Improving wheat yield and water use efficiency by optimizing irrigations in northern China

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Abstract

Recently, to achieve the goal of increasing both crop yield and water/nitrogen use efficiency with a better irrigation regime is a major challenge in semi-arid areas. In this study, we presented a two seasonal-field experiment that considers irrigation regimes, i.e., no irrigation (W0), irrigated in jointing (W1), both in jointing and flowering (W2) after the re-greening, and varieties (S086; J22) to compare the response of the sensitivity of wheat leaf physiological indicators, yield, water/N use efficiency and soil water consumption to irrigation regimes. The results showed that the WUE, IWUE and soil water-holding consumption (SWC) decreased with the increase in amount of irrigation. Additionally, 45.5% of the excessive irrigation water input did not promote wheat yield (W1 vs. W2). The degree of SWC in the 0–120 cm soil layer was highly related to wheat growth. S086 was beneficial for the usage of SWC under a low amount of irrigation. As well, irrigation positively affected the activities of superoxide dismutase (SOD) and catalase (CAT) in the flag leaf ($P<0.05$) during crop yield production. A decrease of irrigation helped to increase the concentrations of SS and Pro and decrease of amount of MDA for S086. Thus, a high yield of S086 was found under deficit irrigation (W1, a 31.3% reduction of irrigation water than that of W2). Thus, our studies suggested that one irrigation event in jointing stage for the S086 variety was essential to meet the win-win goal of high crop yield and water use efficiency with low groundwater consumption.

Highlights

- Irrigation after re-greening was beneficial for flag leaf growth and yield production;
- SOD and CAT were highly influenced by irrigation and then acted on yield production;
- Irrigation promoted the SWC and TWC without significant increase of crop yield;
- S086 was beneficial for SS and Pro increase but MDA decrease under deficit stress;
- S086 under W1 was recommended for future limited irrigation agriculture.

1. Introduction

Intensified winter wheat planting is the primary cropping system in northern China, which produced > 67% of the wheat in China (NSBC, 2020) (He et al., 2017). Northern China is a typical semi-arid area with an average annual precipitation at 556 mm but only compromised 27–32% (150–180 mm) during the winter wheat growing season (Zhang et al., 2020). Consequently, the precipitation cannot meet the requirements, and a lack of adequate water then caused up to 200–300 mm of a shortage of water during the whole winter wheat growing season (Fang et al., 2010; Sun et al., 2019). The traditional irrigation water was pumped from deep groundwater for flood irrigation measurements with 3–5 times per wheat season, which accounts for 80% of total agricultural water used in this region (Deng et al., 2006). In this region, flood irrigation that was used by many farmers caused up to 60% of the irrigation water lost by evaporation or leaching to deeper, and was posing a serious threat for sustainable agriculture production (Rathore *et al.*, 2017). As a result, the groundwater level is declining rapidly at a rate of 0.8 – 1.5 m yr^{-1} in this region (Fang et al., 2010; Zhao et al., 2015), which has become an important issue to restrict sustainable development (Oort et al., 2016; Li et al., 2018). Therefore, formulating optimal irrigation approaches and improving water production in northern China, were essential for future agriculture. Since the 1990s, various sound farming options, e.g., optimized irrigation regimes, limited irrigation water amount, and improved crop planting structure among others, have been implemented and proposed to reduce the use of groundwater without decreasing the wheat yield in this region (Zhang et al., 2017). Because of the important status of wheat in food consumption during the previous 40 years, a focus on improving the productivity of irrigation water was probably the most common strategy for resolving future water-related challenges by adapting proper agricultural managements and implementing irrigation water-saving measurements (Sun et al., 2018; Davarpanah and Ahmadi, 2021).

Deficit irrigation, defined as the application of irrigation water below the full crop evapotranspiration (ET), is an important practical strategy to increase water use efficiency for applying a lower amount of irrigation in key growth stages and has been globally applied for wheat and other crop fields, particularly in dry regions, such as northern China (Ali et al., 2019; Pardo et al., 2020; Yu et al., 2020). A reduction or a total loss of seasonal irrigation treatments may cause drought stress, which stimulates wheat roots to grow into deeper soil (below the 80 cm soil layer) layers and then utilize the soil water and nitrogen found in deep soil (Li et al., 2018). Additionally, an appropriate scheduling of irrigation minimized the effects of water stress on crop yield and the increase in productivity water (Lima et al., 2019). As Li et al. (2018) reported that irrigating after the flowering stage could reduce the consumption of pre-anthesis water and ensure the soil water supply at the critical stage, thus, increasing water use efficiency. However, Davarpanah and Ahmadi (2021) reported that irrigation at the jointing stage was the most critical irrigation event for winter wheat. In addition, the wheat leaf physiological indicators, for example, enzymes in flag leaves, such as superoxide dismutase, peroxidase, catalase, and malondialdehyde (MDA) were directly affected by irrigation regimes. Moreover, the responses of crop yield production and the sensitivity of wheat leaf physiological indicators to the irrigation regimes remain unclear. Thus, the main purpose of this study was to 1) assess the effects of irrigation on soil water consumption, winter wheat yield, water-/N-use efficiency and the sensitivity of wheat leaf physiological indicators, and then to 2) determine the traits of double high wheat varieties, such as WUE and yield, and provides insight into understanding the mechanisms that underlay the influence of irrigation regimes on WUE. Furthermore, this knowledge will aid in the development of appropriate irrigation management strategies and select appropriative wheat, particularly in areas like northern China.

2 Materials And Methods

2.1 Experiment area

This study was conducted in Quzhou County, Hebei Province (36°86' N, 115°02' E), during two wheat seasons of 2018–2019 and 2019–2020, respectively. Quzhou is a typical area with the most serious water shortage in northern China with an annual average temperature at 16.8°C. The long-term average annual precipitation is 541.31 mm, in which most of the rainfall occurred in the summer and comprised 65–80%. The details of soil parameters, precipitation, and air temperature values are shown details in Table 1 and Fig. 1.

Table 1
Soil conditions of 0 ~ 20 cm soil layer.

Year	Bulk density ($g\ cm^{-3}$)	SOM ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	Av-N ($mg\ kg^{-1}$)	Av-P ($mg\ kg^{-1}$)	Av-K ($mg\ kg^{-1}$)
2018 ~ 2019	1.48	14.12	1.21	110.41	16.41	150.15
2019 ~ 2020	1.46	15.35	1.44	100.56	11.62	137.62

2.2 Experimental design

First, we selected two popular local wheat varieties, i.e., J22 and S086. J22 was an extensive planted variety with steady yield especially in northern China, S086 was a drought-resistance variety identified by Institute of Dry Farming, Hebei Academy of Agricultural Sciences, Hebei, China (2015). Secondly, three limited irrigation treatments were considered, i.e., no irrigation after re-greening (W0), irrigation during the jointing stage (W1) and irrigation during the jointing and flowering stages (W2). All the treatments were irrigated before the winter growth period with the same amount at 90 mm. Accordingly, the field experiment was arranged in a randomized block design with three replications in a total of 18 plots. Each plot was conducted in 10 m × 6 m. For cultivation, 150 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1} were applied along with the wheat sowing, and then 60 kg N ha^{-1} was top-dressed at the jointing stage. Wheat was sown with a row spacing of 15 cm after deep ploughing. The amount for irrigation was based on the amount used from local farmer's practice. Precipitation during the wheat growth period between 2019–2020 was 133.7 mm, close to the annual average precipitation of this region. The details of irrigation schedules are shown in Table 2.

Table 2
Irrigation amount (mm) in different growth stages during 2018 ~ 2020.

Year	Varieties	Treatment	Overwinter Dec. 18	Jointing Mar. 20	Flowering May 15	Total
2018 ~ 2019/ 2019 ~ 2020	S086	W0	90	0	0	90
		W1	90	75	0	165
		W2	90	75	75	240
	J22	W0	90	0	0	90
		W1	90	75	0	165
		W2	90	75	75	240

Note: W0, no irrigation events after overwintering stage; W1, irrigated in jointing stage; W2, irrigated in jointing and flowering stages.

2.3 Data calculation

2.3.1 Crop yield

To determine the crop yield, the spikes were all counted in one 1 m^2 area of each plot before harvest. The grain number per spike was then counted from 30 randomly selected plants in each plot. The 1000-grain weight was determined by weighing 1000 grains from each plot and then averaging these three replicates. At maturity, all the wheat plants in a 3-m^2 area in each plot were harvested, threshed, and then dried in 80°C for crop yield calculation. In additional the actual crop yield was reported on a 12.5% moisture basis.

2.3.2 Soil water-holding consumption and water use efficiency

The soil water content was measured at sowing, overwintering, jointing, flowering, filling, and maturity. Soil samples were mixed with three replications in each plot and then collected in 0–200 cm soil layer at 20-cm intervals. The soil gravimetric water content (%) was measured by oven-drying at 105°C for 48 h. The soil water-holding consumption (SWC, mm) was measured by final soil water-holding amount minus the initial one.

Crop evapotranspiration for a given stage (ET) was calculated according to the soil water balance equation:

$$ET=\Delta S+I+P-R-D+CR \quad (1)$$

where ΔS (mm) is soil water extraction based on the difference between near two growth stage, I (mm) is irrigation, P (mm) is rainfall, R (mm) is runoff, D (mm) is drainage deeper than 200-cm soil profile, and CR (mm) is capillary rise into the root zone. R and D can be ignored in northern China according (Wang et al., 2013; Li et al., 2019b). Additionally, the groundwater table at the experimental site is 5–6 m below the ground surface which was deeper than the root activity depth of these two wheat varieties selected in this paper (0–2.5 m); therefore, the CR is negligible.

ΔS was calculated according to Eq. (2):

$$\Delta S=10\sum_{i=1}^{n}\gamma_i H_i(\theta_{i1}-\theta_{i2}) \quad (2)$$

where, *n* is the number of soil layers from 0–200 cm; γ_i (g cm^{-3}) is the bulk density of the *i*th soil layer, H_i (cm) is the soil depth of the *i*th soil layer, θ_{i1} (%) and θ_{i2} (%) are the initial and final gravimetric water content of the *i*th soil layer, respectively.

The water consumption intensity (CD, mm d^{-1}) and percentage (CP, %) for a given stage are calculated as follows:

$$\mathrm{CD}=\frac{\mathrm{ET}}{\mathrm{D}} \tag{3}$$

$$\mathrm{CP}=\frac{\mathrm{ET}}{\mathrm{ET_T}} \tag{4}$$

where, ET (mm) is the crop evapotranspiration for a given stage, D (d) is the days for a given stage, and ET_T (mm) is the total ET for a whole growth stage.

The water use efficiency was evaluated based on the use of the total and irrigation water by crop, which was estimated as crop water use efficiency (WUE) and irrigation water use efficiency (IWUE) as described by Jha et al. (2019).

$$WUE=\frac{\mathrm{GY}}{\mathrm{ET_T}\times 10} \tag{5}$$

$$\mathrm{IWUE}=\frac{\mathrm{GY}}{\mathrm{I}\times 10} \tag{6}$$

where WUE and IWUE were measured in kg m^{-3}; GY is the grain yield (kg ha^{-1}); ET_T is the total evapotranspiration during a growing season (mm), I is irrigation (mm).

2.3.3 Plant nitrogen uptake and utilization

The plant samples were collected at overwintering, jointing, flowering, filling, and maturity stage, and then oven-dried and sieved. The total nitrogen (N) content was determined using the Kjeldahl method. In this study, two NUE indicators were used: N partial factor productivity for fertilizer (PFP_N, kg grain kg^{-1} N_{fert}) and apparent N use efficiency (*ANUE*, %) (Zhang et al., 2017).

PFP_N was defined as the ratio of crop yield per unit of fertilizer N applied (7), apparent N use efficiency (ANUE, %), was defined as the ratio of crop N uptake to fertilizer N applied (8):

$$\mathrm{PFP_N}=\frac{\mathrm{GY}}{\mathrm{N_{fert}}} \tag{7}$$

$$\mathrm{ANUE}=\frac{\mathrm{N_{uptake}}}{\mathrm{N_{fert}}} \tag{8}$$

where, GY is the grain yield (kg ha^{-1}), and N_{fert} is the crop N uptake. N_{fert} is the fertilizer N application rate (kg ha^{-1}).

2.3.4 Physiological factors of the flag leaf

Twenty flag leaves in each plot were randomly collected at 0-, 7-, 14-, 21-, and 24-day after the flowering stage in 2019–2020 and then stored at − 20°C before the biochemical assays were used as previously described (Li et al., 2019c). In this study, the six related indicators were used the most: superoxide dismutase (SOD, U g^{-1} h^{-1}), peroxidase (POD, U g^{-1} h^{-1}), catalase (CAT, U g^{-1} h^{-1}), and malondialdehyde (MDA, nmol g^{-1}), soluble sugar (SS, mg g^{-1}) and proline (Pro, mg g^{-1}) content of flag leaf according to Troll and Lindsley (1955) and Zhang and Kirkham (1993).

2.3.5 Statistical analysis

Microsoft Excel 2010 (Microsoft Co., USA) was used to arrange the experimental data. The effects of different irrigation regimes on crop yield, N and water consumption, soil water content were analyzed according to an analysis of variance (ANOVA) using SPSS 18.0 (SPSS Inc., Chicago, IL, USA). The differences between the means of different treatments were judged by the least significant difference (LSD) test at a level of 0.05.

3 Results

3.1 Crop water consumption

Crop water consumption and ratios were different in differing growth stage and treatments (Table 3). No significant difference of crop water consumption was found between S086 and J22 in seeding-jointing stage for all treatments. For the filling-mature stage, the crop water consumption of W2 was higher ($p < 0.05$) than those of W1 and W0.

Table 3
Water consumption and the ratios in different growth stages.

Year	Varieties	Treatment	Seeding to jointing			Jointing to flowering			Flowering to filling			Filling to mature		
			CD	CP	Total	CD	CP	Total	CD	CP	Total	CD	CP	Total
			mm	%		mm	%		mm	%		mm	%	
2018~2019	S086	W0	0.43a	26.26a	70.92a	2.93b	41.16a	111.17b	3.00b	10.01b	27.04b	3.15b	31.46b	84.97c
		W1	0.40a	20.14b	66.43a	3.61a	41.63a	137.32a	4.68a	12.76a	42.08a	3.83b	31.39b	103.53b
		W2	0.42a	18.04b	69.42a	3.90a	38.55a	148.36a	5.51a	12.90a	49.63a	5.04a	35.34a	136.00a
	J22	W0	0.45a	27.43a	72.34a	3.16b	44.33a	116.92b	2.92b	8.86b	23.38b	2.83b	29.02b	76.53b
		W1	0.46a	23.32b	74.92a	3.84a	44.18a	136.93a	7.12a	17.73a	56.98a	2.98b	25.06b	80.51b
		W2	0.47a	20.08b	76.92a	3.97a	38.35a	146.94a	7.31a	15.27a	58.50a	5.36a	37.79a	144.76a
2019~2020	S086	W0	0.54a	22.84a	88.98a	0.89b	8.65b	33.69b	7.32c	16.92b	65.90c	3.28b	22.71b	88.48c
		W1	0.51a	18.94b	84.99a	1.77a	15.01a	67.32a	16.96b	34.03a	152.65b	4.30b	25.85b	115.99b
		W2	0.56a	19.28b	93.02a	1.83a	14.40a	69.48a	22.24a	41.50a	200.19a	5.39a	30.15a	145.43a
	J22	W0	0.43a	17.89a	68.94a	0.95b	9.08b	34.98b	8.36c	17.37b	66.91c	2.69b	18.83b	72.55b
		W1	0.35a	13.89b	57.45a	1.48a	13.26a	54.84a	18.60b	35.98a	148.80b	3.17b	19.42b	80.29b
		W2	0.35a	12.34b	56.21a	1.52a	12.37a	56.35a	25.88a	45.45a	207.03a	6.14a	36.42a	165.91a

Note: CD: water consumption intensity; CP: water consumption percentage. Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The same letter in the same column denotes no significant difference in different irrigation treatments by LSD ($P < 0.05$) for these two varieties.

In 2018–2019, a 55.62% (W1) and 83.54% (W2) higher of total water consumption (TWC) for S086 and 143.71% (W1) and 150.21% (W2) higher for J22 than W0 treatment were found in flowering-filling stage, respectively. Additionally, a 31.36% (S086) and 79.80% (J22) higher of W2 than W1 treatment was found in filling-mature stage. Similar to 2018–2019, in 2019–2020, TWC in W2 was the highest for all growth stages, but no significant difference was found during the seeding-jointing-flowering stage in 2018–2020 between S086 and J22 (except in flowering-filling-mature stage especially in 2019–2020) (Table 3).

The water consumption ratio especially in jointing-flowering was the highest during the whole season, compromising 38.6–41.6% (S086) and 38.4–44.4% (J22) in 2018–2019, while the one on the flowering-filling stage was the highest for irrigation treatments but not in the seeding-jointing and filling-mature stages in the treatment that lacked irrigation treatment (W0) during 2019–2020. During the whole season, TWC was W2 > W1 > W0 during both years (Fig. 2).

3.2 Soil water-holding consumption (SWC)

In irrigation treatments, TWC by the crop from the soil layer decreased along with the increase in amount of irrigation, amount (as the main source of crop water demand). Additionally, the increase in irrigation amount is related to the increase of TWC and the decrease of SWC. For example, in comparison with W1, when 45.5% of the irrigation water increased, the TWC increased by 7.5–16.7% (S086) and 10.2–19.2% (J22), but the SWC decreased by 27.5–38.2% (S086) and 28.7–30.2% (J22) (Fig. 2). Irrigation events mainly influenced the crop water consumption from 0–120 soil layer (Fig. 3). In 2018–2019, for S086, the SWC in 20–100 cm soil layer was W0 > W1 > W2, while the one in 100–180 cm was W1 > W0 > W2. For J22, the SWC in 20–120 cm soil layer was W0 > W1 > W2, but there was no obvious regularity in deeper soil layer.

In 2019–2020, the SWC in surface soil (0–20 cm) and 40–120 cm soil layer were W0 > W1 > W2 for S086, although there was a lack of an obvious trend in the deeper soil layer, while the one in 20–120 cm was W0 > W1 > W2 for J22 but was not apparently regulatory in the deeper soil layer.

3.3 Dynamics of the physiological factors of flag leaves

Irrigation increased the activities of SOD, POD, and CAT from 7 days and the contents of soluble sugar (SS) and proline (Pro) from 14 days after the flowering stage, but the content of MDA decreased during the whole flowering stage (Figures S1-S6). Accordingly, when irrigated during the flowering stage (W2), the SS content increased by 9.1–19.0% (S086) and 4.3–19.8% (J22) during 2018–2019 and 3.4–8.4% (S086) and 10.2%–16.6 (J22) during 2019–2020, compared with the content of W1. The Pro content of W2 was 5.6–11.7% (S086) and 7.3–15.2% (J22) higher than W1 during 2018–2019 while the one was 9.0–10.4% (S086) and 8.3–12.6% (J22) higher than W1 during 2019–2020 (Figure S5-S6). For J22, irrigation was the main factor that affected SOD, POD and CAT in the 0- to 14-day samples, but SS ($P < 0.01$) and Pro in 14- to 28-day after the flowering stage were positively influenced by irrigation, but no significant difference was found for MDA (Fig. 4). However, for S086, the increase in irrigation could have contributed to the decrease in MDA. Moreover, optimized irrigation could be beneficial for SS and Pro content, particularly in 0–7 days after flowering stage. Additionally, SOD ($P < 0.05$) and SS ($P < 0.01$) concentration were significantly influenced by wheat varieties but no interaction relationships were found (Table 4).

Table 4
Two-way ANOVA of the effects of irrigation and wheat variety on soil water consumption, plant physiological factors, and N-/water- use efficiency. TWC, SWC, SOD, POD, CAT, MDA, SS, Pro, WUE, IWUE, ANUE and PFP are given in caption of Fig. 5. * and ** represent the 0.05 and 0.01 significance levels, respectively.

	ANOVA P value												
	Soil water		Plant physiological factors						N and water use efficiency				
	TWC	SWC	SOD	POD	CAT	MDA	SS	Pro	Yield	WUE	IWUE	ANUE	PFP
Irrigation	0.703	0.734	0.576	0.965	0.347	0.918	0.794	0.86	0.995	0.712	0.968	0.858	0.918
Variety	0.524	0.741	0.025*	0.797	0.116	0.841	0.005**	0.585	0.022*	0.056	0.208	0.04*	0.038*
Irrigation *Variety	0.981	0.978	0.898	0.98	0.944	0.763	0.924	0.984	0.984	0.985	0.99	0.991	0.949

3.4 Crop yield

Irrigation helped to cause an increase in the number of spikes and grains per spike in 2018–2019 (Table 5). The spikes of S086 and J22 increased by 90.51% (W1), 66.52% (W2) and 75.63% (W1), 83.90% (W2) than W0, respectively. In addition, the weight of 1000-grain was increased by irrigation events, in which those of W1 and W2 were 11.2% and 7.9% higher ($P < 0.05$) than that of W0 for S086, respectively, but no significant difference was found for J22. Therefore, the highest wheat yield was found in S086 for all irrigation treatments during these two experimental seasons ($P < 0.05$, Table 4).

Table 5
Wheat yield and related factors under different irrigation treatments.

Year	**Varieties**	**Treatments**	**Spike ($\times 10^4$ ha^{-1})**	**Grains per spike**	**Weight (1000-grain) /g**	**Yield /kg ha^{-1}**
2018 ~ 2019	S086	W0	331.95b	26.33b	36.68b	3106.94b
		W1	632.41a	33.00a	40.79a	7803.26a
		W2	552.75a	33.67a	39.57a	8198.61a
	J22	W0	391.35b	27.67b	34.85a	3512.87b
		W1	687.31a	33.67a	35.70a	7773.67a
		W2	719.70a	32.00a	34.69a	8110.62a
2019 ~ 2020	S086	W0	527.67a	30.61b	49.28a	6536.39b
		W1	612.03a	32.17a	50.33a	8182.29a
		W2	646.03a	32.43a	50.51a	8286.04a
	J22	W0	567.01a	29.81b	48.50a	6501.97b
		W1	598.36a	34.47a	49.08a	8064.46a
		W2	601.03a	35.37a	48.97a	8122.30a

Note: Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The same letter in the same column denotes no significant difference in different irrigation treatments by LSD ($P < 0.05$) for these two varieties.

3.5 Crop water- and N-use efficiency

In addition to irrigation, precipitation was also primarily influenced by the crop yield and water-/N-use efficiency (Table 6). In 2018–2019, the lowest WUE was found in the W0 treatment, while the lowest IWUE was found in W2 for both S086 and J22. However, the highest WUE and IWUE were found in the W1 treatment for both varieties. In 2019–2020, the highest WUE was still found in W1 with no significant difference for S086, but the one of W1 was 15.5% ($P < 0.05$) and 9.4% ($P < 0.05$) were higher than those in W0 and W2 for J22, respectively. However, the highest IWUE was found in W0, followed by W1, which was primarily owing to the higher yield caused by higher rainfall in 2019–2020 in comparison with that of 2018–2019.

Table 6

Crop water- and N- use efficiency in different irrigation treatments.

Year	Varieties	Treatments	WUE(kg m^3)	IWUE(kg m^3)	ANUE (kg kg^{-1})	PFP (kg kg^{-1})
2018 ~ 2019	S086	W0	1.15b	3.45b	0.47c	14.8b
		W1	2.37a	4.73a	0.99b	37.2a
		W2	2.13a	3.42b	1.10a	39.0a
	J22	W0	1.33b	3.90b	0.51c	16.7b
		W1	2.42a	4.71a	0.97b	37.0a
		W2	2.12a	3.38b	1.04a	38.6a
2019 ~ 2020	S086	W0	1.68a	7.26a	0.90c	31.1b
		W1	1.82a	4.96b	1.10b	39.0a
		W2	1.72a	3.45c	1.22a	39.5a
	J22	W0	1.69b	7.22a	0.92c	33.6b
		W1	1.95a	4.89b	1.19b	38.4a
		W2	1.78b	3.38c	1.28a	38.7a

Note: Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The same letter in the same column denotes no significant difference in different irrigation treatments by LSD ($P < 0.05$) for these two varieties.

Different irrigation events influenced the growth and formation of crop growth and yield, which then caused the difference in N use efficiency. As shown in Table 6, ANUE and PFP were W2 > W1 > W0 for both S086 and J22 during 2019–2020. For irrigation treatments after re-greening, the ANUE of W2 was higher ($P < 0.05$) than that of the W1, but no significant difference in PFP was found between W1 and W2. In 2018–2019, the ANUE of W2 was 11.1% ($P < 0.05$, S086) and 7.2% ($P < 0.05$, J22) higher than that of the W1. In addition, in 2019–2020, the ANUE of W2 was 10.9% ($P < 0.05$, S086) and 7.6% ($P < 0.05$, J22) higher than that of W1. As well, ANUE ($P < 0.05$) and PFP ($P < 0.01$) were significantly differed with wheat varieties (Table 4).

3.6 Combined effects of irrigation and water consumption on grain yield, water- and N-productivity

Along with the increase of SWC and TWC, POD increased ($P < 0.05$), but the contents of MDA and SS decreased significantly ($P < 0.05$, Fig. 5). In addition, the crop yield was significantly affected by the SOD, CAT and SS of flag leaves and then indirectly acted on the WUE, PFP and ANUE. Irrigation water productivity, such as IWUE, was positively affected by SWC and TWC ($P < 0.05$). However, irrigation would reduce the consumption of soil water storage, which indicated that deficit irrigation could be beneficial for the increase in antioxidant activity of crops and water productivity.

4 Discussion

4.1 Grain yield, water-/N use efficiency under irrigation

Water and nitrogen (N) were considered to be the main factors that affect crop yields. The N fertilizer applied directly affected the absorptions and transformations of nutrients and yield production. However, the N absorbed by crops was directly influenced by the availabilities of nutrients. Irrigation, another major factor affecting crop yield production, has a direct impact on soil moisture, as well as nutrient availabilities, physiological factors of the flag leaves, and water use efficiency (Fig. 5) (Ierna and Mauromicale, 2012).

In semiarid areas, such as northern China, water is an important limiting factor in crop yield (Wang, 2017; Li et al., 2019a). Rainfall could effectively supplement the demands for crop water demands and supply the soil water stock, particularly in the winter wheat season. Even though, the water that the winter wheat season required was still up to 200–300 mm (Fang et al., 2010; Sun et al., 2010), and irrigation could be contributed to crop yield production, e.g., the yield of S086 for W0 vs. W1 vs. W2 was 6536 vs. 8182 vs. 8286 kg ha^{-1}, in 2019–2020 (Table 5), which indicated that irrigation could increase crop yields by as high as 27–164%, and these results have been proved by previous studies (He et al., 2017; Zhang et al., 2020). The selection of drought-resistant varieties was also beneficial for irrigation water saving with high crop yield. In this study, the highest yield was found in S086 particularly under one irrigation after the re-greening stage, i.e., W1, owing to the higher drought resistance index in this plant than that of J22.

As expected, the grain yield was closely related to spikes, grain number per unit of area and weight per 1000-grain (Bustos et al., 2013; Serrago et al., 2013; Slafer et al., 2014); Table 5), as well as superoxide dismutase (SOD) and CAT (Fig. 5). However, the spikes and grain weights (1000-grain) were highly influenced by irrigation (Table 5; Xu et al., 2018; Sandhu et al., 2019). A soil water deficit in the uppermost soil layers during the jointing to anthesis period would seriously decrease the grain numbers and reduce the aboveground biomass at anthesis (Xu et al., 2018). The activities of SOD and the contents of MDA and Pro would increase under the water deficit, but the activity of CAT and the connect primarily increased after irrigation, particularly during the 14-day to 21-day period after the flowering stage (Fig. 4) (Mu et al., 2021). Therefore, irrigation contributed to the antioxidant effect of crops in the pre-flowering stage and to nutrient transformations during the later stage of flowering. Moreover, a content of SS during 14-day after the flowering stage in irrigation treatments that contributed to osmoregulation and antioxidant ability in pre-flowering and then to the transformations of nutrients to increase the crop yield during the lateflowering stage (Fig. 5) (Hui et al., 2011). Above all, irrigation at the stem extension stage (i.e., the jointing stage) of wheat is the most effective time to increase grain yield and WUE and plant growth and photosynthesis (Song et al., 2018; Xu et al., 2018; Fan et al., 2019).

Between the W1 and W2 treatments, which increased one more irrigation event, crop yield was increased without a significant difference but had a large decrease in the WUE (5.8–12.5%) and IWUE (27.8–30.7%, $P < 0.05$), which was not the appropriate approach to meet the future sustainable agriculture (Si et al., 2020). In addition, irrigation was one of the key factors to influence enzymes (i.e., SOD, POD, and CAT) of that flag leaf, which were related to the crop water-/N- use efficiency (Fig. 5) primarily by directly/indirectly enhancing the yield of crop yield and N uptake, particularly at 7–14 days after the flowering stage. The increase in SOD helped to increase in the loss of resistance of crop oxidation with a decrease in MDA content (Shahzad *et al*., 2018). Drought stress is often linked with increases in oxidative stress and decreases in the contents of SS and Pro, which increased the tolerance to crop drought (Gupta et al., 2011; Kaur et al., 2013). An increase in irrigation contributed to the increase of SOD, POD, CAT, SS and Pro but a decrease of MDA (Fig. 5, $P < 0.05$). However, an increase in irrigation was against to water productivity and use efficiency. Selections of drought-tolerant varieties were beneficial for the win-win goal of irrigation water reduction and steady yield under drought stress (Ashraf, 2010). For S086, when a reduction in the contribution of irrigation water contributed to the increase in SS and Pro, particularly in 0–14 days after the flowering stage ($P < 0.05$, Fig. 4), and then enhanced the ability to reduce drought (Shahzad *et al*., 2018).

As Liu et al. (2020) reported that irrigation at 120 mm per wheat season is appropriate for future sustainable wheat production with high-yielding in the irrigation region. Additionally, limited irrigation (like deficit irrigation) could cause changes in the soil dry-wet conditions, which was beneficial to increase drought resistance of crop (e.g., winter wheat, cotton), and then increase the transformation of plants to protein and increase crop yield and qualities, as well as water use efficiency (Liu et al., 2018; Ali et al., 2019). Thus, the plant system with S086 under W1 (165 mm per wheat season) that was still recommended in this research was in accord with the future agriculture goal in northern China.

4.2 Influence of irrigation on soil water-holding consumption

In our study, the crop water consumption in these two winter wheat varieties was different between these two growth years (Table 3). Typically, after the re-greening stage, the physiological growth rate of winter wheat is so fast with the increase of water and nutrients demanded. This is also the key period for plant nutrients transformation and transport to grain (Li et al., 2019c). Additionally, deficit irrigation could cause the increase of SWC by wheat (Fig. 2) as well, result in the increase in root activities and changes in soil microbial communities with more effective usage of the external water besides irrigation water (Jha et al., 2017).

Therefore, meeting the requirement the crop water in jointing - filling stage could be the key practice to ensure the normal growth of crops and keep the soil water stock, which has also been confirmed by other researchers (Song et al., 2018; Fan et al., 2019). However, SWC primarily differed in the 0–120 cm soil layer in these different irrigation treatments (Fig. 2) (Li et al., 2018; Zhang et al., 2020). In addition, the extraction of deeper soil water was increased when the irrigation water was reduced (i.e., W0 and W1) (Xu et al., 2016). The SWC was higher than the one in 2018–2019, particularly in 2019–2020, mainly because of the higher rainfall after winter wheat harvested in June 2019 and during April-May in 2020 (Fig. 1). Previous studies reported that severe drought could promote the growth of roots to deeper soil layers as deep as 160 cm) for the usage of soil water but with the cost of growth limited and lower biomass and crop yield (Li et al., 2018).

In our study, for no irrigation after re-greening, i.e., W0, the soil water of S086 was higher than the one of J22. When irrigated after re-greening, i.e., W1 and W2, the water required for crop growth primarily originated irrigation water (36.8–62.7%) and increased along with the amount of irrigation amount. In addition, the percentage of irrigation amount to the TWC of S086 was lower than that of J22, which indicated that the S086 variety could be recommended for low irrigation areas. Accordingly, the use efficiency of rainfall and soil water decreased gradually, the irrigation was still the primary process that provided for the crop water demand. As well, the seasonal evapotranspiration would be increased when excessive irrigation water was consumption (Payero et al., 2008; Liu et al., 2013).

Above all, no significant difference of crop yield but significant difference of total water consumption between W1 and W2 were found during these two wheat seasons, indicated that improved limited irrigation regime (i.e., W1) was considered suitable and recommended for future agricultural production, but other optimized practices would be considered (Zhao et al., 2020). Examples include reasonably adjusting or reducing the single irrigation amount in combination with rainfall or delaying irrigation at the jointing stage (Fan et al., 2019), improving irrigation strategies with drip irrigation (Sandhu et al., 2019; Xu et al., 2020), to meet the win-win goal of high crop yield and water use efficiency with a low consumption of groundwater.

5 Conclusions

Irrigation levels were one of the most important factors to maintain high crop yield, water and nitrogen productivities of wheat in semi-arid areas, such as northern China. The TWC and SWC by winter wheat under different irrigation treatments all increased with the increasing irrigation water applied. However, the wheat yield was not significantly higher that of W2 than W1 in 2018–2019 and 2019–2020, but the highest yield was found in the S086 variety in all irrigation treatments between these two years. As well, the SWC in the 0–120 cm soil layer was highly related to wheat growth in all the treatments. During the whole growth period of wheat, the crop water consumption was primarily focused on the jointing to filling stage, particularly in the jointing - flowering stages (comprised 38.4–44.3% of total crop water consumption). Additionally, the drought-resistance variety (i.e., S086) was beneficial for the usage of SWC under an amount of low irrigation. Meanwhile, irrigation after re-greening stage might highly promote physiological growth of flag leaf, i.e., SOD and CAT, which could have highly affected crop yield production and water-/N- use efficiency. This study recommends the use of variety S086 under W1 treatment that would be subjected to irrigation during the jointing stage to meet the win-win goal of high crop yield and water use efficiency with low groundwater consumption. It would also be reasonable at adjusting or reducing the single irrigation amount in combination with rainfall was still needed to be considered for future saving agricultural irrigation managements.

Declarations

Acknowledgments

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Figures

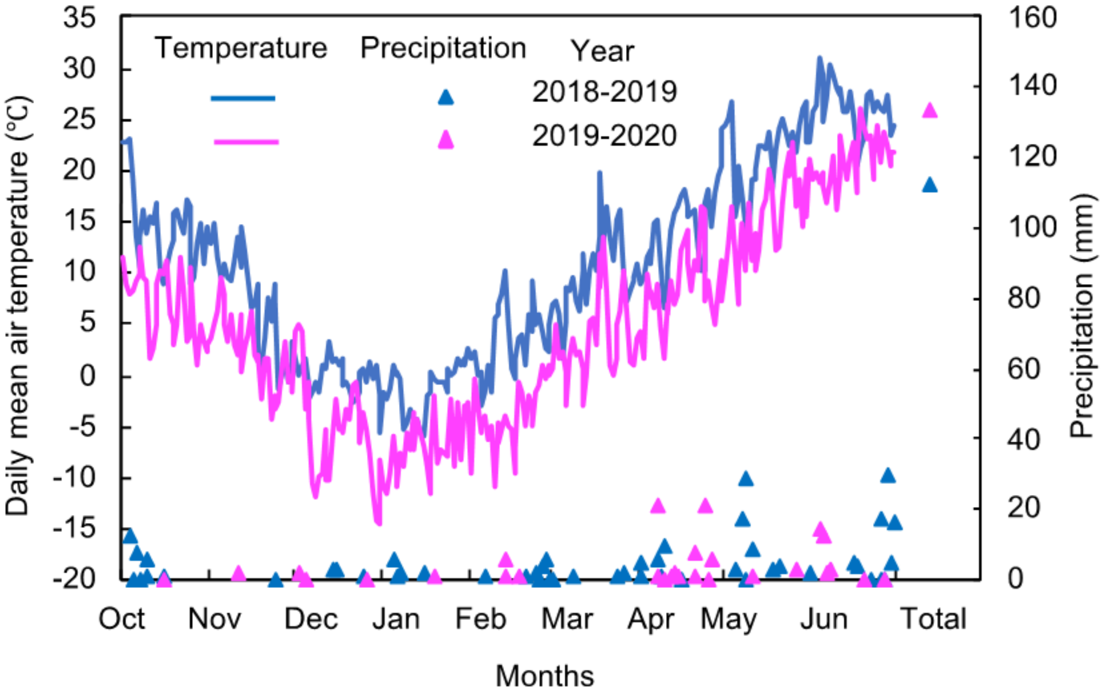


Figure 1

Precipitation and air temperature during the study period.

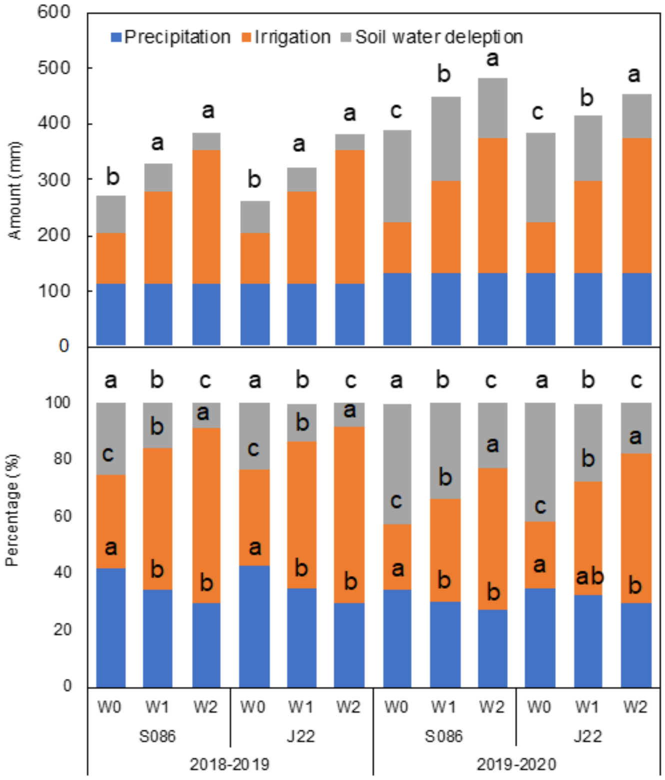


Figure 2

Water consumption and percentage from precipitation, irrigation and soil water depletion in different treatments. Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The same letter in each soil layer denotes no significant difference in different irrigation treatments by LSD (P < 0.05).

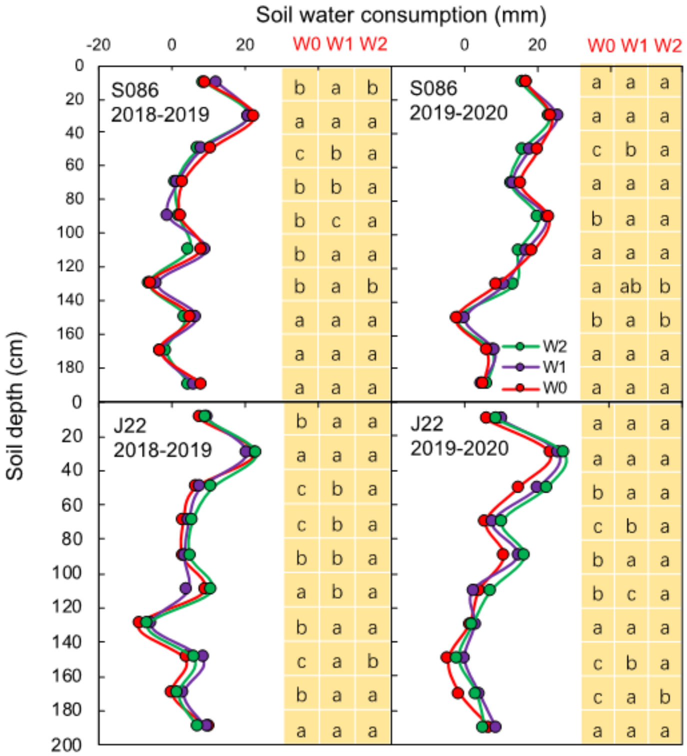
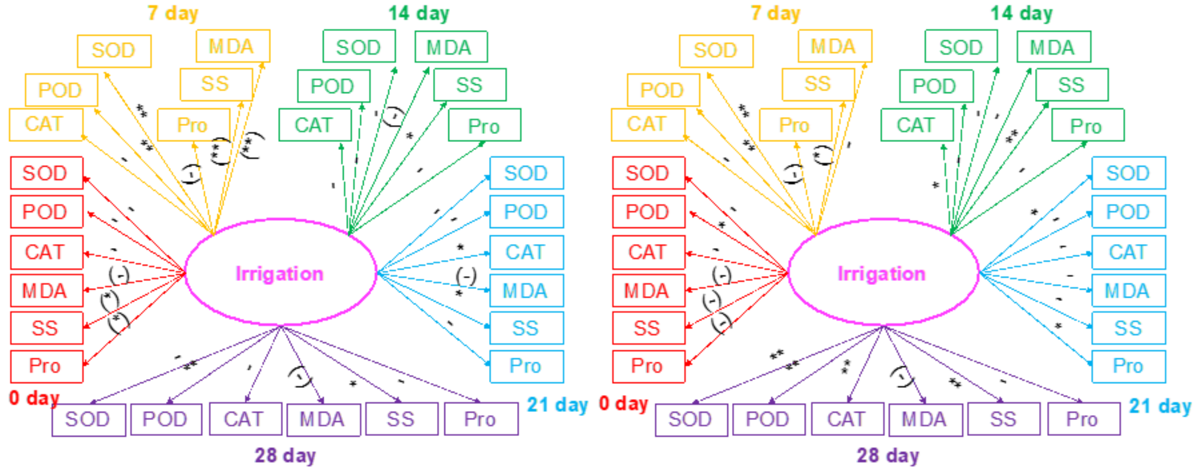


Figure 3

Soil water consumptions under different treatments in 0~200 cm soil layer. Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The same letter in each soil layer denotes no significant difference in different irrigation treatments by LSD ($P < 0.05$).



S086

J22

Figure 4

Relationships between physiological factor of flag leaf and irrigation after flowering stage. SOD, superoxide dismutase; POD, peroxidase; CAT, catalase; MDA, malondialdehyde content; SS, soluble sugar content and Pro, proline content. *, ** indicate a positive significant correlation at 0.05 and 0.01 level, respectively. (*), (**) indicate a negative significant correlation at 0.05 and 0.01 level, respectively. -, (-) indicate no significant difference.

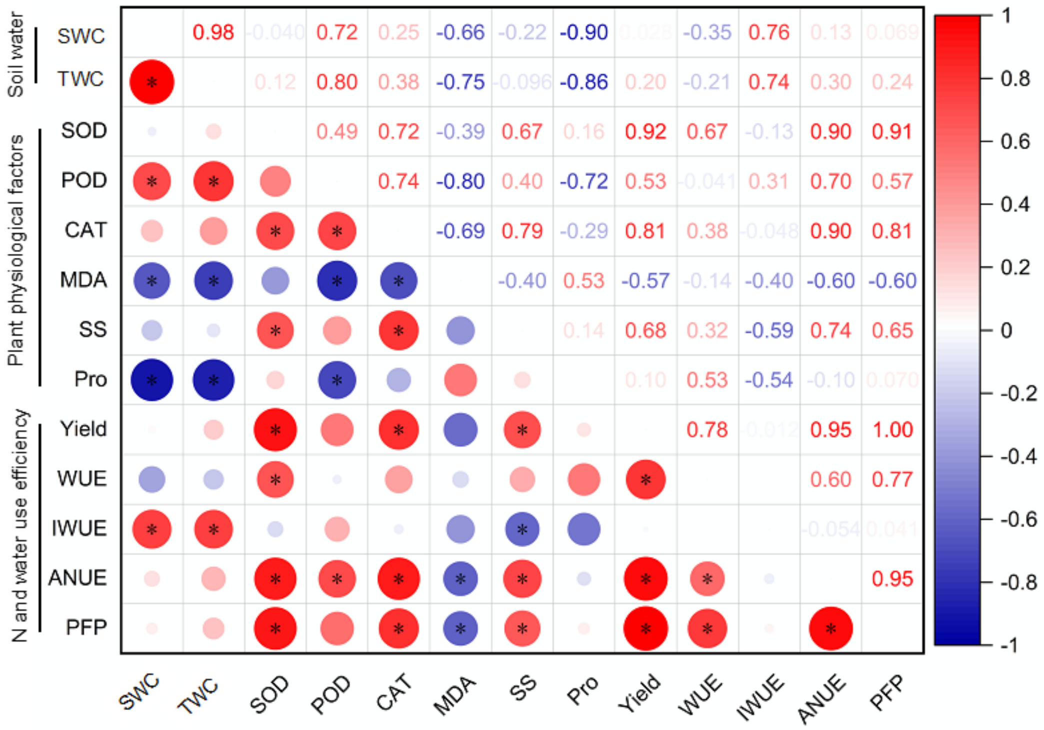


Figure 5

Correlation analysis of physiological factors of flag leaf, yield and water-/N- use efficiency with soil water consumptions (P<0.05). SWC, soil water-holding consumption; TWC, total water consumption; SOD, POD, CAT, MDA, SS, and Pro are given in caption of Figure 4.

Supplementary Files

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