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YIELD FORMATION CAPACITY, SOIL WATER CONSUMPTION PROPERTY, AND PLANT WATER USE EFFICIENCY OF WHEAT UNDER WATER-SAVING CONDITIONS IN NORTH CHINA PLAIN

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ABSTRACT

The drastically reduced underground water and shortage of the water resource have caused limitation for the winter wheat (*T. aestivum*) production in North China Plain. In this study, using a drought-tolerant wheat cultivar Shimai 18 as material, we investigated the yield formation capacity, soil water consumption property, and the plant water use efficiency (WUE) of wheat under various irrigation treatments. Our results indicated that the yield capacities of wheat varied largely across irrigation treatments in three growth seasons with contrasting precipitation patterns. The wheat yields showed constant in growth season with more rainfall and lowered to some extent in seasons with regular or less rainfall under I1 (water-saving condition with one time of irrigation) compared with I3 (regular irrigation with three times of irrigation). Along with increase of the irrigation times, plant WUE lowered drastically in all of three growth seasons examined, together with significantly increased evapotranspiration (ET) amount and relative constant of soil water deposits. These results suggested that the water-saving management is feasible in the winter wheat production in North China Plain. Additionally, the plant leaf area index (LAI), dry matter accumulation, and biomass partitioning rate of vegetative tissues during late growth stage (from flowering to maturity) were consistent with the yield formation capacities of the wheat cultivar. Our investigation indicates that the water-saving management using drought tolerant cultivars is effective in production of winter wheat in North China Plain, which can drastically improve the plant WUE and maintain the sustainable wheat productivity under reduced irrigation conditions.

Keywords: Irrigation treatment, soil water consumption, water use efficiency, wheat (*T. aestivum*), yield

INTRODUCTION

The cropping system in North China Plain consists mainly of two major crops, winter wheat and summer maize, which contributes greatly to the grain production in this region. Climate in this ecological zone is specified by the temperate continental monsoon, with average annual precipitation of 562 mm concentrated in the summer season (Wang et al., 2016a). Owing to less distribution of rainfall amount during the growth season (from early October to next mid-June), more irrigated underground water is needed for the growth of winter wheat plants, resulting in reduced water resource and drastic limitation for the sustainable crop production (Xia et al., 2005; Zhang et al., 2011).

Irrigation at critical growth stage in wheat has been one of the critical cultivation techniques to sustain plant productivity, by which to overcome the limitation of water deficit on plant growth, development, and yield formation potential of winter wheat (Zhang et al., 2005; Elliott et al., 2014; Gao et al., 2015). To date, a suite of investigations performed has focused on suitable irrigation management of winter wheat in North China (Li et al., 2005; Zhang et al., 2008; Hu et al., 2010; Liu et al., 2013). The interaction effects of irrigation and fertilization on water and nutrient utilization (Hu et al., 2006; Meng et al., 2012), yield formation processes (Zhang et al., 2007; Zhao et al., 2013), and the physiological response of crop plants to drought stress have been elucidated (Zhang et al., 2004; Cattivelli et al., 2008). Under a winter wheat-summer maize rotation system, Wang et al. (2018) investigated the effects of reduced irrigation on plant water use efficiency and productivity in the North China Plain. These studies have largely promoted grain production capacity of the winter wheat in North China Plain.

More water irrigated in conventional cultivation system of winter wheat in North China has resulted in serious ecological problems aside from reduction of the water resource (Lan and Zhou, 1995). For example, overdrafting of the underground water by increasing irrigation has led to rapid decline of the groundwater level, with approximately 1 m reduction annually over past 20 years (IGSNRR, 2016). Therefore, application of water-saving management in winter wheat has been becoming an effective pathway for the winter wheat production in North China as well as other similar ecological zones, by which to enhance the yield production and water use efficiency (WUE) (Wang et al., 2002).

Although a line of investigations in wheat focusing on water uptake (Shao et al., 2009; Li et al., 2010), water resource consumption property (Li et al., 2008; 2012), WUE behavior (Zhang et al., 2005; Cattivelli et al., 2008; Sun et al., 2010; Fang et al., 2010; Fulvia et al., 2012), plant growth and development characteristic (Li et al., 2009; 2010), and interaction effects of fertilization and irrigation on biomass production (Meng et al., 2012), has been performed under various irrigation treatments in wheat in North China Plain, the mechanisms as to how reduction of irrigated water affects soil water property and dry mass production and partitioning are needed to be further characterized. Moreover, although the effects of reduced irrigation on plant water use efficiency and productivity in winter wheat-summer maize rotation system have been investigated in the North China Plain (Wang et al. 2018), the mechanisms underlying water-saving production management in winter wheat are necessary for investigation in this region. In this study, using Shimai 18, a drought-tolerant cultivar of winter wheat released recently in North China, we investigated the effects of spring irrigation treatments on the yield formation capacity, plant growth property and WUE under three successive growth seasons with contrasting precipitation patterns.

MATERIALS AND METHODS

Set up of experiments

The experiments were conducted at Liujiazhuang village, Gaocheng city, Hebei province during the growth seasons of 2012-2013, 2013-2014, and 2014-2015. The climate factors during the successive growth seasons, including rainfall amounts, average air temperatures, and solar radiations per month (i.e., from October to next June) are shown in Table 1. The seasons of 2012-2013 (139.5 mm), 2013-2014 (67.2 mm), and 2014-2015 (105.7 mm) represented rainfall patterns of more, less, and regular, respectively. Shimai 18, a wheat cultivar typical by strong drought tolerance that has been widely planted under water-saving condition, was used in this study. The pH for experimental soil was 7.8 and the type of soil was loamy. The soil nutrient contents prior to experiments were as follows: organic matter of 13.22 g/kg, available nitrogen of 68.32 mg/kg, available phosphorus of 33.01 mg/kg, and exchangeable potassium of 128.6mg/kg.

Table 1. Rainfall, average air temperature, and solar radiation during the three successive growth seasons

Factor	Growth season	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	Total
Rainfall (mm)	2012-2013	4.1	26.4	12	5	10.1	0.3	24.6	12.1	44.9	139.5
	2013-2014	9.6	6.2	0	0	5.9	0	13.9	28.2	3.4	67.2
	2014-2015	9.2	4.7	0	0.6	3	0.4	29.1	53.1	5.6	105.7
Average air temperature (℃)	2012-2013	13.2	6.6	-2.3	-6.5	-4.2	10.2	18.6	23.6	27.5	-
	2013-2014	14.1	5.7	-3.2	-7.6	-5.3	8.8	20.2	24.2	28.3	-
	2014-2015	13.6	6.9	-4.2	-7.9	-4.3	12.2	19.0	20.9	24.8	-
Solar radiation (MJ/m^2)	2012-2013	435.6	418.2	310.8	312.4	483.6	501.3	609.8	618.6	656.2	4346.5
	2013-2014	408.3	362.6	306.6	389.5	602.8	512.2	539.3	511.8	612.8	4245.9
	2014-2015	502.2	423.6	397.2	412.6	600.6	613.6	554.2	533.3	586.1	4623.4

The experimental plots were arranged in a randomly block design with three replicates. Each one has an area of 15 m^2 (5 m in length and 3 m in width). The experiment contained four treatments with different irrigation times, including I0 (no irrigation during spring season), I1 (one time of irrigation at jointing stage), I2 (two irrigation times at jointing stage and flowering stage), and I3 (three irrigation times at jointing stage, flowering stage, and filling stage). For each irrigation, the underground water of 75 mm was utilized, in which, the irrigated water amount was controlled by a water amount analyzer.

After harvesting of the summer maize (cv. Zhengdan 958) at late of September, straws of maize were mechanically broken to keep on soil surface after removal of ears. The basal fertilizers including 120 kg/ha of nitrogen (N), 150 kg/ha of phosphorus (P_2O_5), and 150 kg/ha of potassium (K_2O) were applied and mixed well with top layer soil together with the crushed maize straw pieces. Seed sowing dates of the winter wheat were arranged at October 8, 6, and 10 whereas seed harvesting at June 15, 12, and 17 at seasons of 2012-2013, 2013-2014, and 2014-2015, respectively. The seeding rates in irrigation treatments across the three growth seasons were all 187.5 kg/ha with row space of 15 cm. Other cultivation techniques performed such as weed removal and chemical disease and pest control during the growth stages were similar to conventional ones.

Assay of yields and yield components

At maturity stage, the grains from plants of three square meters in each plot were collected using a mini harvesting machine. The practical yields were obtained based on the grain mass mentioned above. The yield components in each plot, including ear numbers per planting area, kernel numbers per ear, and per-1000 grain weights were assessed using conventional approach. Of which, the ear numbers per planting area were obtained based on counting the ears in one square meter area; the kernel numbers per ear obtained by counting seeds in thirty representative ears; the per-1000 grain weights obtained based on weighing 1000 seeds after air drying.

Assays of soil moisture at different depth layers and soil water deposits

Before seeding sowing and harvesting, namely, dates of October 5 and June 16 during 2012-2013, October 1 and June 12 during 2013-2014, and September 29 and June 11 during 2014-2015, respectively, we assessed the soil moisture contents at different soil layers in 2 m soil profile (each with a 20 cm interval) using a neutron TDR analyzer. The deposit amounts of soil water across the whole season were calculated based on the soil water contents assessed prior to the seed sowing and the harvesting.

Assay of water consumption amount and water use efficiency (WUE)

The water consumption amount (ET) in each treatment across the growth circle, which is determined by rainfall amount, irrigated water amount, and the water deposits of soil prior to seed sowing and harvesting, was calculated based on the evaporation amount and the transpiration amount as previously described (Sun et al., 2006; Lu et al., 2011). The ET values were calculated based on follow formula: ET= ET= P+I +SWD. Of which, P indicates precipitation (mm), I stands for irrigated water (mm), and SWD represents water consumption amount (mm) of 2 m soil profile calculated by soil water amounts prior to seed sowing and those at harvesting. The plant WUEs under various irrigation treatments were defined based on yields and water consumption amounts as those reported previously (Kang et al., 2002; Zheng et al., 2008). The WUE was calculated using follow formula: WUE= Y/ET. In which, Y stands for yield (kg/ha), and ET represents total water consumption amount during the growth season (mm).

Assay of leaf area index, plant biomass and biomass partitioning rate

At growth stages before winter, tillering, jointing, flowering, seed filling, and maturity, thirty representative plants were sampled in each plot and subjected to assay of leaf area index (LAI) and biomass accumulation. Of which, the LAI values were evaluated based on leaf areas in the representative plant samples and the planting densities, of which, leaf areas were assessed using a leaf area analyzer (LI3000C, USA) and the planting densities in plots obtained based on counting the seedling numbers in one squire meter. Plant biomass was determined based on dry weight in thirty typical plants after oven drying. To evaluate the biomass parttioning amount (BPA) and biomass partitioning rate (BPR), thirty representative plants sampled at flowering and maturity were departed into tissues of leaf, stem, sheath, and ear and subjected to assay of biomass in each tissue. BPA and BPR for tissues of leaf, stem, and sheath were calculated based on reduction on dry weight in these vegetative tissues. Among these, BPA was defined by follow formula: BPA=BM-BF. In which, BM stands for the biomass at maturity stage, and BF represents the biomass at flowering stage. The BPR was calculated by follow formula: BPR=(BM-BF)/BF×100.

Statistical analysis

All the data under various irrigation treatments across three growth seasons were analyzed using SPSS Statistics version 19.0. Significant differences were compared using the least significant difference test (LSD) at 0.05 probability level.

RESULTS

Effects of irrigation treatments on crop yield and yield components

The yields of winter wheat were drastically affected by the irrigation treatments. As shown in Table 1, wheat yields varied from 7504.5 to 10596.0 kg/ha) among the irrigation treatments (I0 to I3, treatment without no irrigation to treatment with three irrigation times), which displayed a parabola pattern along with increase of the irrigation times. From I0 to I2, wheat yields were increased and from I2 and I3, the yields were constant. Among the growth seasons examined, wheat average yields were the highest in season 2014-2015, followed by season 2012-2013, and the lowest in season 2013-2014. A large reduction on yields in 2013-2014 relative to other two seasons was possibly due to the less precipitation amount in this season (67.2 mm), which negatively affected the plant growth and development. These results indicated that the water amounts from irrigation and rainfall during the growth season together control the yield formation capacity of the winter wheat.

The yield components, including ear number per planting area, kernel number per ear, and per-1000 grain weight, were enhanced by increase of the irrigation times (Table 2); I1, I2, and I3 showed improved yield components compared with I0. However, the yield components displayed different patterns upon irrigation treatments. Of which, the ear number per hectare was gradually increased along with increase of the irrigation times, reaching highest values under I3; the kernel number per ear and per-1000 grain weight both changed in a parabola curve pattern along with increasing irrigation times, in which the former reached highest values under I3 (2012-2013 and 2013-2014 seasons) or under I2 (2014-2015 season) whereas the latter obtained highest values under I2 and then decreased with increase of the irrigation times (Table 2). Across the three growth seasons, the 2012-2013 season had more rainfall (139.5 mm) and the 2013-2014 season less rainfall (67.2 mm) whereas 2014-2015 season shared regular rainfall (105.7 mm), respectively. The rainfall behaviors thus impacted on yield formation capacity and yield components during the growth seasons. In 2012-2013 season, the yield-associated traits were comparable among treatments of I1, I2, and I3 due to more rainfall amounts; in 2013-2014 season, I3 behaved highest values on yield and yield components than other treatments owing to less precipitation; in 2014-2015, a regular rainfall distribution season, I2 and I3 showed comparable yields and yield components and both the yield and yield components were better than I0. These results indicated that an effective irrigation management depends on the precipitation pattern during the growth season of winter wheat.

Table 2. Yields and yield components of winter wheat under irrigation treatments during three growth seasons

Growth season	Treatment	Ear number ($10^4/hm^2$)	Kernel No. per ear	Per-1000 grain Weight (g)	Yield (kg/ha)
2012-2013	I0	931.5ns	30.1ns	36.7ns	9045.3ns
	I1	948.2ns	29.8ns	37.1ns	9123.5ns
	I2	963.6ns	30.4ns	37.0ns	9184.7ns
	I3	967.5ns	30.6ns	37.1ns	9172.6ns
2013-2014	I0	691.5b	30.8ns	40.5ns	7504.5b
	I1	757.4a	31.3ns	40.5ns	8464.5a
	I2	772.3a	32.2ns	40.2ns	8581.5a
	I3	774.8a	32.6ns	40.3ns	8793.0a
2014-2015	I0	822.6b	33.8ns	37.6a	9358.5b
	I1	910.5a	35.8ns	36.2b	9994.8a
	I2	909.3a	36.2ns	36.1b	10596.0a
	I3	912.5a	36.0ns	36.0b	10584.4a

Note: different samllcase letters indicate to be statistical significance among different irrigation treatments in each growth season ($P<0.05$).

Effects of irrigation treatments on water consumption and WUE

Evapotransspiration (ET) represents the total water consumption amount during the whole growth season. In this study, our results indicated that the ET values under various irrigation treatments were drastically increased along with increase of the irrigation times in all growth seasons, suggesting the promotion of total water consumption by increasing irrigation for wheat plants. Plant WUE and WUEet indicate the grain production capacity per unit of consumed water. The values of plant WUE and WUEet under various irrigation treatments are shown in Table 3. Compared with those of I0, plant WUE and WUEet under I1, I2, and I3 were all significantly decreased across the three growth seasons examined. Thus, suitable irrigation-saving management can promote the wheat productivity together with the improved plant WUE behavior.

Table 3. The evapotranspiration (ET), water use efficiency (WUE) and WUEet in winter wheat under different irrigation treatments

Growth season	Treatment	Yield Kg/ha	ET mm	WUE Kg/ha•mm	WUEet Kg/ha•mm
2012-2013	I0	9045.00	355.17	25.47 a	-
	I1	9123.00	382.30	23.86 b	2.88 a
	I2	9184.50	429.45	21.39 c	1.88 b
	I3	9172.50	481.00	19.07 d	1.01 c
2013-2014	I0	7504.50	306.74	24.47 a	-
	I1	8464.50	369.86	22.89 b	15.21 a
	I2	8581.50	424.00	20.24 c	9.19 b
	I3	8793.00	498.70	17.63 d	6.71 c
2014-2015	I0	9358.50	359.66	26.02 a	-
	I1	9994.50	394.33	25.35 ab	18.35 a
	I2	10596.00	426.22	24.86 b	14.59 b
	I3	10584.00	485.70	21.79 c	9.72 c

Note: the lowercase letters in each growth season indicate to be statistical significance ($P<0.05$).

The relationship between yield and ET

Results in this study indicated there is a close correlation between the yield and ET in winter wheat under various irrigation treatments. The relationship between yield and ET was expressed in follow equation: $Y = -0.0095ET^2 + 6.6643ET - 535.37$ (R^2=0.9636 **). Based on this equation, the yield of winter wheat in North China reaches a high and economic value when ET equals to 351 mm. When the ET values are over this point, increase of the wheat yield will consume more water and lead to the lowered WUE. Therefore, economic ET is an important marker in determining the suitable irrigation practice, which helps to effectively manage wheat water use with relatively lower ET and higher WUE.

Soil water deposition characterization

The deposit amounts of water in 2 m soil profile, each with a 20 cm interval, were assessed at dates before seed sowing and maturity under various irrigation treatments across the three growth seasons. As shown in Fig. 1, irrigation treatments impacted on the soil water retention capacity; the increase of irrigation times increased water retention amounts of soil, especially those in soil depth from 50 cm to 2 m. I3 and I2 showed more soil water amounts than I0 and I1 at indicated assay dates (i.e., before sowing on October 5, October 1, and September 29 in 2012, 2013, 2014, and 2015, respectively; at maturity on June 16, 12, and 11 in 2012, 2013, and 2014, respectively) (Fig. 1). These results suggested that increased amounts of irrigated water can help sustain the water retention of soil, especially that of the depth soil layer.

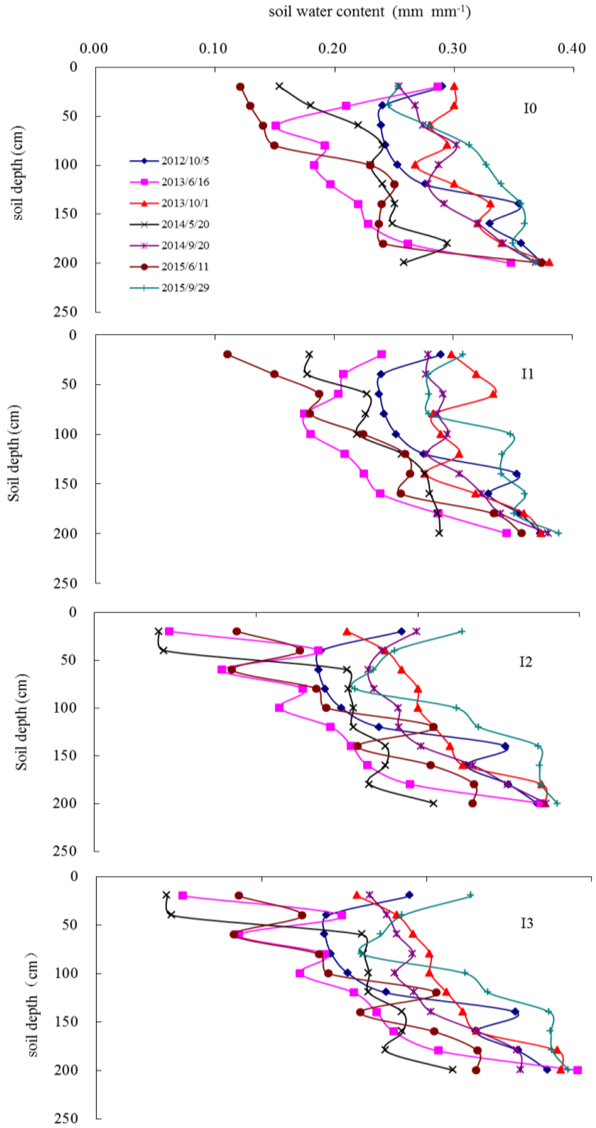


Figure 1. Water contents at different soil depth positions under irrigation treatments across three growth seasons

Across the three growth seasons, the behaviors on water deposits in 2 m soil profile were similar among the irrigation treatments (Fig. 2). At seedling stage to next early spring, the water deposit amounts were relative stable under various irrigation treatments due to the low temperature and the stagnation of seedling growth. From tillering stage to followed growth stages, the water deposit amounts in soil under each irrigation treatment were drastically reduced due to the fast growth rates of plants accompanying with increase of the air temperature and the lowered precipitation, gradually reaching the lowest values at maturity in all treatments. Among the irrigation treatments, the water deposit amounts in soil were promoted by increase of the irrigation times. The soil water deposit amounts varied at maturity among the growth seasons, showing to be highest in 2013-2014, followed by 2014-2015, and lowest in 2012-2013.

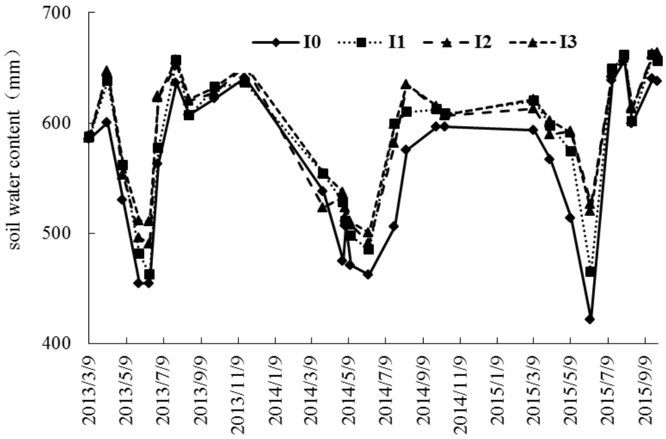
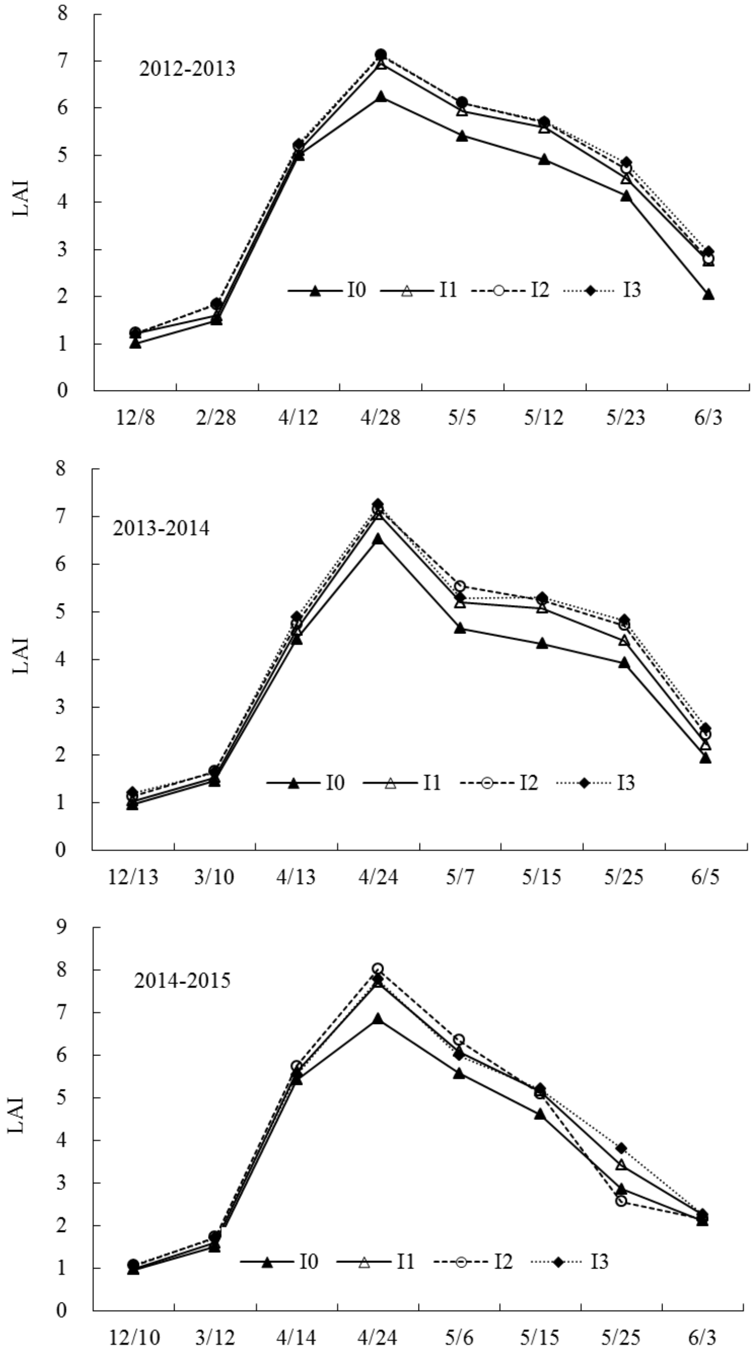


Figure 2. Water deposit amounts in 2 m soil depth under irrigation treatments across growth seasons

The LAI, plant biomass, and biomass partitioning characterization

The LAI values during growth stages showed a curve pattern under various irrigation treatments, reaching highest at the flag leaf expansion stage (April 28, 29, and 27 during 2012-2013, 2013-2014, and 2014-2015 seasons, respectively) (Fig. 3). Compared with those of I0, the LAI values under I1, I2, and I3 were increased at each growth stage. However, the increment on LAI values from I1 to I3 was lowered compared with that between these treatments with I0 (Fig. 3), suggesting the reduced effect of increasing irrigated water on improving LAI. Compared with that of I0, plant biomass was significantly increased at all growth stages in treatments I1 to I3 (Fig. 4), suggesting that irrigation treatments impacted on the plant dry matter production similarly to the LAI behaviors as mentioned above. These results indicated that suitable irrigation can sustain source function and biomass accumulation, contributing to the yield formation potential of winter wheat.

The biomass partitioning amounts (BPA) in vegetative tissues were determined under various irrigation treatments, based on the vegetative tissue biomass at stages of spiking and maturity. As shown in Table 4, the BPA values in tissues of leaf, stem, and sheath were all increased in I1 to I3 compared with I0, showing a pattern to be gradually increased along with increase of the irrigated water. These results suggested that increasing irrigation can improve the biomass partitioning amounts of the vegetative tissues. However, the biomass partitioning rates (BPR) decreased along with increase of the irrigation times (Table 4), suggesting the lowered vegetative biomass partitioning efficiency by irrigated water amounts.



Figute 3. The LAI values under different irrigation treatments

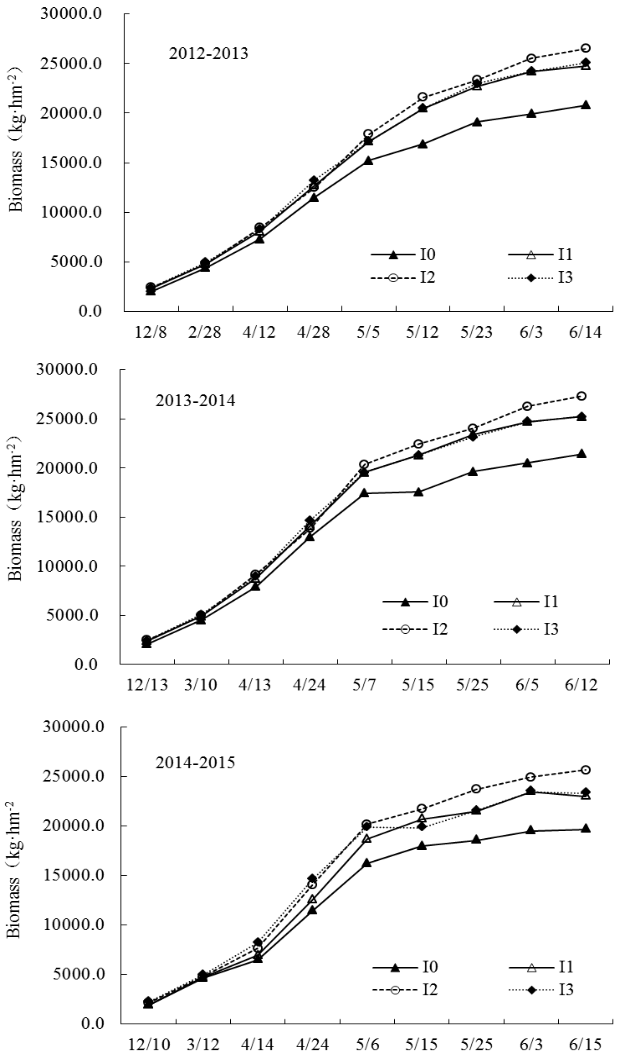


Figure 4. The plant biomass under different irrigation conditions

Table 4. The biomass partitioning amounts (PA) and partitioning rate (PR) under different irrigation treatments

	TA	TR
I0	1008.5b	1.39b
I1	1256.5a	1.56a
I2	1263.0a	1.53a
I3	1278.0a	1.51a

DISCUSSION

The water consumption amount for agriculture has accounted for the most proportion of total freshwater usage around the world (Hoekstra and Mekonnen, 2012; Ridoutt et al., 2009). In past two decades, over 400 mm of irrigated underground water was utilized for the winter wheat production in this region (Li and Zhou, 2000; Wang et al., 2003; Li et al., 2005; Meng et al., 2012), which drastically lowers the groundwater table (IGSNRR, 2016) and leads to unsustainability of the water resource (Gao et al., 2015). Therefore, effective water-saving management has become a practical strategy for crop cultivation in the North China Plain.

Several findings indicate that the wheat yields can sustain a relative high level under the water-saving conditions due to the improved plant WUE (Wang et al., 2018). In this study, our results from Shimai 18, a drought-tolerant cultivar of wheat, showed in different behaviors on yields under various growth seasons with modified rainfall amounts. The yields of this cultivar were relative constant in 2012-2013 with more rainfall amount under treatment I1 (one irrigation time) compared with under I3 (three irrigation times). Thus, it is feasible to cultivate winter wheat using drought-tolerant cultivars under water-saving production system with reduced irrigated water, especially at growth seasons with relative more rainfall amounts.

The yield components, such as ear number per planting area, kernel number per ear, and per-1000 grain weight of cereals display different responses to irrigation treatments (Zhang et al., 2011; Wang et al., 2016a; Wang et al., 2016b). Of which, the ear number per planting area and kernel number per ear show much more variation than per-1000 grain weight (Wang et al., 2018). In this study, our analysis on the yield components is in consistent with previous results. Compared with the ear and kernel numbers, the weight per-1000 grain displayed relatively stable among the irrigation treatments across three successive growth seasons. We speculated that the I1 as well as I0 reduced grain weight to be possibly due to the promoted grain-filling rate during seed filling by which to compensate their deteriorated effects on ear and kernel establishment. These findings are in agreement with the some of previous reports (Wang et al., 2018) but in converse to others that indicated rainfed (no irrigation) conditions decreased kernel weight of wheat (Rebetzke et al., 2016). The behaviors of yield components under various irrigation treatments suggested that they are dependent on the experimental climates or the cultivars.

Total water consumption of the crop plants constitutes rainfall, irrigation, and the depleted water of soil (Oweis et al., 2000; Ridoutt et al., 2009; Li et al., 2012; Xu et al., 2016). To define the effects of irrigation treatments on soil water deposit, we investigated the water moisture contents in 2 m soil profile under various irrigation treatments during the three growth seasons. The soil water deposits were lowered in 50 cm to 2m depth layers under reduced irrigation time treatments. Meanwhile, drastically increased evapotranspiration (ET) and decreased WUE were accompanied by increase of the irrigation times. Therefore, a suitable water-saving management can improve the plant WUE and sustain the yield formation potential, although it relatively reduced the water deposit amounts of soil.

Leaf area index (LAI), dry matter production, and biomass partitioning rate in vegetative tissues of plants are modulated largely by water supplies (Asseng et al., 2004; Cattivelli et al., 2008), which impact on the yield components, yield, and WUE behaviors (Li et al., 2000; Fang et al., 2000; Fulvia et al., 2012; Gao et al., 2015). In this study, our results on LAI, biomass, and biomass partitioning rate are in consistent with the behaviors of yield components and yield under various irrigation treatments across all three growth seasons. These results suggested that the sustainable plant growth traits contribute to yield formation capacity and WUE under the water-saving conditions (I1 in 2012-2013 and I2 in 2014-2015). Altogether, our results in this study indicated that using water-saving management accompanying with drought-tolerant cultivars is beneficial for promotion of the sustainable production of winter wheat in North China Plain and the similar ecological regions.

CONCLUSION

Across four irrigation treatments under three successive growth seasons with contrasting precipitation patterns, the wheat yields are constant under water-saving condition (one irrigation time) in growth season with more rainfall and lowered to some extent in seasons with regular or less rainfall compared with regular more irrigation condition. Increase of the irrigation times results in lowered plant WUE, increased evapotranspiration (ET) amount, and relative constant of soil water deposits. Plant leaf area index (LAI), dry matter accumulation, and biomass partitioning rate of vegetative tissues during late growth stage (from flowering to maturity) can sustain relatively stable under water-saving condition with one spring irrigation using drought-tolerant cultivar. Thus, the water-saving management together with drought tolerant cultivars is feasible in winter wheat production in North China Plain.

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