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Performance of winter wheat under different irrigation regimes associated with weather conditions in the North China Plain

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Abstract

The North China Plain (NCP) is one of the most important regions for grain production in China. However, its agricultural system is being significantly affected by ongoing climate change and is becoming vulnerable with water shortage. This study investigated the responses of wheat production under six irrigation treatments (from rain-fed up to five irrigations) during 2007 to 2012. The results showed that yield of winter wheat under rain-fed condition was around 2974.3 kg ha^{-1} in the driest season of 2010-2011, up to 6248.9 kg ha^{-1} in the wet season of 2007-2008. The larger seasonal variation in yield under rain-fed condition was related to seasonal rainfall and its distribution. The seasonal variation in yield was much reduced when winter wheat was well irrigated, and its seasonal yield variation was significantly related to the seasonal temperature conditions. Evapotranspiration, soil water depletion, drainage and water use efficiency (WUE) were affected both by weather conditions and irrigation. Average yield increase were 1593.7 kg ha^{-1}, 343.4 kg ha^{-1}, 116.7 kg ha^{-1}, 82.9 kg ha^{-1} and 26.2 kg ha^{-1} by adding one more irrigation from rain-fed up to 4 times, respectively, during the five seasons. The benefit of increase irrigation numbers was significantly reduced with the further increase in irrigation. Average WUE for the five seasons was 2.15, 1.83, 1.76, 1.66, 1.48 and 1.38 kg m^{-3} from rain-fed up to five irrigations, respectively. WUE was decreased with the increase in irrigation. Then moderate irrigation (one or two irrigation applications) was recommended in this region for the purposes of relative higher WUE and grain yield. This practice will also reduce percolation that reduced the nitrogen leaching risks.

Keywords: Yield components; Irrigation; Soil water depletion; Weather condition; Water use efficiency.

Abbreviations: NCP_the North China Plain, WUE_Water Use Efficiency, SWD_Soil Water Depletion, D_Drainage from the root zone, ET_Evapotranspiration, ET$_0$_Rreference Evapotranspiration, HI_Harvest Index, LSD_Least Significant Difference, FAO_Food and Agriculture Organisation.

Introduction

Winter wheat is a globally important grain crop. Three main growing phases are relevant for determination of the grain yield of winter wheat (Bindraban et al., 1998). The development of those phases was influenced by temperature, radiation, precipitation and other weather factors. The frequency and magnitude of extreme weather events are predicted to increase with global warming (IPCC, 2007; Mikhail, 2009). The changing climate would affect crop growth, yield and water use. Global warming generally reduces the yield of grain crops because of accelerated plant development, reduced grain fill duration and dryness (Mikhail, 2009). Lobell and Field (2007) reported a 0.6-8.9% reduction in main crop (wheat, rice, maize, barley, soybean, sorghum) yield per 1℃ rise in temperature at the global scale. You et al. (2009) found that a 1℃ increase in wheat growing season reduced wheat yield by approximately 3-10%. Rising temperatures over the past two decades accounts for a 4.5% decline in wheat yields in China (You et al., 2009). Zhang et al. (2013) found that the weather-driven yield of winter wheat was declining by 10% during the past three decades in NCP. It was predicated that winter wheat yields would decrease from approximately 13.5% to 32% under most climate change scenarios in southern Australia (Luo et al., 2005). Crop evapotranspiration (ET) and water use were also altered with climate change (Thomas, 2000; Guo et al., 2010). Ju et al. (2010) found that elevated temperature changed the water distribution and storage in the root-zone soil profile. Liu and Lin (2004) reported that in North China, when the temperature increased 1-4℃ in the growing season of winter wheat, the water requirement was increased by 11.8-153.0 mm. Guo et al. (2010) predicted that the average ET of winter wheat would increase by 3-19% and that Water Use Efficiency (WUE) would vary by -8.1 to 4.3% under future climate change projections in NCP. Soil water contents were negatively related to temperature and positively related to precipitation. Due to the influence of climate warming, rain-fed farming areas showed a decrease in soil moisture in recent years. Climate warming resulted in an increase in evaporation and thus accelerated the drying rate of soil. NCP is one of China's most important grain production areas, contributing approximately 41% of the national wheat yield (Guo et al., 2010). Because the

Table 1. Timing and amount of irrigation for different treatments to winter wheat during 2007-2012.

Treatments	Irrigation timing and amount (mm)					Total irrigation
	Before-wintering	Jointing	Booting	Heading-anthesis	Grain- fill	
Rain fed (I0)	---	----	---	---	---	0
One irrigation (I1)	---	80-90	---	---	---	80-90
Two irrigations (I2)	---	80-90	---	70-90	---	150-180
Three irrigations (I3)	75-90	80-90	---	70-90	---	225-270
Four irrigations (I4)	75-90	80-90	80-120	---	60-75	295-375
Five irrigations (I5)	75-90	80-90	80-120	70-90	60-75	365-465

growing season for winter wheat in this region is from October to June, which is the dry season of the year, irrigation is important for high yielding of this crop. However, the overdraft of groundwater for irrigation has caused a rapid decline in the groundwater table that threatens the sustainable irrigation agriculture in this region. The increase in water scarcity in the NCP has led to many studies on increasing crop water productivity of winter wheat by optimizing the irrigation schedule (Zhang et al., 2003, 2008). Its agricultural systems are also being significantly affected by ongoing climate change and becoming vulnerable with water stress (Mo et al., 2009). Because severe drought had occurred more often since the late 1990s, there was an increasing trend of extreme dryness in NCP. The high frequent extreme dryness was consistent with the warming trend in this region. Changes in climate and extreme weather events are likely to have an impact on the hydrological cycle and consequently on available water resources and agricultural productivity (Tao et al., 2003; Mikhail, 2009). Because of this impact, it is important to study the integrated effects of weather and irrigation on winter wheat production in NCP This study used field experimental data from five seasons to analyze the weather factors on yield, yield components and water use efficiency of winter wheat under six irrigation treatments, and it might provide references for optimizing irrigation management in this region under a changing climatic environment.

Results and Discussion

Weather conditions during the five winter wheat growing seasons

Figure 1 shows the average values of every ten days for daily temperature (Tmean), sunshine hours, ET_0 and accumulative rainfall during the five seasons, as compared with their corresponding long-term average values. There were large variations among the weather factors during the five seasons, especially for rainfall. The seasonal rainfall was 212.5 mm during 2007/2008, 109.7 mm during 2008/2009, 77.4 mm during 2009/2010, 53.3 mm during 2010/2011,82.3 mm during 2011/2012. Compared with the long-term average which was 125 mm, 2007/2008 was a wet season, and the others were dry seasons. The 2010/2011 season was extreme dry, and from sowing to booting, there was no effective rainfall. The dry period lasted 174 days. Accumulated temperature (>0^{o}C) for the five seasons was 1859.8 ^{o}C, 2047.0 ^{o}C, 1649.3 ^{o}C 1869.9 ^{o}C and 1743.2^{o}C. Except for the 2009/2010 season, accumulated temperature was higher than the long-term average of 1743.1 ^{o}C. Unusually low temperature occurred earlier during the seedling stage of winter wheat in the 2009/2010 season (Fig. 1). Total seasonal sunshine duration for the five seasons was 1172.0 hr, 1388.0 hr, 1276.8 hr, 1675.8 hr and 1184.6 hr. The value of the long-term average is 1201.6 hr. Compared with the long-term average, sunshine conditions in the 2007/2008 and in 2011/2012 seasons were poor, whereas it was quite good in the 2010/2011 season. Sunshine conditions affected potential ET. The ET_0 for the five seasons was 663.3 mm, 729.6 mm, 725.6 mm, 869.0 mm and 668.1mm. The long-term average was 716.4 mm. The seasons with longer sunshine hours had higher ET_0. The sunshine duration was in a positive linear relationship with ET_0, with R^2=0.7145**, *Y=4.1199X-1213.3*, Where *Y* was the sunshine (hr), *X* was the ET0 (mm).

Weather factors on the effects of yield and yield components

The three yield components that decide the final yield of winter wheat are spike numbers per area, kernel numbers per spike and kernel weight. A correlation analysis of all the treatments for the five seasons showed that there was no significant relationship between yields with any of the three components. However, the grain yield of winter wheat was significantly related to kernel numbers per area (P<0.01), *Y=2.3696X-493.1*, Where *Y* was the yield and *X* was the kernel number per area. This is decided by the spike number per area and kernel number per spike. No significant relationship was found between yield and seed weight. The results indicated that the combination of the three yield factors decided the final production. Weather factors that affected any of the three factors would significantly affect the other two factors and then the final grain yield. The highest yield in each season was selected to analyze the seasonal yield variation (Table 2). The results showed that there was an approximate 22.8% yield difference among the seasons. Weather conditions significantly affected grain production of winter wheat in NCP. The 2010/2011 season produced the highest yield among the five seasons. Spike numbers per area in that season were the highest among the fives seasons. In contrast, the 2009/2010 season produced the lowest yield. Spike numbers per area in that season were significantly lower than those in the other four seasons, and the low spike number per area was the main reason for the lower yield of the crop in that season. The low spike numbers per area was caused by a rapid temperature decline in the seedling stage that shortened the seedling stage’s duration (Fig. 1). Because tiller numbers were reduced, the final spike numbers per area were lower. The duration from sowing to over-wintering had a positive linear relation with the final spike numbers per area (*P*<0.01). The relatively lower yield in the 2008/2009 and 2011/2012 season was caused by the lower kernel numbers per spike, as affected by the rapid temperature increase from recovery to jointing, which shortened the spike differentiation and reduced the kernel numbers per spike. A positive relationship was found between the duration from recovery to jointing and the kernel numbers per spike (*P*<0.05).

Other researches also showed that kernel numbers per spike fluctuated with changing environmental conditions, such as solar radiation (Fischer, 1975; Savin and Slafer, 1991) and temperature (Wardlaw, 1970). Sun et al. (2004) showed that the main elements affecting kernel numbers per spike for winter wheat were the duration and accumulative temperature from

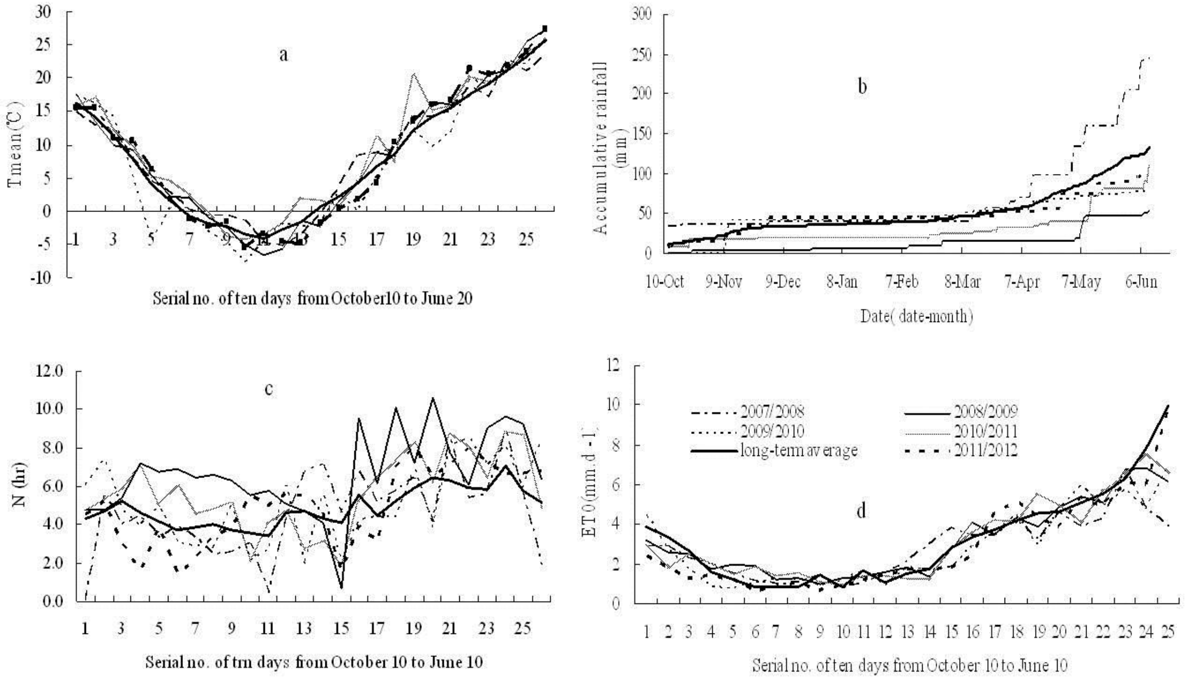

Fig 1. Climatic parameters during the five growing seasons of winter wheat from 2007-2012 and the long-term average (1987-2012). (Value of every ten days' average from sowing to maturity: (a) daily temperature (Tmean), (c) daily sunshine duration (N), (d) daily reference evapotranspiration (ET_0); and (b) accumulative rainfall.

the time when the 5-day average temperature was over 4℃ during the jointing stage after winter dormancy in NCP. When there was a higher accumulative temperature over a longer period of time, the kernel number per spike was higher. The lowest kernels per spike occurred in the 2008/2009 and 2011/2012 seasons, when there was the shortest amount of days over 4˚C and the lowest accumulative temperature. The two seasons had 36 and 30 days over 4˚C and an accumulative temperature of 410.0 and 311.4˚C, respectively. The highest kernel numbers per spike occurred in the 2007/2008 season when there were 45 days over 4℃ and an accumulative temperature of 425.3˚C.

The lower 1000 kernel weight in the 2008/2009 season was caused by the dry-hot wind during the later grain-fill stage, which caused an unbalanced water supply because root water uptake could not match the water lost by transpiration from the crop canopy. The unbalanced water supply then caused an intensified respiration consumption and slowed down the nutrient accumulation in the grain, finally forcing the crop to mature earlier. It was reported that the probability of dry-hot wind occurring was approximately 50% in NCP. With temperature rising and dryness occurring more often, the dry-hot wind could occur more frequently in the future and, as a consequence, would shorten grain-fill duration and reduce the final grain production. Figure 2 shows there was a significant positive relationship between the duration from anthesis to maturity and kernel weight.

Irrigation numbers on the effects of yield under different weather conditions

The water consumption of winter wheat is approximately 450-500 mm under full water supply in NCP (Liu et al., 2002; Zhang et al., 2003). Even in a wet season, there is far less rainfall than the requirements of the crop. Under a deficit irrigation supply, seasonal rainfall and its distribution significantly affected the grain yield of winter wheat. For treatment I0 (no irrigation during the growth period), the yield varied from a low of 2947.3 kg ha^{-1} in the 2010/2011 season to a high of 6248.9 kg ha^{-1} in the 2007/2008 season, a difference of 3303.1 kg ha^{-1} (Fig. 3). The highest and the lowest yield corresponded with the wet and the dry seasons. There was a significant positive correlation between yield and seasonal rainfall under rain-fed conditions (R^2=0.8268*). Figure 4 showed there was an apparent difference in soil moisture among the five seasons under rain-fed conditions. The low soil moisture in the 2010/2011 season during recovery to booting significantly reduced kernel numbers per spike and resulted in the small yield (Table 3). With the increase in irrigation supply, the relationship between winter wheat yield and seasonal rainfall became less significant. Under one irrigation supply (I1), the relationship was still significant (R^2=0.9079**). However, with two irrigations, no significant relationship was found between the two factors. Under increased irrigation supply conditions, the yield of winter wheat was affected more by other weather factors other than rainfall (Fig. 3). The yield increase from irrigation changed with the seasons. In the wet season of 2007/2008, a yield increase occurred from rain-fed to one irrigation application. A further increase in irrigation did not affect the yield. In the dry season of 2010/2011, a yield increase occurred from rain-fed up to five irrigation applications. A positive linear relationship existed between the amount of irrigation and the yield ($P<0.05$). In the 2008/2009 season, no yield increase was found when two or more irrigations were applied, while in the 2009/2010 season, the yield reached its highest when up to four irrigations were applied. While in 2011/2012 season the highest yield was achieved with two irrigations. The results showed that the highest yield in different seasons was not necessary achieved

Table 2. The treatments with the highest seasonal yield and the corresponding yield components for winter wheat during 2007-2012.

Seasons	Treatments	Grain Yield (kg ha^{-1})	Kernel numbers (kernels spike$^{-1)}$	Spikes (spikes m^{-2})	1000 kernel weight (g)
2007/2008	Three irrigations	7139.7b	36.2 a	399.45b	41.13 ab
2008/2009	Two irrigations	6600.3 cd	25.9 b	625.55a	40.6 b
2009/2010	Four irrigations	6432.5 d	35.1 a	393.33b	41.99 a
2010/2011	Five irrigations	7902.3a	34.7 a	725.0a	40.56 b
2011/2012	Two Irrigations	6796.9 c	25.9b	643.33a	41.22 ab
SE		139.05	2.89	76.61	0.32
LSD（5%）		261.81	5.43	144.25	1.07

In each column, the means with the common letter do not differ significantly at the 5% level of probability.

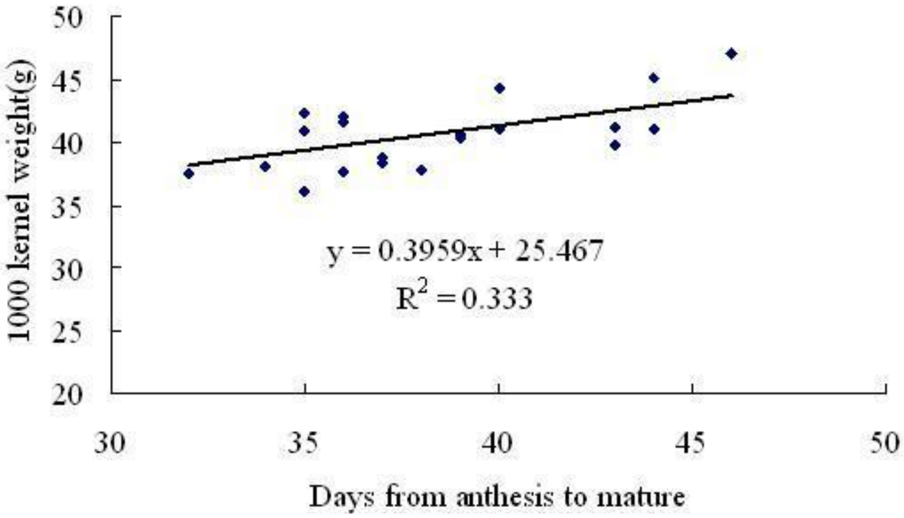

Fig 2. The relation of kernel weight with the length of grain-fill duration. Legends must be more informative.

with the most frequent irrigated treatments.

Water use and water use efficiency under different irrigation

Soil water depletion (SWD), drainage from the root zone (D), evapotranspiration (ET) and water use efficiency (WUE) for winter wheat with different irrigation treatments from 2007 to 2012 were listed in Table 4. Irrigation applications significantly affected SWD, D, ET and WUE. SWD was decreased and D was increased with the increase in irrigation applications. ET of rain-fed treatment was the lowest, and its WUE was generally the highest among the six irrigation treatments for each season. An increase in irrigation applications increased D and ET simultaneously, reduced SWD and resulted in lower WUE. There was a significant positive correlation between drainage and irrigation amount (R=0.599**, $P<0.05$) and significant negative correlation between SWD and irrigation amount (R=-0.359**, $P<0.05$).

ET was affected by weather conditions. Under a full water supply, seasonal ET of winter wheat was positively related to seasonal ET_0 ($P<0.05$). The 2010/2011 season had the highest ET_0, and ET during that season under irrigated conditions (from I3 to I5) was also the highest. Under limited irrigation, ET was affected by both weather conditions and irrigation amount.

The results from Table 4 indicated that the proportion of SWD and D over ET was influenced by rainfall and irrigation applications. The ratio of SWD over ET was reduced with more irrigation applications in each season. In a wet season such as 2007/2008, the highest ratio of SWD/ET was approximately 28%, and in a dry season such as 2010/2011, the highest ratio of SWD/ET was approximately 80%. The results showed that soil water depletion played an important role in supplying crop water use under dry conditions with a limited water supply. The role of the stored soil moisture before sowing was negatively related to irrigation applications. The ratio of D over ET was increased with more irrigation applications in each season. In a wet season such as 2007/2008, the highest ratio of D/ET was approximately 20.9%, and in a dry season, such as 2009/2010 and 2010/2011, the highest ratio of D/ET was approximately 4.7% to 8.6%. The results indicated that over-irrigation in a wet season increased the risk of deep percolation that might increase the risk of nitrogen leaching (Li et al., 2007). Generally, as shown in Fig. 5, with the increase in ET, WUE was decreased and grain yield was increased. The results from this study showed that the average yield increase was 1593.7 kg ha^{-1} from rain-fed to one irrigation, 343.4 kg ha^{-1} from one irrigation to two irrigations, 116.7 kg ha^{-1} from two to three irrigations, 82.9 kg ha^{-1} from three to four irrigations and 26.2 kg ha^{-1} from four to five irrigations during the five seasons. The maximum yield increase occurred from rain-fed to one irrigation, while the average yield increase decreased with further increase in irrigation numbers. Thus, in a water deficit region, total grain production might be increased more by expanding the irrigation area than that by increasing the irrigation water use per area. The reduction in yield with increased irrigations could be attributed to the delayed development

Table 3. Yield and yield components under rain-fed condition for winter wheat during 2007-2012.

Seasons	Grain Yield (kg ha^{-1})	Kernel numbers (kernels $spike^{-1}$)	Spikes (spikes m^{-2})	1000 kernel weight (g)
2007/2008	6248.9 a	31.2 a	422.2 ab	47.2 a
2008/2009	4330.5 b	26.1 b	398.3 ab	40.3 c
2009/2010	4555.6 b	32.8 a	300.0 c	36.1 d
2010/2011	2974.3 c	21.6 c	336.7 bc	42.0 b
2011/2012	4597.3 b	26.6 b	440.6 a	39.9 c
SE	200.35	1.57	46.22	0.51
LSD(5%)	377.23	2.95	87.02	0.96

In each column, the means with the common letter do not differ significantly at the 5% level of probability.

Table 4. Soil water depletion(SWD), drainage from the root zone(D), evapotranspiration(ET), and water use efficiency(WUE) for winter wheat under different irrigation treatments from 2007 to 2012.

	2007 to 2008				2008 to 2009				2009 to 2010				2010 to 2011				2011 to 2012			
Treat-ments	SWD	D	ET	WUE	SWD	D	ET	WUE	SWD	D	ET	WUE	SWD	D	ET	WUE	SWD	D	ET	WUE
I0	83.7a	4.9c	291.3d	2.14a	74.3b	19.2c	164.8e	2.77a	147.6a	27.1a	185.8d	2.45a	199.4a	7.6a	244.9d	1.23b	132.8b	0.01c	215.1e	2.12a
I 1	59.8a	24.2c	338.0cd	2.09a	95.8a	29.0bc	355.8d	1.58b	146.8a	28.7a	273.4c	1.91b	227.1a	12.2a	348.1c	1.63a	149.4a	0.74c	321.0d	1.94b
I 2	48.9a	58.6b	366.6c	1.93b	74.5b	37.3bc	356.9cd	1.63b	131.2a	34.2a	322.3b	1.81b	196.4a	10.5a	389.1bc	1.66a	145.2ab	10.68bc	381.8c	1.78c
I 3	47.7a	78.1ab	423.3b	1.69c	65.1b	56.5ab	388.3c	1.60b	112.4b	62.1a	345.6b	1.81b	192.0a	10.8a	444.4b	1.66a	117.9c	27.72ab	412.5b	1.54d
I 4	42.9a	97.5a	472.8b	1.52d	42.1c	47.1abc	444.7b	1.45b	105.4b	37.9a	362.7b	1.77b	221.7a	9.3a	555.5a	1.30b	107.7c	46.45a	47.5a	1.39e
I 5	-1.9b	104.1a	496.9aa	1.42d	39.9c	68.9a	510.7a	1.21c	100.0b	53.5a	411.9a	1.50c	170.0a	13.4a	569.6a	1.39b	44.8d	45.08a	487.0a	1.36e

Note：Values marked with the same letter in the same column were not significant at $p < 0.05$.

Abbreviations : SWD(mm):Soil water depletion , D,(mm):drainage from the root zone , ET (mm): evapotranspiration, WUE(kg m^{-3}) :water use efficiency.

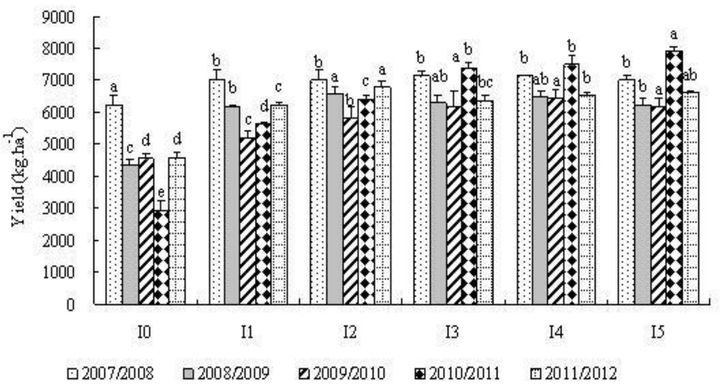

Fig 3. Yield of winter wheat under six irrigation treatments for five seasons during 2007-2012 (I0: no irrigation; I1: One irrigation; I2: Two irrigations; I3: Three irrigations; I4: Four irrigations; I5: Five irrigations). (Bars represent standard deviation of four replicates).

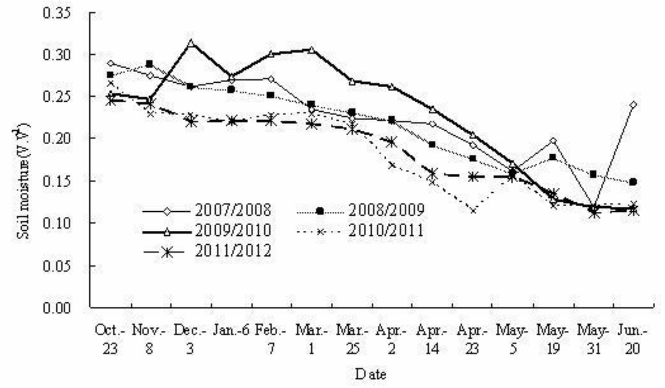

Fig 4. Changes of average soil water contents of the top 50 cm of soil layer under rain-fed condition for the five seasons of winter wheat during 2007 to 2012.

of winter wheat. The anthesis date of more frequently irrigated wheat was usually delayed by 2 to 4 days when compared with deficit irrigated winter wheat in NCP. The frequently occurring hot-dry wind during the later grain-fill stage often shortened the duration of grain-fill that reduced seed weight. The full yield potential of well irrigated winter wheat could not be achieved, resulting in reduced yield and WUE (Zhang et al., 2003). The lower WUE of the full irrigated winter wheat might also be attributed to the wet soil surface that increased soil evaporation. Liu et al. (2002) found that approximately 30% of ET was from soil evaporation and it was highly affected by surface soil water contents. The more frequently irrigated winter wheat increased surface soil moisture, which increased soil evaporation consumption. Zhang et al. (2008) found that deficit irrigation scheduling might be more suitable for winter wheat grown in the NCP, where water shortage is becoming more serious.

Variation trend in weather parameters on yield and irrigation requirements

Analysis of the weather parameters in the past three decades from 1980 to 2012 at the experimental site showed that seasonal rainfall during winter wheat growing season was in a slightly declining trend, around 7 mm decade^{-1}. Atmospheric evaporation demand (ET_0) was relatively constant over the three decades. Though there was a decrease in humidity and an increase in temperature that had positive effects on ET_0, while decrease in wind speed and sunshine had negative effects on ET_0. The four factors counteracted each other and their overall effects on ET_0 were smaller (Zhang et al., 2011). With a relative constant ET_0 and slightly reduced seasonal rainfall, the irrigation water requirements for winter wheat would increase in future if this climate change continued.

The results from this study showed that temperature was the main factor influenced winter wheat yield under good water supply condition. Analysis of the temperature change in the past three decades at the experimental site showed that there was increase trend ($P<0.01$) for daily mean T (Tmean). Tmean was increased by 0.07 ^{o}C per season. The increase in temperature would shorten crop phenological phases and reducing carbon assimilation (Liu et al., 2010). Results from this study showed that the longer duration from recovery to jointing and grain-fill benefited seed numbers per spike and seed weight, respectively. The increasing in Tmean would shorten the durations of spikelet differentiation and grain-fill that would negatively affect grain production. Statistic analysis showed that the duration from recovery to jointing was shortened around 1.8 d and dry-hot wind occurred earlier by 2 d from 1980s to present at the experimental site. This trend of climate change in temperature might have negative effects on local grain production.

Materials and Methods

Experimental site

This study was conducted at the Luancheng Agro-Eco Experimental Station of the Chinese Academy of Sciences, which is located at the base of Mt. Taihang (37.53′N, 114.40E, and 50 m above sea level) in NCP. The average annual precipitation is 482 mm with 70% falling in summer (from June to September). In winter wheat growing season (October to May), precipitation is approximately 130 mm. The loamy soil at the experimental site is moderately well drained and has a deep profile. Soil pH was around 8. In the tillage layer (0-20 cm), the average organic matter content was around 1.7%, and the available N, P, and K contents were approximately 75 mg kg^{-1}, 25 mg kg^{-1} and 140 mg kg^{-1}, respectively.

Winter wheat and summer maize are grown annually as the dominant double cropping system. Winter wheat was generally sown during early October with row spacing of 0.16 m and a density of 300 seeds m^{-2}. Initial tillering began in early November and continued through the month. December, January and February then formed a long dormant period. At the end of the dormancy in March, winter wheat began to recover. The jointing stage was at the beginning of April, followed by booting during the rest of the month. The ear emergency and flowering stages occurred at the end of April or the beginning of May. From then on, the grain filling began. Harvesting typically occurred during the first 10 days of June. Chemical fertilizers (N, P) were applied as base fertilizer. At the jointing stage, nitrogen was applied again with a rate of 150 kg ha^{-1}. Maize was planted immediately after winter wheat and harvested at the end of September. At the beginning of October, land was plowed to prepare for winter wheat planting and the two-crop rotation was repeated. Depending on rainfall amounts during the rainy season, land was irrigated in some dry years to ensure that soil moisture conditions were favorable for sowing wheat.

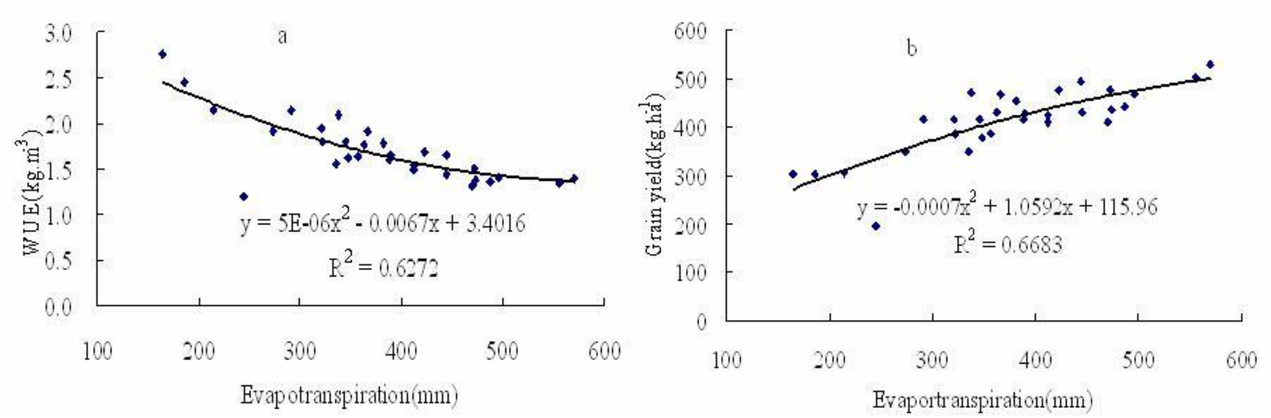

Fig 5. Relation of water use efficiency (WUE) with evapotranspiration (a), and yield with evapotranspiration (b) during 2007 to 2012

Irrigation treatments

The experiment was conducted during the winter wheat growing seasons from 2007 to 2012. Winter wheat was sown in small plots in a randomized block design with four replications of six irrigation treatments. Each plot was 5 m × 8 m, and separated by a 2 m wide zone planted with non-irrigated winter wheat to minimize the mutual effects of adjacent plots. The six irrigation treatments were from rain-fed (I0) up to five irrigations (I5) (Table 1). Except for the irrigations, other field management measures were the same for all the treatments. At each irrigation treatment, 60-90 mm of water was applied to the soil by surface irrigation using a low-pressure tube water transportation system with a flow meter to record the irrigation applied to each plot.

Plant materials

The winter wheat cultivar "Kenong199" was used for the study. It was a national certificated cultivar (in 2006) and breeded by traditional breeding method at the center for agricultural resources research, institute of genetics and developmental biology of Chinese Academic of Science. The cultivar was a widely grown cultivar in NCP.

Weather parameters

Weather parameters (including daily temperature, humidity, wind speed, radiation and precipitation) were monitored at a standard weather station approximately 100 m from the experimental site. The average values for every ten days during the growing period (except for rainfall) were calculated. Accumulated rainfall during the whole growing seasons and during different growing stages were also calculated. The factors during the experimental duration were compared with the long-term average (from 1980s to present). Daily ET_0 was calculated using the FAO Penman-Monteith equation, which represents the definition of the grass reference (Allen et al., 1998).

Measurements

The date of the appearance of a certain phenology was recorded, in particular, the heading and anthesis date for all the irrigation treatments. At maturity, plots were harvested manually and then threshed using a stationary thresher. Grain was air-dried prior to recording weights. Prior to harvest, spike numbers per unit area were counted again, and 80 plants were collected from each plot to determine kernel numbers per spike, kernel weight and harvest index (HI). Soil water contents were monitored regularly at 20 cm intervals to a depth of 2 m using a neutron meter (IH-II, Cambridge) with access tubes installed in the center of the plots. Total water use or ET was calculated from initial soil water content minus final soil water content, precipitation, irrigation, runoff, drainage and capillary rise using the following equation: $ET=P + I + SWD - R - D + CR$, where ET was evapotranspiration in the growing season (mm), P was precipitation (mm), I was irrigation (mm), SWD was soil water depletion in the 200 cm soil profile (it was the total soil moisture at sowing minus the total soil moisture at harvest for the 2 m soil profile), R was runoff (mm), D was drainage from the root zone (mm) and CR was capillary rise to the root zone (mm). Since the small rainfall during winter wheat growing season, runoff was zero. CR was taken as zero because of the deep groundwater table (40 m below surface). D was calculated following Zhang et al. (2008) and Liu et al. (2013). It was determined based on the Darcy's law. Soil water potential at 160 cm and 180 cm was used to calculate the water leaching from the bottom of the root zone in this study. Soil matric potential was calculated from the soil water retention curves developed at the same site. Soil hydraulic conductivity was calculated using an exponential relationship with soil volumetric water content. Water use efficiency (WUE, kg m^{-3}) was defined as WUE = Y / ET, where Y is grain yield.

Data analysis

All data collected were statistically analyzed as a completely randomized design with four replications using an analysis of variance (ANOVA) to examine differences among treatments (Clewer and Scarisbrick, 2001). The mean separation was done with the Least Significant Difference (LSD) test at 5% probability level using the computerized Statistical Analysis System Software (SAS version 9.0). Linear regression was used to examine the relationship between two factors.

Conclusions

Results from this study showed that weather variation resulted in a 22.8% seasonal yield change under good water supply. This yield change was significantly related to kernel numbers per area that was related to the temperature conditions during the seedling and spike differentiation stages. Though there was a trend of increased temperatures, extremely low temperatures still occurred that significantly reduced the yield. In addition to temperature, rainfall was the main factor deciding the grain yield of rain-fed winter wheat. In an extremely dry season, the yield of rain-fed wheat only produced 37% of the wheat yield with good water supply. The large variation in seasonal rainfall resulted in a large variation in grain yield of dry land winter wheat. The yield of winter wheat response to irrigation was different under different seasonal rainfall and weather conditions. However, with an increase in irrigation numbers, yield increase was decreased. For water conservation purposes, it would be better to adopt a deficit irrigation schedule to reduce irrigation water use for a moderate yield of winter wheat, while the saved water could be used to extend the irrigation area, which would increase total production in the region.

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