RESEARCH

Effects of supplemental irrigation on water consumption characteristics and grain yield in different wheat cultivars

Weiwei Meng[1], Zhenwen Yu[1], Yongli Zhang[1*], Yu Shi[1], and Dong Wang[1]

Shortage of water resources is a major limiting factor for wheat (*Triticum aestivum* L.) production in the North China Plain. The objectives of this study were to evaluate the effects of supplemental irrigation (SI) on water use characteristics and grain yield of the wheat cultivars 'Jimai 22'and 'Zhouyuan 9369'. Two supplemental irrigation treatment regimens were designed based on target relative soil moisture contents in 0-140 cm soil layers at jointing rising to 75% of field capacity (FC) for each cultivar, and at anthesis rising to 65% and 75% (W1), and 70% and 80% (W2) in 2009-2010 and 2010-2011, respectively. Rain-fed (W0) treatment was used as control. Under W1, grain yield of 'Jimai 22' was 5.22% higher than that of W2, and water use efficiency (WUE) of 'Zhouyuan 9369' was 4.0% higher than that under W2. No significant differences in WUE of 'Jimai 22' and grain yield of 'Zhouyuan 9369' were observed for the two treatment regimens in 2009-2010. Grain yield and WUE in W1 were higher than those of W2 for both cultivars in 2010-2011. W1 enhanced soil water consumption compared to W2, especially in the 100-200 cm soil layers, for both cultivars in 2009-2011. Meanwhile, 'Jimai 22' showed higher soil water consumption and ET from anthesis to mature stage, which resulted in increase in grain yield and WUE of 'Jimai 22' by 8.15-21.7% and 7.75-11.73% in 2009-2010 and 2010-2011, respectively, compared with 'Zhouyuan 9369'. Thus, our results showed that SI increased the yield and WUE of 'Jimai 22' and W1 was the better treatment regimen.

Key words: Grain yield, supplemental irrigation, *Triticum aestivum*, water use characteristic, water use efficiency, winter wheat cultivars.

INTRODUCTION

The North China Plain is one of the most important regions for agricultural production in China. Evapotranspiration (ET) during the winter wheat (*Triticum aestivum* L.) growing season is approximately 400-500 mm in this region. However, annual precipitation during wheat growth is typically below 200 mm (Li et al., 2007). In recent years, sustainable development of agriculture in this region has been threatened by water shortages and overexploitation of groundwater (Li et al., 2008; Zhang et al., 2010b). Hence, adoption of water-saving agriculture measures is critical to ensure wheat production and to increase the water use efficiency (WUE) in this region (Wang et al., 2001; Shao et al., 2007).

For maximal wheat yield, irrigation is applied at critical stages of wheat development. However, the recommended irrigation schemes differ across experimental conditions. Xue et al. (2003) found that maximizing wheat yield and WUE requires three applications of irrigation, one each at jointing, booting, and anthesis, totaling 300 mm. Zhang et al. (2004b) recommended three applications at jointing, booting to heading, and anthesis to the early milk stages, with 180 mm of total irrigation. Li et al. (2010) showed that two applications of 60 mm irrigation, one each at jointing and heading, increased grain yield and resulted in the highest WUE compared with one and three applications of irrigation during the winter wheat growing season. According to Zhang et al. (2007), irrigation should be applied twice during the wheat growing season—one in the reviving stage and the other in the heading stage, with the optimal irrigation amounts being 60, 75, and 90 mm for furrow irrigated raised bed-planting (FIRB), mulched ridge and furrow planting (MRFP), and conventional flat planting (FP), respectively. The FIRB system with 60 mm irrigation resulted in higher yield and WUE than both MRFP and FP.

The physiological and genetic bases of high WUE vary significantly across crop varieties (Gupta et al., 2001; Monclus et al., 2009). In monocultures, recent cultivars were found to have significantly higher grain yield and WUE for grain (WUE_G) than old cultivars (Song et al., 2009; Fang et al., 2011; Yang et al., 2013), and a stable low yield was observed in the old cultivar with low response to irrigation treatment (Rizza et al., 2012). Zhang et al. (2010a) showed variation in yield and WUE of about 20% among 16 winter wheat cultivars released between 1998 and 2002, and the ones with higher yield were also generally associated with higher WUE. Selection of water-saving, drought-resistant, higher-yielding cultivars has the potential to improve grain yield and WUE, which is

[1]Shandong Agricultural University, College of Agronomy, Tai'an 271018, China. [*]Corresponding author (zhangyl@sdau.edu.cn).
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critical for water-scarce regions. Many irrigation regimes for wheat production in the North China Plain region have been studied, but most experiments conducted to date have tested the effects of fixed irrigation amounts.

In this study, a new method of recharging soil water via supplemental irrigation (SI) to different target relative water contents in 0-140 cm soil was adopted for different winter wheat cultivars. This study aimed to: (1) determine optimal scheduling of SI in different wheat cultivars; (2) investigate the response of ET, soil water use, grain yield, and WUE to soil water content (SWC) at critical growing stages; and (3) determine differences between two wheat cultivars in ET, soil water use, grain yield, and WUE under different SI treatments. We believe that the results will be highly informative in drafting useful guidelines to optimize agro-management practices for water-saving and high-yielding wheat cultivation.

MATERIALS AND METHODS

The field experiments were conducted from October 2009 to June 2011 at the experimental station of Shandong Agricultural University (36'17" N, 117'15" E). The station is located in the center of the North China Plain, and the environment is typical and representative of the plain. The mean annual temperature in the study area is 14.1 °C. The average annual rainfall is 660.1 mm, 70% of which occurs between July and September. The agrotype of the field was loam based on the soil classification system of China (CRGCST, 2001), with a composition of 29.6% clay, 37.3% silt, and 33.1% sand, and pH of 7.6. The chemical properties of the 0-20 cm topsoil in the experimental plots, field capacity of the 0-200 cm soil layers before sowing in each growing season, and rainfall during the 2009-2010 and 2010-2011 growing seasons are shown in Table 1a, 1b, and 1c, respectively.

Two irrigation treatments were designed based on the target relative soil moisture content in the 0-140 cm soil layers at jointing and anthesis stages for each cultivar rising to 75% and 65% of field capacity (FC) (W1) and 75% and 70% of FC (W2) in 2009-2010, and 75% and 75% of FC (W1) and 75% and 80% of FC (W2) in 2010-2011, respectively. Rain-fed (W0) treatment was used as the control in both growing seasons. The amount of supplemental irrigation (SI) was calculated using Equation [1] (Jalilian et al., 2012):

$$CIR = 100\gamma bd\, D_h(\theta t - \theta n) \quad [1]$$

where *CIR* (mm) is the amount of SI, γbd (g cm^{-3}) is the soil bulk density, D_h (cm) is the depth of the soil layer (140 cm in this study), θt (mg water g^{-1} dry soil) is the target soil water content (SWC) on a weight basis after SI, and θn (mg water g^{-1} dry soil) is the water content of the soil on a weight basis before irrigation. θt was calculated using Equation [2] as follows:

$$\theta t = \theta max\, \theta r/100 \quad [2]$$

where θmax (mg water g^{-1} dry soil) is the field capacity, and θr (%) is the target relative SWC. Water was sprayed evenly on the experimental plots under pressure. A flow meter (DN50-R80, Juxingwang Inc., Ningbo, China) was used to measure the amount of water applied. The actual relative SWC in the 0-140 cm soil layers after SI, as well as the amount of SI under different treatments, are shown in Table 2.

The experiment was conducted in a split block design with three replicates, including the wheat cultivars in main block and the irrigation treatments in secondary block in a 2 m × 5 m plot. Between two adjacent irrigation plots, a 1.5 m-wide unirrigated zone was maintained to minimize the effects of adjacent plots.

The winter wheat cultivars 'Jimai 22' (the most widely planted commercial cultivar in the North China Plain with strong resistance and high yield) and 'Zhouyuan 9369' (a widely planted commercial specialty cultivar in Shandong province with strong high quality gluten) were used in each growing season. Wheat seeds were sown at a density of 180 plants m^{-2} on 7 October 2009 and 7 October 2010. All plots were supplied with 240 kg N ha^{-1}, 112.5 kg P_2O_5 ha^{-1}, and 112.5 kg K_2O ha^{-1}. All P and K fertilizers and 105 kg ha^{-1}

Table 1. Properties in the 0-20 cm topsoil layer (a), field water capacity of 0-200 cm soil layers (b), and rainfall (mm) during wheat growth (c) in 2009-2010 and 2010-2011.

a)

Years	Total N	Alkali-hydrolyzable N	Available K	Available P	Organic matter
	g kg^{-1}	mg kg^{-1}			g kg^{-1}
2009-2010	1.2	93.33	110.46	31.80	16.9
2010-2011	1.3	105.01	105.75	30.24	18.6

b)

Years	Soil layers (cm)									
	0-20	20-40	40-60	60-80	80-100	100-120	120-140	140-160	160-180	180-200
2009-2010	16.21	17.31	19.24	18.83	19.80	22.52	25.56	27.30	24.96	25.58
2010-2011	16.34	17.84	19.22	19.84	21.01	22.45	24.11	29.70	27.06	27.43

c)

Years	Months								
	10	11	12	1	2	3	4	5	6
2009-2010	12.9	21.3	6.2	3.2	18.9	14.8	20.5	42.0	9.3
2010-2011	2.5	0.0	0.2	0.0	24.0	2.6	10.4	132.0	0.3

Table 2. **Target relative soil water content (θ_{tr}, % field water capacity) and the actual relative soil water content after supplemental irrigation (θ_{ar}, % field water capacity) in the 0-140 cm soil layer for irrigation treatments (W0, W1, W2) at different stages of plant growth in 2009-2010 and 2010–2011. The amount of supplemental irrigation (CIR, mm) is also indicated.**

Years	Cultivars	Treatments	Irrigation at jointing stage			Irrigation at anthesis stage			Total CIR
			θ_{tr}	θ_{ar}	CIR	θ_{tr}	θ_{ar}	CIR	
2009-2010	Jimai 22	W0	-	62.14	0.00	-	53.45	0.00	0.00
		W1	75	76.24	70.12	65	63.72	21.82b	91.94b
		W2	75	76.24	70.12	70	69.46	49.07a	119.19a
	Zhouyuan 9369	W0	-	62.54	0.00	-	53.35	0.00	0.00
		W1	75	76.02	67.95	65	62.44	19.52b	87.47b
		W2	75	76.02	67.95	70	70.68	46.78a	114.73a
2010-2011	Jimai 22	W0	-	59.88	0.00	-	66.79	0.00	0.00
		W1	75	73.27	85.88	75	74.95	0.00	85.88b
		W2	75	73.27	85.88	80	79.72	27.53	113.40a
	Zhouyuan 9369	W0	-	63.10	0.00	-	70.19	0.00	0.00
		W1	75	77.92	64.57	75	75.26	0.00	64.57c
		W2	75	77.92	64.57	80	77.24	25.83	90.39b

Values followed by different letters within the same column in each growing season are significantly different at 0.05 probability level.

N fertilizer were applied pre-sowing, and the remaining N fertilizer was top-dressed at jointing. The fertilizers used were urea (46% N), ammonium dibasic phosphate (46% P_2O_5 and 18% N), and potassium sulfate (52% K_2O).

ET was calculated using the water balance Equation [3] (Miranzadeh et al., 2011):

$$ET = (P + I + S_G) - (D + R) - \Delta S \quad [3]$$

where P is the growing seasonal rainfall (mm), I is irrigation (mm), S_G is the groundwater contribution to plant available water (mm), D is downward drainage out of the root zone (mm), R is surface runoff (mm), and ΔS is the change in soil water stored in the upper 200 cm of the soil between sowing and maturity (mm). In this experiment, the groundwater was 15 m below the surface, and runoff was prevented from the experimental plots. Thus, S_G, D, and R were negligible.

Oven drying was used to measure the SWC every 20 cm up to a depth of 200 cm, and these values were used to calculate soil water consumption (ΔS). Soil core samples were collected randomly using a steel sampling tube (50 mm diameter) driven manually into the soil. The soil cores were weighed to obtain the current weight, oven-dried at 105 °C for 48 h, and re-weighed to determine the gravimetric water content. Measurements were obtained at sowing, jointing, anthesis, and maturity (Gan et al., 2000).

Grain yields were determined by manually harvesting 2 m^2 samples of each plot, and expressed at 12.5% moisture content (Xue et al., 2006).

The WUE was calculated based on Equation [4] (Sun et al., 2006; Liu et al., 2011).

$$WUE = Grain\ yield/ET \quad [4]$$

Irrigation benefit (IB) was calculated using Equation [5] (Yu et al., 1995; Duivenboodew et al., 2000):

$$IB = (Y_I - Y_0)/I \quad [5]$$

where Y_I is the grain yield of irrigation treatment (kg ha^{-1}), Y_0 is the grain yield of no irrigation treatment, and I is the amount of irrigation (mm).

Statistical analysis was performed using SPSS Version 10.0 (SPSS for Windows, IBM, Armonk, New York, USA). All data are presented as the mean of three replicates. ANOVA was used to establish significant differences, and treatment means were compared using the least significant differences ($P = 0.05$).

RESULTS

Grain yield, WUE, and IB

W0 treatment had the lowest grain yield and WUE for both cultivars in both growing seasons (Table 3). In 2009-2010, grain yield in with W1 treatment significantly increased by 5.22% than that in W2 for ‘Jimai 22’, but there was no significant differences in grain yield for ‘Zhouyuan 9369’ between W1 and W2. W1 treatment showed no significant increase in WUE for ‘Jimai 22’, but resulted in 4.0% increase in WUE for ‘Zhouyuan 9369’ compare to W2 treatment. In 2010-2011, the grain yield, WUE, and IB in W1 treatment were higher than those in W2 for both cultivars. These results indicate that W1 treatment provided the appropriate amount of water for both cultivars in both growing seasons.

‘Jimai 22’ showed significant increases in grain yield and WUE compared with ‘Zhouyuan 9369’ under the same irrigation conditions in both growing seasons (Table 3). In 2009-2010, grain yield and WUE increased by 12.26% and 7.75%, respectively, under W1, and by

Table 3. Effects of different treatments on grain yield, water use efficiency (WUE) and irrigation benefit (IB) in 2009-2010 and 2010-2011.

Years	Cultivars	Treatments	Grain yield	WUE	IB
			kg ha^{-1}	kg ha^{-1} mm^{-1}	kg ha^{-1} mm^{-1}
2009-2010	Jimai 22	W0	7474.68d	19.47c	
		W1	9387.25a	21.55a	20.80a
		W2	8921.75b	20.93ab	12.14c
	Zhouyuan 9369	W0	6868.50e	18.09d	
		W1	8362.41c	20.00b	17.08b
		W2	8249.20c	19.23c	12.03c
2010-2011	Jimai 22	W0	7069.25d	19.47c	
		W1	9076.45a	21.49a	23.30b
		W2	8743.10b	20.19b	14.76d
	Zhouyuan 9369	W0	5665.90e	16.32e	
		W1	7546.00c	19.65c	29.12a
		W2	7183.90d	18.07d	16.79c

Values followed by different letters within the same column in each growing season are significantly different at 0.05 probability level.

8.15% and 8.84%, respectively, under W2 for 'Jimai 22' compared to 'Zhouyuan 9369'. The IB for 'Jimai 22' was significantly higher by 21.78% compared to that for 'Zhouyuan 9369' under W1 condition, and no significant difference in IB was observed between the two cultivars under W2 condition. In 2010-2011, grain yield and WUE increased by 20.28% and 9.36%, respectively, under W1, and by 21.7% and 11.73%, respectively, under W2 for 'Jimai 22' compared to 'Zhouyuan 9369'. The IB for 'Jimai 22' was significantly lower than that for 'Zhouyuan 9369' under W1 and W2 conditions.

Irrigation, soil water consumption, and total ET during the winter wheat growing season

In both growing seasons for both cultivars, W0 treatment had the highest soil water consumption and ratio to ET, but its ET was the lowest (Table 4). No significant difference in ET was observed between W1 and W2 treatments, but W1 treatment had lower SI and higher soil water consumption. This result indicates that W1 treatment decreased the irrigation amount and increased soil water consumption compared with W2, but no increase in ET occurred in both cultivars. The ratio of precipitation to ET was not found to be significantly different between the two treatments for both cultivars in both growing seasons. From 2009 to 2010, ET of 'Jimai 22' was significantly higher than that of 'Zhouyuan 9369' under W1 condition, and soil water consumption showed similar changes.

From 2010 to 2011, ET for 'Jimai 22' showed a significant increase compared with 'Zhouyuan 9369' under W1 and W2 treatments, and soil water consumption exhibited the same trend. These results show that 'Jimai 22' could utilize more soil water under different precipitation rates, especially with lower rainfall before jointing (only 26.7 mm).

ET at different stages and its consumption percentage

The daily consumption rates from jointing to anthesis were the highest among all treatments conditions for both cultivars, followed by those from anthesis to maturity. The daily consumption rates of all treatments in these two stages were higher than 3.16 mm (Table 5). The daily consumption rates before jointing were the lowest at less than 1 mm. This finding indicates that water consumption before jointing was low, so low irrigation amount is appropriate for this stage. However, jointing to anthesis

Table 4. Sources of water consumption and their percentage of total water consumption amount under different treatments in 2009-2010 and 2010-2011. Where ΔS is the change in soil water stored in the upper 200 cm of the soil between sowing and maturity (mm).

Years and cultivars	Treatments	Total water consumption amount (mm)	Amount (mm)			Percentage (%)		
			Irrigation	Precipitation	ΔS	Irrigation	Precipitation	ΔS
2009-2010								
Jimai 22	W0	383.88c	0.00	149.1	234.78a	0.00	38.84a	61.16a
	W1	435.70a	91.94b	149.1	194.66b	21.10b	34.22b	44.68b
	W2	429.99ab	119.19a	149.1	161.70d	27.72a	34.68b	37.61c
Zhouyuan 9369	W0	379.77c	0.00	149.1	230.67a	0.00	39.26a	60.74a
	W1	418.12b	87.47c	149.1	181.55c	20.92b	35.66b	43.42b
	W2	428.98ab	114.73a	149.1	165.15d	26.74a	34.76b	38.50c
2010-2011								
Jimai 22	W0	373.32c	0.00	172	201.32a	0.00	46.07b	53.93a
	W1	422.44a	86.15b	172	164.29c	20.39c	40.72d	38.89c
	W2	433.02a	113.40a	172	147.61d	26.19a	39.72d	34.09d
Zhouyuan 9369	W0	347.21d	0.00	172	175.21b	0.00	49.54a	50.46b
	W1	384.02bc	64.57c	172	147.45d	16.81d	44.79bc	38.40c
	W2	397.45b	90.39b	172	135.06e	22.74b	43.28c	33.98d

Values followed by different letters within the same column in each growing season are significantly different at 0.05 probability level.

Table 5. Water consumption amount (CA), daily consumption (CD) and its consumption percentage (CP) at different growth stages of different treatment in 2009-2010 and 2010-2011.

Years and cultivars	Treatments	Sowing to jointing			Jointing to anthesis			Anthesis to maturity		
		CA	CD	CP	CA	CD	CP	CA	CD	CP
		mm	mm	%	mm	mm	%	mm	mm	%
2009-2010										
Jimai 22	W0	144.13a	0.80a	37.55a	122.65b	4.09b	31.95b	117.10d	3.16d	30.51d
	W1	144.13a	0.80a	33.08b	138.23a	4.61a	31.73b	153.34a	4.14a	35.19a
	W2	144.13a	0.80a	33.52b	138.23a	4.61a	32.15b	147.62ab	3.99ab	34.33ab
Zhouyuan 9369	W0	142.81a	0.79a	37.60a	109.18c	3.64c	28.75c	127.77c	3.45c	33.65bc
	W1	142.81a	0.79a	34.16b	141.47a	4.72a	33.83a	133.84bc	3.62bc	32.01c
	W2	142.81a	0.79a	33.29b	141.47a	4.72a	32.98ab	144.70b	3.91b	33.73bc
2010-2011										
Jimai 22	W0	141.28a	0.78a	37.85a	108.49c	3.62c	29.06c	123.54c	3.34c	33.09c
	W1	141.28a	0.78a	33.44b	135.78a	4.53a	32.14b	145.37ab	3.93ab	34.41bc
	W2	141.28a	0.78a	32.63bc	135.78a	4.53a	31.36b	155.95a	4.21a	36.02ab
Zhouyuan 9369	W0	110.74b	0.61b	31.89c	114.97b	3.83b	33.11b	121.51c	3.28c	35.00b
	W1	110.74b	0.61b	28.84d	139.21a	4.64a	36.25a	134.07b	3.62b	34.91b
	W2	110.74b	0.61b	27.86d	139.21a	4.64a	35.03a	147.51ab	3.99ab	37.11a

Values followed by different letters within the same column in each growing season are significantly different at 0.05 probability level.

and anthesis to maturity were key stages with high water needs, so SI is appropriate for these stages.

ET from jointing to anthesis (ET_{J-A}) and anthesis to mature (ET_{A-M}), and daily consumption in these two stages in the W0 treatment group were significantly lower than those in W1 and W2 treatments groups for both cultivars in both growing seasons (Table 5). From 2009 to 2010, ET from anthesis to maturity (ET_{A-M}) and its consumption percentage to ET in W1 treatment for 'Jimai 22' were higher than those in W2. For 'Zhouyuan 9369', ET_{A-M} under W1 treatment was lower than that under W2, and no significant difference in the consumption percentage of ET_{A-M} to ET was observed between W1 and W2 treatments. From 2010 to 2011, W2 treatment had the highest ET_{A-M}, daily consumption, and consumption percentage of ET_{A-M} to ET for both cultivars. The results showed that increasing the target relative soil moisture content in the 0-140 cm soil layers at jointing and anthesis increased ET_{J-A} and ET_{A-M}, which resulted in higher ET for both cultivars.

In both growing seasons, ET_{A-M} for 'Jimai 22' was significantly higher than that for 'Zhouyuan 9369' under W1 treatment. This indicates that 'Jimai 22' had a higher ET_{A-M} than 'Zhouyuan 9369', which may explain why 'Jimai 22' had higher ET.

Soil water consumption amount in different soil layers

Soil water consumption under W0 treatment in various soil layers for both cultivars was significantly higher than those for W1 and W2 treatments in both growing seasons (Table 6). From 2009 to 2010, soil water consumption in the 20-200 cm soil layers under W1 treatment for 'Jimai 22' was significantly higher than that under W2 treatment. For 'Zhouyuan 9369', soil water consumption in the 100-200 cm soil layers under W1 treatment was significantly higher than that under W2 treatment. From 2010 to 2011, soil water consumption in the 0-200 cm soil layers under W1 treatment for 'Jimai 22' was significantly higher than that under W2 treatment. For 'Zhouyuan 9369', soil water consumption in the 60-200 cm soil layers under W1 treatment was significantly higher than that under W2 treatment. These results show that W1 treatment increased soil water consumption in deep soil layers, which resulted in higher soil water consumption by both cultivars in both growing seasons.

From 2009 to 2010, soil water consumption in the 20-140 cm soil layers for 'Jimai 22' was significantly higher than that for 'Zhouyuan 9369' under W0 and W1 conditions (Table 6). From 2010 to 2011, soil water consumption in the 60-200 cm soil layers for 'Jimai 22' was significantly higher than that for 'Zhouyuan 9369' under the three irrigation conditions. These results indicate that 'Jimai 22' had high capacity for utilizing soil water from deep soil layers in different precipitation years.

DISCUSSION

Wheat growth is affected by SWC, but irrigation at 100% of field capacity does not necessarily lead to higher yields (Saeedipour and Moradi, 2012). Moreover, scarcity of water resources and low irrigation water use efficiency pose serious threats to wheat production in many parts of the world (Marano et al., 2012; Pask and Reynolds, 2013; Chebil et al., 2014). Previous studies have shown that moderate deficit in irrigation or water stress from the start of growth to the jointing stage can reduce water consumption with no significant reduction in wheat yields, effectively increasing the WUE (Zhang et al., 2004a; Zhang et al., 2006; Yang et al., 2006; Fereres and Soriano, 2007; Du et al., 2010; Karrou et al., 2012). Dong et al. (2011) found that total irrigation water amounts of 120-150 mm at jointing and anthesis produced grain yield of 7213.6-7586.7 kg ha^{-1} and WUE of 19.7-21.4 kg ha^{-1} mm^{-1} under the condition of adequate soil moisture before sowing. Therefore, it is essential to develop the most suitable irrigation scheme to produce optimum plant yields under limited water supplies for different ecological regions (Zhang et al., 2013). The present study adopted a new method, in which the amount of irrigation water was calculated based on measurement of soil moisture

Table 6. Soil water consumption amount in 0-200 cm soil layers of the whole growth of wheat under different treatments in 2009-2010 and 2010-2011 (mm).

			Soil layers (cm)				
Years	Cultivars	Treatments	0-20	20-60	60-100	100-140	140-200
2009-2010							
	Jimai 22	W0	27.53a	65.39a	57.77a	60.33a	23.77b
		W1	25.71b	60.48b	52.29b	46.80c	9.39d
		W2	24.97b	55.77c	48.69c	26.95f	1.64f
	Zhouyuan 9369	W0	27.66a	63.08ab	53.84b	54.03b	32.06a
		W1	25.94b	57.53c	44.00d	39.19d	14.89c
		W2	25.52b	57.03c	44.13d	31.16e	7.31e
2010-2011							
	Jimai 22	W0	26.98a	46.77a	48.52a	52.88a	26.17a
		W1	26.70a	45.54a	37.15d	33.91bc	20.99c
		W2	23.80b	39.32b	39.27c	29.05d	16.17d
	Zhouyuan 9369	W0	27.77a	46.65a	41.71b	35.43b	23.65b
		W1	26.66a	37.90b	35.05e	32.37c	15.47d
		W2	24.11b	37.70b	36.93d	27.58e	8.75e

Values followed by different letters within the same column in each growing season are significantly different at 0.05 probability level.

content to achieve different target SWCs in a soil profile of 0-140 cm at jointing and anthesis of wheat. The results showed that the highest grain yields were obtained under W1 treatment in both 'Jimai22' and 'Zhongyuan9369' wheat cultivars. The same trend was observed for WUE under W1 treatment from 2009 to 2011. The grain yield of water-sensitive wheat cultivars decrease significantly compared with drought-resistant cultivars under water deficit conditions (Saeedipour, 2011). In this study, wheat 'Jimai 22' showed higher grain yield and WUE compared with 'Zhouyuan 9369' in different rainfall years in both growing seasons, suggesting that 'Jimai 22' is a water-saving cultivar with high and stable yield. This indicated that appropriate SI after jointing could result in higher yield and WUE in water-saving wheat cultivars. The amount of SI used in this study was based on the SWC before irrigation, which reflected precipitation and crop water consumption. Taken together, our results indicate that this new method can be used to achieve higher water efficiency and yield.

Total ET of wheat consists mainly of precipitation, irrigation, and soil water consumption. Sun et al. (2006) showed that ET is linearly related to the amount of irrigation. A negative correlation exists between soil water consumption and irrigation water consumption (Wang et al., 2006). Moderate water deficit can increase soil water consumption and rainfall utilization in wheat, but reduce the total ET of wheat (Panda et al., 2003; Sun et al., 2006). In the present study, soil water consumption and percentage of soil water consumption and precipitation relative to total water consumption decreased in two different wheat cultivars. The amount of irrigation and its percentage increased with increase in SI level. This result is consistent with that of previous studies (Sun et al., 2006; Wang et al., 2006). W1 treatment, which resulted in lower SWC in 0-140 cm soil at anthesis, demonstrated higher soil water consumption than W2 treatment, which produced the highest SWC 0-140 cm soil at anthesis. The ET of W1 treatment did not decrease significantly compared with that of W2 treatment. This result may be due to increase in SI level, which significantly reduced soil water consumption under W2 treatment. No significant difference in ET and soil water consumption was observed between the two cultivars from 2009 to 2010, but this was not the case from 2010 to 2011 (precipitation was only 31.4 mm before jointing stage, but rose to 117.7 mm between jointing and anthesis). Both ET and soil water consumption of 'Jimai 22' were significantly higher than those of 'Zhouyuan 9369' in all treatments conditions. Thus, different cultivars exhibited different water consumption levels. Our results suggest that cultivars with higher utilization efficiency of soil water should be selected because they are also more conducive to saving irrigation water.

Water extraction from 60 cm surface is highest under maximum irrigation treatment (240 mm), but limited irrigation (120 mm) results in high soil water extraction from the 90-120 cm soil layers compared with maximum irrigation treatment (Lenka et al., 2009). According to Li et al. (2010), irrigation during the later part of the winter wheat growing season and increase in irrigation frequency decreases the amount of available soil water. In this study, W0 treatment promoted the absorption utilization of soil water storage in the 0-200 cm soil layers by wheat. W1 treatment resulted in high soil water consumption in the 100-200 cm soil layers compared with W2 treatment. This finding suggests that SI based on relatively low water contents at anthesis resulted in higher utilization of deep soil water for both cultivars. Wheat 'Jimai 22' utilized more soil water in the 60-140 cm soil layers compared with wheat 'Zhouyuan 9369' under W1 condition in different precipitation years. Thus, 'Jimai 22' with high grain yield had higher capacity for efficient use of soil water in deep soil layers.

CONCLUSIONS

The new irrigation scheme of recharging soil water at critical developmental stages of wheat by supplemental irrigation (SI) to different target relative water contents in 0-140 cm soil can produce high yield and save irrigation water in different winter wheat cultivars. In this study, suitable supplemental irrigation applied at critical growing stages (rising SWC to 65% or 75% of field capacity at anthesis) based on target relative soil moisture content of 75% in the 0-140 cm soil layers at jointing after SI improved winter wheat yield, water use efficiency (WUE) and irrigation benefit (IB) in different cultivars. Moreover, the yield and water consumption characteristics of two winter wheat cultivars under supplemental irrigation were different. Hence, increasing soil water content in the 0-140 cm soil layers to a suitable level during critical growing stages of wheat can be an effective strategy to deal with shortage of water in the North China Plain. Finally, our results indicate that the winter wheat cultivar 'Jimai 22' is a high-yielding cultivar with higher WUE compared to 'Zhouyuan 9369'.

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