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Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain

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Abstract

In the North China Plain (NCP), excessive groundwater pumping is a serious problem. In this study, different groundwater irrigation schedules were applied. A simple soil water balance approach was introduced to evaluate crop evapotranspiration (ET) and water use efficiency (WUE). Under normal irrigation scheduling, groundwater mining occurs at a rate of over 200 mm per year from a rapidly depleting aquifer system. Severe soil water deficit (SWD) decreases grain yield (GY) of wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), while slight SWD in a growth stage from spring green up to grain-filling winter wheat did not evidently reduce GY and WUE. A severe or slight SWD significantly reduces ET, which mainly depends on irrigation amounts. Thus, it is possible to reduce ET somewhat without significantly decreasing GY. ET was correlated to GY in a parabolic function, and maximum yield for winter wheat occurred when optimal ET for winter wheat was about 447 mm. It was important for wheat and maize to be irrigated before sowing

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to improve soil water storage (SWS), and the effect of the irrigation apparently increased wheat GY.

Keywords: Soil water deficit (SWD); Evapotranspiration (ET); Grain yield; Water use efficiency (WUE); Irrigation; Winter wheat; Maize; North China Plain

1. Introduction

North China Plain (NCP), with an area of 3,50,000 km^2, is one of the most important centers of agricultural production in China. Because of monsoon influence, rainfall is highly variable; mean averaged precipitation is 500–600 mm, a majority of which comes in the period from June to September (Jin et al., 1999). Annual crop actual evapotranspiration (ET) of 800–900 mm greatly exceeds the annual precipitation (Liu et al., 2002). Therefore, to offset this deficit and maintain a high crop grain yield (GY) in this area depends on irrigation.

Shortage of water resources has become a big concern affecting sustainable crop production. With the lack of surface water, especially in the northern part of the NCP, groundwater becomes a very significant source of irrigation water in the area. Groundwater levels are persistently declining, and there are a number of regions with large significant zones of groundwater depression (Jia and Liu, 2002). The decline becomes severe in the regions of Shijiazhuang, Cangzhou and Tianjin, etc. In order to achieve high crop GY, NCP farmers tend to over irrigate in order to meet the ET deficit (Zhang et al., 2002). Therefore, it becomes critically important to reduce ET to save groundwater pumped for irrigation in the NCP. There are two main ways to do this: to reduce the cropped area or to reduce ET from the current levels of total cropped area. The government regulates the percentage of different cropping systems of agricultural planting by reducing the cropped area. An effective way is to reduce ET without decreasing the cropped area by reducing soil evaporation.

It is important to improve water use efficiency (WUE) by reducing soil evaporation and increasing GY in semi-arid and arid regions (Shan, 1994; Howell, 2001; Gregory et al., 2000; Kang et al., 2002). Reducing irrigation frequency and amount can improve irrigation efficiency (Wang et al., 2001), and it is an effective way to reduce water use by placing the wheat under water stress in early growing stages. It has been shown that a certain degree of soil water deficit (SWD) is recommended during these stages at which wheat plants are not sensitive to water stress (Zhang et al., 1999; Zhang and Qweis, 1999; Zhai et al., 2001). Analysis of supplemental irrigation scenarios showed that maximizing wheat profit under limited water resource conditions or for a targeted yield of 4–5 Mg/ha was recommended for sustainable utilization of water resources and higher WUE (Zhang et al., 1999). Too much irrigation led to a decrease of crop WUE and effective deficient irrigation may result in a higher production and WUE (Jin et al., 1999). On the contrary, Olesen et al. (2000) showed that the effect of irrigation on wheat yield was almost solely via an effect of increased transpiration, whereas WUE and harvest index was unaffected. Hatfield et al. (2001) suggested that it was possible to increase crop WUE by 25–40% through soil management. Maize GY reduction was nearly proportional to the duration of deficit irrigation imposed during its growing season under a semi-arid Sahelian environment (Pandey et al., 2000). Thus, it is helpful to interpret the relationship between crop and water for improving crop WUE by SWD, whereas the crucial part of the calculation of WUE is to acquire accurate data of ET under different soil water scenarios.

The water balance method has been widely used to calculate ET on a field scale (Musick et al., 1994; Li et al., 2000; Li et al., 2001a; Sadeh and Ravina, 2000; Aase and Pikul, 2000; Wang et al., 2001). However, many researchers ignored losses of water from drainage because they assumed that there was no drainage from the soil profile (Musick et al., 1994; Li et al., 2000; Wang et al., 2001; Kang et al., 2002). In fact, these studies erroneously included drainage in ET, and therefore overestimated ET. We used a one-dimensional soil water balance model to calculate the effect of both drainage and ET from the soil profile to correct this oversight (Kendy et al., 2003).

In this paper, we will focus on a water-shortage puzzle in the North China Plain trying to paraphrase the effect of saving irrigation on groundwater decline. Using a simple soil water balance model under different irrigation schedules with respect to irritation amount and frequency, we manage to discover the impact of irrigation on grain yield and WUE, and show the influence of soil water storage (SWS) to analyze the influence of SWD on ET, GY and WUE. The objectives of this study are thus as follows:

(1) To discover the effects of irrigation applied to the components of soil water balance.
(2) To analyze the effects of irrigation amount and frequency on ET, GY and WUE.
(3) To interpret the impact of SWS on crop growth and the importance of SWS before sowing.

2. Site description

Experiments were conducted at Luancheng Agro-ecosystem station (37°53′N, 114°41′E, a.s.l. 50.1 m), one of 34 agricultural ecosystem stations of Chinese Ecological Research Network. It is located at Luancheng county of the NCP (Fig. 1), with fertile topsoil, plenty of organic matter in loam soil, and high grain yield (Zhang et al., 2002), and in a temperate semi-arid monsoon climate, with mean annual temperature 12.2 °C, mean annual global radiation 524 kJ/cm^2, and mean annual precipitation 481 mm, most of which occurs from late June to September (Table 1). Winter wheat and maize is the main crop rotation system. Growing season of winter wheat is from early December to mid-June, and for maize from early-June to later September (Table 2). Rainfall does not meet the need of wheat for its normal growth, especially during the dry, windy spring season. Therefore, 5–6 irrigations are needed to maintain high GY. During summer, rainfall is usually adequate for the water consumption of maize, though 2–3 irrigations may be needed in a dry year. Large quantities of groundwater are pumped for this purpose. As a result, the ground water table at the station has fallen from a depth of 10 m in the early 1980s to more than 30 m at present.

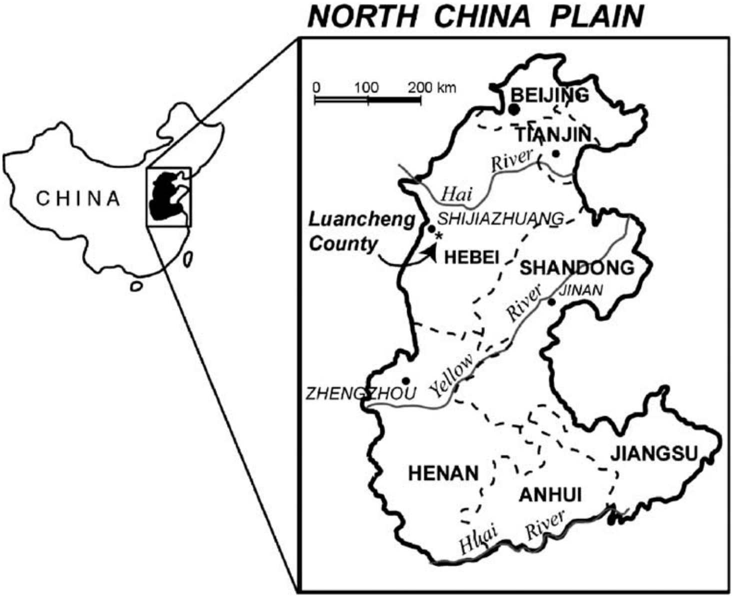

Fig. 1. The location of Luancheng Station and the North China Plain.

3. Materials and methods

3.1. Experimental treatments

Experiments on winter wheat and maize were conducted from 1998 to 2001. There were fifteen 5 m × 10 m plots divided by concrete walls for five irrigation schedules. The walls are 24.5 cm thick and extend 1.5 m beneath the surface, in accordance with specifications set by Food and Agricultural Organization (FAO). Five kinds of irrigation schedules were tested for winter wheat and two for maize, and each treatment was replicated three times (Table 3). The area of GY measurement was from the 3 m × 8 m portion in the heart of each plot, and the area for plant sampling was the surrounding 1 m wide the area of GY measurement.

Winter wheat, Gaoyou No. 503, was sown at the rate of 150 kg/ha with 20 cm wide per row by hand. Before sowing, each plot was irrigated with about 80 mm water containing ammonium phosphate 300 and 150 kg/ha urea. Maize, Yandan No. 21, was sown at a rate of 60 kg/ha per plot after the winter wheat season. All experimental maize plots were pre-irrigated with 40 mm water following by an application of urea 450 kg/ha. The first schedule irrigation was on 26 March 1999, coinciding with the spring green up of winter wheat after winter dormancy. Supplemental experiment of mulching was conducted for maize and winter wheat in 2001–2002.

The data of different treatments were statistically analyzed in the MS-EXCEL 2000 and SPSS 10.0 and means of different treatments were compared using least significant difference test ($P = 0.05$) using the software SPSS 10.0.

Table 1
Rainfall during winter wheat and maize seasons from 1998 to 2001, at Luancheng Station (unit: mm)

	Seasons												
	October	November	December	January	February	March	April	May	June	July	August	September	Total
1998–1999	10.3	0	0.7	0	0	0	6.6	43.1	18.5	104.9	144.1	19.6	347.8
1999–2000	24.3	6.1	0.2	7.6	0	0.8	2.5	11.8	45.8	233.0	5.9	64.1	402.1
2000–2001	73.9	8.4	0	20.1	6.9	0.5	23.3	6.2	47.5	100.4	47.8	16.2	351.2

Table 2
Growth stages of winter wheat and maize at Luancheng Station

Crop	Growth stage								
	Sowing	Emergence	Winter dormancy	Spring green up	Stem-extension	Heading	Flowering	Grain-filling	Harvesting
Winter wheat	1 October	7 October	22 November	3 March	10 April	1 May	5 May	10 May	10 June
Maize	12 June	15 June	–	–	18 July	–	10 August	20 August	25 August

Table 3
Levels of soil water content under different treatments of winter wheat and maize at Luancheng Station (1998–2001)

Crop	Treatment	Growth stage and irrigation treatment (θ/θ_{FC})[a]				
		Winter dormancy	Spring green up	Stem-extension	Heading	Grain-filling
Winter wheat	A	1.0[a]	–[b]	0.8	0.8	0.8
	B	1.0	0.8	–	0.8	0.8
	C	1.0	0.8	0.8	0.8	–
	D	1.0	1.0	1.0	1.0	1.0
	E	1.0	–	–	–	–
Maize	D	–	–	1.0	1.0	1.0
	E	–	–	–	–	–

[a] θ is average soil water content of crop root depth; θ_{FC} is average field capacity of crop root depth. 1.0 or 0.8 means the ratio of θ to θ_{FC}.

[b] "–" shows that there is no irrigation applied.

3.2. Measurements

Volumetric soil moisture was measured with a neutron probe (Institute of Hydrology, UK). One access tube was installed in each of the 15 experimental plots. Soil moisture was measured at 20 cm intervals from a depth of 20–200, or 180 cm, approximately every 5 days. Precipitation was measured on-site daily by summing hourly tipping-bucket measurements. Manual spray irrigation was adopted through a outlet of a soft plastic tube connected with a groundwater inlet where a water meter was installed to measure irrigation applications.

Crop measurements were taken weekly. For winter wheat, an electronic leaf-area meter was used to measure the green leaf-area of 10 randomly selected plants harvested from the sampling area of each plot, and the dry matter of 10 plants was measured after drying for 8–10 h in an oven; for maize, five plants were harvested for the leaf-area and the dry matter determination. GY of winter wheat and maize was obtained from the central 3 m × 8 m harvested area of each plot; 1000-kernel weight was determined from harvested grains. Biomass was calculated by weighing air-dried harvested samples.

3.3. Calculation

Water use efficiency is generally defined in agronomy as the ratio of crop yield (usually economic yield) to water used to produce the yield. Usually, many irrigation practitioners defined WUE as:

$$\mathrm{WUE} = \frac{\mathrm{GY}}{\mathrm{ET}} = \frac{\mathrm{GY}}{P + I - \Delta \mathrm{SWS} - R - D} \qquad (1)$$

where GY is grain yield; ET actual evapotranspiration; P precipitation; I irrigation; ΔSWS the difference of soil water storage between harvest stage and seeding stage; R surface runoff, D soil water drainage from the root zone during the growing season. In the NCP, there usually is no R, and R is ignored in the water balance equation.

The ET and soil water drainage (D) in the study were simulated for each irrigation treatment in the 3 years using a simple one-dimensional soil water balance model that calculates the water balance of a multi-layered soil column. Inputs to the model include daily precipitation, irrigation, potential evapotranspiration (according to evaporation pans), leaf-area index, and plant-root depth, effective porosity, field capacity, wilting point, and saturated hydraulic conductivity of every user-defined soil layer. Outputs include daily actual evapotranspiration, groundwater recharge (drainage from the soil profile), and water content of each soil layer. An agreement between measured and modeled groundwater declines indicates that the calculated ET and D values are reasonable (Kendy et al., 2003).

Net WUE and irrigation WUE and can be expressed by $\mathrm{WUE_{ET}}$ and WUE_I, respectively (Bos, 1985). $\mathrm{WUE_{ET}}$ and WUE_I can be written as:

$$\mathrm{WUE_{ET}} = \frac{\mathrm{GY}_i - \mathrm{GY_d}}{\mathrm{ET}_i - \mathrm{ET_d}} \tag{2}$$

$$\mathrm{WUE}_I = \frac{\mathrm{GY}_i - \mathrm{GY_d}}{I_i} \tag{3}$$

where GY_i is the yield and ET_i the ET for irrigation level i, $\mathrm{GY_d}$ the yield and $\mathrm{ET_d}$ the ET for an equivalent dryland or rain-fed plot, and I_i is the amount of irrigation applied for level i. In most cases, $\mathrm{GY_d}$ would be zero or small in rain-fed conditions. $\mathrm{WUE_{ET}}$ can be regarded as net ET efficiency because it is based on the yield produced above the rain-fed yield divided by net ET difference for the irrigated crop. WUE_I can be taken as irrigation efficiency. In this study, all experimental plots are irrigated before sowing so that seed can emerge from the soil. So, we use grain yield ($\mathrm{GY_s}$) and evapotranspiration ($\mathrm{ET_s}$) under severe water deficit condition to replace $\mathrm{GY_d}$ and $\mathrm{ET_d}$. Thus, $\mathrm{WUE_{ET}}$ is defined as:

$$\mathrm{WUE_{ET}} = \frac{\mathrm{GY}_i - \mathrm{GY_s}}{\mathrm{ET}_i - \mathrm{ET_s}} \tag{4}$$

where $\mathrm{GY_s}$ is the yield and $\mathrm{ET_s}$ is the ET under severe soil water deficit condition with only irrigation before sowing.

4. Results and discussion

4.1. *The impact of soil water deficit (SWD) on the components of soil water balance*

The influence of SWD on crop evapotranspiration and groundwater drainage (D) is shown in the Table 4. ET for winter wheat varied between 209 and 457 mm under different irrigation schedules. ET of treatment E for winter wheat was apparently smaller than that of the other four treatments; ET of treatment A, B and C was significantly lower than that of treatment D, for which most water was irrigated in wheat season, and among A, B and C treatments, ET differed in 1999–2000 and 2000–2001, but not in 1998–1999, which depended mainly on irrigation amounts (Table 4). Soil water drainage also is an important component of soil water balance. More than 6% precipitation and irrigation inputs were recharged through the soil profile into aquifers under normal soil water conditions (treatment D). Under severe soil water deficit condition (treatment E), there was still significant groundwater drainage.

Table 4
Components of soil water balance for winter wheat and maize in different soil water treatments from 1998 to 2001[a]

Crop	Year	Treatment	Rainfall (mm)	Irrigation (mm)	ΔSWS (mm)	ET (mm)	Drainage (mm)	$D/(R+I)$[b]	I–D[b] (mm)
Winter wheat	1998–1999	A	63.2	252.0 ab	−107.5	375.2 b	47.5	0.15	204.5
		B		239.5 b	−163.6	391.6 b	74.7	0.25	164.8
		C		202.3 b	−217	390.4 b	92.1	0.35	110.2
		D		362.1 a	−96.9	435.3 a	86.9	0.20	275.2
		E		5.0 c	−171.4	209.5 c	30.5	0.45	−25.5
	1999–2000	A	53.5	281.5 c	−55.6	381.0 c	9.6	0.03	271.9
		B		323.9 b	−49.2	419.5 b	7.1	0.02	316.8
		C		247.9 c	−97	386.7 c	11.7	0.04	236.2
		D		404.8 a	−46.2	456.7 a	47.8	0.10	357
		E		90.0 d	−85.8	221.4 d	7.9	0.06	82.1
	2000–2001	A	139.3	234.0 b	−43.6	403.6 b	13.3	0.04	220.7
		B		230.0 b	−41	405.6 b	4.7	0.01	225.3
		C		216.7 b	−66.3	403.8 b	18.5	0.05	198.2
		D		364.7 a	18.4	453.0 a	32.6	0.06	332.1
		E		80.0 c	−62	277.7 c	3.6	0.02	76.4
Maize	2000	D	348.3	125.7 a	−41.1	387.9 a	127.2	0.27	−1.5
		E		40.0 b	89.5	281.3 b	17.5	0.05	22.5
	2001	D	211.9	67.3 a	−90.8	358.0 a	12.0	0.04	55.3
		E		0.0 b	−46.4	253.3 b	5.0	0.02	−5.0

[a] Values are means of three replicates (treatment E with four replicates). Letters indicate statistical significance at $P_{0.05}$ level within the same column, and "a", "b", "c" and so on show the statistical difference from the highest to the lowest.

[b] *I*, *R* and *D* represent irrigation, rainfall and soil water drainage (groundwater recharge), respectively.

Drainage for winter wheat in 1998–1999 was up to the maximum among the three consecutive wheat seasons, which was caused by about 100 mm irrigation input before seeding in 1998. Water-table declines are directly proportional to the difference between irrigation (*I*) and drainage (*D*) because irrigation water is pumped from the underlying unconfined aquifer. Under normal soil water condition, for winter wheat there was more than 200 mm water deficit (*I*–*D*) in the consecutive three seasons, whereas, for treatment *E* *I*–*D* was negative in 1998–1999, positive in 1999–2000 and 2000–2001 (Table 4). For maize, SWD (treatment *E*) also significantly reduced ET, and there was significant groundwater recharge in 2000, but little recharge in 2001 owing to normal precipitation (*P*) and irrigation input in 2000, lower $P + I$ input in 2001.

The impact of SWD on the soil water balance for winter wheat and maize shows that SWD, severe or slight, all significantly reduced ET, compared with normal soil water condition, and the reduced degree mainly depended on irrigation amount. For winter wheat, groundwater mining of about 200 mm per year from the rapidly depleting aquifer system supplied the deficit under normal soil water condition; under severe SWD condition (treatment *E*) there was also evident groundwater deficit. In 2000, soil water recharge for maize was basically the same as groundwater mining under normal irrigation condition due to much rainfall, while in the summer of 2001, a below normal precipitation summer, groundwater pumping was not offset by soil water recharge (Table 4).

4.2. The impact of soil water stress on crop grain yield (GY) and WUE

Different irrigations affect plant growth and reduce their GY, whereas, the effects are different under different irrigation schedules. Treatment *E* represents a severe SWD condition. Mean GY and biomass of treatment *E* were evidently lower than those of the other treatments, and the 3-year average GY of treatment *E* was only 58.3% of treatment *D* (Table 5), which showed that severe SWD markedly decreased winter wheat GY and its biomass, compared with other the four treatments. The average GY of treatments A and B was not significantly lower than that of treatment *D*, while the harvest index of treatment *D* was lower than that of treatments A, B, C, and basically the same as that of treatment E. The mean 1000-kernel weight of treatments A and B was higher than that of treatment D. Severe SWD (treatment E) severely reduced 1000-kernel weight, and the 3-year mean weight was the lowest among the five treatments with the value 29.12 g. The 3-year mean 1000-kernel weight of treatment C was only higher than that of treatment E. The impact of SWD on crop GY shows that severe SWD reduced wheat grain-filling, markedly decreased wheat 1000-kernel weight or wheat GY; certain SWD owing to no irrigation during spring green up stage or stem-extension stage did not prevent grain-filling, did not reduce its 1000-kernel weight or wheat GY; certain SWD during early grain-filling stage reduced 1000-kernel weight, and reduced GY (2000–2001) even though the SWD during the stage did not slow down spikes to differentiate and did not decreased seed number of the wheat, compared with normal irrigation condition (Fig. 2). The SWD during the stage did not reduce GY in 1998–1999 and 1999–2000, which is probably caused by the great increase of kernel numbers because yield reductions were associated with reduction in kernel numbers and to a lesser extent, kernel weight at same time (Pandey et al., 2000).

Because 348.3 mm rainfall basically satisfied the need of maize normal growth during the summer, irrigation had little influence on grain yields of maize in 2000. Thus, the average GY of treatment E for maize was almost the same as that of treatment D. In 2001, the average GY, and 1000-kernel weight of treatment E for maize was lower than those of treatment D owing to less rainfall in the maize season of 2001. Harvest index of treatment D for maize in 2000 and 2001 was not significantly different from that of treatment E, which showed that irrigation influenced maize harvest index little during this season.

WUE for winter wheat in this study ranged between 1.11 and 1.61 kg/m^3 under different irrigation schedules, and WUE in this study is evidently higher that by the others (Table 6) because they had overestimated ET by ignoring losses to groundwater recharge. There was no significant difference among the five treatments except that WUE of treatment E was lower than that of the other four treatments in 1998–1999 and WUE of treatments B, and D was lower than that of the other three treatments in 1999–2000. The difference of WUE_{ET} among the four irrigation schedules (except for treatment E) was similar to that of WUE. The impact of SWD on WUE and WUE_{ET} showed that certain SWD did not reduce WUE and WUE_{ET} compared with normal irrigation condition. On the contrary, normal water supply reduced irrigation use efficiency, namely WUE_I. So, we can draw the conclusion that it is suitable to reduce irrigation amount in the NCP in a certain growing stage.

Table 5
Crop grain yield (GY) and water use efficiency (WUE) for winter wheat and maize under different soil water treatments from 1998 to 2001[a]

Crop	Year	Treatments	Yield (Mg/ha)	Biomass (Mg/ha)	Harvest index	1000 kernel weight (g)	WUE (kg/m^3)	WUE $_{ET}$ (kg/m^3)	WUE$_I$ (kg/m^3)
Winter wheat	1998–1999	A	5.32 a	10.06 a	0.53 a	34.38 a	1.42 a	1.98 a	1.07 a
		B	5.33 a	10.35 a	0.52 a	34.98 a	1.36 a	1.77 a	1.13 a
		C	5.88 a	10.75 a	0.55 a	33.94 ab	1.50 a	2.15 a	1.62 a
		D	5.41 a	11.21 a	0.48 b	35.49 a	1.24 a	1.41 a	0.77 ab
		E	2.55 b	5.20 b	0.49 b	30.17 c	1.22 a	–[b]	–
	1999–2000	A	5.67 a	11.71 a	0.48 a	35.82 a	1.49 a	1.32 a	1.05 a
		B	5.49 a	11.63 a	0.47 a	31.77 b	1.31 ab	0.98 ab	0.79 ab
		C	5.58 a	12.19 a	0.46 a	29.96 c	1.45 a	1.23 a	1.2 a
		D	5.31 a	12.73 a	0.42 ab	27.08 d	1.16 b	0.75 b	0.54 b
		E	3.55 b	8.10 b	0.44 a	29.08 c	1.61 a	–	–
	2000–2001	A	5.22 a	10.24 bc	0.51 a	33.92 a	1.29 a	1.50 a	1.23 a
		B	5.11 a	10.51 b	0.49 a	33.50 a	1.26 a	1.39 a	1.19 a
		C	5.00 ab	10.25 b	0.49 a	29.63 b	1.24 a	1.33 a	1.28 a
		D	5.46 a	12.0 a	0.46 c	33.64 a	1.20 a	1.22 a	0.75 b
		E	3.33 b	8.51 c	0.39 c	28.1 b	1.20 a	–	–
	2000	D	3.92 a	9.90 a	0.40 a	–[b]	1.01 a	−0.05	−0.06
	2000	E	3.97 a	9.22 a	0.43 a	–[b]	1.41 a	–	–
Maize	2001	D	6.17 a	12.43 a	0.50 a	311.53 a	1.72 a	2.52	3.44
	2001	E	3.53 b	7.20 b	0.49 a	219.55 b	1.39 b	–	–

[a] Values are means of three replicates (treatment E with four replicates). Letters indicate statistical significance at $P_{0.05}$ level within the same column and “a”, “b”, “c” and so on show the statistical difference from the highest to the lowest.
[b] The “–” shows that there is no value.

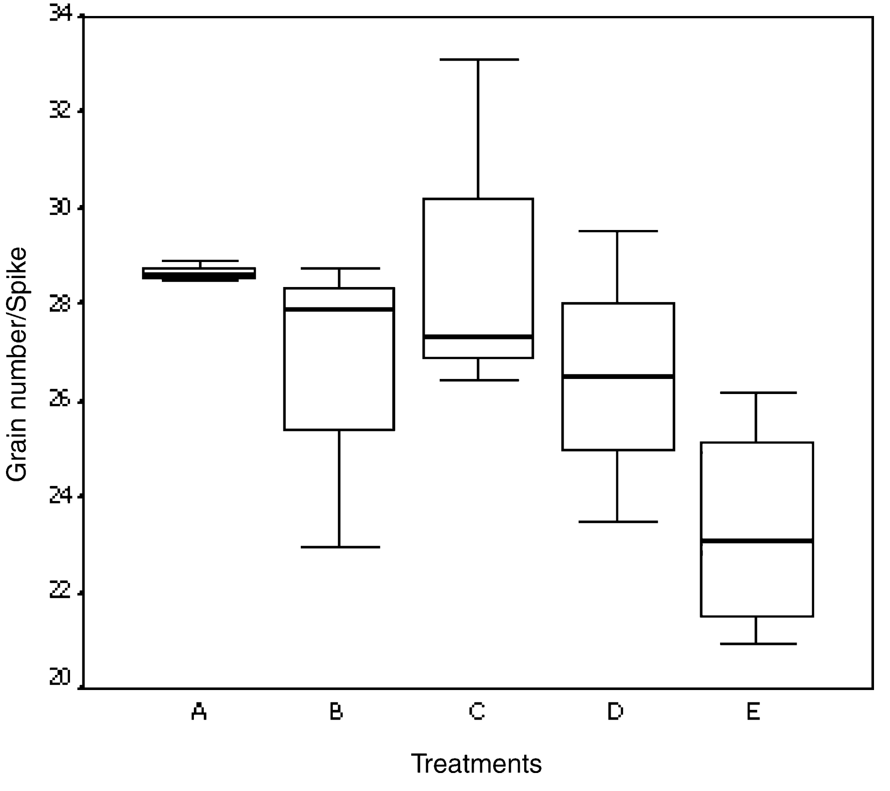

Fig. 2. Grain numbers per spike for winter wheat under different treatments condition (2000–2001).

4.3. Grain yield (GY)–ET, WUE–ET relationships

ET was related to GY and WUE in a way represented by a parabola (Fig. 3). The optimal ET for winter wheat appeared to be 447 mm. Previous experiments at Luancheng Station, which had ignored drainage from the soil profile and therefore overestimated ET, showed that ET at maximum yield and maximum WUE was 482 mm (Wang et al., 2001). The GY–ET relationship for maize was not found in our experimental conditions because much rainfall in summer lessened the difference between treatments D and E.

Table 6
The experimental results of water use efficiency (WUE) of winter wheat by different researchers

Authors	Experimental site	Variable range of WUE
Kang et al. (2002)	Loess Plateau	0.77–1.46
Zhang et al. (1999)	North China Plain	0.84–1.39
Wang et al. (2001)	North China Plain	0.70–1.30

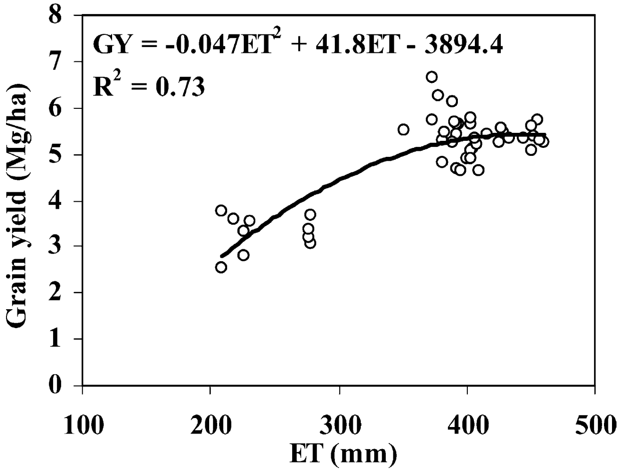

Fig. 3. The relationship between evapotranspiration (ET) and grain yield (GY) and for winter wheat from 1998 to 2001.

4.4. Function of irrigation applied at sowing time

Under the semi-arid climate condition, SWS for winter wheat at sowing has extremely important effects on GY without irrigation. There was a linear correlation for winter wheat between SWS at sowing and GY, but there was no correlation for maize between SWS at the sowing time and GY (Fig. 4). We can conclude that it is very crucial for irrigated and rain-fed winter wheat to increase its SWS by more irrigation at sowing time. The pre-sowing irrigation for wheat resulted in stronger seedlings and larger and deeper root systems, and it has improved water use and GY of wheat (Li et al., 2001b). It is also important for maize seeds to emerge from the soil to add some quantities of water before sowing stage.

The difference between SWS at sowing and harvest stage (ΔSWS) is mainly caused by crop growth and soil evaporation. ΔSWS/ET showed the contribution of soil water to ET

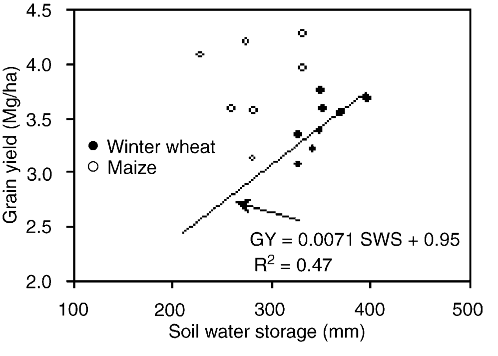

Fig. 4. The relationship of soil water storage (SWS) at sowing stage to grain yield (GY) for winter wheat and maize under treatment E condition.

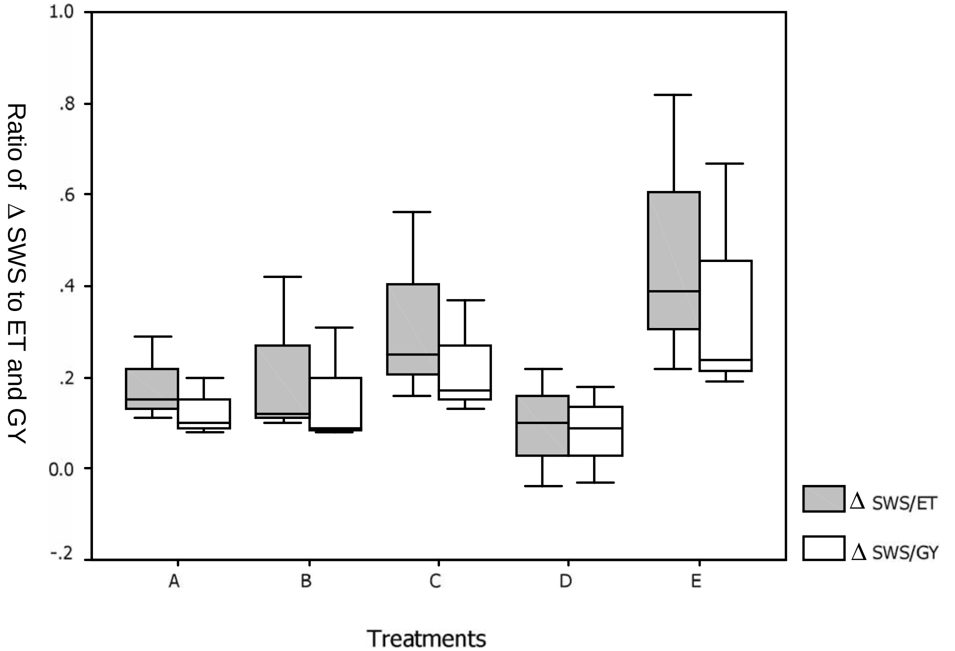

Fig. 5. The ratio of ΔSWS (the difference of SWS at sowing stage to that at harvesting stage) to ET and the ratio ΔSWS to grain yield (GY) for winter wheat under different soil water treatment conditions during 1998–2001.

(Shen and Yu, 1998); ΔSWS/GY reflects the contribution of soil water to crop GY. Treatment E gave the highest ΔSWS/ET while the treatment D gave the lowest (Fig. 5). Comparison of ΔSWS/GY for the irrigation treatments appeared the same as that of ΔSWS/ET. This suggests that under a severe SWD condition, wheat can make the fullest use of soil water for GY accumulation and evapotranspiration, and certain SWD also can improve wheat to use soil water for its GY and evapotranspiration, compared with the normal soil water condition.

5. Concluding remarks

In some semi-arid or arid regions, including the North China Plain, excessive groundwater pumping is a serious problem, causing a continuous decline in groundwater elevations. Under no soil water deficit condition, there was groundwater mining of over 200 mm per year from the rapidly depleting aquifer system supplying the water deficit in winter wheat season; slight SWD or severe SWD is helpful for groundwater recharge owing to reducing irrigation amounts, but still supplied the groundwater deficit in the NCP. At present, it is still acceptable to reduce irrigation amounts in a growth stage from spring green up to early grain-filling because it did not reduce GY and WUE, while it decreased crop ET, and the decrease mainly depended on irrigation amounts. Severe SWD is not suggested in the NCP because it limits winter wheat and maize normal growth and reduces GY even though it did not reduce WUE and WUE_{ET}. Slight SWD (SWS in root depths is less than 80% field capability in the same depths) during early grain-filling stage may decrease GY, while some irrigation may show compensation function which means that wheat spikelets are formed more quickly and there is enough time to grain-filling, provided it is supplied during post grain-filling stage after the short-term SWD (Yang and Yu, 1999; Yu, 1995, 2000). At leaf scale, a compensation function that photosynthesis rate is increased has found (Zhang et al., 2001) and it can speed up the formation of wheat spikelets.

Soil water is highly important for crop growth and SWS before sowing plays an important role in crop growth and GY. Through the increase of SWS before sowing, winter wheat can produce stronger seedlings and larger and deeper root systems (Li et al., 2001b), and it can make full use of available soil water. This is very important for rain-fed wheat because it can use more of the available soil water for its growth. It is also important for maize seeds to emerge from soil via a pre-irrigation treatment before sowing.

Slight or severe SWD is helpful for reducing groundwater pumping, while it is not sustainable. In a long view, it is imperative to reduce wheat-cropped area for suitable groundwater use in the NCP. The reduced area can be grown using alliterative low water-demand economic crops. With China joining into the World Trade Organization, economic crops with lower water requirements will play an important part for the future agriculture in the NCP.

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