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REGULAR ARTICLE

Response of winter wheat grain yield and water use efficiency to deficit irrigation in the North China Plain

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ABSTRACT

Water resources in the North China Plain (NCP) are limited, so it's in urgent need to optimize deficit by irrigation for sustainable winter wheat production in this area. Winter wheat grain yield (GY), contribution of dry matter (DM) remobilization to GY (CDMRG), and water use efficiency (WUE) were investigated in NCP. Compared with non-irrigation treatment, irrigated with 60 mm each at the winter wheat jointing stage (JS) and heading stage (HS) achieved reasonable winter wheat GY and WUE. Compared with irrigation with 120 mm only at JS and irrigation with 40 mm each at JS, HS, and milking stage (MS) of winter wheat, irrigation with 60 mm each at JS and HS provided the highest CDMRG, which resulted to the highest GY and WUE; this result was mainly due to a significant increase of the spike numbers (SN) per m^2. The results suggest that in the NCP, in order to achieve reasonable GY and WUE, winter wheat should be irrigated with 60 mm each at JS and HS.

Keywords: Aboveground dry matter; Soil water content; Evapotranspiration; Precipitation; Growing season

INTRODUCTION

The NCP, covers an area of more than 1.5 million hectare. In this region, winter common wheat is the most important cultivated crop, and produces about 50% of the total winter wheat GY (Tian et al., 2013). Many results indicated that the water requirement over the growing season of winter wheat was more than 400 mm (Bian et al., 2016; Zhao et al., 2013; Zhou et al., 2011); however, during the growing season of winter wheat, precipitation ranges from 100 to 180 mm. Therefore, water is the most important limiting factor for the production of winter wheat.

In order to increase winter wheat GY in the NCP, additional irrigation is required. For the shortage of surface water, groundwater has become the most important source of irrigation water (Sun et al., 2010). In recent years, 70% of irrigation water is used for winter wheat (Li et al., 2005). With the increase of winter wheat cultivated land, groundwater levels are persistently declining, and resulting in serious environmental problems, it has already been the widest funnel-shaped zone of groundwater in the world (Guo et al., 2010). Current limitation of water resources is threatening winter wheat productivity, and this trend is expected to increase in the future. Hence, farmers are obliged to deal with this problem by implementing sustainable agricultural water managements aimed at maintaining winter wheat GY with less water. In order to increase irrigation water productivity in arid area, many researchers found that deficit irrigation was an effective measure (James et al., 2012; Neal et al., 2012; Romulus et al., 2012).

Deficit irrigation has been successfully used on potatoes (Wang et al., 2009), tomatoes (Cristina et al., 2011), cotton (Fazlullah et al., 2013), rice (Soundharajan and Sudheer, 2009), forages (Neal et al., 2012; Neal et al., 2011), corn (Nader et al., 2010), oilseed rape (Istanbulluoglu et al., 2010), onion (Igbadun et al., 2012), and peach trees (Bartolomeo et al., 2007). It was also used in cereal crops and showed that it improved yield performance in winter wheat (Zhang et al., 2006). However, compared with full irrigation, many results showed that winter wheat GY in deficit irrigation decreased (Xue et al., 2003; Abolfazl and Hossein 2007).

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Deficit irrigation is very easy to be applied in field, it has been raised and attracted considerable interest in recent years. This irrigation method may improve winter wheat WUE (Blum, 2007; Dong et al., 2011), but GY could be decreased. In China, 80% of the food is produced on irrigated farmland and this plays an important role in feeding the 1.3 billion populations (Wu et al., 2006). About 50% of winter wheat GY is produced in the NCP. If GY will decrease significantly under deficit irrigation, it will not ensure food security of China. Hence, the only method to maintain winter wheat production in this area is to develop water-saving agriculture and improve WUE without a significant GY reduction. Rao et al. (2013) showed that deficit irrigation subject to 75% of soil water deficit can maximize wheat yield, and Li et al. (2013) found that reasonable winter wheat GY and WUE could be achieved under the condition of deficit irrigation. Hence, we hypothesized that there maybe a considerable scope for raising winter wheat GY by the effect of deficit irrigation in the NCP.

In this paper, field experiments have been conducted on winter wheat in 3 typical regions in the NCP to investigate the improved WUE and GY of winter wheat and provide scientific basis and useful guidelines to farmers on how to optimize deficit irrigation technology for sustainable winter wheat production.

MATERIALS AND METHODS

Experimental site

During 2002–2003 winter wheat growing season, the experiment was conducted at the Yucheng Comprehensive Experimental Station of Chinese Academy of Science (36°57'N, 116°38'E). The mean annual precipitation at the Station is 590 mm, of which approximately 38% falls during the winter wheat growing season. The soil at the Station is classified as sandy loam soil with an organic matter content (OMC) of approximately 0.5%, soil organic carbon content was 8.9 g/kg, the level of rapidly available phosphorous (RAP) was 12.6 mg/kg, potassium was 171.0 mg/kg, nitrogen was 68.3 mg/kg, and field capacity (FC) and wilting point of 25.1% and 8.0% by volume, respectively. During 2004–2005 and 2005–2006 growing seasons of winter wheat, the experiment was conducted at the Taian Agronomy Station of Shandong Agricultural University (36°10'N, 117°09'E), the mean annual precipitation is 700 mm, of which approximately 34.8% falls during the winter wheat growing season. The soil at this experimental site is classified as loam soil with an OMC of approximately 1.4%, soil organic carbon was 10.7 g/kg, the level of RAP was 13.2 mg/kg, potassium was 78.5 mg/kg, nitrogen was 83.1 mg/kg, and FC and wilting point of 25.8% and 7.7% by volume, respectively. During 2006–2007 and 2007–2008 growing seasons of winter wheat, the experiment was conducted at the Luancheng Experimental Station of Chinese Academy of Science (37°50'N, 114°40'E), the mean annual precipitation at the Station is 485 mm, of which approximately 30% falls during the growing season of winter wheat. The soil at the experimental site is classified as loam soil with an OMC of approximately 1.2%, soil organic carbon was 10.7 g/kg, the level of RAP was 15 mg/kg, potassium was 150 mg/kg, nitrogen was 80 mg/kg, and FC and wilting point of 36.4% and 9.6% by volume, respectively. At Yucheng and Taian, the experiments were conducted in pool cultures. The areas of the pool cultures at Yucheng and Taian were 6.7 and 8.0 m^2, respectively, at a depth of 1.5 m; the pool cultures were enclosed with a concrete wall, and the bottom surfaces of the plots were not sealed. The plot surface was 15.0 cm above the ground surface from all sides to prevent runoff and subsurface movement of water between the plots. At Luancheng, the experiment was conducted at field condition, and the area of the irrigation plots was 16 m^2, and there were 15-cm beds around the plots. Between 2 adjacent irrigation plots, there was a 1.5 m wide zone without irrigation to minimize the effects of 2 adjacent plots on each other. All the agronomy practices during the trial were officially approved by the above three stations.

Experimental design

Preliminary experiment and experiment 1

Preliminary experiment was conducted at Yucheng during one growing season 2002–2003. Experiment 1 was conducted at Taian during two growing seasons 2002/03–2003/04. The following 4 irrigation regimes were applied for both experiments during the winter wheat growing season: non-irrigation (T0), irrigated 60 mm at JS (T1), irrigated 60 mm each at JS and HS (T2), and irrigated 60 mm each at JS, HS, and MS (T3).

Experiment 2

Based on the results obtained in experiment 1, during the growing season of winter wheat, irrigated 120 mm could get reasonable GY and WUE; hence, at Luancheng, the following 3 irrigation regimes were applied during the winter wheat growing season: irrigated 120 mm only at JS (I1), irrigated 60 mm each at JS and HS (I2), and irrigated 40 mm each at JS, HS, and MS (I3).

In the three experiments, at the time of sowing, 30.0 g m^{-2} of triple superphosphate, 30.0 g m^{-2} of urea, and 7.5 g m^{-2} of potassium chloride were applied to the soil. Water was supplied from a pump outlet to the experiment sites by using plastic pipes, a flow meter was used to measure the amount of water supplied. Each of the three independent experiments was conducted in triplicate, using a randomized block design.

The winter wheat varieties 93-52, 8049, and 9204 were used at Yucheng, Taian, and Luancheng, respectively, all of them were not drought-tolerant varieties.

In preliminary experiment during 2002 year winter wheat cultivars were sown on October 4 and was harvested on June 6 2003. Irrigation was applied at JS on April 6, at HS on April 30 and at MS on May 16.

In the first experiment cultivars were sown on 6 and 11 October during 2004 and 2005 years and was harvested on June 7 and 9 2005, 2006 year. Irrigation was applied at JS on April 7–2004/05 and on April 6–2005/06, at HS on April 27– 2004/05 and April 28–2005/06 and at MS on May 14–2004/05 and on May 16–2005/06.

In the second experiment, wheat cultivars were sown on 12 and 17 October 2006 and 2007 years and was harvested on 11, 12 June 2007 and 2008, respectively. Irrigation was applied at JS on April 7, 9, at HS on April 30, 29, and at MS on May 17, 21 in 2006–2007, and 2007–2008 growing seasons of winter wheat, respectively. At the time of sowing, 30.0 g m^{-2} of triple superphosphate, 30.0 g m^{-2} of urea, and 7.5 g m^{-2} of potassium chloride were applied to the soil.

Measurements

Grain yield and yield components

When the plants had reached maturity, 1-m stretches of 2 rows were selected at random in each experimental plots to measure SN, 1000-kernel weight, and GY. The plants were harvested manually and air-dried. An additional 20 plants were harvested to determine the kernel numbers per spike.

Volumetric soil water content

The volumetric soil water content (SWC) of the cores obtained at every 10 cm down to 120 cm at Yucheng and Taian and 180 cm at Luancheng in the planting zone was measured by a CNC503B neutron moisture meter (Super Energy. Nuclear Technology Ltd., Beijing, China). The SWC in the top 20 cm soil layer was measured by oven-drying method. Measurements were performed at approximately 7-day interval. Before and after precipitation and irrigation, additional measurements were performed.

Evapotranspiration

Evapotranspiration of winter wheat was calculated using the following equation (Zhao et al., 2013):

$$ET = I + P - R - D - SW \tag{1}$$

In equation 1, ET (mm), the evapotranspiration; I (mm), the amount of irrigation water; P (mm), precipitation, which was measured from the weather station at the sites by using a standard rain gauge; R (mm), the surface runoff, which was assumed as not significant since concrete slabs or beds were placed around each plot; D (mm), the downward flux below the crop root zone, which was ignored since SWC indicated that drainage at the sites were negligible; and SW (mm), the change in water storage in the soil profile exploited by plant roots.

Water use efficiency

WUE was defined as follows (He et al., 2009):

$$\mathrm{WUE} = \frac{Y}{ET} \tag{2}$$

In equation 2, Y (kg/m^2), the winter wheat GY; ET (mm), the growing-season evapotranspiration derived from equation 1.

Contribution of DM remobilization to grain yield

Contribution of DM remobilization to GY (CDMRG) was calculated using the following equation (Li et al., 2010):

$$\mathrm{CDMRG} = \frac{DMR}{Y} \times 100 \tag{3}$$

In equation 3, DMR (g/m^2), the DM remobilization to GY, is the difference between aboveground DM at flowering and maturity; Y (g/m^2), the GY, was measured at maturity.

Data analysis

The date of the experiment 2 was analyzed for variance using the analysis of variance (ANOVA) of SAS software package (SAS Institute, 1996). For ANOVA, $\alpha = 0.05$ was set as the level of significance to determine whether significant differences existed among the yearly means of the various treatments. Multiple comparisons were performed for significant effects with the least significant difference (LSD) test at $\alpha = 0.05$.

RESULTS

Precipitation

Precipitation during the 5 growing seasons of winter wheat was presented in Table 1. Based on the annual mean precipitation during the growing seasons of winter wheat, 2002–2003 and 2006–2007 were classified as moderate growing seasons, 2004–2005 and 2005–2006 were classified as dry growing seasons, and 2007–2008 was classified as humid growing season, respectively.

Table 1: Precipitation during the growing seasons of winter wheat (mm)

Experimental sites	Growing seasons	Oct [a]	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun [b]	Total
Yucheng	2002–2003	8.7	20.0	3.3	23.9	12.4	31.8	63.2	44.1	14.8	222.2
Taian	2004–2005	2.2	27.0	4.0	0.0	14.5	0.0	51.8	94.4	0.0	193.3
	2005–2006	4.6	5.4	3.8	4.7	7.8	0.0	23.5	77.0	0.0	126.8
Luancheng	2006–2007	0.6	17.1	3.9	0.0	1.4	52.1	16.7	48.2	0.0	140.0
	2007–2008	1.3	86.0	2.8	1.4	0.0	0.0	40.0	61.9	82.8	276.2

[a] Precipitation in October was the mean monthly from sown day to Oct 31; [b] Precipitation in June was the mean monthly from June 1 to harvested day

Preliminary experiment and Experiment 1

Grain yield

As shown in Fig. 1, in both dry and moderate growing seasons, winter wheat GY increased with irrigation amount increased. In 2002–2003 winter wheat growing season, the GY was significantly higher in T2 and T3 than in T0 and T1; however, the difference between T2 and T3 was not significant. Compared with T0, the GY in T1, T2, and T3 was increased by 29.7, 71.5, and 89.6 g/m^2, respectively. In both 2004–2005 and 2005–2006 growing seasons of winter wheat, the GY was significantly higher in T1, T2, and T3 than in T0, and the GY was significantly higher in T2 than in T1; however, there were no significant differences between T2 and T3 in the both growing seasons. In 2004–2005 winter wheat growing season, compared with T0, the GY in T1, T2, and T3 were increased by 46.1, 76.7, and 83.8 g/m^2, and in 2005–2006 winter wheat growing season, were 76.2, 123.2, and 136.7 g/m^2, respectively. Hence, the potential irrigation production decreased with irrigation amount increased. The results indicate that irrigated 120 mm during the growing seasons of winter wheat could result in reasonable GY.

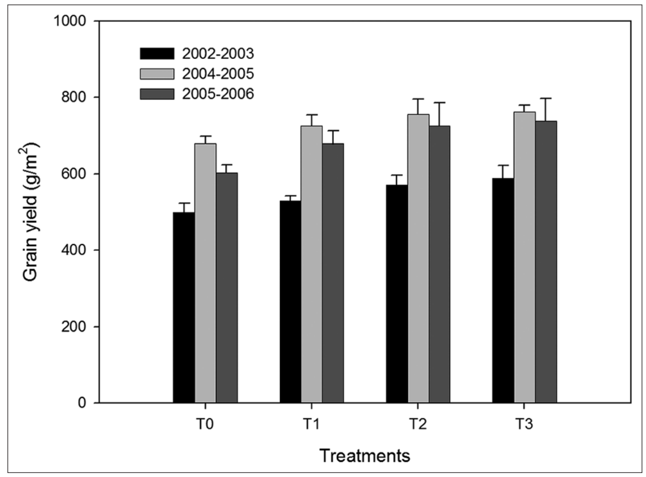

Fig 1. Winter wheat grain yield in different deficit irrigation regimes. Vertical bars are standard errors. T0, T1, T2, and T3 represent non-irrigation, irrigated 60 mm at JS, irrigated 60 mm each at JS and HS, and irrigated 60 mm each at JS, HS, and MS of winter wheat, respectively. In 2002–2003 winter wheat growing season, the result was the mean results of plant 93-52 used in the experiment; in 2004–2005 and 2005–2006 growing seasons of winter wheat, the result was the mean results of plant 8049 used in the experiment.

Water use efficiency

Fig. 2 presented the WUE in 2002–2003, 2004–2005 and 2005–2006 growing seasons of winter wheat. In 2002–2003, the WUE was significantly higher in T1, T2, and T3 than in T0, and T2 attained the highest WUE; however, it was not significantly different than that in T1 and T3. In both 2004–2005 and 2005–2006 growing seasons of winter wheat, the trend was opposite, the WUE was declined with irrigation amount increased. In the both growing seasons, the WUE was significantly lower in T1, T2, and T3 than in T0, and the WUE was significantly higher in T2 than in T3. However, in 2005–2006 winter wheat growing season, the difference between T1 and T2 was not significant.

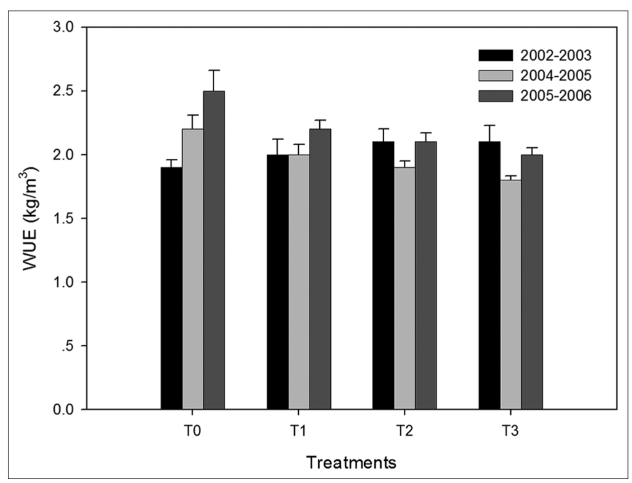

Fig 2. WUE of winter wheat in different irrigation regimes. Vertical bars are standard errors. T0, T1, T2, and T3 represent non-irrigation, irrigated 60 mm at JS, irrigated 60 mm each at JS and HS, and irrigated 60 mm each at JS, HS, and MS of winter wheat, respectively. In 2002–2003 winter wheat growing season, the result was the mean results of plant 93-52 used in the experiment; in 2004–2005 and 2005–2006 growing seasons of winter wheat, the result was the mean results of plant 8049 used in the experiment.

The GY was not significantly higher in T3 than in T2; however, its WUE was significantly lower. Hence, in both dry and moderate growing seasons of winter wheat, combined with winter wheat GY and WUE as a whole, it is suggests that winter wheat should be irrigated 120 mm, which will achieve reasonable GY and WUE.

Experiment 2

Contribution of DM remobilization to grain yield

As shown in Fig. 3, CDMRG in I2 was 54.7% and 58.9% in 2006–2007 and 2007–2008 growing seasons of winter wheat, which was higher than those in I1 and I3 by 3.5% and 5.1% in 2006–2007, and by 3.6% and 2.5% in 2007–2008, respectively. This indicates that DM translated from stem and leaves to grain was much in I2 than in I1 and I3. The variation of CDMRG could affect winter wheat GY and yield components.

Grain yield and yield components

Winter wheat GY and yield components are presented in Table 2. In 2006–2007 winter wheat growing season, I2 resulted in the highest GY, was 678.29 g/m^2, which was significantly higher than that in I1, and the lowest GY was found in I3, which was only 409.29 g/m^2. The highest SN was found in I2, which was significantly higher than those in I1 and I3. Effect of irrigation frequency on kernel numbers per spike and 1000-kernel weight was not significant. In 2007–2008 winter wheat growing season, the highest GY was found in I2, it was significantly different from that in I3, and the lowest GY was found in I1, which was significantly lower than that in I2. I2 resulted in the highest SN, which was significantly higher than those in I1 and I3. As for 1000-kernel weight, I3 resulted in the highest, which was significantly higher than those in I1 and I2. Effect of irrigation frequency on kernel numbers per spike was not significant. In the both growing seasons, I2 resulted in the highest GY, which was attributed to increase SN significantly. Therefore, selecting suitable irrigation timing under irrigated 120 mm is of great importance to improve yield potential.

Water use efficiency

As shown in Fig. 4, in both 2006–2007 and 2007–2008 growing seasons of winter wheat, I2 resulted in the highest WUE, which was significantly higher than that in I3, and the lowest WUE was found in I1. Hence, in both dry and humid growing seasons of winter wheat, irrigated 60 mm each at JS and HS of winter wheat not only achieved the highest GY but also the highest WUE.

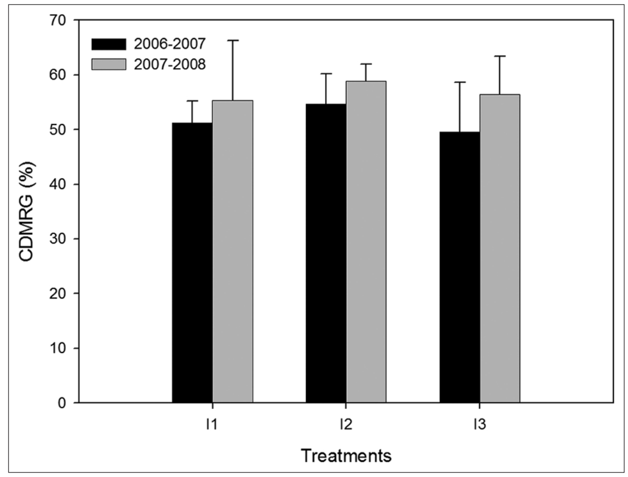

Fig 3. CDMRG of winter wheat under different irrigation frequency. Vertical bars are standard errors. I1, I2, and I3 represent irrigated 120 mm only at JS, irrigated 60 mm each at JS and HS, and irrigated 40 mm each at JS, HS, and MS of winter wheat, respectively. The result was the mean results of plant 9204 used in the experiment.

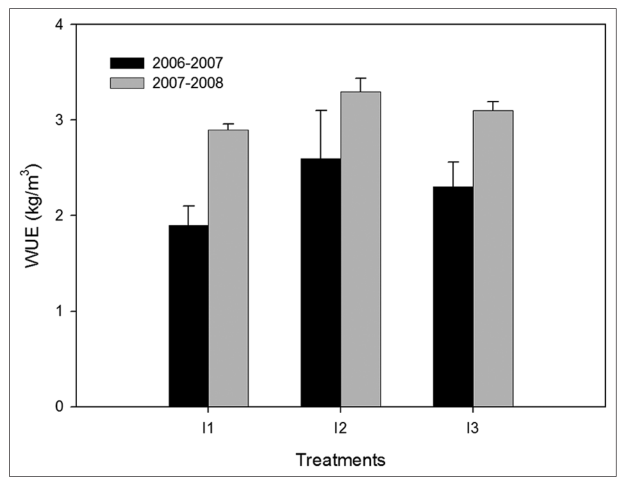

Fig 4. Effect of irrigation frequency on WUE of winter wheat. Vertical bars are standard errors. I1, I2, and I3 represent irrigated 120 mm only at JS, irrigated 60 mm each at JS and HS, and irrigated 40 mm each at JS, HS, and MS of winter wheat, respectively. The result was the mean results of plant 9204 used in the experiment.

DISCUSSION

Many researchers considered that irrigation could significantly increase winter wheat GY (Ali and Seyedeh 2008; Thind et al., 2010; Kiran et al., 2008). In this experiment, the result indicated that no matter in moderate, humid, or dry growing seasons of winter wheat, irrigated 60 mm each at JS and HS could get the reasonable GY and WUE. With irrigation amount increased, the potential irrigation production was limited. Li et al. (2008) studied the relationship of evapotranspiration with GY and WUE of winter wheat under various conditions of irrigation and straw mulching, found that in both mulching and non-mulching conditions, the relationship between evapotranspiration and GY fit for curve of the second degree. Fang et al. (2004) indicated that photosynthesis rate, DM accumulation of population, and GY had a quadratic relationship with winter wheat water consumption, which resulted in a linear decrease on WUE at leaf and population levels and quadratic changes in WUE at yield level. In experiment 1, GY in T3 was not significantly higher than that in T2, maybe due to the GY in T3 was nearly maximum. Under the condition of full irrigation, photosynthetic rate of crops can not increase any more; however, transpiration rate sustainable increased (Fang et al., 2004). As a result, under the condition of full irrigation, crops could consume

Table 2: Winter wheat grain yield and yield components in 2006–2007 and 2007–2008 growing seasons

Growing seasons	Treatments	Spike numbers (spikes/m^2)	Kernel numbers per spike (kernel/spike)	1000-kernel weight (g)	Grain yield (g/m^2)
2006–2007	I1	556.25b	30.71a	39.09a	557.92b
	I2	580.42a	29.41a	37.90a	678.29a
	I3	528.33c	31.61a	39.53a	409.29c
2007–2008	I1	556.27b	29.2ab	40.16b	699.14ab
	I2	658.05a	30.0a	39.32b	769.16a
	I3	547.45bc	30.7a	42.22a	505.85bc

much soil water. Hence, crop transpiration has invalid water consumption (Hu et al., 2009), this is a most important reason why increasing irrigation result in low WUE.

In experiment 2, the CDMRG in I2 was higher than that in I3, this maybe due to the following 2 reasons: firstly, SWC could affect root length density of winter wheat significantly. Zuo et al. (2006) found that compared with surface irrigation, the root length density in sub-irrigation was higher. Under the same irrigation amount, reducing irrigation frequency could store much irrigation water in the deeper soil layer, this will aid root growth (Shao et al., 2008). Increasing root length density not only makes full use of deeper soil water but also consumes much photosynthate. Hence, the much photosynthetic product transferred to root, the less transferred to grain, which will result to decrease GY. Under field conditions, reducing photosynthetic product transferred to root is a key measure to increase crops GY. Secondly, controlled soil drying may aid to remobilize of stem-stored carbohydrate to grain. Wang et al. (2005) indicated that during rapidly remobilized stage of stored food, compared to well-watered treatments, sucrose contents of wheat stem under water deficit conditions was increased by 15.9–40.5%.

In the NCP, since the 1970s, annual precipitation has been declining (Sun et al., 2010). Therefore, effective use of irrigation water is a key for sustainable development of winter wheat production. Under field conditions, crops WUE is determined by transpiration rate through leaves and water absorbing capacity through roots; hence, as for crops effective use of water in essence, is to achieve the optimum balance conditions of the structure and function of crops canopies and roots (Chen et al., 2005; Gao et al., 2007). In the NCP, as the saving water agriculture boots, to ensure the sustainable development of agriculture and effective use of water resources, it is in urgent need to study the key techniques and basic theory concerned root-shoot balance.

CONCLUSIONS

In dry and moderate growing seasons of winter wheat, GY and WUE in treatment which irrigated 60 mm each at JS, HS, and MS were not significantly increased, it is suggests that winter wheat should be irrigated with 60 mm each at JS and HS to achieve reasonable GY and WUE. Under the condition of irrigated 120 mm in dry and humid growing seasons of winter wheat, irrigated 60 mm each at JS and HS resulted in the highest CDMRG, which led to significantly increase GY and WUE. The results indicate that in the NCP, winter wheat should be irrigated 60 mm each at JS and HS to achieve reasonable GY and WUE.

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AUTHOR CONTRIBUTIONS

Quanqi Li: Conceived and designed the experiments; Huifang Han and Yujie Ren: Performed the experiments; Yujie Ren and Chao Gao: Analyzed the data; Zhenxing Yan: Contributed reagents/materials/analysis tools; Huifang Han and Quanqi Li: Wrote the paper.

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