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Full Length Article

Optimal Nitrogen Supply Improves Grain Yield and Resource Use Efficiency in Winter Wheat under Supplemental Irrigation

Xin Wang[1], Yu Shi[1], Zhenwen Yu[1] and Chengyan Zheng[2*]
[1]*College of Agronomy, Shandong Agricultural University/Key Laboratory of Crop Physiology & Ecology, Tai'an 271018, China*
[2]*Institute of Crop Science, Chinese Academy of Agricultural Sciences/Key Laboratory of Crop Ecophysiology and Farming System, Beijing 100081, China*
[*]For correspondence: zhengchengyan@caas.cn
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Abstract

Water scarcity is a great challenge for wheat production. Recently, a new supplemental irrigation (SI) regime, which considers crop requirement and soil water storage, is being widely adopted for saving water in wheat fields. However, the effects of nitrogen (N) fertilization rates on wheat under this new SI regime have been rarely assessed. A two-year field experiment was conducted using four N rates (0, 180, 210, 240 kg ha^{-1}) under SI to address the research gap. Compared to the conventional flood irrigation, SI increased the total dry matter accumulation at maturity and dry matter allocation to grain in post-anthesis phase, increasing grain yield. At 210 kg N ha^{-1}, the higher nitrogen use efficiency (NUE) and water use efficiency (WUE) were attained under SI than under conventional flood irrigation. For different N rates, soil water consumption from 80–120 cm soil layer was higher at 210 kg N ha^{-1}. The flag leaf water potential, ΦPSII, and Fv/Fm at 210 kg N ha^{-1} during 14–28 days after anthesis were higher which resulted in high dry matter accumulation. The WUE and grain yield were higher at N rate of 210 kg ha^{-1} treatment, which also recorded higher NUE than 240 kg N ha^{-1} but lower than 180 kg N ha^{-1}. Therefore, 210 kg N ha^{-1} with SI regime can be the optimum nitrogen and water management for increasing wheat yield, WUE and NUE in semi-arid regions.

Keywords: Nitrogen rates; Supplemental irrigation; Grain yield; Winter wheat; Water use efficiency; Nitrogen use efficiency

Introduction

Wheat (*Triticum aestivum* L.) as the principal food crops accounts for 29.8 and 25.9% of the harvested area and production worldwide (FAO 2019). The wheat production should be increased by approximately 70–100% over its present levels to meet the future consumption needs (Chen *et al.* 2014). Wheat acreage has decreased from 1997 to 2017 (FAO 2019; NBSC 2019); thus, meeting the increased food demand will depend on the ability to achieve higher average yield of wheat. Therefore, efforts on agronomic innovation should be made.

Irrigation and application of fertilizers, especially nitrogen (N), are important agronomic practices in crop production and contribute significantly to the increase in wheat production (Mueller *et al.* 2012; Thapa *et al.* 2019). However, excessive N application and over-exploitation of groundwater for irrigation not only decrease NUE and WUE but also cause adverse environmental impacts (Zhu and Chen 2002; Behera and Panda 2009; Qi *et al.* 2019). Moreover, water scarcity is causing severe drought stress for plant growth (Farooq *et al.* 2009, 2014). Supplemental irrigation (SI) is one of the key agronomic practices for stabilizing and improving crop yield and WUE in semi-arid and arid regions. SI increases wheat roots length density in deeper soil and enhances availability of soil water; consequently, higher WUE and grain yield are obtained (Xu *et al.* 2016). Tavakkoli and Oweis (2004) confirmed that SI significantly increased yield and maximises WUE. A specific SI method has been developed in North China in which soil water content is recharged to 70–75% field capacity in 0–140 cm layers at jointing and anthesis stages of wheat by SI. This method can increase flag leaf area and photosynthesis rate, delay leaf senescence, and improve yield as compared with conventional flood irrigation practice (Lin *et al.* 2016). Nitrogen (N) is the most required nutrient for crops amongst the main influential factors of plant growth (Halitligil *et al.* 2000), as it affects cell building, photosynthetic activity, and protein assimilation rates (King *et al.* 2003; Sadras and Lawson 2013). Hence, N application optimization is essential for crops. Despite much has been investigated regarding N management, the optimum N application under the new SI regime in wheat

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needs attention in order to evaluate if grain yield, WUE and NUE can be simultaneously increased.

Annual precipitation cannot satisfy the wheat demand in major wheat production regions. Thus, irrigation is necessary for maintaining high wheat production. Moreover, shortage of water resources and over-exploitation of groundwater for irrigation threaten the winter wheat production (Yang *et al.* 2019). Therefore, the new SI method with limited irrigation at key wheat growing stages that substantially increases wheat production should be adopted. Nevertheless, the effects of N rates on WUE and NUE and grain yield in this new SI regime have been rarely explored through field experimentation. Therefore, the present study aimed to evaluate various nitrogen rates under SI regime for (1) post-anthesis dry matter translocation and allocation, (2) soil water use and (3) wheat yield, NUE and WUE.

Materials and Methods

Experimental site

This 2-year field experiment was conducted at Shandong Agricultural University (36°18' N, 117°16' E, 128 m asl). The average annual precipitation in study area is 683.2 mm with 195 frost-free days and 2627 sunshine hours. As pre-sowing soil analysis, the content of soil organic matter was 13.7 g kg^{-1} with available N, K and P were respectively 102.1, 88.4, 39.4 mg kg^{-1}. Corresponding values for 0–140 cm deep soil profile (20 cm increment) were 28.83, 26.70, 26.43, 22.91, 23.66, 24.11 and 26.33% for average field capacity (FC) and 1.45, 1.51, 1.54, 1.56, 1.58, 1.58, and 1.58 g cm^{-3} for bulk density.

Experimental design and treatments

The experimental design was a split-plot with three replications. Main plots consisted of SI regime and conventional flood irrigation treatments, whereas sub-plots consisted of four nitrogen levels ***i.e.***, 0, 180, 210 and 240 kg N ha^{-1}. Each sub-plot was 20 m^2 in size. In SI regime treatment, two supplemental irrigations brought the soil water content in 0–140 cm soil profile to 70% of field capacity at jointing and anthesis stages. In conventional flood irrigation treatment, two 60-mm irrigations were applied at jointing and anthesis stages.

Soil water contents were measured to calculate the supplemental irrigation amount for treatment SI regime (Wang *et al.* 2013):

$$I = 10 \times B \times D \times (\alpha - \beta)$$

$$\alpha = FC \times \theta / 100$$

Where I (mm) is SI amount; B (g cm^{-3}) is soil bulk density; D (cm) is soil layer depth (140 cm for this experiment); α (%) is the target soil water content after SI, and β (%) is the soil water content before irrigation; FC (%) is field capacity, and θ (%) is the target relative soil water content at jointing and anthesis stages. At jointing stage, the average SI amounts for 0, 180, 210 and 240 kg N ha^{-1} treatments were respectively 80.7, 58.3, 52.0 and 69.6 mm in 2012–2013 growth season and 84.9, 72.4, 53.9 and 81.1 mm in 2013–2014 growth season. At anthesis stage, the average SI amounts for 0, 180, 210 and 240 kg N ha^{-1} treatments were respectively 55.7, 61.9, 48.8 and 59.5 mm in 2012–2013 growth season and 40.4, 32.9, 38.3 and 43.9 mm in 2013–2014 growth season. Water was evenly sprayed onto the plots with a flow meter measured the irrigation amount.

Crop management

The wheat variety used in this experiment was Jimai22, which was sown in 20-cm apart rows on 7 October 2012 and harvested on 8 June 2013 for the first growth season. Similarly, sowing and harvesting was done on 7 October 2013 and 4 June 2014, respectively, for the second growth season. The P_2O_5 and K_2O rate were 120 kg ha^{-1} and 100 kg ha^{-1} for each treatment. All P and K fertilizers and 50% of N were applied as basal dressing. At jointing stage, the remaining N fertilizer was used as side dressing.

Measurement

Crop evapo-transpiration: For the entire growth period, soil samples were collected from 0–200 cm depth (20 cm increment) in each plot. Crop evapo-transpiration (ET) was calculated as follows (Wang *et al.* 2013):

$$ET = \triangle W + P + I$$

Where ET (mm) is crop evapo-transpiration; △W (mm) is soil water storage at sowing stage minus soil water storage at maturity stage; P (mm) is precipitation amount and I (mm) is irrigation amount.

Water use efficiency

$$WUE = Y/ET$$

Where WUE (kg ha^{-1} mm^{-1}) is water use efficiency; and Y (kg ha^{-1}) is grain yield.

Nitrogen use efficiency

Nitrogen use efficiency (NUE) was calculated by Cassman *et al.* (2002) and Du *et al.* (2017):

$$NUE = Y/N_r$$

Where NUE (kg kg^{-1}) is nitrogen use efficiency; and N_r (kg ha^{-1}) is nitrogen applied rate.

Plant determinations

Plants were harvested from 1 m row length for determination of dry matter production at anthesis and maturity phase. The plant samples were separated into three parts (spike, leaves, and stem + sheaths) at anthesis and four parts (grains, spike axis + glume, leaves, and stem + sheaths) at maturity. Dry matter allocation and translocation were calculated using formulas described by Jiang *et al.* (2004) and Masoni *et al.* (2007).

Statistical analysis

ANOVA was used to determine effects of irrigation, nitrogen and their interaction. Significant differences among treatments were identified with Duncan's test at $P < 0.05$. Data were analyzed with S.P.S.S. 13.0 statistical software.

Results

Soil water consumption

Nitrogen management significantly affected soil water consumption of 0–200 cm layers, but there was no difference between SI regime and conventional flood irrigation treatments (Fig. 1). In SI regime treatment, the soil water consumption rates of 60–120 cm were higher by 58.0, 21.2 and 9.5% in the 210 kg N ha^{-1} treatment than in the 0, 180 and 240 kg N ha^{-1} treatments, respectively ($P < 0.05$). In conventional flood irrigation treatment, the soil water consumption rates under 210 kg N ha^{-1} were 38.9, 23.2 and 13.8% higher than in 0, 180 and 240 kg N ha^{-1} in 80–120 cm for the first season. For the second season, it was 39.2, 21.2 and 13.7% higher in 60–100 cm, respectively. There were no significant differences in 0–40 and 160–200 cm.

Crop evapo-transpiration and proportional contributions

Crop evapo-transpiration and proportional contributions of soil water consumption, precipitation and irrigation, towards crop evapo-transpiration were significantly affected by nitrogen levels (Table 1). In SI regime treatment, 210 kg N ha^{-1} decreased evapo-transpiration on average by 4.8% ($P < 0.05$) as compared with 240 kg N ha^{-1} but had no significant difference with 0 and 180 kg N ha^{-1}. In conventional flood irrigation treatment, 210 kg N ha^{-1} increased evapo-transpiration by 9.2 and 4.9% as compared with 0 and 180 kg N ha^{-1}, respectively. As compared with N application rates of 0, 180 and 240 kg ha^{-1}, 210 kg N ha^{-1} increased soil water consumption by 33.6, 18.0 and 6.3% in SI regime, and by 29.0, 15.7 and 6.4% in conventional flood irrigation treatment, respectively. The lowest irrigation amount and its proportional contributions to evapo-transpiration were found in SI regime with 210 kg N ha^{-1} whereas the highest values for same occurred in SI regime with 0 kg N ha^{-1}.

Water potential, ΦPSII and Fv/Fm of flag leaves

The water potential (*Ψ*w) after anthesis was significantly influenced by irrigation and nitrogen management (Fig. 2).

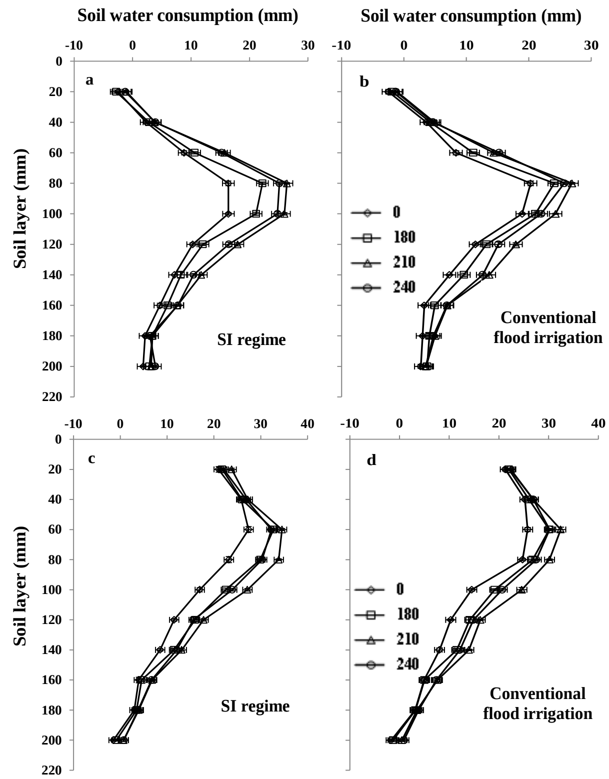

Fig. 1: Effect of nitrogen application and irrigation regime on soil water consumption in the 0-200 cm soil layers in 2012-2013 (**a**, **b**) and 2013-2014 (**c**, **d**)

In both years, there was no significant difference for *Ψ*w amongst treatments at 7 days after anthesis. However, from day 14 to 28 after anthesis, high *Ψ*w values in flag leaves were found in 210 kg N ha^{-1}. In particular, at 28 days after anthesis, the *Ψ*w values in 210 kg N ha^{-1} were higher than those in 0 and 180 kg N ha^{-1} by respectively 25.0 and 16.8% under SI regime treatment and 29.1 and 16.7% under conventional flood irrigation treatment.

During 2012–2013, similar trends of ΦPSII and Fv/Fm were observed after anthesis across all treatments (Fig. 3). In both SI regime and conventional flood irrigation treatments, ΦPSII and Fv/Fm values were significantly affected by nitrogen management. In SI regime treatment, 210 kg N ha^{-1} increased ΦPSII after anthesis. Compared 180 and 240 kg N ha^{-1} treatments, ΦPSII values in 210 kg N ha^{-1} treatment were higher by respectively 16.7 and 8.3% at 14 days after anthesis and 19.7 and 6.2% at 21 days after anthesis. In conventional flood irrigation treatment, higher ΦPSII values were found in 210 and 240 kg N ha^{-1} than in 180 kg N ha^{-1}. Fv/Fm values in 0 kg N ha^{-1} were the lowest during 7–28 days after anthesis. At 14 days after anthesis, and afterwards, 210 and 240 kg N ha^{-1} increased the Fv/Fm. Particularly in conventional flood irrigation treatment, the Fv/Fm values in 210 and 240 kg N ha^{-1} were higher than in 180 kg N ha^{-1} by respectively 5.9 and 4.8% at 21 days after anthesis and 8.4 and 9.7% at 28 days after anthesis.

Table 1: Evapo-transpiration and proportional contributions of water sources to evapo-transpiration of winter wheat

Season	Treatments		Evapo-transpiration	Amount of water consumption sources			Proportional contributions of water sources to evapo-transpiration		
	Irrigation type	N levels ($kg\ ha^{-1}$)	(mm)	Irrigation (mm)	Soil water consumption (mm)	Precipitation (mm)	Irrigation (%)	Soil water consumption (%)	Precipitation (%)
2012-2013	SI regime	0	399.60d	136.32a	67.48e	195.8	34.11a	16.89e	49.00a
		180	402.51cd	120.24b	86.47cd	195.8	29.87b	21.48cd	48.65ab
		210	411.44bcd	100.78c	114.86a	195.8	24.49d	27.92a	47.59abc
		240	434.08a	129.05a	109.23ab	195.8	29.73b	25.16ab	45.11d
	Conventional flood irrigation	0	392.13d	120	76.33de	195.8	30.60b	19.47de	49.93a
		180	409.92bcd	120	94.12bc	195.8	29.27b	22.96bc	47.77abc
		210	432.22ab	120	116.42a	195.8	27.76c	26.93a	45.30cd
		240	424.92abc	120	109.12ab	195.8	28.24c	25.68ab	46.08bcd
2013-2014	SI regime	0	430.70cd	125.27a	139.93d	165.5	29.08a	32.49c	38.43ab
		180	438.40bcd	105.33b	167.56bc	165.5	24.03b	38.22b	37.75abc
		210	446.61bc	92.14c	188.97a	165.5	20.63c	42.31a	37.06bcd
		240	464.88a	125.02a	174.36ab	165.5	26.89ab	37.51b	35.60d
	Conventional flood irrigation	0	421.93d	120	136.43d	165.5	28.44a	32.33c	39.22a
		180	442.24bcd	120	156.74c	165.5	27.13ab	35.44bc	37.42bcd
		210	463.93a	120	178.43ab	165.5	25.87b	38.46b	35.67d
		240	452.27ab	120	166.77bc	165.5	26.53ab	36.87b	36.59cd
Significance based on a repeated-measures ANOVA (*P* value)									
Y (year)			< 0.001	-	< 0.001	-	< 0.001	< 0.001	< 0.001
I (irrigation)			0.677	-	0.497	-	0.191	0.315	0.679
N (nitrogen)			< 0.001	-	< 0.001	-	< 0.001	< 0.001	< 0.001
Y × I			0.665	-	0.023	-	0.022	0.012	0.642
Y × N			0.941	-	0.576	-	0.643	0.228	0.63
I × N			0.012	-	0.771	-	0.001	0.127	0.022
Y × I × N			0.999	-	0.907	-	0.813	0.757	0.952

Note: Mean values within columns at the same growth season of wheat followed by the different letters differ significantly ($P < 0.05$)

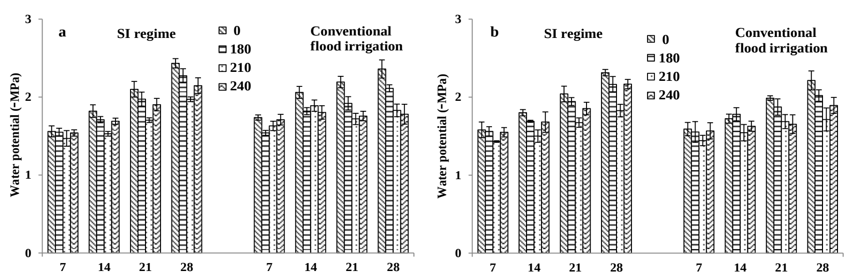

Fig. 2: Effect of nitrogen application and irrigation regime on water potential (Ψw) of flag leaf after anthesis in the 2012-2013 (**a**) and 2013-2014 (**b**) growth season

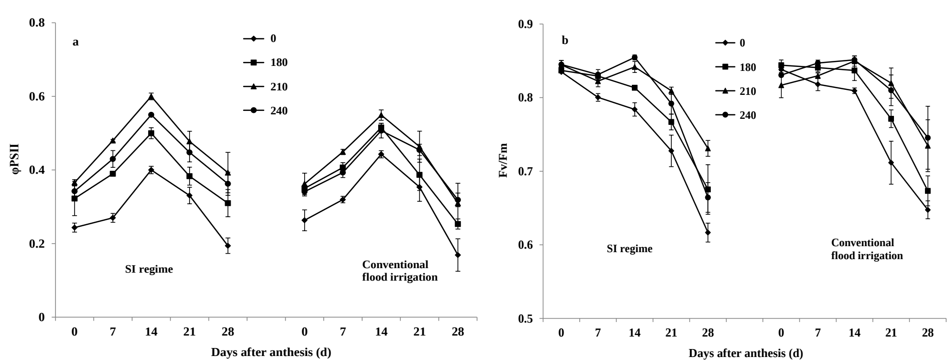

Fig. 3: Effect of nitrogen application and irrigation regime on ΦPSII (**a**) and Fv/Fm (**b**) of flag leaf after anthesis in 2012-2013

Dry matter allocation and translocation

Irrigation and nitrogen management significantly affected total dry matter accumulation, allocation and translocation to grains of assimilated dry matter after anthesis (Table 2). In both growth seasons, the highest dry matter accumulation amounts at maturity and dry matter allocation to grain of post-anthesis were found in SI regime with 210 kg N ha^{-1}.

Table 2: Dry matter allocation and translocation before and after anthesis of winter wheat

Season	Treatments		Dry matter accumulation at maturity (kg ha^{-1})	Pre-anthesis reserves		Post-anthesis dry matter	
	Irrigation type	N levels (kg ha^{-1})		Translocated into grain (kg ha^{-1})	Contribution to grain (%)	Allocation to grain (kg ha^{-1})	Contribution to grain (%)
2012-2013	SI regime	0	13860.99e	2763.19ab	36.29b	4851.90e	63.71d
		180	17135.79d	2755.66a	32.33c	5768.71d	67.67c
		210	21018.33a	2387.29d	25.12e	7116.15a	74.88a
		240	19051.13b	2669.57bc	29.41d	6406.07b	70.59b
	Conventional flood irrigation	0	13553.19e	2777.08ab	37.48a	4633.28e	62.52c
		180	17258.43d	2726.79abc	32.53c	5656.68d	67.47b
		210	19423.61b	2624.36c	29.47d	6279.37bc	70.53a
		240	18179.86c	2820.69a	32.05c	5980.00cd	67.95b
2013-2014	SI regime	0	13913.17e	2781.75c	36.60b	4818.38d	63.40c
		180	17522.88d	2862.41b	32.86cd	5847.95b	67.14b
		210	21005.16a	2620.17d	27.25e	6994.52a	72.75a
		240	18842.22c	2779.00c	31.21d	6125.97b	68.79b
	Conventional flood irrigation	0	13508.51e	2859.22b	39.09a	4456.02d	60.91d
		180	17362.13d	3083.55a	36.57b	5348.06c	63.43c
		210	19812.87b	2883.67b	31.37d	6308.37b	68.63a
		240	18229.12c	3020.91a	33.96c	5873.41b	66.04b
Significance based on a repeated-measures ANOVA (*P* value)							
Y (year)			0.479	< 0.001	< 0.001	0.082	< 0.001
I (irrigation)			< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
N (nitrogen)			< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Y × I			0.781	0.001	0.050	0.619	0.050
Y × N			0.772	< 0.001	0.414	0.816	0.414
I × N			0.003	< 0.001	0.030	0.084	0.030
Y × I × N			0.754	0.075	0.140	0.466	0.140

Note: Mean values within columns at the same growth season of wheat followed by the different letters differ significantly ($P < 0.05$).

Table 3: Grain yield, water use efficiency and N use efficiency of winter wheat

Season	Treatments		Grain yield (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})	N use efficiency (kg kg^{-1})
	Irrigation type	N levels (kg ha^{-1})			
2012-2013	SI regime	0	7608.05e	19.04d	——
		180	8519.45cd	21.17b	47.33a
		210	9400.38a	22.85a	44.76b
		240	9047.45ab	20.84bc	37.70d
	Conventional flood irrigation	0	7391.40e	18.85d	——
		180	8368.68d	20.42c	46.49ab
		210	8893.15bc	20.58bc	42.35c
		240	8761.23bcd	20.62bc	36.51d
2013-2014	SI regime	0	7576.50e	17.59d	——
		180	8673.57cd	19.78b	48.19a
		210	9587.30a	21.47a	45.65b
		240	8867.63bc	19.08bc	36.95d
	Conventional flood irrigation	0	7298.70e	17.30d	——
		180	8396.85d	18.99c	46.65ab
		210	9156.77b	19.74b	43.60c
		240	8860.45bc	19.59bc	36.92d
Significance based on a repeated-measures ANOVA (*P* value)					
Y (year)			0.443	< 0.001	0.168
I (irrigation)			< 0.001	< 0.001	< 0.001
N (nitrogen)			< 0.001	< 0.001	< 0.001
Y × I			0.762	0.204	0.680
Y × N			0.437	0.618	0.326
I × N			0.395	< 0.001	0.150
Y × I × N			0.739	0.448	0.524

Note: Mean values within columns at the same growth season of wheat followed by the different letters differ significantly ($P < 0.05$)

On the contrary, the dry matter translocation and its contribution to grain dry matter were lowest in SI regime with 210 kg N ha^{-1} amongst all treatments.

Yield, WUE and NUE

Wheat yield, WUE, and NUE were significantly affected by nitrogen levels and irrigation regimes (Table 3). The grain yields were higher in 210 kg N ha^{-1} than those in 180 and 240 kg N ha^{-1} by respectively 9.5 and 5.6% under SI regime treatment and 7.1 and 2.4% under conventional flood irrigation treatment. The highest WUE was found in SI regime with 210 kg N ha^{-1}, which was 7.6 and 10.0% higher than those in SI regime with 180 kg N ha^{-1} and SI regime with 240 kg N ha^{-1}, respectively. The NUE in 210 kg N ha^{-1} was lower than in 180 kg N ha^{-1} under both irrigation treatments; however, 210 kg N ha^{-1} recorded higher NUE than 240 kg N ha^{-1} by 17.4 and 14.6% under SI regime and conventional flood irrigation treatments, respectively ($P < 0.05$).

Discussion

There are three contributors to the total crop evapo-transpiration *i.e*. soil water supply, irrigation, and precipitation. Various evidences showed that optimum fertilization and irrigation significantly affect crop evapo-transpiration and WUE (Duncan *et al.* 2018; Yang *et al.* 2019). As mentioned earlier, limited irrigation is beneficial in decreasing crop water consumption and, thus, improving WUE (Panda *et al.* 2003; Yang *et al.* 2019). In this study, a new supplemental irrigation (SI) regime was adopted in which calculated irrigation amounts were applied to recharge the soil water content to the target soil relative water content. It appeared that the new SI regime increased the soil water supply from deeper soil layers (80–100 cm). A previous study showed that crop evapo-transpiration under N rate of 80 kg ha^{-1} was lower by 5.8 and 8.3 mm, on average, than under N rate of 120 and 160 kg ha^{-1} treatments, respectively (Behera and Panda 2009). The present study also showed that crop evapo-transpiration increased with the increase in N rate under the new SI regime. However, there was no significant difference in crop evapo-transpiration between N rate of 210 and 180 kg ha^{-1}. Moreover, the highest WUE was obtained under the SI regime at 210 kg N ha^{-1}, which might be ascribed to the highest proportion of soil water usage under this treatment combination. It seems that increasing the use of stored water from deeper soil layers by optimizing N and water management can decrease irrigation amount and, thus, achieve higher WUE (Man *et al.* 2014; Rathore *et al.* 2017).

Generally, irrigation and N application rate affect wheat physiology and growth (Wang *et al.* 2013: Deng *et al.* 2014). For example, Guo *et al.* (2014) found that SI regime increases flag leaf area and ETR at anthesis stage and delays leaf senescence, thereby increasing dry matter accumulation amounts at maturity phase and wheat yield. In the present study, the SI regime also increased ΦPSII and Fv/Fm after anthesis as compared with conventional flood irrigation regime. In addition, the higher dry matter allocation of post-anthesis assimilated dry matter to grains was obtained under SI regime. Nitrogen significantly affects crop growth of wheat. In current study, the flag leaf Ψw of post-anthesis increased with the increase in N application rate, thereby enhancing ΦPSII and Fv/Fm of the flag leaf. The higher ΦPSII and Fv/Fm might be the reason for the higher dry matter accumulation under the treatment of 210 kg N ha^{-1} (Table 2). Furthermore, application of excess N fertilizer resulted in a diminution of post-anthesis dry matter assimilation into grains and its relative contribution to total grain dry matter, which was consistent with previous findings (Deng *et al.* 2014; Dai *et al.* 2017). It is believed that the increase in carbon remobilisation from vegetative tissues to grains is conducive to high grain yield (Yang and Zhang 2006; Rivera-Amado *et al.* 2019). In summary, the treatment of 210 kg N ha^{-1} in the SI regime promoted dry matter assimilation into grains and resulted in the highest grain yield in the current study.

The main challenge in crop production is to simultaneously increase resource use efficiency and grain yield. Optimum nitrogen and water management are crucial to enhance the grain yield (Chen *et al.* 2014; Rathore *et al.* 2017; Thapa *et al.* 2019). The N input for wheat production in this study area is approximately 220–325 kg N ha^{-1} (Ju *et al.* 2009; Lu *et al.* 2015) and the irrigation amount is approximately 300 mm (Zhang *et al.* 2006). Although such high nitrogen and irrigation amounts can maintain high wheat yields, the NUE and WUE are merely about 20 kg kg^{-1} (Ju *et al.* 2009) and 13.5 kg ha^{-1} mm^{-1} (Wang 2010), respectively, which are correspondingly 1.5 (Zhang *et al.* 2008) and 1 times lower than in the developed countries (Wang 2010). In the present study, the highest WUE of 22.85 kg ha^{-1} mm^{-1} in 2013 and 21.47 kg ha^{-1} mm^{-1} in 2014 were obtained when received 100.78 and 92.14 mm irrigation and N application rate of 210 kg ha^{-1}. The lower crop evapo-transpiration and the highest wheat yield were the reasons for higher WUE. Moreover, the NUE under N rate of 210 kg ha^{-1} was lower than that under 180 kg ha^{-1}, but higher than 240 kg ha^{-1}. It was showed that nitrogen application rate of 210 kg ha^{-1} in SI regime was a desirable practice for simultaneously enhancing yield, WUE and NUE.

Conclusion

The SI regime with N application of 210 kg ha^{-1} reduced the irrigation amount and increased the use of stored water from deeper soil layers, resulting in lower crop evapo-transpiration and higher WUE. Moreover, the highest total dry matter accumulation amounts at maturity phase and dry matter allocation to grain of post-anthesis led to highest grain yield. Meanwhile, NUE under nitrogen application rate of 210 kg ha^{-1} were higher. Taken together, it appeared that nitrogen application rate of 210 kg ha^{-1} in SI regime can maintain sustainable winter wheat production in semi-arid regions.

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Author Contributions

Xin Wang, Zhenwen Yu and Chengyan Zheng designed the research. Xin Wang, Yu Shi and Chengyan Zheng conducted the experiments and collected data. Xin Wang and Chengyan Zheng contributed to data analysis and wrote the manuscript. All authors approved the final manuscript.

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