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Winter wheat grain yield and its components in the North China Plain: irrigation management, cultivation, and climate

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Irrigation has been identified as the main driving factor of groundwater drawdown in the North China Plain (NCP). In order to develop appropriate irrigation strategies for satisfactory yields of wheat (*Triticum aestivum* L.), grain yield (GY), yield components, and water use efficiency (WUE) were studied. A field experiment was conducted with two types of winter wheat, 'Shimai15' and 'Shixin733', and five irrigation treatments, including rainfed and four spring irrigation water applications, in four growing seasons (2005 to 2009). Results showed that maximum GY was achieved with three irrigation treatments in the 2005-2006 and 2008-2009 dry seasons and two irrigation treatments in the 2006-2007 normal season. However, in the 2007-2008 wet season, the four irrigation treatments, especially the additional irrigation event at the reviving stage (28), produced maximum GY. Grain yield was significantly related to seasonal full evapotranspiration (ET) and 410 to 530 mm of seasonal full ET, including 143 mm rainfall and 214 mm irrigation water, which led to maximum GY. The two types of cultivars responded differently to irrigation management in different rainfall years. The yield of the water-saving cv. 'Shimai 15' was much higher in the dry seasons than in the other seasons. Variations of yield components were mainly caused by irrigation time and meteorological factors. The higher accumulated temperature during the sowing and tillering stages (24) and irrigation or precipitation at the reviving stage (28) significantly improved tiller growth. The lower average temperature in March and April greatly increased grain number per spike. Sunshine duration played a decisive role in improving grain weight. Our results provide very useful information about irrigation time and frequency of winter wheat in the NCP in order to obtain high yield but reduce the use of underground water.

Key words: Evapotranspiration, grain yield, North China Plain, soil water depletion, *Triticum aestivum*.

INTRODUCTION

The North China Plain (NCP) is one of the most important agricultural regions and supplies more than 50% of China's wheat production. The region has a monsoon climate with less than 30% precipitation falling in winter (approximately 109 mm), which is much lower than wheat requirements. Moreover, annual precipitation in the study area was observed to have decreased by 170 mm from the 1960s to 2005 (Sun et al., 2010). Irrigation using groundwater is therefore quite necessary to maintain the high agricultural production. Today, approximately 70% of extracted water resources for agriculture, of which approximately 70% is for wheat irrigation, are pumped from groundwater in Hebei Province of the NCP. The expansion of irrigation over the years has led to a rapidly falling groundwater table. The groundwater table in the Piedmont Plain has decreased approximately 1 m yr^{-1} in the last 20 yr (Jia and Liu, 2002). It is urgent and essential to develop an optimum policy to avoid further over-exploitation of groundwater and maintain sustainable crop production.

Cultivation, irrigation practices, and climate are the most important factors that influence wheat growth and yield (Al-Kaisi et al., 1997; Ghahraman and Sepaskhah, 1997; Zhang et al., 2003). There is a need to develop drought-resistant cultivars with higher grain yield (GY) in water deficit conditions. The superior performance of cultivation under dryland conditions is attributed to the ability of cultivars to extract a significant proportion of water from deep soil layers (Angadi and Entz, 2002). The scarcity of roots in deep soil layers often restricts full utilization of available soil water (Barraclough and Weir, 1988).

Many studies have been carried out to search for the best ways to efficiently use irrigation water and improve crop yield (Shen and Yu, 1998; Zhang et al., 2010). Plant

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water use efficiency (WUE) depends on the quantities applied and timing. Deficit irrigation, defined as applying water below full crop-water requirements, is an important tool to achieve the goal of reducing irrigation water use (Fereres and Soriano, 2007). Improving irrigation efficiency by applying deficit irrigation is an important management practice, especially in regions with serious water shortage. A more frequently irrigated crop might increase soil evaporation, so that with a limited irrigation supply, balancing the irrigation amount per application and irrigation frequency with root water uptake would be expected to affect yield as well as WUE.

Despite ongoing improvements in technology and crop varieties, weather is still the main uncontrollable factor that affects agricultural production. Williams (1971-1972) found that within a large wheat growing region, large differences were found in the relationships between wheat yield fluctuations and weather variations, especially in the driest areas. The amount of annual precipitation and its seasonal distribution are crucial for agricultural production in the NCP (Sun et al., 2010). Some studies found that precipitation at sowing is important to increase yield. Low rainfall and low soil water content at sowing slow down the germination process, reduce the percentage of germination, and planting density (Passioura, 2006). However, if plants use too much water before flowering, subsequent water stress caused by lower rainfall levels leads to premature crop senescence, low yield, or often poor grain quality. This is because plants set a large number of seeds but cannot produce enough carbohydrates to fill them all (Angus and Van Herwaarden, 2001). It is therefore imperative to establish a rational irrigation schedule in accordance with annual precipitation, its seasonal distribution, and crop water requirements.

The rate of many crop plant growth and development processes is controlled by temperature. Soil moisture loss through evaporationincreased by 35 to 45 mm and WUE decreased by 7.3% from the 1950s to the 1990s because temperatures increased (Xiao and Gen, 1999). Supplemental irrigation is beneficial to increase crop yields. Extreme temperature fluctuations can affect the survival of crop plants or plant organs. Winter rye crop density and number of kernels of are positively influenced by warm weather in autumn at Berlin-Dahlem. An early start of the growing season after winter is also important for the satisfactory development of these components. Moderate temperatures prior to the beginning of shooting prolong the spikelet formation period and leads to an increased number of kernels per ear. High temperatures at the flowering stage can reduce the potential number of grains; it also reduces the duration of the milk grain period and kernel weight of winter rye (Chmielewski and Kohn, 2000). The current extreme temperature will be more frequent for the NCP. We consider how episodes of hot temperatures will affect winter wheat yield. It is very important to identify the atmospheric conditions that control the formation and reduction of yield components.

One of the major factors affecting GY in May is solar radiation. Grain yields have been found to be very sensitive to changes in radiation levels around anthesis (Mitchell et al., 1996). The date of anthesis determines the onset of the milk grain phase. To analyze the importance of the influence of climate on yield, Landau et al. (2000) applied a sub-model and found a positive effect of radiation around the early reproductive phase and anthesis because of increased photosynthesis. The model predicts that rainfall and radiation levels in the early reproductive phase interact with each other. Once a drought threshold is reached, radiation has a negative effect, which depends on the drought level.

The NCP is one of the places with extreme water shortage and climatic changes in China. Applying rational irrigation is an important management practice to relieve the pressure of water shortage and climate change. In the present study, we investigated the influence of irrigation management, meteorological variables, and specific genotype in winter wheat GY, yield components, and WUE. The main objectives of this study were to develop appropriate irrigation strategies to obtain satisfactory yields using the least amount of irrigated water and to look for optimal measures that adapt to different types of weather by assessing the impact of weather changes on yield.

MATERIALS AND METHODS

Experimental site

Winter wheat (*Triticum aestivum* L.) was grown in the Gaocheng Experimental Base of the Institute of Cereal and Oil Crops, Hebei Academy of Agricultural and Forestry Sciences from 2005 to 2009. The experimental site is located at the base of Taihang Mountain (37°56' N, 114°42' E), which is high-yield farmland in the NCP. The area is in a monsoon climatic zone with an average annual precipitation of approximately 484 mm. However, rainfall in the winter wheat growing season is less than 30% of total rainfall. Irrigation is quite important for this winter crop. Its well-drained loamy soil with a deep profile is most suitable for crop growth. Soil organic matter for the 0 to 20 cm tillage soil layer is 15.5 g kg^{-1}. Total N is 0.97 g kg^{-1} and available P and K are 19.46 and 91.00 mg kg^{-1}, respectively.

Winter wheat cultivars

The wheat cultivars under study were 'Shimai15' (SM15) and 'Shixin733' (SX733), which were commonly grown in the region. SM15 is widely recognized as a water-saving wheat (Guo et al., 2010), and it was produced by the Shijiazhuang Academy of Agricultural Science in 2002. SX733 is a high-yielding cultivar and was produced by the Institute of Shijiazhuang New Wheat Breeding Technology in 1998. Both are semi-winter cultivars with a 240 to 243 d growth period. SM15 differs from SX733 in that it has a stronger tillering ability.

Trial arrangements

Winter wheat was sown in early to middle October and harvested within the first 10 d of June with a plot combine seeder (2756285100100, Wintersteiger, 4910 Ried im Innkreis, Upper Austria, Austria). The sowing and harvest dates and seedling density are shown in Table 1. Chemical fertilizers were applied before cultivation at a base rate of 120 kg N ha^{-1} (using urea plus diammonium phosphate [DAP]), 60 kg P ha^{-1} (DAP), and 85 kg K ha^{-1} (KCl). Nitrogen (urea) was top-dressed again during the first spring irrigation event in at the rate of 120 kg ha^{-1}. Plots were randomly chosen for the field experiments with four replicates of the five irrigation treatments (Table 2). They were separated by a 1.5 m wide zone planted with non-irrigated winter wheat to minimize mutual effects of adjacent plots. The size of each plot was 25.2 m^2. Row spacing was 0.15 m. The five irrigation treatments were rainfed (I0), and one (I1), two (I2), three (I3), and four (I4) irrigation events based on the crop development stage (Table 2). For each irrigation event, 60 to 70 mm water (90 to 100 mm in 2008-2009) was applied to the soil by surface irrigation with a low-pressure tube water transportation system and a flow meter to record the amount of irrigation applied to each plot. Irrigation times and amounts are shown in Table 2.

Rainfall during winter wheat growth from 2005 to 2009 is shown in Table 3. Compared with the long-term average, 2005-2006 and 2008-2009 were dry seasons, while 2006-2007 and 2007-2008 were a normal and wet season, respectively. Other meteorological parameters, such as air temperature, humidity, sunshine duration, and wind speed, were also collected by a weather station installed 200 m away from the experimental field where reference evapotranspiration was calculated.

Table 1. Seedling density, sowing, flowering, and harvest dates for both winter wheat cultivars in the four growing seasons between 2005 and 2009.

Season	Seedling density	Sowing date	Flowering date	Harvest date
	plants m^{-2}		month/day	
2005-2006	300	10/6	5/7	6/10
2006-2007	300	10/10	5/5	6/8
2007-2008	375	10/18	5/2-5/5	6/8
2008-2009	375	10/14	5/4	6/9

Measurements

Grain yield and yield components. Wheat was harvested with a plot combine harvester (CLASSIC, Wintersteiger, 4910 Ried im Innkreis, Upper Austria, Austria). Grains were air-dried prior to recording weight. Grain water content was approximately 13%. Spike number per unit area (0.3 m^2) was counted before harvest and 40 winter wheat plants were collected from each plot to determine kernel number per spike (ear). Winter wheat 1000-seed weight was measured.

Soil water balance. Soil water content was monitored at an interval of 10 cm to a depth of 2 m with a neutron soil moisture meter (CNC503B, Beijing Keyuan ChaoNeng Company, Beijing, China) with access tubes installed at the center of the plots. Total water use or ET was calculated by the soil water balance equation for the growing season as follows:

$$ET = P + I + \Delta W - R - D + CR$$

where *ET* is total water volume used during a given growing period, *P* is precipitation, *I* is irrigation, ΔW was obtained by soil water content at sowing minus soil water content at harvest in the 2 m root zone depth, *R* is runoff,

Table 2. Irrigation time and amount of water from 2005 to 2009.

Season	Treat-ment	Irrigation frequency	Irrigation time	Irrigation in growth stage and amount (mm)						Total irrigation amount (mm)
				Tillering (24)	Reviving (28)	Erecting (30)	Jointing (31)	Anthesis (60)	Grain milk (75)	
2005-2006	I0	1	30 Nov	51.4	-	-	-	-	-	51.4
	I1	2	30 Nov, 6 April	51.4	-	-	71.4	-	-	122.8
	I2	3	30 Nov, 6 April, 2 May	51.4	-	-	71.4	57.1	-	179.9
	I3	4	30 Nov, 6 April, 2 May, 23 May	51.4	-	-	71.4	57.1	51.4	231.3
	I4	5	30 Nov, 20 March, 6 April, 2 May, 23, May	57.1	-	65.7	57.1	57.1	51.4	288.4
2006-2007	I0	0		-	-	-	-	-	-	
	I1	1	8 April	-	-	-	66.1	-	-	66.1
	I2	2	8 April, 3 May	-	-	-	66.1	64.3	-	130.4
	I3	3	8 April, 3 May, 24 May	-	-	-	66.1	64.3	52.5	182.9
	I4	4	14 March, 8 April, 3 May, 24 May	-	71.4	-	66.1	64.3	52.5	254.3
2007-2008	I0	0		-	-	-	-	-	-	
	I1	1	7 April	-	-	-	56.6	-	-	56.6
	I2	2	26 March, 6 May	-	-	77.9	-	67.6	-	145.5
	I3	3	26 March, 6 May, 24 May	-	-	69.4	-	66.1	57.6	193.1
	I4	4	10 March, 7 April, 6 May, 24 May	-	77.3	-	56.6	66.1	57.6	257.6
2008-2009	I0	0		-	-	-	-	-	-	
	I1	1	8 April	-	-	-	99.5	-	-	99.5
	I2	2	8 April, 4 May	-	-	-	101.5	111.0	-	212.5
	I3	3	8 April, 4 May, 25 May	-	-	-	101.5	111.0	101.6	314.1
	I4	4	13 March, 8 April, 4 May, 25 May	-	104.2	-	88.3	83.4	97.5	373.4

Table 3. Monthly precipitation at Gaocheng Station.

Season	Treatment	Rainfall (mm)									Total
		Oct	Nov	Dec	Jan	Feb	March	April	May	June	(mm)
2005-2006	I0, I1, I2	3.5	0.0	0.4	1.6	0.5	0.0	14.2	62.0	8.2	90.4
	I3	3.5	0.0	0.4	1.6	0.5	0.0	14.2	62.0	18.7	100.9
	I4	3.5	0.0	0.4	1.6	0.5	0.0	14.2	62.0	19.9	102.1
2006-2007	I0, I1, I2, I3, I4	0.5	18.9	5.5	0.0	0.0	46.4	2.7	64.0	0.0	125.4
2007-2008	I0, I1	1.6	0.3	2.4	0.9	0.0	18.5	46.1	58.8	34.1	162.7
	I2, I3, I4	1.6	0.3	2.4	0.9	0.0	18.5	46.1	58.8	85.4	214.0
2008-2009	I0, I1, I2, I3, I4	11.5	0.0	0.0	0.0	8.7	6.5	6.0	30.5	29.4	92.6
Average (1986-2010)		14.7	15.8	3.3	4.3	6.1	12.6	21.9	42.3	21.5	142.6

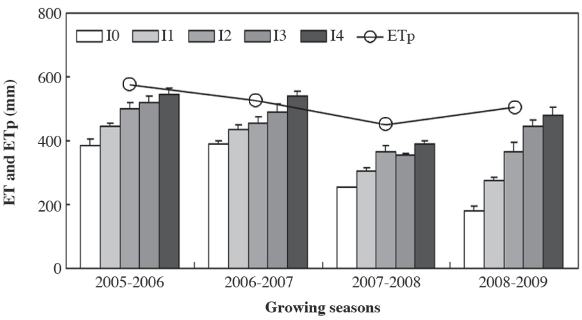
October represents period from the sowing date to 31 Oct and June represents period from 1 June to harvest date. For the average of 1986-2010, Oct represents the last 20 d of Oct and June represents the first 10 d of June. Winter wheat was generally harvested around 10 June.
I0: rainfed; I1: one irrigation event; I2: two irrigation events; I3: three irrigation events; I4: four irrigation events.

D is root zone drainage, and *CR* is capillary rise to the root zone. The groundwater table at the station was 28 m below soil surface and CR was negligible (Liu and Wei, 1989). Runoff was also ignored because it was scarce in the NCP. Drainage was obtained by multiplying a recharge coefficient (α) with the sum of water from irrigation (*I*) and effective rainfall (*P*): D = α (P + I). In the present study, a different coefficient was chosen in accordance with the event water input (EWI), 0.1 for EWI less than 90 mm, 0.15 for EWI between 90 and 250 mm, and 0.2 for EWI greater than 250 mm (Ministry of Geology and Mineral Resources, 1986). The equation used under these experimental conditions was ET = P + I + ΔW - D.

Water use efficiency (WUE). WUE was calculated as WUE = GY/ET where *GY* is grain yield (kg m^{-3}) and *ET* was obtained by the abovementioned formula.

Potential ET (ETp). Evapotranspiration without water deficit (ETp or full ET) was calculated by ET_0 multiplied by a crop coefficient derived from the Luancheng station of the NCP (Liu et al., 2002); ET_0 was calculated by the Penman-Monteith equation recommended by FAO (Allen et al., 1998). The seasonal potential ET (ETp) is shown in Figure 1.

Statistical analysis
All data collected were statistically analyzed as a



I0: rainfed; I1: one irrigation; I2: two irrigations; I3: three irrigations; I4: four irrigations.

Figure 1. Evapotranspiration (ET) and potential ET (ETp) in different water supply conditions from 2005 to 2009.

completely randomized design with four replicates by ANOVA to test the difference in GY, spike number, grain number per spike, 1000-grain weight, water storage at harvest, soil water depletions (SWD), water supply, ET, root weight, and root-shoot ratio among different treatments. When the F-test indicated statistical significance at P ≤ 0.05, mean comparisons were made by LSD.

The ET regression analysis, pre-sowing soil water storage (PSWS) at the 2 m depth, and water supply (total volume of rainfall and irrigation) was performed with the DPS 11.5 data processing system (Tang, 2009) to analyze the correlation between ET and these variables and the contribution of each dependent variable to ET. Similarly, regression analysis of 1000-grain weight and its dependent variables, such as sunshine duration, wind speed, average temperature, humidity, rainfall, hot and dry wind, and irrigation were also performed with DPS.

RESULTS AND DISCUSSION

Influence of irrigation on GY, ET, and WUE

Grain yield. Mean GY, yield components, and WUE values of SM15 and SX733 with different irrigation treatments between 2005 and 2009 are shown in Table 4. The weather was dry with seasonal precipitation less than 95 mm during the 2005-2006 and 2008-2009 seasons. However, it was normal in 2006-2007 and slightly wet in 2007-2008 with 120 to 165 mm seasonal rainfall in both seasons (Table 3). In the 2007-2008 season, delayed sowing and less ET significantly reduced GY (16.8%) as compared with the other three seasons (Table 4). The most frequently irrigated treatment (I4) in three of the four seasons slightly decreased maximum GY by 0.7% to 2.3% instead of the expected increase. Although late sowing resulted in an insufficient plant population in the 2007-2008 season, the last irrigation event at the reviving stage significantly increased spike number (14%) and produced maximum GY for four irrigation treatments. The three irrigation events greatly improved GY in the 2005-2006 and 2008-2009 dry years, but slightly reduced it in the 2006-2007 normal season (0.6%) and in the 2007-2008 wet season (1.2%). Two irrigation events (I2)

Table 4. Mean grain yield, yield components, and water use efficiency (WUE) for both wheat cultivars from 2005 to 2009.

Treatments	Spike number	Grain number per spike	1000-kernel weight	Grain yield	WUE
	10^4 plant ha^{-1}		g	kg ha^{-1}	kg m^{-3}
2005-2006					
I0	608.6b	29.5b	39.9c	6986c	1.82b
I1	771.4a	29.1b	38.3c	8619b	1.94a
I2	766.5a	30.2b	41.1a	8960ab	1.79bc
I3	783.6a	31.0ab	40.7b	9322a	1.79bc
I4	808.5a	32.5a	37.6c	9261ab	1.70c
2006-2007					
I0	699.0a	30.4a	39.2ab	8720b	2.24a
I1	728.6a	31.3a	38.3b	9533ab	2.18a
I2	743.8a	30.6a	40.4a	9732a	2.14a
I3	742.9a	31.5a	40.5a	9672a	1.98b
I4	741.0a	30.7a	38.1b	9511a	1.76c
2007-2008					
I0	584.0c	29.3ab	41.7b	6884d	2.71a
I1	643.3b	29.2b	39.8c	7530c	2.48b
I2	635.6b	29.8ab	42.9ab	7700bc	2.11c
I3	633.0b	30.2a	43.0a	7970 ab	2.24cd
I4	702.3a	30.0ab	39.7c	8063a	2.07d
2008-2009					
I0	647.3c	26.5c	42.1a	7559c	4.20a
I1	765.0abc	29.7ab	39.1b	9710b	3.52b
I2	755.5bc	30.1a	43.0a	9801b	2.67c
I3	776.8ab	30.9a	42.4a	10158a	2.28d
I4	845.3a	29.4b	40.6ab	10037a	2.09d

Different letters in a row indicate significant differences according to LSD test ($P \leq 0.05$).
I0: Rainfed; I1: one irrigation event; I2: two irrigation events; I3: three irrigation events; I4: four irrigation events.

Table 5. Mean soil water depletion (SWD), water supply, and evapotranspiration (ET) for both wheat cultivars with different water supply conditions from 2005 to 2009.

Treatments	PSWS	Water storage at harvest	SWD	Water supply	ET	Percentage of SWD
	mm					%
2005-2006						
I0	610	369c	241a	142e	383d	63a
I1	610	379c	232a	213d	445c	52b
I2	610	381c	229a	270c	499b	46c
I3	610	421b	190b	332b	522b	36d
I4	610	455a	156c	390a	546a	29e
2006-2007						
I0	587	323c	264a	125e	389d	68a
I1	587	341c	246a	192d	437c	56b
I2	587	387b	200b	256c	456c	44c
I3	587	407ab	180bc	308b	488b	37d
I4	587	427a	160c	380a	539a	30e
2007-2008						
I0	472	381d	91a	163e	254d	36a
I1	472	388d	84a	219d	303c	28b
I2	472	467c	5b	359c	365b	1c
I3	472	524b	-52c	407b	355b	-15d
I4	472	554a	-82d	472a	390a	-21e
2008-2009						
I0	512	425c	87a	93e	180d	48a
I1	512	428c	84a	192d	276c	30b
I2	512	450bc	62ab	305c	367b	17c
I3	512	474ab	38bc	407b	445a	9d
I4	512	498a	14c	466a	480a	3d

PSWS: Pre-sowing soil water storage; I0: rainfed; I1: one irrigation event; I2: two irrigation events; I3: three irrigation events; I4: four irrigation events.
Values followed by the same letter in the same season and column, were not significant at $P < 0.05$.

produced the highest GY in the 2006-2007 normal season, but significantly decreased it in the 2008-2009 and 2005-2006 dry years. A reduction of 6.5% in GY only occurred in the 2005-2006 dry season and it was 2% in the 2006-2007 normal season. Approximately 75% to 90% of the maximum yield was obtained under rainfed conditions in the dry and normal seasons with abundant PSWS in the 0 to 200 cm soil profile. Grain yield for I2 was not higher ($P \leq 0.05$) in the 2008-2009 dry season than for I1. This was possibly due to rainfall of 23.8 mm on 10 May, which was just after wheat anthesis and counteracted the effect of the second irrigation event during this stage. Some studies report that more frequent irrigation enhances yield (Wallach et al., 2003), but others find no difference (Xu et al., 2004). Recently, many research studies have shown that more water supply optimization resulted in decreased GY and WUE (Zhang et al., 2003), which agrees with the reports of our research. These contradictory results may be a consequence of differences in cultivation, soils, irrigation methods, and climate.

Yield components. Drought caused by lack of rainfall resulted in a 13.1% plant population reduction for I0 as compared with other treatments (Table 4). The grain number per spike tended to decrease during the dry period caused by low rainfall, but the significant decline was only observed in 2008-2009 (dry year). One irrigation treatment around the early jointing stage (31) can ensure proper spike number and grain number per spike as evidenced by similar values among I1, I2, and I3. An additional early irrigation event at the reviving stage (28-29) for I4 usually further increased spike number with no influence on grain number. Compared with other treatments, higher kernel weight was 5.6% higher when either I2 or I3 was conducted. This suggests that a supplemental irrigation event at the milk grain stage (75) for I4 was not very effective to promote grain weight. In contrast, I2 or I3 and I1 and I4 led to the lowest kernel weight because of the too dry or excessively moist soil conditions. As compared with I1 and I4, grain weight increased by 5.0% when there was no irrigation at all. This was mainly obtained by the self-adjustment mechanism among the three yield components and higher mobilization efficiency to the grain (Zhang et al., 2008).

WUE. Our results showed that WUE decreased with increasing water supply in three of the four years. Given the severe water shortage situation in the NCP, a balance between yield and WUE would be useful to evaluate the irrigation system. When irrigation increases, WUE decreases (Zhang et al., 2008; 2010). However, it is possible to achieve both objectives simultaneously, that is, satisfactory WUE and yield, by regulating irrigation times. In the 2005-2006 season, I3 had the highest GY but a lower WUE as compared with I2. In 2006-2007, I2 produced the highest GY, but only decreased WUE by

1.8% as compared with I1. In 2007-2008, I4 achieved the highest GY, while its WUE was 1.9% lower as compared with I2. Therefore, I3, I2, and I4 were recommended because they achieved maximum yield and satisfactory WUE in those three seasons. In 2008-2009, I1 should be suggested because there was a 4.4% yield reduction and a 54.3% increase in WUE as compared with the highest yield treatment (I3). In the 2008-2009 dry season, mean WUE was as high as 3.0 kg m^{-3} with a 41.2% increase as compared with the mean of the other three seasons due to a 10.3% yield increase and 16.8% ET reduction (Table 5). Especially compared with the 2006-2007 season, mean water supply in the 2008-2009 season increased by 16%, but mean ET decreased by 24%. Lower ET in this season was primarily attributed to a 71.9% reduction of SWD as compared with the 2005-2006 and 2006-2007 seasons. In the 2007-2008 wet season, a 17.1% reduction in PSWS also significantly reduced ET by 16.8% as compared with the other three seasons; therefore, its WUE was higher than in the 2005-2006 and 2006-2007 seasons. Results indicate that PSWS has a great impact on WUE.

The most frequently irrigated treatment (I4) in three of the four seasons slightly decreased maximum GY; maximum GY can be achieved with three irrigation treatments (irrigation at jointing, flowering, and milk stages) in the dry seasons and two irrigation treatments (irrigation at jointing and flowering stages) in normal seasons, which agrees with Zhang et al. (2003) and Sun et al. (2010). In three of the four years (2006-2008), the highest yield was achieved with an acceptable WUE decrease (< 2%). In 2008-2009, an acceptable yield loss (< 5%) was used to obtain a significant operating profit water use index (up to 50%).

ET. ETp, ET, and its components in different growing seasons are shown in Figure 1 and Table 5. ET and ETp followed the same trend. Winter wheat ET ranged from 180 to 546 mm in the different precipitation seasons and irrigation treatments. It increased gradually when the water supply increased and the highest value occurred when four irrigation events were conducted each year. Evapotranspiration of I4 was close to ETp, especially in the 2006-2007 season and was just 14 mm higher than ETp. Analysis of the results showed that the total volume of water used during the maximum production year was below ETp in the four seasons. Maximum yield can be achieved with an ET from 8% to 27% less than ETp. These results indicate that four irrigation events are excessive and it is necessary to reduce irrigation.

The relationships between water supply:ET and GY of winter wheat in the different rainfall years are shown in Figure 2. The simulation result of the quadratic curve model showed that the highest yields can be achieved when water consumption from 2005 to 2009 was 532, 487, 414, and 408 mm, respectively, with an average of 460 mm.

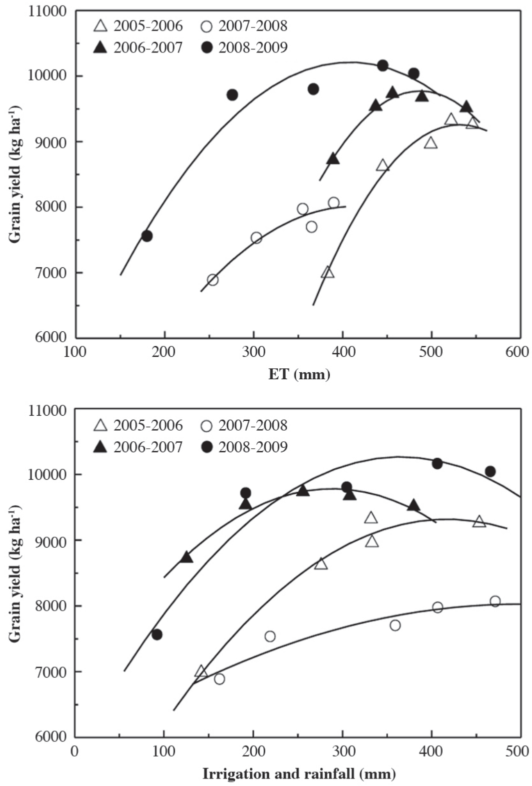


Figure 2. Relationship between grain yield and seasonal evapotranspiration (ET) or water supply in different water supply conditions from 2005 to 2009.

The average amount of water to obtain maximum GY was estimated as 357 mm (289 to 417 mm) in the three 2005-2006, 2006-2007, and 2008-2009 seasons, which was 66.6% of ETp (55.0% to 72.5%). With an average seasonal rainfall of 143 mm in the NCP, supplemental irrigation water was approximately 214 mm in a normal year in order to obtain maximum yield.

Evapotranspiration of irrigated winter wheat in the NCP was influenced by many factors, including water supply, irrigation time, PSWS, and ETp. Stepwise multiple regression statistical analysis showed that water supply amount and PSWS were the main impact factors. The following regression equation displayed the relationship among ET (Y), PSWS (X1), and water supply amount (X2) for the 2005 to 2009 period: $Y = -548.9 + 1.425X1 + 0.624X2$, ($R = 0.969^{**}$, $n = 19$). The partial correlation coefficients of the two variables were similar and higher PSWS and water supply led to higher ET (Table 6). The same order existed between the direct path coefficient and the partial correlation coefficient (Table 7); the direct path coefficient was P1y (0.821) > P2y (0.725). This result indicates that PSWS played a decisive role in ET composition, while the direct effect of water supply on ET was less important when compared to PSWS.

Since soil water storage was different during the growing seasons, SWD showed PSWS depletion (Table 5), which was mainly controlled by PSWS and later rainfall.

Table 6. **Partial correlation of evapotranspiration (Y) with pre-sowing soil water storage (X1) and water supply amount (X2).**

Partial correlation coefficient	Partial correlation coefficient value	t value	Significant level (P)
r(y,X1) =	0.955	13.335	0.000
r(y,X2) =	0.944	11.768	0.000

Table 7. Contribution to evapotranspiration of dependent variables.

Variable	Path coefficient		
	Direct coefficient	→X1	→X2
X1	0.821		-0.159
X2	0.725	-0.180	

Coefficient of determination = 0.937.

It contributed greatly to grain production when PSWS was higher in the 2005-2006 and 2006-2007 seasons. Due to the deep soil profile within the root zone (about 2 m), stored soil moisture extracted by the winter wheat root system was 66% of ET for I0. Even for I1, I2, I3, and I4, SWD was still 54%, 45%, 37%, and 29% of total seasonal ET (Table 5). Therefore, the irrigation treatment must take into account stored soil moisture in the root zone profile. In the 2007-2008 and 2008-2009 seasons, lower PSWS and more rainfall in early June resulted in lower SWD. The stored soil moisture extracted by the winter wheat root system was 42%, 29%, 9%, -3%, and -9% of ET of I0, I1, I2, I3, and I4, respectively, in these two seasons.

Soil water depletion, precipitation, and irrigation contributed to 45%, 23%, and 32%, respectively, of the total seasonal ET for maximum yield production when PSWS was higher. They were 8%, 47%, and 45%, respectively, when PSWS decreased. It is generally believed that maximum PSWS in the NCP should be obtained by pre-planting irrigation when rainfall is insufficient in the summer rainy season. However, the present study reveals that an appropriate PSWS, rather than the maximum, should be established for better GY and WUE.

Different responses of the two cultivars to irrigation regimes related to grain yield and its components

The two cultivars responded differently to irrigation treatments throughout the four years (Figure 3). In dry years, the water-saving cv. SM15 demonstrated remarkable superiority over the higher yielding cv. SX733, with increases of 6.1% and 16.6% in mean and maximum yields, respectively. In the normal year (2006-2007) and in wet year (2007-2008), yields of cv. SM15 tended to be higher than cv. SX733 when less irrigation was applied. This tendency was reverted when more irrigation was applied. In the four years, both cultivars achieved maximum yields under three irrigation treatments. Yields of SM15 usually varied less than SX733 among different irrigation applications and achieved 82.4%, 96.5%, and 98.6% of the maximum with the I0, I1, and I2 irrigation treatments, respectively, as compared with 80.1%, 94.2%, and 96.3% for SX733. This suggests that yield of the water-saving cv. SM15 is more stable in a dry environment.

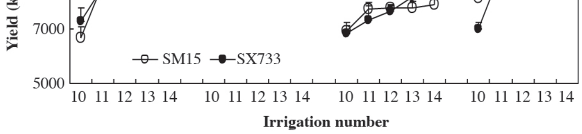


Figure 3. Grain yield, spike number, grain number per spike, and 1000-grain weight of wheat 'Shimai15' (SM15) and 'Shixin733' (SX733) under different water supply conditions from 2005 to 2009.

Total ET was very similar in the two wheat cultivars (Table 8). Root distribution in the soil profile is an important factor in plant water and nutrient availability. Some studies found that the soil water depletion front was closely related to rooting depth (Angadi and Entz, 2002), and the scarcity of roots in deep soil layers often restricted the full utilization of available soil water (Barraclough and Weir, 1988; Zhang et al., 2004). However, other studies highlighted the primary role of the top root system in soil water uptake (Clothier and Green, 1994) and considered that the roots in the top soil were more important for water uptake when soil moisture was not restricted. For SM15, whose total root weight was 48% higher than SX733, approximately 82% and 18% of roots were distributed in 0 to 70 cm and 70 to 140 cm soil layers, respectively (Table 9). Roots of SX733 were much deeper than SM15 roots and approximately 80%, 15%, and 5% of roots were distributed in 0 to 70, 70 to 140, and 140 to 200 cm soil

Table 8. Change in soil water content, irrigation, precipitation, and evapotranspiration (ET) of wheat 'Shimai15' (SM15) and 'Shixin733' (SX733) in different water supply conditions in 2007-2008 season (mm).

2007-2008		PSWS	Water storage at harvest	SWD	Water supply	ET
SM15	I0	472	388c	84a	163e	247d
	I1	472	384c	89a	219d	308c
	I2	472	464b	8b	359c	368b
	I3	472	531a	-58c	407b	349b
	I4	472	546a	-74c	472a	398a
SX733	I0	472	373d	99a	163e	261c
	I1	472	393d	79a	219d	298b
	I2	472	471c	2b	359c	361a
	I3	472	517b	-45c	407b	362a
	I4	472	562 a	-89 d	472 a	382 a

PSWS: Pre-sowing soil water storage; SWD: soil water depletion.
Values followed by the same letter in the same season and column were not significant at $P < 0.05$.

Table 9. Root weight and root-shoot ratio of wheat 'Shimai15' (SM15) and 'Shixin733' (SX733).

Treatments	Root weight 0 - 70 cm	70 - 140 cm	> 140 cm	Total root weight	Root-shoot ratio
	g plant⁻¹				%
SX733	0.917B	0.174B	0.056A	1.147B	7.3B
SM15	1.390A	0.304A	0.000B	1.694A	10.5A

Values followed by the same letter in the same season and column were not significant at $P < 0.05$.

layers, respectively. The analysis of the results indicates that the higher total root weight and root-shoot ratio is important for the water-saving cv. SM15 and massive soil profile water was absorbed by the roots in the top soil layers; the water-saving cv. SM15 demonstrated remarkable GY over the higher yielding cv. SX733, especially in dry years. Its larger root system contributed to yield stability by absorbing more water from deep soil, while most soil profile water was absorbed by deeper roots in the higher yielding SX733 cultivar. Thus, due to the frequent extreme climate in the NCP, especially dry weather, high-yielding and strongly drought-resistant wheat should first be considered.

Relationship between yield components and meteorological factors

The variation of yield components mainly depends on cultivation practices, varieties, and meteorological factors, such as seasonal precipitation distribution, active accumulated temperature ($\sum t \geq 0$ °C), average temperature, sunshine duration, hot and dry wind, and air humidity. The spike number was greatly stimulated by the higher $\sum t$ (≥ 0 °C) during the sowing and dormant periods. Before the winter wheat reviving stage (28), suitable climatic conditions can promote effective spikelet number, which is the foundation of high yield. Moreover, a larger population will be formed if the accumulated temperatures are high enough before winter (Xing et al., 2005). The results in the present study showed that there was a significantly positive correlation between spike number and $\sum t$ from sowing to the dormant period from 2005 to 2009 ($r = 0.585^{**}$, n = 19) (Figure 4); an appropriately high temperature in the winter improves wheat production, which agrees with Li et al. (2009).

Some studies found that the growth rate and many crop plant development processes are controlled by temperature. Lobell and Field (2007) reported a 0.6% to 8.9% reduction in mean crop (wheat, maize, rice) yield for each 1 °C increase in temperature on the global scale. Spike differentiation is one of the most essential stages for wheat reproductive development and the foundation of spike characters. Some environmental factors affect spike differentiation processes and result in yield variability. Results showed that grain number per spike was negatively correlated with average temperature in March and April ($r = -0.514^{*}$, n = 19) during the spike differentiation period (Figure 5). The lower average temperature (approximately 11.7 °C) in March and April tended to delay spike differentiation and significantly promoted grain number per spike.

Meteorological changes from the milk to harvest stage are important factors influencing grain weight. The relationship between 1000-grain weight and meteorological factors is shown in Figure 6. There were significant correlations between grain weight and average temperature, sunshine duration, and wind speed. Since the variation of grain weight is caused by the interaction of many factors, including meteorological changes and irrigation, a stepwise regression equation is used here to show their relationships from 2005 to 2009: $Y = 30.232 + 1.079X2 - 0.549X4$ where Y is 1000-grain weight, X2 and X4 are sunshine duration and wind speed, respectively. Furthermore, other dependent variables of X include average temperature (X1), humidity (X3), rainfall (X5), dry and hot wind days (X6), and irrigation (X7). Results showed that sunshine duration and wind speed were the most important factors influencing grain weight; there was a significant correlation between these two variables and grain weight ($R = 0.999^{*}$, n = 3). The partial correlation coefficients of the two variables were similar (Table 10). Results showed that longer daylight hours and an appropriate wind speed (1.5-2 m s^{-1}) were beneficial to improve grain weight. The direct path coefficient and the partial correlation coefficient were in the same order (Table 11), and the direct pass coefficient was P2y (1.160) > P4y (0.200). Results exhibited that sunshine duration played a key role in the formation of grain weight, while the direct influence of wind speed on grain weight was less important. The highest 1000-kernel weight was achieved in the 2007-2008 and 2008-2009 seasons with 5.1% increase as compared with other seasonal gains. In this research study, the effect of rainfall at the milk stage was not apparent. However, some studies (Li et al., 2009) found that the highest correlation time between GY and periodical precipitation was in the milk stage; moreover, a high level of soil moisture during the milk grain stage

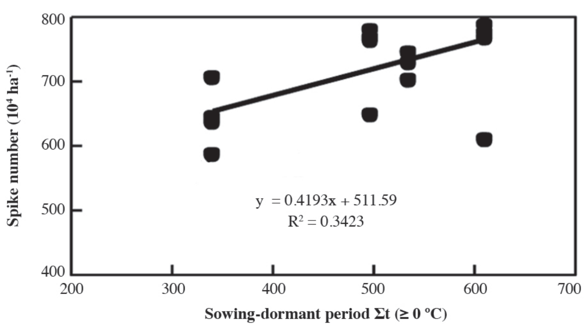


Figure 4. Relationship between spike number and $\sum t$ (≥ 0 °C) in sowing to dormant period from 2005 to 2009.

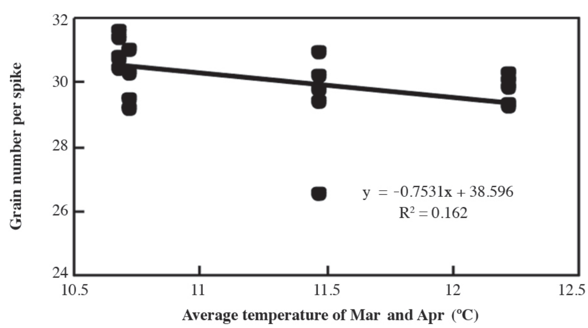


Figure 5. Relationship between grain number per spike and average temperature in March and April from 2005 to 2009.

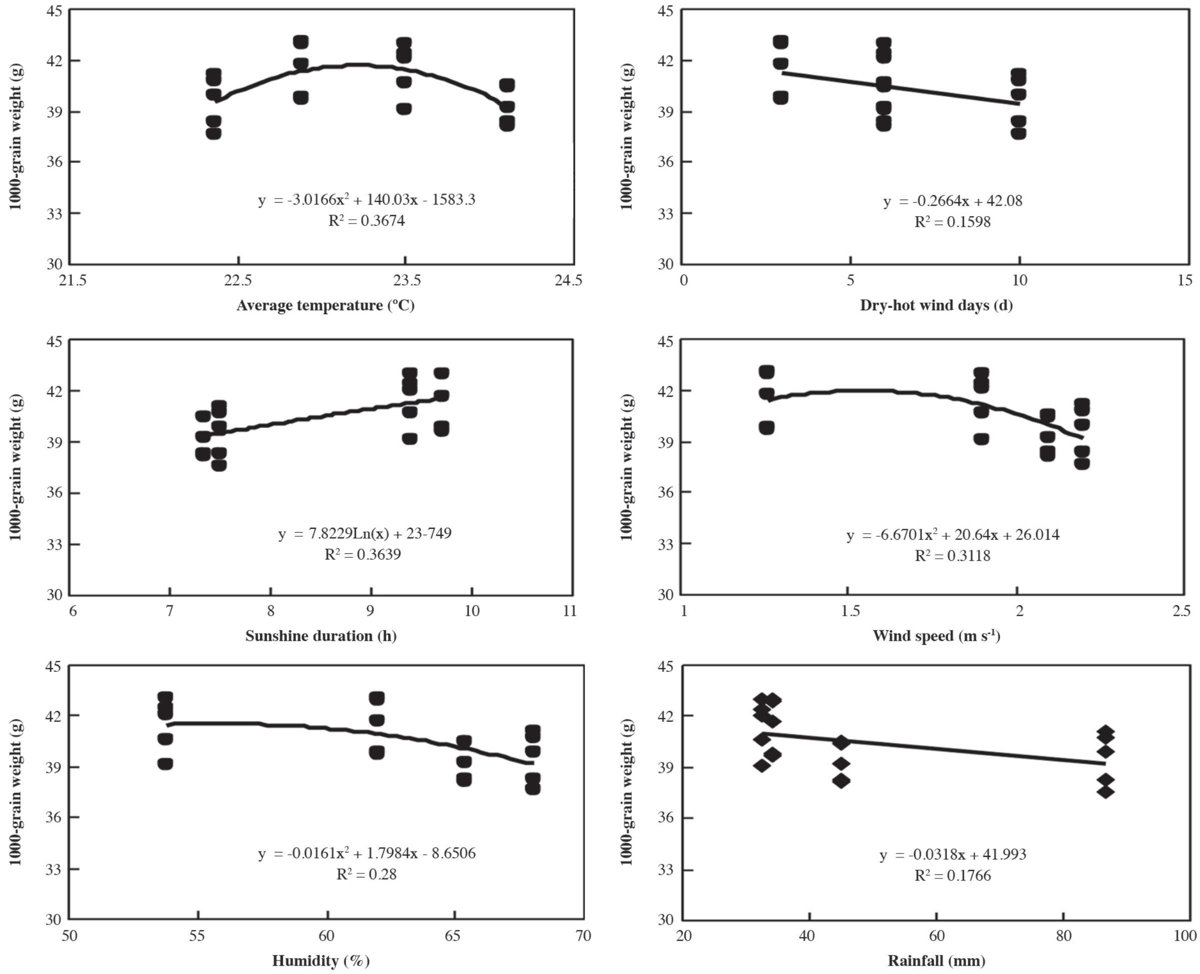


Figure 6. Relationship between 1000-grain weight and meteorological factors for the last 20 d before harvest for 2005 to 2009.

is not beneficial and can lead to reduced grain weight and GY (Jia et al., 2009).

High temperatures reduce wheat yield in the NPC. An extreme climate frequently occurs, such as extreme high temperatures at the late milk stage and chilling damage at the pre-winter or reviving stage. This should therefore be considered when deciding the sowing date, variety selection, and all other agronomic practices.

Table 10. Partial correlation of the 1000-grain weight (Y) with sunshine duration (X2) and wind speed (X4) from the late milk stage to harvest stage.

Partial correlation coefficient	Partial correlation coefficient value	t value	Significant level (P)
r(y,X2)	1.000	45.243	0.000
r(y,X4)	0.992	7.787	0.016

Table 11. Contribution to grain weight of dependent variables.

Variable	Path coefficient		
	Direct coefficient	→X2	→X4
X2	1.160		-0.166
X4	0.200	-0.967	

Coefficient of determination = 0.999.

CONCLUSIONS

The most frequently irrigated treatment (I4) in three of the four seasons slightly decreased maximum GY, which can be achieved with three irrigation treatments (irrigation at jointing, flowering, and milk stages) in dry seasons and two irrigation treatments (irrigation at jointing and flowering stages) in normal seasons. An additional irrigation at the reviving stage can significantly promote yield by increasing spike number in those years with insufficient wheat population at the pre-winter stage due to late sowing or insufficient accumulated temperature.

Grain yield was significantly related to seasonal full ET and a 410 to 530 mm seasonal full ET, including 143 mm rainfall and 214 mm irrigation water, which led to maximum GY. The present study shows that an appropriate PSWS, rather than the maximum, should be established for better GY and WUE. With the integrated contribution of optimal irrigation manipulation, appropriate PSWS, favorable weather conditions, WUE was as high as 3.52 kg m^{-3} with yield up to 9710 kg ha^{-1} in 2008-2009.

In dry years, the water-saving SM15 cultivar demonstrated remarkable GY over the higher yielding SX733 cultivar, while both cultivars achieved very similar GYs in the normal and wet years. For SM15, its larger root system contributed to yield stability by absorbing more water from deep soil. Thus, due to the frequent extreme climate in the NCP, especially dry weather, high-yielding and strongly drought-resistant wheat should first be considered.

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