45 a	306.65 a	326.27 b
W_3	N_0	165.38 c	237.01 c	335.95 b
	N_{195}	219.64 b	254.57 b	392.58 a
	N_{255}	248.84 a	267.88 a	331.17 b
F-test	(W)	0.0036*	0.0369*	0.0056*
	(N)	0.0018*	0.0117*	0.0259*
	(W×N)	0.0101*	0.0001**	0.0205*

Note: different lowercase letters in the same row showed that the difference among treatments reached $P<0.05$ of significant level. * and ** respectively showed that water, nitrogen or water-nitrogen interaction were significant at $P<0.05$ or $P<0.01$ level.

3.5 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization on nitrogen distribution of plant at mature stage The research of Tang Li *et al.* [13] showed that the nitrogen distribution in seed and vegetative organs of wheat reflected effective use degree of nitrogen by crop. When nitrogen distribution proportion in seed was larger, it illustrated that effective use degree of nitrogen was higher. Seen from Table 5, nitrogen accumulation amount and distribution proportion of each organ at mature stage was all seed > stem + leaf > glume + spike stalk, showing that seed was nitrogen accumulation center. Under the same supplemental irrigation amount, single-stem nitrogen accumulation amount of seed and stem + leaf increased with nitrogen fertilization amount increased, and the difference reached significant level ($P<0.05$). Nitrogen distribution proportion in seed showed negative correlation with nitrogen fertilization amount, and nitrogen distribution proportion in N_0 treatment was significantly higher than that in N_{195} and N_{255} ($P<0.05$). Nitrogen distribution proportion in stem + leaf was contrary. It illustrated that nitrogen fertilization amount increase improved nitrogen absorption ability of wheat, but excessive nitrogen fertilization amount was not favorable for nitrogen transferring and distributing toward seed. Under the same nitrogen fertilization treatment, single-stem nitrogen accumulation amount of seed showed the trend of firstly increasing and then declining with supplemental irrigation amount increased. Single-stem nitrogen accumulation amount of seed in W_2 was the maximum and significantly higher than W_1 ($P<0.05$). Except N_{255}, nitrogen distribution proportion in seed declined with irrigation amount increased, and nitrogen distribution proportion of seed in W_1 and W_2 was significantly higher than that in W_3 ($P<0.05$). But under N_{255}, nitrogen distribution proportion in seed showed the trend of firstly increasing and then declining with supplemental irrigation amount increased, and nitrogen distribution proportion of seed in W_2 was significantly higher than that in W_1 and W_3 ($P<0.05$). Maybe it was caused by positive effect of water and fertilizer coupling. The above results showed that the nitrogen fertilization amount of 195 kg/hm^2 and W_2 were favorable for improving single-stem nitrogen accumulation amount and nitrogen proportion of seed.

Table 5 Nitrogen distribution in different organs of wheat at mature stage

Main treatment (W)	Secondary treatment (N)	Single-stem nitrogen accumulation amount//mg			Nitrogen distribution proportion//%		
		Seed	Stem + leaf	Glume + spike stalk	Seed	Stem + leaf	Glume + spike stalk
W_1	N_0	29.22 f	5.59 g	1.81 g	79.79 a	15.28 e	4.93 d
	N_{195}	32.39 e	6.80 f	2.28 e	78.10 b	16.39 d	5.50 c
	N_{255}	36.21 b	9.75 b	3.98 a	72.50 e	19.54 b	7.96 a
W_2	N_0	33.17 de	6.68 f	2.09 f	79.08 ab	15.93 de	4.99 d
	N_{195}	35.48 bc	8.44 d	2.40 d	76.60 c	18.21 c	5.18 d
	N_{255}	39.61 a	9.55 b	3.26 b	75.56 c	18.22 c	6.22 b
W_3	N_0	30.61 f	7.59 e	2.05 f	76.04 c	18.88 bc	5.08 d
	N_{195}	34.27 cd	9.18 c	2.66 c	74.32 d	19.92 b	5.76 c
	N_{255}	34.58 cd	10.37 a	2.46 d	72.94 e	21.87 a	5.19 d

Note: different lowercase letters in the same row showed that the difference among treatments reached $P<0.05$ of significant level.

4 Discussions

4.1 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization on growth condition of winter wheat Water and fertilizer have obvious coupling effect in growth process of crop, and are regulatable agricultural production factors by human measures. The research of Jiang Guiying *et al.* [14] showed that nitrogen fertilization was main factor of affecting plant height and leaf area of winter wheat in prior growth period under the abundant water supply condition. Under water supply deficit condition, crop's growth was abnormal, such as plant height and leaf area decreasing. The test research showed that the influence effects of supplemental irrigation and nitrogen fertilization on plant height and leaf area of winter wheat were different. Under the same supplemental irrigation amount, plant height and leaf area of winter wheat treated by nitrogen were significantly higher than that not treated by nitrogen ($P<0.05$), and N_{195} and N_{255} treatments were significantly higher than N_0 treatment, but there was not significant difference between N_{195} and N_{255} ($P>0.05$). But further increase of nitrogen fertilization amount did not have obvious increase effect on plant height and leaf area. Plant height and leaf area of winter wheat were the maximum under the nitrogen fertilization amount of 195 kg/hm^2 and W_2 (569.4 m^3/hm^2). It was basically consistent with research result of Dang Jianyou *et al.* [15]. Under the same nitrogen fertilization treatment, when supplemental irrigation amount exceeded 70% of field moisture capacity, plant height and leaf area of winter wheat at mature stage no longer significantly increased. It was basically consistent with research result of Ma Donghui *et al.* [9]. In the test, the influence on the growth of winter wheat was initially explored only under supplemental irrigation and nitrogen fertilization treatments, and the above conclusions needed further research and verification to obtain more accurate result.

4.2 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization on the yield of winter wheat The research of Li Tingliang *et al.* [16] showed that soil moisture at 0 – 130 mm during growth period of winter wheat should be controlled as 60% – 80% of field moisture capacity. When nitrogen fertilization amount was 150 – 225 kg/hm^2, nitrogen fertilizer had the best effect, and water use efficiency was the biggest. The research of Zhang Yongli *et al.* [17] showed that no matter whether irrigating, when nitrogen fertilization amount was less than 180 kg/hm^2, the yield of winter wheat increased with nitrogen fertilization amount increased. When nitrogen fertilization exceeded 180 kg/hm^2, wheat yield showed declining or not increasing trend. The research of Zhao Xuefei *et al.* [18] showed that spike number and grain number of winter wheat had similar change rules under interaction of different supplemental irrigation and nitrogen fertilization. The test result showed that grain number and spike number per mu of winter wheat basically showed an increasing trend with supplemental irrigation amount and nitrogen fertilization amount increased, but thousand-grain weight had a declining trend, which was consistent with research result of Duan Wenxue *et al.* [12]. Under the same nitrogen fertilization level, yield increase effect of winter wheat by supplemental irrigation showed a declining trend with nitrogen fertilization amount increased, illustrating that fertilization and supplemental irrigation had certain critical values on yield of winter wheat. When exceeding critical value, the yield declined. The test results showed that the highest yield 8500 kg/hm^2 could be reached when nitrogen fertilization amount was 195 kg/hm^2, and supplemental irrigation amount was W_2 (569.4 m^3/hm^2). When nitrogen fertilization amount and supplementary irrigation amount were 255 kg/hm^2 and 873.45 m^3/hm^2, the yield of winter wheat declined, which was basically consistent with the research results of Li Tingliang *et al.* [9, 16]. But it was also not same as research conclusion of Zhang Yongli *et al.* [17], maybe it was because that soil self nitrogen supply ability, soil entropy value and natural rainfall were different.

4.3 The impacts of supplemental irrigation based on soil moisture measurement and nitrogen fertilization on nitrogen accumulation, absorption and distribution of winter wheat

Nitrogen accumulation, absorption and distribution efficiency of crop and suitable quantity depended on farmland irrigation capacity. The research of Yang Xianlong *et al.* [19] showed that nitrogen fertilizer efficiency declined with application amount increased under the limited irrigation treatment. The highest yield could be reached under 225 kg/hm^2 of pure nitrogen treatment. On this basis, when increasing nitrogen fertilizer, the yield declined. With nitrogen fertilization amount increased, nitrogen in plant was more distributed in vegetative organs. The research of Dang Tinghui *et al.* [20] showed that moderately increasing irrigation capacity could improve nutrient accumulation amount of crop and transfer amount toward overground part under arid condition, while excessive irrigation effect was insignificant. Soil drought promoted nitrogen transferring from leaf to seed, which improved nitrogen content of seed[21]. The test results showed that nitrogen accumulation amount of plant treated by nitrogen was significantly higher than that not treated by nitrogen at mature stage of winter wheat ($P<0.05$). But under the W_2(569.4 m^3/hm^2) and W_3(873.45 m^3/hm^2) treatments, nitrogen accumulation amount in N_{255} treatment significantly declined when compared with N_{195} treatment ($P<0.05$). Especially under W_3(873.45 m^3/hm^2) level, nitrogen accumulation amount in N_{255} was even lower than that in no nitrogen treatment. Under N_0 and N_{195}, nitrogen accumulation amount of plant significantly increased with supplemental irrigation amount increased ($P<0.05$). But under N_{255} condition, there was not significant difference ($P>0.05$). It was consistent with research result of Xie Wenyan *et al.* [22]. It illustrated that moderate supplemental irrigation and nitrogen fertilization could improve nitrogen absorption ability of wheat, but excessive supplemental irrigation and nitrogen fertilization were not favorable for nitrogen absorption by plant. The research result of Shen Rongkai *et al.* [23] showed that nitrogen accumulation amount was the maximum when nitrogen fertilization amount was 270 kg/hm^2 under the same irrigation treatment. Maybe it was caused by different basic soil fertility in different regions. The research of Zhao Junye *et al.* [24] showed that it could not significantly increase nitrogen accumulation amount of winter wheat when nitrogen fertilization amount was more than 150 kg/hm^2. Nitrogen distribution amount in seed declined, and seed yield did not synchronously increase with nitrogen fertilization amount. The test results showed that nitrogen distribution proportion in seed of winter wheat showed negative correlation with nitrogen fertilization amount, and nitrogen distribution proportion of seed in no nitrogen treatment was significantly higher than that in nitrogen fertilization treatment ($P<0.05$). It illustrated that excessive nitrogen fertilization was not favorable for nitrogen in vegetative organs of winter wheat transferring toward seed. Except N_{255}, nitrogen distribution proportion in seed declined with supplemental irrigation amount increased, and nitrogen distribution proportion of seed in W_1 and W_2 were significantly higher than that in W_3 ($P<0.05$), which was consistent with research result of Zhang Dianshun *et al.* [25]. It illustrated that supplemental irrigation amount increase improved nitrogen absorption ability of winter wheat and promoted winter wheat absorbing more nitrogen, but inhibited nitrogen transferring and distributing toward seed.

5 Conclusions

Nitrogen fertilization and supplemental irrigation significantly affected plant height and leaf area of winter wheat. Under the nitrogen fertilization amount of 195 kg/hm^2 and supplemental irrigation amount as 70% of field moisture capacity (569.4 m^3/hm^2), plant height and leaf area of winter wheat reached the maxima. Under the same nitrogen fertilization level, yield increase effect of winter wheat by supplemental irrigation showed a declining trend with nitrogen fertilization amount increased. It illustrated that nitrogen fertilization and supplemental irrigation had certain critical values on the yield of winter wheat. When exceeding critical value, the yield declined. When nitrogen fertilization was 195 kg/hm^2 and supplemental irrigation amount was 70% of field moisture capacity (569.4 m^3/hm^2), the highest yield 8500 kg/hm^2 could be reached. Although supplemental irrigation amount increase at jointing stage improved wheat's nitrogen absorption ability and promoted wheat absorbing more nitrogen, it inhibited nitrogen transferring and distributing toward seed. Due to the difference of rainfall, heat and soil fertility in different regions[26], comprehensively considering growth condition of winter wheat and nitrogen risk condition, it is suggested that the nitrogen fertilization amount of 195 kg/hm^2 and supplemental irrigation to 70% of field moisture capacity were taken as suitable water and fertilizer amounts in the region.

References

[1] Science and Technology Department, China Rural Technology Development Center Group. Water-saving agriculture in China [M]. Beijing: China Agricultural Science and Technology Press,2006. (in Chinese).

[2] TANG SZ, HU XT, CAI HJ, *et al.* New ideas and development tendency of theory for water saving in modern agriculture and ecology[J]. Journal of Hydraulic Engineering, 2004,12(12):1 –7. (in Chinese).

[3] YAN X. Study on the high efficient utilization of nutrient resources and the status quo of the chemical fertilizer utilization in China[D]. Beijing: Chinese Academy of Agricultural Sciences, 2008. (in Chinese).

[4] ZHANG YM, ZHANG JB, HU CS, *et al.* Effect of fertilization and irrigation on wheat-maize yield and soil nitrate nitrogen leaching in high agricultural yield region in North China Plain[J]. Chinese Journal of Eco-Agriculture, 2011,19(3):532 –539. (in Chinese).

[5] HUANG L, GAO Y, XIU XQ, *et al.* Effects of irrigation amount and stage on yield and water consumption of different winter wheat cultivars [J]. Transactions of the Chinese Society of Agricultural Engineering, 2013, 29(14): 99 –108. (in Chinese).

[6] DETTORI M, CESARACCIO C, MOTRONI A, *et al.* Using CERES-wheat to simulate durum wheat production and phenology in Southern Sardinia, Italy[J]. Field Crops Research, 2011,120(1): 179 –188.

[7] PAOLO ED, RINALDI M. Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment[J]. Field Crop Research, 2008, 105(3):202 –210.

[8] HE JQ, DUKES MD, HOCHMUTH GJ, *et al.* Evaluation of sweet corn yield and nitrogen leaching with CERES-maize considering input parameter uncertainties[J]. Transactions of the ASABE, 2011, 54(4): 1257 –1268.

[9] MA DH, ZHAO CX, WANG YF, *et al.* Effects of nitrogen fertilizer rate and post-anthesis soil water content on photosynthetic characteristics in flaa leaves and yield of wheat[J]. Acta Ecologica Sinica,2008,28(10): 4896 –4901. (in Chinese).

[10] HAN ZJ, YU ZW, WANG D, *et al.* Effects of supplemental irrigation based on measured soil moisture on nitrogen accumulation, distribution and grain yield in winter wheat[J]. Acta Ecologica Sinica,2011,31(6): 1631 –1640. (in Chinese).

[11] YANG XL, LU YL, TONG YA, *et al.* Effects of long-term N application and straw returning on N budget under wheat-maize rotation system[J]. Plant Nutrition and Fertilizer Science,2013,19(1):65 –73. (in Chinese).

[12] DUAN WX, YU ZW, ZHANG YL, *et al.* Effects of supplemental irrigation on water consumption characteristics and dry matter accumulation and distribution in different spike-type wheat cultivars based on testing soil moisture[J]. Acta Phytoecologica Sinica, 2010,34(12):1424 –1432. (in Chinese).

[13] TANG L, MI GH, ZHANG FS. Assimilation, distribution and regulation of C^{14} in winter wheat grouting period[J]. Journal of China Agricultural University, 2000,5(1):75 –79. (in Chinese).

[14] JIANG GY, WEI JJ, LIU P, *et al.* Spring wheat growth and water use efficiency under drip irrigation[J]. Agricultural Research in the Arid Areas, 2012,30(6):50 –54. (in Chinese).

[15] DANG JY, PEI XX, WANG JA, *et al.* Effects of irrigation time on the growth and water – fertilizer use efficiencies of winter wheat[J]. Chinese Journal of Applied Ecology, 2012, 23(10):2745 –2750. (in Chinese).

[16] LI YL, XIE YH, HONG JP, *et al.* Effects of nitrogen application rate on photosynthetic characteristics, yield, and nitrogen utilization in rainfed winter wheat in southern Shanxi[J]. Acta Agronomica Sinica, 2013, 39(4): 704 –711. (in Chinese).

[17] ZHANG YL, YU ZW, ZHENG CY, *et al.* Effects of different irrigation treatments on water consumption characteristics and grain starch components accumulation in strong gluten wheat Jimai 20[J]. Scientia Agricultura Sinica,2009,42(12):4218 –4227. (in Chinese).

[18] ZHAO XF, WANG LJ, LI RQ, *et al.* Effect of irrigation times and nitrogen application rate on population dynamics and grain yield of winter wheat[J]. Journal of Triticeae Crops,2009,29(6):1004 – 1009. (in Chinese).

[19] YANG XL, LU YL, TONG YA, *et al.* Effects of long-term N application and straw returning on N budget under wheat – maize rotation system [J]. Plant Nutrition and Fertilizer Science,2013,19(1):65 – 73. (in Chinese).

[20] DANG YH, XI LH, GUO SL, *et al.* Relationship between soil nitrate, nitrogen balance and utilization in rainfed land[J]. Plant Nutrition and Fertilizer Science,2009,15(3):573 –577. (in Chinese).

[21] BAI XB, YUE SC, LI SQ, *et al.* Effects of various cultivation systems on soil water space-time dynamics and yield of rainfed spring maize[J]. Agricultural Research in the Arid Areas, 2015, 33(3): 164 –170. (in Chinese).

[22] XIE WY, ZHOU HP, GUAN CL, *et al.* Characteristics of N, P and K uptake at different growth stages of spring millet on dry land[J]. Chinese Agricultural Science Bulletin, 2009,25(3):158 – 163. (in Chinese).

[23] SHEN RK, WANG K. Field test and study on yield, water use and N uptake under varied irrigation and fertilizer in crops[J]. Transactions of the Chinese Society of Agricultural Engineering, 2001,17(5):40 –43. (in Chinese).

[24] ZHAO JY, YU ZW. Effects of nitrogen fertilizer rate on uptake, distribution and utilization of nitrogen in winter wheat under high yielding cultivated condition[J]. Acta Agronomica Sinica,2006,32 (4):484 –490. (in Chinese).

[25] ZHANG DS, DONG XY, LIU SQ. Effect of different nitrogen application on growth and nitrogen metabolic indices of spring wheat[J]. Acta Agriculturae Boreali-Sinica, 2006,21(B11):42 –45. (in Chinese).

[26] WANG Y, BAI LX, ZHAO J, *et al.* Dynamic variations of soil moisture and water use efficiency of maize under sprinkler irrigation[J]. Transactions of the Chinese Society of Agricultural Engineering,2012,28(S1): 92 –97. (in Chinese).

(From page 46)

[3] FENG LS, LI CH, LIU HY, *et al.* Study on properties of removing dyes from aqueous soulution by taking maize straw as adsorbent [J]. Journal of Anhui Agricultural Sciences, 2010, 38(24):13325 –13328. (in Chinese).

[4] TANG S, CHEN Y, XIE R, *et al.* Preparation of activated carbon from corn cob and its adsorption behavior on Cr(VI) removal [J]. Water Science & Technology, 2016, 73(11):2654 –2661.

[5] HUANG H, WANG YX, TANG JC, *et al.* Properties of maize stalk biochar produced under different pyrolysis temperatures and its sorption capability to naphthalene [J]. Environmental Science, 2014, 35(5):1884 –1890. (in Chinese).

[6] CHEN S, YUE Q, GAO B, *et al.* Removal of Cr(VI) from aqueous solution using modified corn stalks: Characteristic, equilibrium, kinetic and thermodynamic study[J]. Chemical Engineering Journal, 2011, 168(2):909 –917.