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Much Improved Irrigation Use Efficiency in an Intensive Wheat-Maize Double Cropping System in the North China Plain

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Abstract

Crop yield and water use efficiency (WUE) in a wheat-maize double cropping system are influenced by short and uneven rainfalls in the North China Plain (NCP). A 2-year experiment was conducted to investigate the effects of irrigation on soil water balance, crop yield and WUE to improve irrigation use efficiency in the cropping system. Soil water depletion (ΔSWS) by crop generally decreased with the increase of irrigation and rainfall, while ΔSWS for the whole rotation was relatively stable among these irrigation treatments. High irrigations in wheat season increased initial soil moisture and ΔSWS for subsequent maize especially in the drought season. Initial soil water influenced mainly by the irrigation and rainfall in the previous crop season, is essential to high yield in such cropping systems. Grain yield decreased prior to evapotranspiration (ET) when ET reached about 300 mm for wheat, while maize showed various WUEs with similar seasonal ET. For whole rotation, WUE declined when ET exceeded about 650 mm. These results indicate great potential for improving irrigation use efficiency in such wheat-maize cropping system in the NCP. Based on the present results, reasonable irrigation schedules according to different annual rainfall conditions are presented for such a cropping system.

Key words: cropping system; crop yield; irrigation schedule; North China Plain; soil water balance; water use efficiency.

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Winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) double cropping is the main cropping system in the North China Plain (NCP) and produces about 45% of the total cereals production in China. Available water is the most important factor to limit crop yields, especially for winter wheat. Supplemental irrigation is the necessary and useful method to maintain and enhance crop yields in the area (Lan and Zhou 1995) since nitrogen fertilizer inputs are general sufficient for crop requirements in the double cropping system (Zhu and Chen 2002). However, excessive irrigation water from groundwater and surface rivers (Liu and Wei 1989; Zhang et al. 2003) have resulted in low water use efficiency and other environmental problems in this region (Liu and Wei 1989; Lan and Zhou 1995). Therefore, improving irrigation and rainfall use efficiency by scheduling irrigation reasonably in the wheat-maize rotation cropping system is essential to sustainable agricultural production in the area.

Management practices such as crop rotation or tillage have great influences on grain yield (GY) and water use efficiency (WUE) in cropping systems (Singer and Cox 1998; Hatfield et al. 2001). Norwood (2000) reported that significant influences on dryland winter wheat by previous crops were due to the different soil water storages (SWS) at planting wheat. Nielsen et al. (2002) reported that there was a positive linear relationship between GY and soil water at planting winter wheat in the central Great Plains of the USA. These studies indicated that the initial soil water before planting was associated closely with the rainfall and water use in the previous crop season, made a substantial contribution to GY and WUE of crops in the semiarid areas. Therefore, improving WUE and crop producers in such areas should consider the influences of the previous crop season on the subsequent season and the profits of whole

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cropping systems. In the NCP, high irrigation is usually applied in winter wheat seasons, but less or none is applied in maize seasons mainly due to the shortage and uneven distribution of the annual rainfall. Most of studies in the area, therefore, have focused mainly on a single growth season (wheat season) and have not taken the effects of irrigation in the wheat season on the subsequent maize growth and whole year crop-water production into account. It is still not clear weather or how the irrigations in the wheat season influence the subsequent maize growth and water use in the NCP under various annual rainfall conditions, and understanding of this knowledge could provide a useful basis for improving irrigation management and WUE in the wheat-maize double cropping systems in these areas.

Water use efficiency is influenced greatly by many environmental conditions, and shows high variations over different regions and seasons (Wang et al. 2002; Zwart and Bastiaanssen 2004). The NCP, with an area of over 350 000 km^2, shows great spatial variations in climate, soil type, water resources and agronomic managements (Liu and Wei 1989), which generally induces different responses of GY and WUE to water stresses as reported by Howell (2001). Therefore, additional studies are needed not only for improving water use efficiency and saving water in specific areas, but also for the regional assessments and optimal allocations of the limited water resources in the region.

In this paper, we provide data on soil water dynamics and crop yield parameters in an intensive wheat-maize double cropping system under various irrigation schedules in the NCP, and analyze soil water balance and its effects on crop yield and water use efficiency in a single crop season or whole cropping rotation across various irrigation schedules. Then we discuss ways for improving crop yield and water use efficiency in the intensive wheat-maize double cropping system in the NCP.

Results and Discussion

Soil water dynamics

Soil water moisture fluctuated acutely in the 0–30 cm and 30–60 cm layers due to rainfall, irrigation and ET, and held relatively stable values in the deeper soil layers from 2001 to 2003 (Figure 1). This indicates that the water supply for ET was the highest in the 0–90 cm soil profiles. This result is consistent with the report from Li et al. (2001) in the Beijing area. High irrigations in treatment III resulted in high moisture in the 0–30 cm or 30–60 cm soil layer in the first rotation (2001–2002), compared with treatment NNN, while similar soil moisture between the two treatments was found in the second rotation (2002–2003) due to the high seasonal rainfall (Figure 2).

Soil water storage (SWS) in the 0–100 cm profiles fluctuated from April to September in 2002 or 2003 (Figure 3). Compared with the first year (Figure 3A), relatively high and stable SWS in the 0–100 cm soil profiles were found in the second year (Figure 3B), and more serious water deficit stresses may have occurred in the first year (2001–2002) than the second year (2002–2003). At the end of the first wheat season (2002-06-01) and the second one (2003-06-02), treatment III held higher soil moisture in the 20–60 cm soil profiles than treatment NNN (Figure 3A, 3B), and provided more soil moisture for the establishment of subsequent maize.

Soil water depletion and evapotranspiration

The growing season reference evapotranspiration calculated by a modified Penman equation (Equation 1) were about 578 mm and 514 mm for winter wheat, and about 487 mm and 450 mm for maize, respectively during the 2 years, but actual ET varied with different treatments and seasons types (Table 1). In the

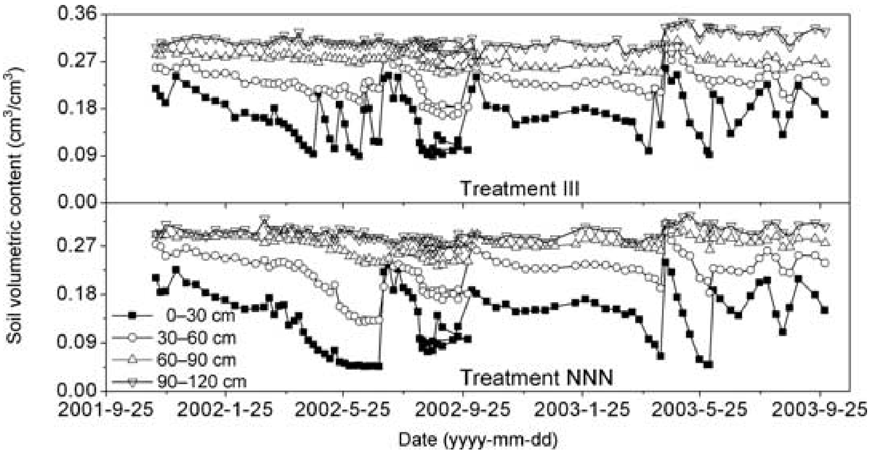

Figure 1. Soil water content in the different soil layers as influenced by irrigation and rainfall in the wheat-maize cropping system from 2001 to 2003 in the North China Plain.

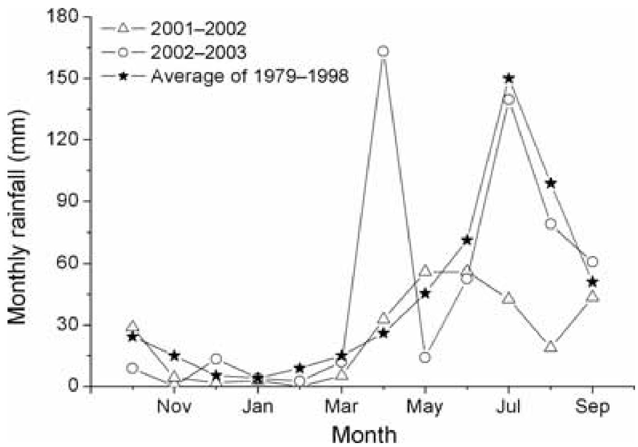

Figure 2. Monthly rainfall in the winter wheat-maize double cropping rotation system from 2001 to 2003 at Yucheng Ecological Station in the North China Plain.

first dry rotation, ET ranged from 149.3 mm to 375.8 mm for winter wheat and from 202.1 mm to 382.1 mm for maize, which was much lower than the other results for winter wheat in the NCP (Zhang et al. 1999; Zhang et al. 2004) and in the Mediterranean region (Zhang and Oweis 1999). In the second year, ET ranged from 300.1 mm to 454.5 mm for winter wheat and from 332.1 mm to 363.5 mm for maize mainly due to the high seasonal rainfall. Though actual ET was generally low under the current conditions, higher ET than 300 mm contributed little to crop yield indicating that factors other than water had become the main limitations to further increases in crop yield. This result suggests that there is great potential for improving WUE considering the high variability in annual rainfall and other production limitation factors in the area.

Water supply from initial SWS is essential to crop establishment and high production in the semiarid or semi humid areas (Singh et al. 1979; Norwood 2000; Li et al. 2001; Zhang et al. 2004). In the current conditions, positive values of soil water depletion (ΔSWS) decreased from 106.6 mm to 64.6 mm in the first wheat season and from 78.1 mm to 47.7 mm in the second wheat season (Figure 4) with the supplemental irrigations. There was a negative relationship with ET for the two seasons ($\Delta SWS = -0.15 \pm 0.03\ ET + 126.8 \pm 9.8$, $R^2 = -0.81^{**}$, $n = 12$), indicating that irrigation increases seasonal ET, but decreases soil water depletion by crop (ΔSWS). This result was consistent with the result for winter wheat at Luancheng in the NCP reported by Zhang et al. (2004). Negative values of ΔSWS were found in the maize seasons due to high irrigations in the first season or high rainfall in the second season (Figure 4A). Significant ($P = 0.02$ in the first season; $P = 0.03$ in the second season, $n = 24$) influences of irrigations applied in wheat seasons on ΔSWS in the subsequent maize seasons were found. In the first maize season, treatments III showed higher ΔSWS by 41 ± 11 mm than treatment NNN, and even with 150 mm irrigation, treatments INI and NII still depleted more water from

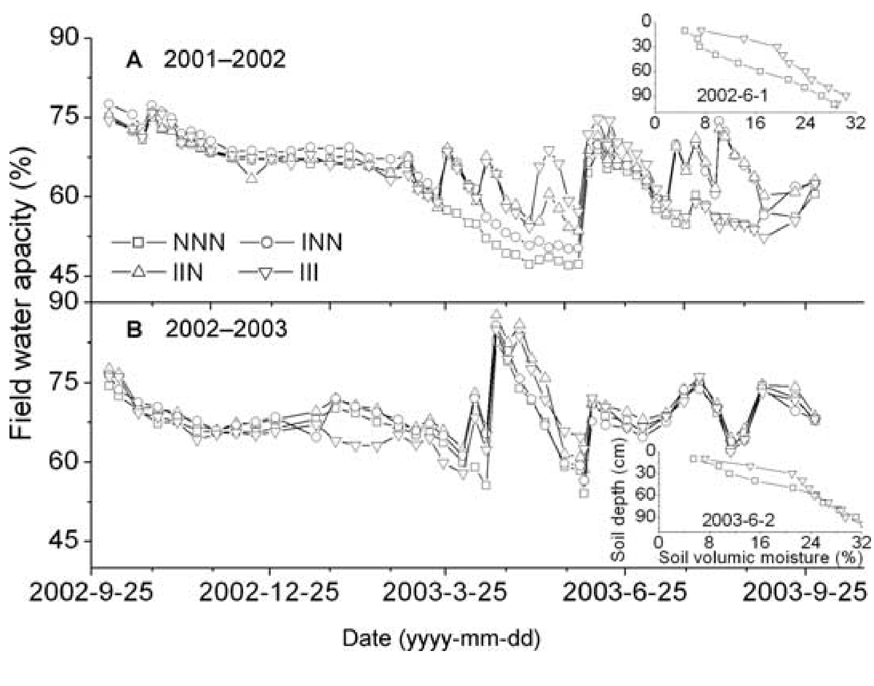

Figure 3. Soil water storage (SWS) dynamics in 0–100 cm profiles in the different treatments, and soil water content in different soil layers in treatments NNN and III at the end of the two wheat seasons (**(A)** for the first wheat season and **(B)** for the second one) in winter wheat-maize cropping systems from 2001 to 2003 in the North China Plain.

Table 1. Evapotranspiration (ET), grain yield (GY) and its components, and water use efficiency (WUE) in the winter wheat-maize cropping systems from 2001 to 2003 at Yucheng Station in the North China Plain

Year	Treatments	Winter wheat					Maize					Winter wheat-maize rotation		
		ET (mm)	GY (Mg/ha)	WUE (kg/m^3)	Grain number (grain/m^2)	Grain weight (mg/grain)	ET (mm)	GY (Mg/ha)	WUE (kg/m^3)	Grain number (grain/m^2)	Grain weight (mg/grain)	ET (mm)	GY (Mg/ha)	WUE (kg/m^3)
2001–2002	NNN	149.3 ****	2.11 ***,****	1.41 ****	6543 **	42.64 ***,****	202.1 ****	3.84 ****	1.90 **	1793 ***	244.4 **,***	351.4 ****	5.95 e	1.69 **,***
	INN	208.5 ***	3.16 **	1.52 *******	7222 **	48.19 *,**,***	337.5 **	5.74 **	1.70 ***	2236 **	242.1 **,***	546.0 ***	8.90 ***	1.63 ***
	NIN	188.7 ***,****	2.56 ***	1.36 ****	8617 **	38.29 ****	360.6 *,**	5.08 ***	1.41 ****	2250 **	227.8 ***	549.3 ***	7.65 ****	1.39 ****
	NNI	209.7 ***	3.03 **	1.44 ****	7489 **	44.72 **,***	345.9 **	5.87 **	1.70 ***	2362 **	245.9 **,***	555.6 ***	8.90 ***	1.60 ***
	IIN	335.2 *,**	6.16 *	1.84 *,**	15057 *	44.43 **,***	344.0 **	7.41 *	2.16 *	2882 *	270.9 *	679.2 *	13.57 *	2.00 *
	INI	315.9 **	6.03 *	1.91 *	12921 *	49.41 *,**	362.8 *,**	7.54 *	2.08 *	2770 *	268.6 *,**	678.7 *	13.56 *	2.00 *
	NII	322.6 **	5.93 *	1.84 *,**	12759 *	50.64 *	382.1 *	7.60 *	1.99 *,**	2854 *	273.7 *	704.7 *	13.52 *	1.92 *,**
	III	375.8 *	6.29 *	1.67 **,***	15675 *	46.12 *,**,***	247.9 ***	5.21 **,***	2.10 *	2288 **	240.0 **,***	623.7 **	11.53 **	1.85 **
2002–2003	NNN	300.1 **	4.79 **	1.58 *	15571 **	30.26 *,**	332.3 **	6.70 *	2.02 *	2507 *	289.5 *	632.4 **	11.49 **	1.82 *
	INN	358.8 **	5.08 **	1.45 *,**	17536 **	28.43 **	340.0 *,**	6.67 *	1.96 *	2434 *	297.0 *	698.8 **	11.75 **	1.68 *,**
	IIN	414.2 *	5.19 **	1.25 **	18387 *,**	29.53 **	341.3 *,**	7.07 *	2.07 *	2580 *	297.0 *	755.5 *,**	12.26 *,**	1.62 **
	III	454.5 *	6.23 *	1.36 *,**	20100 *	32.11 *	363.5 *	7.29 *	2.01 *	2674 *	295.5 *	818.0 *	13.52 *	1.65 *,**

Symbols within the same column indicate statistical significance at $P = 0.05$ level and *, **, *** and **** shows the statistical difference from the highest to the lowest. ET, evapotranspiration; GY, grain yield; WUE, water use efficiency.

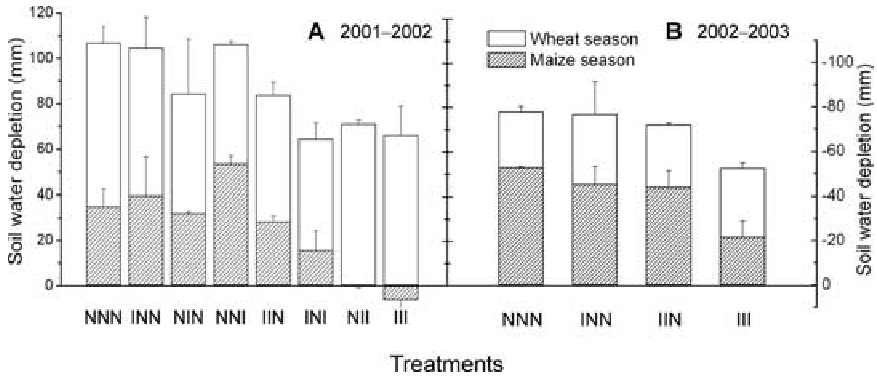

Figure 4. Soil water depletion (ΔSWS) in the 2 years (**A**, 2001–2002; **B,** 2002–2003) as influenced by irrigation and rainfall in the winter wheat-maize cropping system from 2001 to 2003 in the North China Plain.

Positive and negative values of ΔSWS occurred in wheat and maize seasons respectively, and the sum of the ΔSWS between wheat and maize seasons was the ΔSWS for the whole rotation of the double cropping system.

the initial SWS than the other four treatments (INN, NIN, NNI and IIN) by an average 30 ± 11 mm (Figure 4A). In the second maize season, treatment III also showed higher ΔSWS by an average 31 ± 8 mm than treatment NNN (Figure 4B). These results were mainly caused by the high initial SWS before planting maize in the 2 years (Figure 3A, 3B) associated with high irrigations in the previous wheat seasons, suggesting that high irrigations in the previous wheat season could increase water supply from the initial SWS for the subsequent maize, especially under drought climate conditions in the area.

The soil water depletion for the whole year was generally higher by about 40 mm in the first year than the second year due to the different annual rainfalls (Figure 4), but showed no significant differences between the irrigation treatments with 61 ± 13 mm in the first year and 28 ± 8.4 mm in the second one. This result indicates that ΔSWS may be lower for one crop season or higher for another depending mainly on irrigation managements and rainfall distributions, and could maintain relative stable values for the whole rotation irrespective of the different irrigation managements. Therefore, ΔSWS should be studied in view of successive crop growth seasons (whole cropping rotation systems). High irrigation in the wheat season may reduce ΔSWS, but can increase wheat yield and provide high initial soil water storage for the subsequent maize, which may be beneficial considering the whole crop rotation systems in drought seasons. These results provide alternative irrigation management guidelines for reasonable allocations of the limited water resource to improve rainfall and irrigation use efficiency in the wheat-maize double cropping systems in the areas.

Grain yield and water use efficiency

For the two winter wheat seasons (Table 1), GY generally increased with seasonal ET. Compared with the two rotations, higher WUE of wheat was obtained in the first season than the second one under the same irrigation conditions, while higher WUE of maize was obtained in the second season than the first one. These results indicate that seasonal rainfalls have substantial influences on water use efficiency, and effective irrigation for high crop water-productivity in the cropping system should be implemented according to the various seasonal rainfalls in the area.

The highest WUE was found in the treatment INI in the first wheat season and treatment NNN in the second one associated with very similar seasonal ET (315 for the first season or 300 mm for the second season). From the results of the second year, it can be concluded that high WUE with stable GY of winter wheat could be obtained by scheduling irrigation reasonably according to the seasonal rainfall in the local areas. In a drought year with rainfall below 150 mm in the wheat season, irrigation with 120 mm applied at the jointing and grain filling stage will be recommended to provide high initial soil water for wheat. In normal years with rainfall of more than 200 mm in the wheat season, a single irrigation with 60 mm should be applied at the jointing or grain filling stage according to the distribution of rainfall. Similar results for winter wheat were reported in the Beijing (Zhang et al. 1998; Li et al. 2005) and Luancheng areas (Zhang et al. 1999; Zhang et al. 2004) of the NCP.

For the first maize season, increased GY of 35.7% and WUE of 10.5% were found in treatment III compared to NNN, when no irrigation was applied, and GY had an increase of 35.1 ± 1.7% and WUE of 29.5 ± 5.3% in treatments IIN, INI and NII, compared to treatments INN, NIN and NNI when 150 mm irrigation was applied (Table 1). These results indicate that high irrigations applied in the previous wheat season substantially contributed to GY and WUE of the subsequent maize in drought seasons by providing high amounts of initial soil water (Figure 3) for crop establishment and a deep root system to make full use of soil water storage in deep layers as reported by Li et al. (2001). Soil water stresses at the early vegetative growth stages (Figure 1) significantly reduced GY and WUE of maize even when irrigation was applied at the late growth stages in the first maize season. This result indicates that vegetative stages of maize are very sensitive to soil water stresses in the area as reported in the sub-Saharan Africa by Pandey et al. (2000). No significant effect of irrigation in the previous wheat season on the GY of subsequent maize in 2003 was found due to the high seasonal rainfall (Table 1). These results confirm that uneven seasonal rainfall has substantial influences on maize yield in semiarid areas. From the two maize seasons, we can conclude that the influences of irrigation in the previous wheat season on the subsequent maize growth are greatly different with the rainfalls in maize season. Reducing irrigation in wheat seasons may have increased WUE of wheat as recommended in the NCP (Zhang et al. 1998; Wang et al. 2002; Zhang et al. 2003; Zhang et al. 2004), but may not be profitable in drought years when the whole rotation (wheat-maize double cropping system) is considered. Therefore, there is great potential to increase GY and WUE for the whole double cropping system considering the uneven rainfalls and other management conditions.

Compared with treatment NNN in the first maize season, the increase in GY in treatment III was associated with a higher grain number (GN) by 27.6% (Table 1). This result was consistent with other studies about winter wheat influenced by previous crops in the central Great Plains of the USA (Norwood 2000; Nielsen et al. 2002). The compensations between different yield components are important for the stable high GY and WUE of crops under various soil water deficit conditions (Aggarwal and Sinha 1987; Berenguer and Faci 2001). Similar results about wheat and maize were found in the current experiment in the NCP. However, the ability of compensation between GN and grain weight (GW) showed significant differences with water deficit stresses. Compared with the treatments IIN, INI, NII and III in the first rotation, very low GY of wheat in other treatments was mainly due to reductions in GN by 88.8 ± 19.8%, but little reductions in GW by 9.6 ± 6.6%, and similar results were found in the second wheat season, where the differences in GN or GW between the four treatments (NNN, INN, IIN and III) were more than 27% or less than 10% respectively. This result suggests that the reduction in GY of wheat caused by soil water stress is contributed to more by the reduction in GN than in GW. This result was consistent with other findings in the Sahelian environment in Africa for maize (Pandey et al. 2000) and in the NCP for winter wheat (Zhang et al. 2004).

Relationships between GY, WUE and ET

Evapotranspiration was correlated to GY and WUE in winter wheat seasons by a parabola (Figure 5A). It could be deduced from the equations that the optimal ET for the highest GY and WUE of winter wheat appeared to be 402 mm and 289 mm in

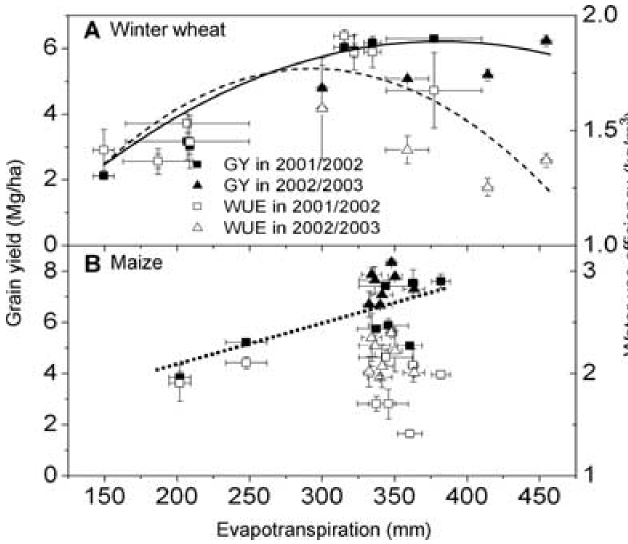

Figure 5. Relationships between grain yield (GY), water use efficiency (WUE) and evapotranspiration (ET) for winter wheat **(A)** and maize **(B)** from 2001 to 2003 in the North China Plain.

Solid line in **(A)** is GY: $GY = -5.97\,10^{-5}\ ET^2 + 0.048;\ ET - 4.14$, $R^2 = 0.80^{***}$, $n = 12^a$; dashed line in **(A)** is for WUE: $WUE = -1.71\ 10^{-5}\ ET^2 + 0.099\ ET + 0.22$, $R^2 = 0.44^*$, $n = 12$; dotted line in **(B)** is for GY of maize in 2002: $GY = 0.016\ ET + 0.67$, $R^2 = 0.59^*$, $n = 8$. [a]n = 12 including eight treatments with three repetitions in 2001–2002 and four treatments with four repetitions in 2002–2003.

the present experimental conditions. The ET for maximum GY was close to these values for winter wheat (406 mm) in the Loess Plateau of China (Kang et al. 2002) and at Luancheng (447 mm) in the NCP (Zhang et al. 2004), but lower than that reported by Wang et al. (2002) in the NCP. The ET for maximum WUE under the current conditions was generally lower than the values reported by the aforementioned studies. These results suggest that seasonal ET for maximum GY and WUE varies with different regions and growth season types, and irrigation should be optimized according to the different conditions. To balance the increasing food requirements and the decreasing fresh water resource, reasonable ET for the winter wheat season should be controlled at the range from 289 mm to 402 mm to maintain high GY and reasonable WUE for winter wheat, and GY with 5.43 Mg/ha and WUE with 1.59 kg/m^3 could be obtained with 345 mm seasonal ET from the parabolic relation (Figure 5A). This result confirmed that irrigation with 120 mm or 60 mm with less than 150 mm or above 200 mm seasonal rainfall, respectively, were reasonable for high GY and WUE of winter wheat given a high initial SWS (~75% field water capacity). The GY and WUE for the two maize seasons related to seasonal ET are plotted in Figure 5B. A weak linear relation between GY and ET was found in the first season in 2002. The great deviations in GY and WUE with stable seasonal ET

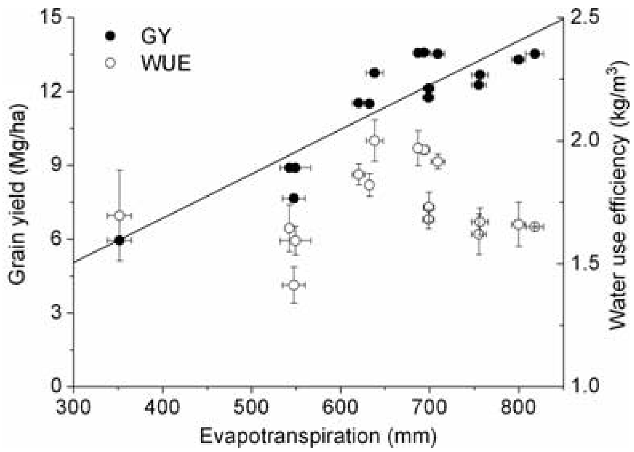

Figure 6. Relationships between grain yields (GY), water use efficiency (WUE) and evapotranspiration (ET) for the whole winter wheat-maize double rotation system from 2001 to 2003 in the North China Plain ($GY = 0.018\ ET - 0.35$, $R^2 = 0.81^{***}$, $n = 12$).

Vertical bars denote standard errors for grain yield or water use efficiency, and horizontal bars denote standard error for evapotranspiration.

(350 ± 25 mm) in the first season indicated that water stresses at early stages due to low initial SWS had substantial influences on GY and WUE of maize in the drought year.

Considering the total yield of wheat and maize in the whole cropping system (Figure 6), a positive linear relationship between GY and ET was found during the two rotations (2001–2003). When ET of the whole rotation increased from about 600 to 800 mm, the WUE of the whole rotation showed an obvious decrease from about 2.00 to 1.65 kg/m^3 by about 18.5%, while the GY of the whole rotation systems only increased by about 6.0%, and additional ET above 800 mm made little contribution to the production of cropping systems. Similar results in such cropping rotation systems were reported at Luancheng in the NCP (Zhang et al. 2004). The optimal ET for WUE in the whole rotation appeared at about 650 mm, confirmed by treatments IIN, INI and NII in the first rotation and treatment NNN in the second rotation (Table 1). In the first rotation with annual rainfall of 292.1 mm, crop yield and WUE were 10.4 ± 3.0 Mg/ha and 1.76 ± 0.22 kg/m^3, while in the second rotation with annual rainfall of 549.1 mm, crop yield and WUE were 12.5 ± 0.7 Mg/ha and 1.73 ± 0.13 kg/m^3. This result indicates that high annual rainfall could maintain stable crop yield across the various irrigation schedules, and the variations in annual rainfalls have substantial influences on the functions of supplemental irrigation in the cropping system.

Conclusion

Farmers generally adjust the amount and timing of irrigation application according to uneven rainfall over seasons by their experience. As presented in this paper, identifications of the functions of irrigation coupled with various rainfall conditions on GY and WUE in the intensive wheat-maize rotation system could allow farmers to better manage irrigation. In the present study, irrigation in wheat season had great different influences on ΔSWS, ET, GY and WUE in both wheat and maize seasons across various seasonal rainfalls. In the drought year, high irrigation in the wheat season substantially increased GY and WUE of the subsequent maize due to the high initial SWS for crop establishment and development of a deep root system.

Given the high initial SWS for wheat and maize in a normal year with annual rainfall of more than 550 mm, irrigation with about 60 mm was recommended at the stem extension or grain filling stage according to the distributions of rainfall in the wheat season, and no irrigation was needed in the subsequent maize season. While in a drought year, irrigation with 120–180 mm applied at the stem extension and grain filling stages of crops was reasonable for high GY and WUE considering the whole years' production. This conclusion may be limited to some degree because it was drawn from the results of only 2 years, and the interactions between amounts and distributions of irrigation and rainfall were not fully explored in the present experiment. Further evaluations on irrigation management in the cropping system need to consider long-term rainfall variations in the areas, which can be better carried out with the assistance of simulation modeling.

Materials and Methods

Site description

The field experiment was conducted at Yucheng Ecological Station (36°50′N, 116°34′E, and 20 m above sea level) from 2001 to 2003. It is one of 34 agricultural ecosystem stations of the Chinese Ecological Research Network and is located at Yucheng County in Shandong province of the NCP. The soil is formed from the sediments carried by the Yellow River and is calcareous; hence alkaline, and rich in phosphorus and potassium. Agriculture in the area is intensified by the use of multi-cropping systems with high-yielding cultivar and high fertilizer and water inputs. The site climate is characterized by high temperatures and high rainfall in summer with annual rainfall of 515 mm, with 70–80% of it concentrating in the maize season from July to September. In the present experiment (Figure 2), the rainfall was much shorter in 2001–2002 than in 2002–2003 and induced a higher potential water deficit stress in the first rotation.

The soil was a sandy loam texture. The lower limit of plant available soil water in the 0–100 cm layer was 0.11 cm^3/cm^3 and the upper limit of plant available soil water in the 0–100 cm layer was 0.32 cm^3/cm^3. The top layer of the soil (0–30 cm)

Table 2. Irrigation schedules in the winter wheat-maize double cropping system from 2001 to 2003 under different treatments (unit: mm)

Years	Treatments[a]	Winter wheat season			Maize growth season		
		Stem extension	Booting	Grain filling	Before planting	Stem extension	Flowering
2001–2002	NNN	–	–	–	100	–	–
	INN	60	–	–	100	60	90
	NIN	–	60	–	100	60	90
	NNI	–	–	60	100	60	90
	IIN	60	60	–	100	60	90
	INI	60	–	60	100	60	90
	NII	–	60	60	100	60	90
	III	60	60	60	100	–	–
2002–2003	NNN	–	–	–	75	–	–
	INN	60	–	–	75	–	–
	IIN	60	60	–	75	–	–
	III	60	60	60	75	–	–

[a] All eight treatments were applied in the first rotation (2001–2002), where four treatments (NNN, INN, NIN and NNI) were excluded from rainfall with shelters from the stem extension stage to maturity of winter wheat. In the second rotation (2002–2003), only four irrigation treatments (NNN, INN, IIN, and III) without rain shelters were conducted. We used the irrigation schedules in the winter wheat season as the treatments for the whole rotation system. –· indicates no irrigation during these crop growth stages. I, irrigation; N, no irrigation.

contained 1.51% total organic matter, 0.11% nitrogen, 0.026% available phosphate and 0.035% available potassium. The groundwater table was 3.0–4.5 m below the soil surface during crop growth seasons, which may have induced certain water exchanges between soil water and groundwater when soil moisture in the deep layers was depleted.

Crop management and experimental treatments

A typical winter wheat-summer maize double cropping system was chosen, representative of the common farming practices in the area, where winter wheat is usually planted in October and maize in June. Winter wheat, 93–52, was sowed at the rate of 250 plants/m^2 in 25-cm rows by hand on 4 October of both years. Maize, Nongda 108, was sowed at the density of 6.6 plants/m^2 in 67-cm rows by hand after the winter wheat season (in June). Before planting winter wheat, 300 kg nitrogen, 300 kg P_2O_5, 75 kg K_2O and 5 000 kg hen manure per hectare were applied into 0–30 cm soil for each pool with irrigation. Before planting maize, only 200 kg nitrogen fertilizer per hectare was applied with 100 mm or 75 mm irrigation in each pool. This management guaranteed healthy seedlings and adequate fertilizer supply for wheat and maize in the cropping system. The experiment was carried out in concrete pools without sealed-bottom, 6.67 m^2 (2.58 $\times$ 2.58 m) in area, and 1.8 m in depth, which prevented the exchanges of soil water between the inside and outside of the pools. There are adjacencies with 5 m between the concrete pools where crops were planted the same as in the pools, and no obvious boundary predominance within the pool was found during the growth seasons.

In the first year (2001–2002), eight treatments were arranged in randomized blocks designed with three replicates (Table 2), where four treatments (NNN, INN, NIN and NNI) were excluded from rainfall with shelters from the stem extension to crop maturity in the winter wheat season. In the second year (2002–2003), only four selected treatments (NNN, INN, IIN, and III) were conducted with six replications. Irrigations of 0–180 mm in wheat seasons or 0–150 mm in maize seasons were applied, and the irrigation amounts and timings are presented in Table 2. Irrigation water was applied using the surface flood method with plastic pipe 40 mm in diameter, where a water meter was equipped to measure the irrigation amounts.

Measurements

Air temperature, air humidity, wind speed, hours of sunshine, air pressure, daily rainfall and solar radiation were measured continuously from 2001 to 2003 in a meteorological station beside the experimental site.

Soil moisture was measured every 10 cm to a 120 cm depth using a neutron moisture meter (CNC503D2 developed by the institute of modern physics, CAS) by placing aluminum access tubes into the soil in the middle of each pool, and the soil moisture in the top 20 cm soil layer was calibrated by oven. Measurements were taken at weekly intervals as well as after irrigation or rainfall.

At harvest, plants in 2 m^2 for winter wheat and 15–20 plants for maize were sampled in each pool to determine above biomass and grain yield. Yield components including grain number per m^2 (spike numbers per m^2 $\times$ grains of spike), and 1 000-grain weight were determined by the sub samples with about 15 plants for winter wheat and five plants for maize.

Calculations

Soil water storage (SWS) was calculated in each pool based on field capacity in the 0–100 cm soil layer, because most of the crop roots were distributed in the 0–90 cm depth in the area as reported by Liu et al. (2003), and soil moisture in the soil profiles below 100 depth maintained relatively stable values during the two rotations indicating that little exchange between soil water and groundwater occurred in this period.

The reference crop evapotranspiration ET_0 (Equation 1) can be calculated according to the modified Penman formula (Doorenbos and Pruitt 1977) as follows:

$$ET_0 = \frac{(P_0/P)(\Delta/\gamma)\left\{(1-\alpha)Q_A(a+bn/N) - \sigma T_K^4(0.56-0.079\sqrt{e_a})(0.1+0.9n/N)\right\} + 0.26(e_s-e_a)(1+Cu_2)}{(P_0/P)(\Delta/\gamma+1)}, \quad (1)$$

where P and P_0 are air pressure and the standard air pressure at the sea level; Δ the slope of the saturation vapor pressure curve; γ the psychrometric constant; α the reflection ratio of reference crop and usually equals to 0.25; σ the constant equal to 5.673×10^{-8} W/m^2 per K^4; Q_A the maximum solar radiation without cloud, it can be calculated by theoretical formula; n and N the actual sunshine hours and potential sunshine hours, respectively; T_K the air temperature (K): e_s and e_a the saturation vapor pressure at the current air temperature and actual vapor pressure of the air; u_2 the wind speed at 2 m height; C the modification coefficient of wind speed; a and b are the empirical coefficients of net radiation calculation based on the ratio of actual sunshine hours and potential sunshine hours, 0.29 and 0.55, respectively based on solar radiation measurements at the Yucheng Ecological Station, Shandong, China.

Actual crop evapotranspiration (ET) was estimated for each pool by Equation 2:

$$ET = \Delta SWS + I + P + S - D - R, \quad (2)$$

where ET is evapotranspiration; ΔSWS is the change in soil water storage (SWS) for a growth season (i.e. soil water depletion during a growth period); P is precipitation; I is irrigation; S is the capillary rise from the lower soil layer to the crop root zone; D is the downward soil water drainage from the root zone and R is surface runoff from the pools. In the present experimental conditions, there was no R in the concrete pools. S and D are small and assumed to be negligible, as the groundwater table was generally 3.5 m below the soil surface and no heavy rainfall or great change in soil moisture below 100 cm depth occurred during the two rotations. When calculating ET for the whole wheat-maize rotations, the ΔSWS was calculated by the soil water depletion for the whole rotation (the changes in soil water storage from the seeding stage of winter wheat to the harvest stage of subsequent maize in next year).

Water use efficiency (WUE) was calculated by (Equation 3):

$$WUE = GY/ET, \quad (3)$$

where GY is the grain yield of wheat or maize to calculate the WUE for a single growth season. We used the sum grain yield of wheat and maize and ET for the whole rotation estimated by Equation 2 to calculate WUE for the whole cropping rotation with (Equation 4):

$$WUE = (GY_W + GY_M)/ET_T, \quad (4)$$

where GY_W and GY_M are grain yields of winter wheat and maize respectively, and ET_T is the evapotranspiration for the whole wheat-maize rotation.

Statistical analysis

The data of different treatments in 2001–2002 or 2002–2003 were statistically analyzed using ANOVA, and the means among treatments were compared using Least Significant Difference (LSD) at $P = 0.05$ probability.

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