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Effect of precipitation change on water balance and WUE of the winter wheat–summer maize rotation in the North China Plain

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ABSTRACT

Limited precipitation restricts crop yield in the North China Plain, where high level of production depends largely on irrigation. Establishing the optimal irrigation scheduling according to the crop water requirement (CWR) and precipitation is the key factor to achieve rational water use. Precipitation data collected for about 40 years were employed to analyze the long-term trend, and weather data from 1984 to 2005 were used to estimate the CWR and irrigation water requirements (IWR). Field experiments were performed at the Luancheng Station from 1997 to 2005 to calculate the soil water consumption and water use efficiency (WUE). The results showed the CWR for winter wheat and summer maize were similar and about 430 mm, while the IWR ranged from 247 to 370 mm and 0 to 336 mm at the 25% and 75% precipitation exceedance probabilities for winter wheat and summer maize, respectively. The irrigation applied varied in the different rainfall years and the optimal irrigation amount was about 186, 161 and 99 mm for winter wheat and 134, 88 and 0 mm for summer maize in the dry, normal and wet seasons, respectively. However, as precipitation reduces over time especially during the maize growing periods, development of water-saving management practices for sustainable agriculture into the future is imperative.

1. Introduction

The North China Plain (NCP) is the largest region of agricultural importance in China. It covers about 18 million hectares of farm lands (18.3% of the national total) and produces about 21.6% of the total grain yield in the country. However, the sustainability of NCP for contribution to China's food supply is facing a great risk, i.e. the shrinking of available water resources. Water shortage in NCP became a great concern in the recent decade (e.g. Liu and He, 1996; Brown and Halweil, 1998; Chen et al., 2003). Since the 1980s, most of the rivers in this region have dried up and now about 70% of water resources for agricultural use are pumped from groundwater. According to Liu and Wei, 1989 more than 70% of the total water consumption in the region has been used by agricultural sector. As a result, the excessive exploitation of groundwater resources from shallow and deep aquifers has caused falling water tables and many other environmental problems (e.g. land subsidence) within the plain. Even in the piedmont plain, the groundwater table was falling around 1 m/year during the last 20 years and there are a number of regions with significant zones of groundwater depression (Jia and Liu, 2002). The situation will continue to deteriorate as area of irrigation increases.

Agricultural sector is the largest water use in NCP region and is considered as the major reason for groundwater decline. The annual agricultural water consumption is about 800–900 mm, based on multi-year observations of evapotranspiration in winter wheat–summer maize double cropping system using a large scale weighing lysimeter (Liu et al., 2002). The wheat–maize double cropping system is dominant in NCP region and annually produces grain yields of about 12000–15000 kg ha^{-1}. This increase in grain yield is at the expenses of ground water resources, since the annual water consumption from croplands greatly exceeds the annual precipitation, 400–600 mm, and requires groundwater extraction to offset the deficit for maintaining the high yield. The optimal irrigation amount is about 300 mm for winter wheat in the NCP (Sun et al., 2006). However, the reasonable exploitation rate to avoid the declining water table was reported as 150 mm/year according to the calculation by a statistical model (Chen et al., 2003). Under a drying climate in NCP (Shen et al., 2004), the current water use is obviously unsustainable. So it is expected that

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Table 1
Irrigation and related agricultural activities calendar throughout an entire crop year.

Crop	Irrigation	Apply period	Growing stage	Quantity (mm)	Others
Wheat	1	Beginning of October	Pre-planting	(60–80)[a]	Plough, manure-apply
	2	November 20–December 10	Pre-dormancy	(60–80)	
	3	March 25–April 10	Revival	60–80	
	4	April 25–May 5	Blooming	60–80	Fertilizer-apply
	5	May 10–20	Milking	(60–80)	
Maize	6	June 15–20	Emergence	60–80	
	7	July 10–20	Jointing	(60–80)	Fertilizer-apply

[a] The number with a parenthesis means some of them are possibly not applied if enough precipitation during those growing stages. Totally, the annual irrigation amount ranges from 300–400 mm.

the irrigation quantity or irrigation area would be unavoidably reduced in future if the deteriorating situation cannot be mitigated. The food security will thus be unstable. It is therefore urgent to develop optimum irrigation water managements to avoid further over-exploitation of groundwater and maintain a sustainable crop production (Zhang et al., 2003).

Until now, several efforts on the study of supplemental irrigation and limited or deficit irrigation have been made for improving crop yield and/or increasing irrigation water use efficiency (e.g. Shen and Yu, 1998; Zhang et al., 1999; Wang et al., 2001; Zhang et al., 2003). Currently, the irrigation practices to meet full water requirement are prohibitive due to limited groundwater in the NCP. However, because of the importance of wheat production in the NCP, the interests of researchers and farmers in wheat production are focused on enhancing water use efficiency (WUE) on the basis of increasing crop yields, rather than enhancing WUE by simply limiting irrigation.

Precipitation is one of the most important factors affecting agricultural production, especially in the arid and semi-arid regions. The amount of annual precipitation and its seasonal distribution are crucial for the agricultural production in the NCP because the precipitation directly affects water balance, irrigation requirements, and water use efficiency of the different crops. Studies of such precipitation distribution and trend are thus helpful in defining risk levels in arable agriculture, length of growing periods, and sustainable cropping system. So it is imperative to establish a rational irrigation scheduling according to annual precipitation, its seasonal distribution, and crop water requirements.

The objectives of this study were, therefore:

To analyze the growing season precipitation trend from 1960 to 2005 and crop water requirements and irrigation water requirements for winter wheat and summer maize;

To investigate the effects of precipitation and irrigation on grain yield and water use efficiency for winter wheat and summer maize.

2. Materials and methods

2.1. Study area and agricultural activities

The study area, located at Luancheng County, Hebei Province, China, has a temperate semi-arid monsoon climate, with annual mean temperature of 12.2 °C, annual mean global radiation of 5240 MJ/m^2, and annual mean precipitation of 477 mm over the past 40 years. Precipitation mostly occurred from late June to September. Rotation of winter wheat and summer maize dominates agricultural activities in the region. The typical growing season for winter wheat is from early October to the middle of the following June, and summer maize is planted at the end of winter wheat season and harvested in late September.

Mean precipitation during 1960–2005 was 358 mm in the summer maize season, which can almost meet the water consumption of maize. However, the mean precipitation in winter wheat season is only about 119 mm, which is less than one-third of the water requirement for achieving the average production, so irrigation is mainly applied during wheat season. Generally, there are 4–5 irrigations applied during winter wheat season and 0–2 irrigations during maize season in the region (Table 1). Fertilizer applications are shown along with the irrigations in Table 1. The 3rd, 4th and 6th irrigations listed in Table 1 were always applied. Other irrigations could be avoided if the precipitation was adequate in the corresponding growing stages. So in the study area, the annual total irrigation amount ranges from 300–400 mm by the traditional cultivation and management which is widely adopted by the farmers.

2.2. Data and field experiments

Long-term monthly and growing season precipitation between 1960 and 2005 were collected from the weather station at Luancheng agricultural experiment station. The monthly and annual total precipitation was calculated from the daily precipitation. Growing-season precipitation was obtained by summing precipitation quantity during the two crop growing seasons. Other meteorological variables such as air temperature, humidity, sunshine duration, and wind speed were also collected for calculating the reference evapotranspiration.

2.3. Irrigation experiments

The field experiments were conducted at Luancheng Experimental Station on Agro-ecosystem Research (37.53N, 114.41 E, i.e. 50.1 m), one of the 40 ecosystem stations of Chinese Ecological Research Network (CERN). Irrigation experiments on the double cropping systems were conducted from October of 1997 to October of 2005. There were nine 5 m × 10 m irrigation plots divided by

Table 2
Controlled soil moisture level during different growth stages of winter wheat and summer maize (units: θ/θ_{FC}).

Crops	Treatments	Pre-sowing	Winter dormancy	Recovering	Stem-elongation	Heading	Grain-filling
Winter wheat	A	1.0	1.0	–	–	–	–
	B	1.0	1.0	0.8	0.8	0.8	–
	C	1.0	1.0	1.0	1.0	1.0	1.0
Summer maize	A1	1.0			–	–	–
	B1	1.0			1.0	1.0	1.0

θ: soil water contents; θ_{FC}: soil water contents at field capacity; "–"shows no irrigation applied; 1.0 and 0.8 means the ratio of θ/θ_{FC}.

concrete walls for the treatments for the different irrigation treatments. The walls are 24.5 cm thick and extend 1.5 m beneath the surface. Three kinds of irrigation schedules were tested for winter wheat and two for maize, and each treatment was replicated three times (Table 2). Three kinds of irrigation scheduling were utilized in winter wheat seasons including: treatment A (low irrigation) which was only irrigated before the winter dormancy; treatment B (medium irrigation) which had no irrigation applied during grain-filling stage, irrigating to 80% of the field capacity during other growing stages, which was applied when the moisture of 0–100 cm soil less than 65% of the field capacity; and treatment C (high irrigation) which was irrigated to field capacity with each irrigation applied when soil moisture less than 65% of the field capacity any time during the growing season. Treatment C is adopted as the common irrigation scheduling in the study region. Two kinds of irrigation scheduling were applied in summer maize seasons including: treatment A1 which was only irrigated after sowing; and treatment B1 which was irrigated to field capacity in each irrigation when soil moisture was less than field capacity any time during the growing season. Winter wheat was sown manually at a rate of 150 kg/ha with 20 cm row spacing. Summer maize was sown also manually after the harvest of winter wheat without tillage at the rate of 50 kg/ha with 60 cm width per row.

2.4. Measurements

Soil volumetric moisture was measured by a neutron probe (IH-II, Institute of Hydrology, Wallingford, UK). Access tube was buried in each of the nine experimental plots. Soil moisture was measured at 20 cm intervals from a depth of 20–180 cm approximately every 5 days. Irrigation was manually sprayed and a water meter was installed in the inlet of the tube to measure irrigation water amount. At the end of each growing season the 3 m × 8 m area at the center of each plot was harvested for yield.

2.5. Analysis methods

2.5.1. Crop water requirement (CWR)

The reference evapotranspiration was estimated using FAO Penman–Monteith (1998) equation, which was recommended using the FAO, Rome as a standard method for irrigation planning (Allen et al., 1998):

$$\mathrm{ET}_0 = \frac{0.408\Delta(\mathrm{Rn}-G)+\gamma\frac{900}{T+273}U_2(e_s-e_a)}{\Delta+\gamma(1+0.34U_2)} \qquad (1)$$

ET_0 is the reference crop evapotraspiration (mm/day), Rn the net radiation at crop surface (MJ/m^2/day), G the soil heat flux (MJ/m^2/day), T the average daytime air temperature (°C), U_2 the average daytime windspeed measured at 2 m height (m/s), e_s the saturation vapour pressure (KPa), e_a the actual vapour pressure (KPa), Δ the slope of vapour pressure curve (kPa °C^{-1}), and γ the psychometric constant (= 0.66) (kPa °C^{-1}).

The crop water requirement (CWR) of winter wheat and maize were computed by multiplying the crop coefficient (Kc) with ET_0 at different growth stages (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979). The monthly crop coefficient was taken from locally available values (source from: Liu et al., 2002). The irrigation water requirements (IWR) were estimated by the difference between CWR and precipitation at a monthly time step.

2.5.2. Soil water balance

ET was calculated using the soil water balance equation for the growing season and for individual growth periods as follows:

$$\mathrm{ET} = P + I - D + W_g - R + \mathrm{SWD} \qquad (2)$$

where ET is evapotranspiration (mm), P precipitation (mm); I irrigation applications (mm); D soil water drainage (mm); R surface runoff; W_g water used by crop through capillary rise from groundwater (mm); and SWD the soil water depletions in the measured soil depth during the growing stage, or the change in soil water storage in the root zone. When the groundwater table is lower than 4 m below the ground surface, the capillary rising of groundwater is negligible (Liu and Wei, 1989). The runoff is also ignored because there usually is no runoff in the NCP. Therefore, W_g and R were treated as zero in this study.

Drainage was estimated using a recharge coefficient (α) multiplied by the amount of irrigation and the effective rainfall (mm):

$$D = \alpha(P + I) \qquad (3)$$

The recharge coefficient (α) depends on soil texture and on the amount of irrigation and the effective rainfall. The coefficient ranges from 0.1 for clay soil to 0.3 for sandy soil, which was determined by monitoring the change of groundwater table after irrigation event with water input in a large area. The value of α was taken to be 0.1 for event water input (EWI) amounts less than 90 mm, 0.15 for EWI between 90 and 250 mm, and 0.2 for EWI more than 250 mm in this study (Ministry of Geology and Mineral Resources, 1986).

2.5.3. Water use efficiency

Crop water use efficiency was calculated as (Hussain et al., 1995):

$$\mathrm{WUE} = \frac{\mathrm{GY}}{\mathrm{ET}} \qquad (4)$$

where WUE is the water use efficiency of ET for the grain yield (kg m^{-3}), GY is the grain yield, and ET is calculated from Eq. (2).

Irrigation water use efficiency can be expressed by WUE*i* (Bos, 1985), which can be defined as follows:

$$\mathrm{WUE}i = \frac{(\mathrm{GY}i - \mathrm{GYd})}{\mathrm{I}i} \qquad (5)$$

where GY*i* is the grain yield for irrigation levels *i* and GYd is the grain yield for an equivalent dry land or rain-fed plot, and I*i* is the amount of irrigation water applied. In the present study, we considered the grain yield from treatment A as GYd.

3. Results and discussion

3.1. Characteristics of precipitation

Precipitation is the most important water resource for agricultural activities. In rainfed agriculture, the spectrum of rainfall events determines the yield. In order to bridge the long dry spells, irrigation is applied for improving yield. One important analysis for agro-climatologists is investigating the temporal characteristics of precipitation, such as the annual precipitation trend, seasonal distribution, etc., coupled with the agricultural activities.

An obvious decreasing trend of annual precipitation is observed at the study area from 1960 to 2005 (Fig. 1). The annual mean precipitation in 1960s, 1970s, 1980s, 1990s and 2000–2005 was 580, 491, 448, 423, and 410 mm, respectively. The decadal-mean precipitation decreased by 170 mm from 1960s to 2000–2005 and the significant decrease occurred during 1970s and 1980s.

Fig. 2 shows the probability of precipitation throughout the year, winter wheat season, and maize season from 1960 to 2005. Precipitation with exceedance probability of 25%, 50%, and 75% for winter wheat precipitation were 136, 130, and 77 mm, respectively. The corresponding precipitation for summer maize was 433,

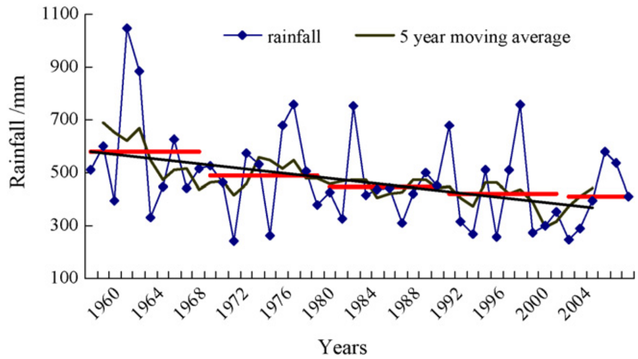

Fig. 1. Annual precipitation observed at Luancheng, China, from 1960–2005. The solid heavy line shows 5-year moving mean; and the real lines show decadal-mean.

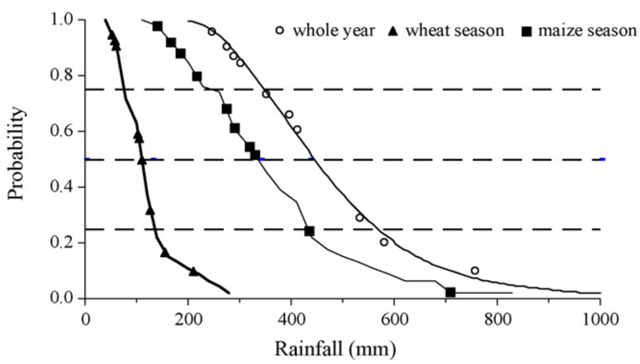

Fig. 2. The probability of precipitation throughout the year, winter wheat season, and maize season from 1960–2005.

340, and 234 mm, respectively, and that for the whole year it was 542, 433, and 344 mm, respectively. Even during wet years (exceedance probability of 25%), the precipitation in winter wheat season is only 136 mm, much less than the water requirement of around 430 mm suggesting that the water deficit for irrigation reaches almost 290–300 mm in wet and normal years and 350 mm in dry years.

3.2. Crop water requirements and irrigation water requirements

The average monthly CWR and precipitation from 1984 to 2005 are illustrated in Fig. 3. Results showed that annual CWR reached 871 mm and about 84% CWR occurred between April and September. The CWR in June was less than that of May and July because the winter wheat was harvested and summer maize was sown in this month. The highest CWR occurred in May and

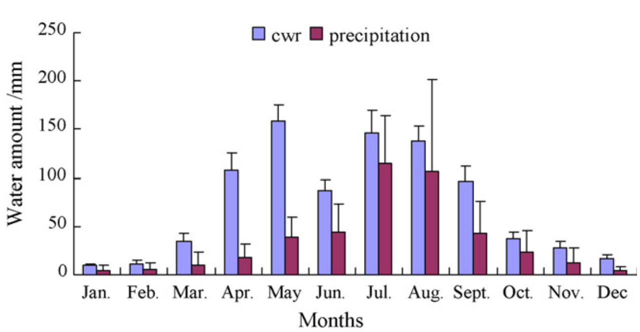

Fig. 3. The average monthly CWR and precipitation from 1984 to 2005.

reached 159 mm/month and the lowest CWR occurred in January, which was only 9 mm/month. The seasonal CWR for winter wheat and summer maize are nearly at equal level, about 429 and 433 mm, respectively (Table 3). However, the CWR changed with the different precipitation seasons. It was 413.9, 421.1 and 432.0 mm in the wet, normal and dry seasons for winter wheat, respectively. For summer maize, it was 432.6, 509.3 and 515.1 mm in the wet, normal and dry seasons, respectively. In the different years, it was 820.6, 937.0 and 940.9 mm, respectively.

Monthly mean precipitation varied from 4 to 117 mm. About 52% of precipitation occurred between July and August. The highest precipitation occurred in July and reached 117 mm and the lowest precipitation occurred in January with only 4 mm. The coefficient of variation (CV) changes significantly among monthly precipitation. The highest and lowest CV for monthly precipitation occurred in January and July, being 1.88 and 0.43, respectively. The precipitation during winter wheat and summer maize growing seasons varies considerably. The mean precipitation varied from 57 to 182 mm and from 179 to 507 mm for winter wheat season and summer maize season, respectively.

Irrigation water requirements (IWR) ranged from 247 to 370 mm and from 0 to 336 mm at the 25% and 75% precipitation exceedance probabilities for winter wheat and summer maize, respectively. Although IWR increased as precipitation decreased, the soil water storage can partially meet crop requirement. The IWR in this region mainly occurred in the winter wheat seasons and it was more than that in the summer maize seasons. This IWR difference between winter wheat seasons and summer maize seasons was caused by the intra-annual precipitation distribution. Hence, the intra-annual precipitation distribution is an important factor to influence the IWR and the crop production; we should therefore investigate the effects of precipitation distribution on the IWR.

3.3. Seasonal water balance under different irrigation levels

ET and its components in different crop growing seasons are shown in Table 4. ET ranged from 275 to 480 mm for winter wheat and varied between 361 and 490 mm for summer maize in the different precipitation seasons and irrigation schedules. There is a significant difference of ET in different seasonal precipitation between treatment A and A1, which ranged from 275 to 310 mm for winter wheat and from 361 to 404 mm for summer maize. ET increased with seasonal precipitation for the treatment A. However, ET for treatment B and C was similar. ET of treatment C was higher during dry years due to increased irrigation amounts and treatment B1 had less ET during the dry years compared to other years.

The SWD (soil water depletions) showed the difference of soil water storage during the growing seasons, which was mainly caused by water extraction at the different precipitation seasons. It ranged from 47 to 152 mm under treatment A, from 112 to 152 mm under treatment B, and from 95 to 122 mm under treatment C for winter wheat. However, it was less for summer maize than for winter wheat due to higher precipitation; SWD ranged from −143 mm to 141 mm, and from −106 mm to 108 mm for the two irrigation levels.

Irrigation is one of the key factors in ET and it varied according to the soil water content. When the crop growing season was dry, irrigation was necessary in order to offset the water deficit and the amount of irrigation increased with the decreasing precipitation. The irrigation amount was therefore significant in the different precipitation seasons and decreased with the increased precipitation. It ranged from 187 to 313 mm for treatment C and from 135 to 223 mm for treatment B. The irrigation amount was significantly

Table 3
The precipitation and irrigation water requirements under the different precipitation probability based on the meteorological records of the period between 1984–2005.

	Probability of precipitation (%)	Precipitation (mm)	CWR (mm)	IRW (mm)
Wheat season	25	181.5 ± 35.5	413.9 ± 46.9	246.9 ± 72.2
	50	109.5 ± 17.2	421.1 ± 62.8	302.9 ± 43.8
	75	56.6 ± 3.2	432.0 ± 23.0	370.4 ± 20.0
Maize season	25	507.3 ± 134.3	432.6 ± 32.9	−74.7 ± 157.0
	50	330.5 ± 48.4	509.3 ± 63.2	178.8 ± 77.3
	75	179.4 ± 30.9	515.1 ± 48.6	335.7 ± 48.9
Total years	25	671.6 ± 87.8	820.6 ± 19.8	149.0 ± 104.6
	50	452.1 ± 56.4	937.0 ± 103.9	478.7 ± 130.5
	75	283.9 ± 24.9	940.9 ± 61.2	657.1 ± 59.4

Table 4
Water balance, grain yield, WUE and WUE*i* for different precipitation years from 1997 to 2005 under different irrigation levels.

Growing seasons	Precipitation years	Treatments	Rainfall (mm)	Irrigation (mm)	SWD (mm)	ET (mm)	Grain yield (kg ha^{-1})	WUE (kg m^{-3})	WUE*i* (kg m^{-3})
Winter wheat	<25%	A	184 ± 35	80	47 ± 21	310 ± 18	3732.6 ± 923.2	1.21	–
		B		135 ± 9	112 ± 25	430 ± 4	4467.7 ± 602.5	1.04	5.45
		C		187 ± 8	109 ± 17	431 ± 28	4467.4 ± 472.4	1.03	3.93
	50%	A	114 ± 17	80	81 ± 9	275 ± 6	3634.8 ± 467.6	1.32	–
		B		176 ± 12	124 ± 11	414 ± 14	5404.3 ± 282.2	1.30	10.05
		C		256 ± 11	95 ± 4	435 ± 10	5195.9 ± 350.2	1.19	6.10
	>75%	A	59 ± 3	80	152 ± 21	291 ± 19	2928.5 ± 565.5	1.01	–
		B		223 ± 18	152 ± 21	433 ± 36	5050.9 ± 489.1	1.11	9.52
		C		313 ± 4	122 ± 6	480 ± 8	5023.1 ± 795.9	1.04	6.69
Summer maize	<25%	A_1	506 ± 134	40	−143	403.6	6720.5	1.66	–
		C_1		87	−106	487.4	8109.5	1.66	15.96
	50%	A_1	331 ± 48	40	21 ± 6	391.6 ± 12	5334.4 ± 434.9	1.36	–
		C_1		106 ± 13	53 ± 11	489.5 ± 14	7733.6 ± 342.5	1.58	22.63
	>75%	A_1	179 ± 31	40	141 ± 15	360.6 ± 15	4040.8 ± 324.1	1.12	–
		C_1		162 ± 19	108 ± 18	449.1 ± 17	7164.4 ± 269.1	1.60	19.28

Winter wheat dry years are 1999/2000, 2000/2001; normal years 1997/1998, 1998/1999, 2001/2002, 2002/2003, 2005/2006; wet years 2003/2004, 2004/2005. Summer maize dry years are 1997, 1998, 2000, 2001; normal years 1999, 2002, 2003 and 2005; wet years 2004.

decreased for treatment B compared to that for treatment C and the largest difference was 90 mm for the dry seasons and the smallest difference was 52 mm in the wet seasons.

3.4. Crop water use efficiency and irrigation water use efficiency

Table 4 also shows the grain yield, crop water use efficiency (WUE), and irrigation water use efficiency (WUE*i*) of the different irrigation levels in the different years. There was significant difference in grain yield in treatment A in the different precipitation seasons and the largest difference in dry and wet years under minimal irrigation conditions, i.e. treatment A, was 804 and 2680 kg ha^{-1} for winter wheat and summer maize, respectively. This indicated that the variation of grain yield was quite large under the minimal irrigation conditions and additional irrigation is necessary to obtain a stable grain yield. However, there was no large difference in grain yields between treatment B and C for winter wheat. Treatment C did not increase the grain yield obviously over treatment B although more irrigation was applied in treatment C. This indicated that excessive irrigation did not produce more grain yield and an optimal irrigation that can produce maximum grain yield should be applied. The standard deviation for winter wheat and summer maize grain yield under treatment A was higher than that of other treatments in the dry and normal years, which indicated that the precipitation distribution may be another important factor affecting grain yield.

WUE under treatment A varied among years, ranging from 1.01 to 1.32 for winter wheat. WUE under treatment B was higher than that under treatment C. Compared with treatment B, the WUE*i* under treatment C decreased with irrigation for winter wheat. This result was consistent with the findings of Li et al. (1995) in the Loess Plateau of China, who reported that WUE*i* significantly decreases with increasing irrigation. For summer maize, grain yield under treatment B1 was significantly higher than that under treatment A1 and WUE was similar at the different precipitation levels. This indicated that the summer maize has more grain yield potential with irrigation.

Figs. 4 and 5 shows the relationships between irrigation applied and the WUE in the different rainfall years for summer maize and winter wheat. The quadratic equations used for summer maize and

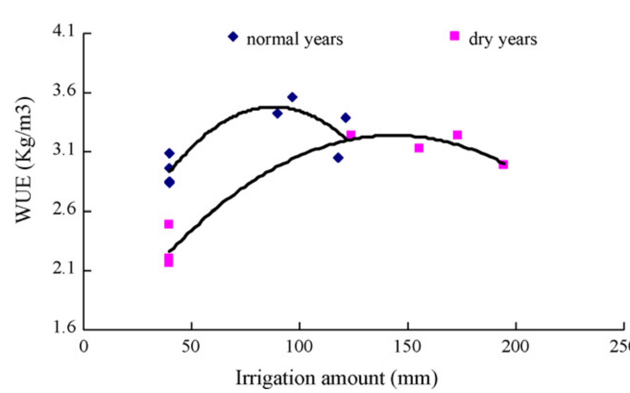

Fig. 4. The relationships between irrigation amount and WUE for summer maize in the different rainfall years.

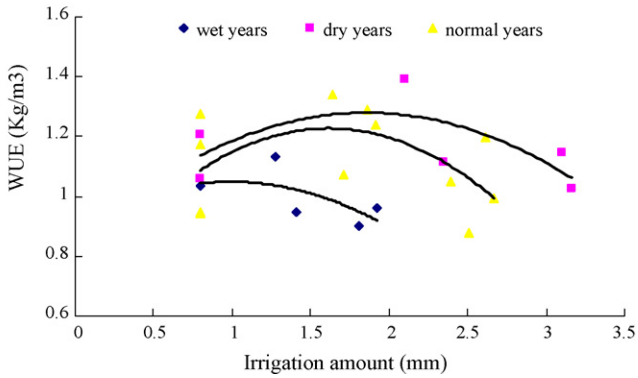

Fig. 5. The relationships between irrigation amount and WUE for winter wheat in the different rainfall years.

winter wheat in the different years are expressed as follows:

$$\mathrm{WUE} = -0.0001IA^2 + 0.0209IA + 0.8197\,R^2 = 0.7608 \quad f\text{or summer maize in normal years} \tag{7}$$

$$WUE = -0.00006IA^2 + 0.017IA + 0.5521\,R2 = 0.9332 \quad \textit{for summer maize in dry years} \tag{8}$$

$$\mathrm{WUE} = -0.00001IA^2 + 0.0048IA + 0.8374\,R^2 = 0.4298 \quad \text{for winter wheat in dry years} \tag{9}$$

$$\mathrm{WUE} = -0.00002IA^2 + 0.0068IA + 0.6804\,R^2 = 0.2747 \quad f\text{or winter wheat in normal years} \tag{10}$$

$$\mathrm{WUE} = -0.00002IA^2 + 0.003IA + 0.9007\,R^2 = 0.437 \quad \text{for winter wheat in wet years} \tag{11}$$

Note: IA is the irrigation amount (mm) in the above formula.

According to the above quadratic equations, the optimal amounts of irrigation for obtaining the maximal WUE are 186, 161 and 99 mm in the dry years (with precipitation less than 77 mm), normal years (with precipitation ranged from 77 to 136 mm), and wet years (with precipitation more than 136 mm) for winter wheat, respectively. The optimal amount of irrigation for summer maize is 134 and 88 mm in the dry years (less than 234 mm) and normal years (more than 234 mm), respectively.

4. Conclusions

In this study, analysis of weather data indicated that the long-term precipitation trend had a negative with an averaged decreasing rate of 5.1 mm/year between 1960 and 2005. CWR for winter wheat and summer maize were similar and approximately 430 mm for both crops. However, IWR were significantly different for winter wheat and summer maize seasons. IWR ranged from 247 to 370 mm for winter wheat and varied between 0 and 336 mm for summer maize. Therefore, groundwater extraction is usually required to meet the winter wheat growing demands. But for maize season, precipitation can almost meet the crop water requirement in normal and wet years, and only in dry years irrigation is required. In other words, the continuously declining groundwater levels in NCP are mainly caused by agricultural water use for wheat season. Our field experiments revealed that the irrigation applied was less than the IWR and more irrigation is not necessary for achieving more grain yield and higher WUE. The optimal amount of irrigation for summer maize is 170 and 105 mm in the dry years and normal years, respectively. The optimal amount of irrigation for winter wheat is 186, 161 and 99 mm in the dry years, normal years, and wet years, respectively.

However, the distribution of seasonal precipitation is also an important factor to influence the crop production and WUE. Although irrigation can significantly increase grain yield, water resource scarcity is a very important issue for the society and environment. Optimal irrigation can significantly increase wheat yields and WUE (Zhang et al., 1999; Zhang et al., 2003). Water-saving agricultural practices are therefore imperative and we must adjust the irrigation according to seasonal precipitation.

With respect to the forecast of precipitation in the future, some people point to a probable reduction in annual amount for this region, especially during the summer maize growing periods (Zhang et al., 2002; Hu et al., 2002). With the reduction of the total precipitation amount, more irrigation water may be necessary to maintain the high agricultural production. If precipitation continues to decline in the future, water resource shortages will become more and more serious and will threaten the food security in the region.

Considering the actual situation of water use efficiency and economic efficiency criterion in China, farmer's profitability may be higher with less input when the cost of irrigation water is included. Cost of water application along with crop price should be considered with the development of water use in the future; more water application in one crop may increase yield but may not necessarily increase farmer's profitability. A profitability analyses will help farmers determine optimal allocation of water on these crops and decrease the irrigation water applied. Adjustment for the cropping system, such as reducing winter wheat cropping area which has a higher IWR, is perhaps a useful path for sustainable agricultural development.

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