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Characteristics of water consumption in water-saving winter wheat and effects on the utilization of subsequent summer rainfall in the North China Plain

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Abstract

Winter wheat (*Triticum aestivum* L.) grows in dry season but summer maize (*Zea mays* L.) coincides with rainfall in the North China Plain (NCP). Increasing rainfall use efficiency and harmonizing its utilization between the two species is an effective way to mitigate impact on groundwater deriving from wheat irrigation. One to four times water supply (W_1, to W_4) were employed in wheat, three water treatments (W_1, W_2, and W_4) in 2007-2008 and four (W_1, W_2, W_3, and W_4) in 2008-2009 were established in the field condition, the characteristics of water consumption in wheat and effects on rainfall utilization during subsequent maize were studied. The maximum wheat grain yield and the maximum water use efficiency were observed on the limited water treatment W_2. Wheat consumed water mainly came from irrigation and precipitation on excessive water treatments. Limited water supply enhanced water consumption from soil and vacated more water storage space. Compared with W_4, the vacated water storage space increased 103-116 mm (W_2) and 162-168 mm (W_1). The difference of soil water content derived from previous wheat disappeared ($P>0.05$) around at maize elongation stage because of subsequent summer rainfall, and the rainfall stored in 2 m soil body increased more 83-88 mm (W_1), and 69 mm (W_2) than the treatment of W_4, respectively. Drainage from 2 m soil profile on excessive water treatments (55-61 mm on W_4, 9 mm on W_3 during wheat growth period, and 36-40 mm on W_4, 18 mm on W_3 from wheat harvest to maize elongation) was determined but not on limited water treatments. These results indicate that the limited irrigation would be an effective practice for water-saving and high-yielding production of wheat in the NCP.

Keywords: Winter wheat-Summer maize rotation; Limited water management; Water consumption; Rainfall utilization.

Abbreviations

DAA, day after anthesis; SET, seasonal evapotranspiration; WUE, water use efficiency; SWC, soil water content; SWS, soil water storage; Δ SWS, apparent change of soil water storage; NCP, North China Plain.

Introduction

Winter wheat (*Triticum aestivum* L.)-summer maize (*Zea mays* L.) rotation is the principal cropping system in the North China Plain (NCP), contributed 48 and 39% of total wheat and maize production in China, respectively (Liu and Mu, 1993). The two crops play a key role in ensuring food security in China. NCP is located at the north edge of the East Asian summer monsoon region. The climate is warm-temperate, sub-humid continental monsoon, with cold winter and hot summer. The annual precipitation is 500-700 mm, with 60-70% of rainfall occurring in summer (June-August), and the rainfall coincides with summer maize growth, but far from enough to satisfy the demand of wheat. Traditionally, farmer irrigated four or five times for meeting water demand of winter wheat. The water consumption of winter wheat accounted for about 70% of total agricultural water consumption in this region (Lan and Zhou, 1995). Excessive exploitation of groundwater resources from shallow and deep aquifers in this region has caused the groundwater table is falling steadily at the rate of about 1 m per year (Hu et al., 2002; Zhang et al., 2003) and induced many other environmental problems within the plain (Shi et al., 2006; Huang and Guo, 2008). The high-yielding production of winter wheat depending on excessive exploitation of groundwater is seriously threatening the sustainable development of agriculture in the region.

Limited irrigation provides a potential way to avoid further over-exploitation of groundwater, while increasing grain yield and water use efficiency (WUE) significantly combining with appropriate agronomic practices (Musick and Dusek, 1980; Eck, 1988; Oweis et al., 1998; Oweis et al., 2000; Xue et al., 2006). The average rainfall during winter wheat growth period over the last 20 yr was 125 mm in Wuqiao county, Hebei province, where the groundwater resource is the least in NCP, accounting for 22% of the total annual rainfall. From 1990s, the high-yielding and water-saving techniques of winter wheat were investigated by our predecessors by reducing irrigation frequency from conventional four or five times to no irrigation or only one or two at Wuqiao Experimental Station, China Agricultural University, and three modes for fitting different water resource district was put forward: (1) irrigation before sowing, no irrigation during the growing period, grain yield 5250-6000 kg ha^{-1}; (2) irrigation before sowing, one irrigation during the growing period, grain yield 6000-6750 kg ha^{-1}; (3) irrigation before sowing, two irrigations during the growing period, grain yield 6750-7500 kg ha^{-1}. Compared with traditional irrigation system, achieving the same yield (for example, 6000-7500 kg ha^{-1}), 1-2 irrigations is enough (in a rich rainfall year, 1 irrigation), 750-1500 m^3 ha^{-1} irrigation water can be saved (Lan and Zhou, 1995). Until now, the techniques had been released for many years in NCP.

Precipitation is one of the most important factors in agricultural production, especially in arid and semiarid regions, because it directly affects water balance, available water amount, irrigation requirement, and cropping system. In the arid and semiarid regions, increasing rainfall use efficiency and harmonizing its utilization in a year is crucial for the cropping system design and sustainable development or the crop production growing in dry season. Larney and Lindwall (1995) reported that continuous cropping greatly depleted soil water reserves, resulting in some crop failures in a semiarid environment. In a Mediterranean environment, it is a major research challenge to devise cropping systems that maximize WUE. Wheat-legume rotation systems with additional N input in the wheat phase not only can maintain sustainable production system, but also are more efficiency in utilizing limited rainfall (Pala et al., 2007). Schillinger et al. (2008) provided a decision tool based on available soil water to determine whether to plant spring wheat, or instead leave the land fallow and plant winter wheat in late summer. In the other hand, available soil water stored prior to planting from precipitation during rainy season is an important water source for crop growing in dry season. A positive relationship between available water at planting and wheat grain yield was reported (Nielsen et al., 2002; An et al., 2003; Schillinger et al., 2008). Sepaskhah et al. (2006) provided equations to determine water and nitrogen levels at variable seasonal rainfall for leading to maximum crop yield or profit with controlled water conditions for winter wheat in a semiarid region.

In the NCP, It is found that the relationship between the utilizable water resource and precipitation was very close (Huang and Zhang, 1996), and heavy precipitation contributed to the main part of summer rainfall (Liang et al., 2007). In traditional irrigation system in winter wheat, percolating loss of rainfall in flood season was reported because of the vacated soil storage space for rain water after wheat harvest lower than the rainfall (Lan and Zhou, 1995), so the use efficiency of rainfall was low. In the water-saving system, the used proportion of soil storage water by winter wheat should be increased significantly, and bigger soil storage space for subsequent rainfall was vacated after wheat harvest. As a consequence, more rainfall would be stored in 2 m soil body, the winter wheat rooting zone (Zhou et al., 2008). However, there are no details available on this aspect.

In this paper, we discussed the components of seasonal evapotranspiration (SET), variation of soil water in 2 m soil body during winter wheat growing season under different water regimes, and the effects on rainfall storage during subsequent summer maize in the NCP. The objectives of this study were: (1) to clarify the components of SET and the characteristics of soil water consumed by winter wheat under different water regimes, and (2) to evaluate the effects of limited irrigation in winter wheat on rainfall storage during subsequent summer maize in the NCP.

Materials and Methods

Study site

The study was conducted during Oct 2007 and Jul 2009 for two wheat growth seasons (Oct 2007 to Jul 2008 [2007-2008] and Oct 2008 to Jul 2009 [2008-2009]) at an experimental station in Wuqiao county (37˚29'-37˚47' N; 116˚19'-116˚42' E) of Hebei Province, China. The study area has a temperate semi-arid monsoon climate. The altitude is 14-22.6 m above sea level. The annual mean air temperature was 12.6 ˚C, annual cumulative temperature (≥0 ˚C) was about 4863 ˚C. The average annual rainfall over the last 20 yr was 562 mm, with a sharp yearly fluctuation and erratic seasonal distribution. Generally, 60-70% of the yearly precipitation occurs from June to August. The soil at the site is classified as Calcaric Fluvisol with a sandy clay loam texture. The particle size, bulk density, water contents at field capacity and permanent wilting point of the soil are listed in Li et al. (2005).

Experimental design and management

The experiments were conducted in filed condition. The irrigation timing was set at raising, jointing, booting, anthesis and 20 d after anthesis (DAA) of wheat growth, respectively. The water amount of each irrigation was set to 750 m^3 ha^{-1}, an average value in normal practice for wheat irrigation. The heavy precipitation (>50 mm) was considered as an irrigated action during winter wheat growth period. So three water treatments (W_1, W_2 and W_4) in 2007-2008 and four water treatments (W_1, W_2, W_3 and W_4) in 2008-2009 were established (Table 1). All treatments for each growth season were replicated three times in a randomized block design.

Table 1. Irrigation timing and amount (m^3 ha^{-1}) on the various water treatments in winter wheat during the two research cycles. DAA, days after anthesis.

Year	Treatment	Timing and water amount					Total implemented
		Raising	Jointing	Booting	Anthesis †	20 DAA †	
2007-2008	W_1	0	0	0	679	0	679
	W_2	0	750	0	679	0	1429
	W_4	900	0	800	679	900	3279
2008-2009	W_1	0	0	0	0	711	711
	W_2	0	700	0	0	711	1411
	W_3	0	650	0	1100	711	2461
	W_4	750	0	900	1000	711	3361

† The heavy precipitation (>50 mm) was considered as an irrigated action during the two winter wheat growth seasons. The 679 m^3 ha^{-1} at anthesis in 2007-2008 was the amount of two precipitations ocurred before anthesis, the 711 m^3 ha^{-1} at 20 DAA in 2008-2009 was the amount of a heavy precipitation occurred at 3 d after the irrigation at anthesis.

Before preparation of the experimental land, 750 m^3 ha^{-1} irrigation was applied, 158 kg N ha^{-1} together with 139 kg P_2O_5 ha^{-1}, 113 kg K_2O ha^{-1} and 30 kg $ZnSO_4$ ha^{-1} were applied, and then the field was plowed, leveled and divided into plots of 5 m × 5 m, separated by 1 m wide non-irrigation alleys, in which winter wheat was also sown. The seeds of the winter wheat cultivar ‘Shijiazhuang 8’ were sown on 14 Oct 2007 and 14 Oct 2008. Winter wheat was harvested on 11 and 7 Jun of the two seasons, respectively. After wheat harvest, all the plots were irrigated with 500 m^3 ha^{-1} water in 2007-2008, but no irrigation in 2008-2009 because of a heavy precipitation before maize sowing. The hybrid maize cultivar, ‘Nongda 108’ was sown on 15 Jun 2008 and 11 Jun 2009, with zero-tillage. 180 kg N ha^{-1} was split-applied with 40% at sowing and 60% at side-dressing on the twelve-leaf stage. At the first split N fertilization, 104 kg P_2O_5 ha^{-1}, 163 kg K_2O ha^{-1}, and 30 kg $ZnSO_4$ ha^{-1} were also applied to all plots.

The distribution of rainfall and cumulative rainfall from Oct 2007 to Jul 2008 and from Oct 2008 to Jul 2009 is shown in Figure 1. During winter wheat growth season, the cumulative rainfall was 157 mm in 2007-2008 and 144 mm in 2008-2009, respectively. From wheat harvest to the stage of maize elongation, the cumulative rainfall was 143 mm in 2007-2008 and 195 mm in 2008-2009, respectively.

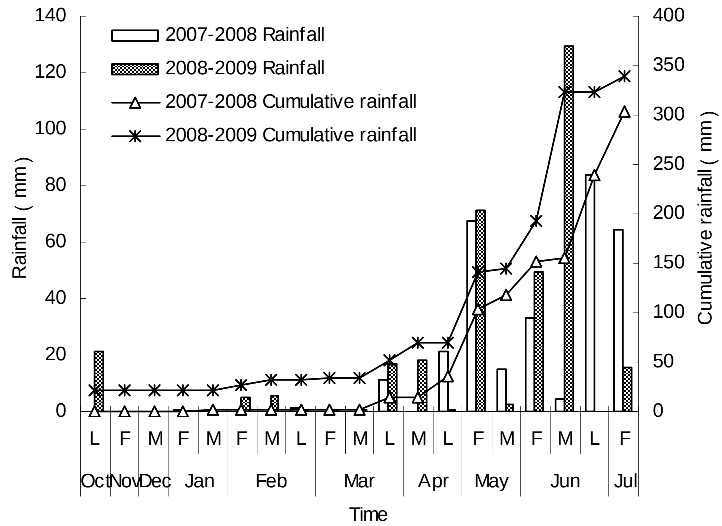

Figure 1. Rainfall and cumulative rainfall from Oct 2007 to Jul 2008 and from Oct 2008 to Jul 2009 at Wuqiao Experimental Station, Hebei Province, China. F is the first 10 days of a month; M, the middle 10 days of a month; and L, the last 10 days of a month.

Measurements

Soil water content (SWC) was monitored manually throughout the crops growing seasons using a coring auger. Soil samples were taken at pre-sowing, raising, elongation, anthesis, 20 DAA and harvest of winter wheat, and pre-sowing, heavy precipitation day (only in 2008-2009) and elongation of summer maize. Two auger samples per plot were taken at 0.2 m intervals from ground surface to the 2 m depth. SWC was determined after oven-drying at 105 ˚C to a constant weight.

At physiological maturity stage of winter wheat, samples of 3 m^2 in each plot was harvested, the grains were sun-dried to a water content of about 13% and weighted for grain yield.

Estimation of water use efficiency (WUE) and seasonal evapotranspiration (SET)

WUE was calculated as follows:

$$WUE=GY/SET \quad (1)$$

Where WUE is in kg m^{-3}, GY is grain yield (kg ha^{-1}), SET is seasonal evapotranspiration (m^3 ha^{-1}) over the wheat growing season.

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

$$SET=\Delta SWS+R+I+W_g-D-R_f \quad (2)$$

Where ΔSWS is the apparent change of soil water storage in the measured soil depth (m^3 ha^{-1}), R is rainfall (m^3 ha^{-1}), I is irrigation (m^3 ha^{-1}), W_g is water used by crop through capillary rise from groundwater (m^3 ha^{-1}), D is drainage (m^3 ha^{-1}), and R_f is soil surface run off from the field (m^3 ha^{-1}). When the groundwater table is lower than 4 m below the ground surface, W_g is negligible (Liu and Wei, 1989). W_g was ignored in the equation because the average groundwater table is 6-9 m in the study site. When D<0, D will be ignored in the equation; When D>0, D will be calculated in the equation. The soil surface run off from the field in the study was not observed, R_f was ignored in the equation, too.

Drainage is estimated as follows:

$$D=TSW_s+I \text{ (or R)}-FWHC_m \quad (3)$$

Where D is in m^3 ha^{-1}, TSW_s are total soil storage water (m^3 ha^{-1}) before irrigation or precipitation, R is rainfall (m^3 ha^{-1}), I is irrigation (m^3 ha^{-1}), and $FWHC_m$ is the maximum field water holding capacity (m^3 ha^{-1}) in the measured soil depth.

Statistics

All data were subjected on an analysis of variance. Differences among treatment means were made by the LSD (the least significant difference) method. Associations between characters were examined by correlation analysis.

Results and Discussion

Grain yield and water use efficiency (WUE)

Mean grain yield and WUE of winter wheat are shown in Table 2 for each water treatment. Grain yield ranged from 5214 to 7547 kg ha^{-1} during the two growth seasons, and irrigation improved grain yield significantly comparing with the treatment of W_1. The maximum grain yield was not observed on the highest water treatment (W_4) although more water was applied, but on the treatment of W_2 during the two growth seasons. This means that proper limited irrigation had greater potential for improving grain yield than excessive irrigation leading to higher WUE as indicated below.

From the data in Table 2, WUE presented a quadratic parabola trend as water amount increased. The limited water treatment (W_2) gave the highest WUE while the excessive water treatments (W_3, W_4) and lower water treatment (W_1) had lower WUE. WUE ranged from 1.50 to 2.26 kg m^{-3}, were much higher than those previously reported for winter wheat (Sun et al., 2006; Sun et al., 2010; Fang et al., 2010). The higher WUE should be attributed to the higher grain yield archived using a water-saving and high-yielding management practice for winter wheat produced by Lan and Zhou (1995) and improved by Li et al. (2000) and Wang et al. (2006), and the techniques has been released for many years in NCP. These results suggested that proper limited irrigation (W_2) was able to produce higher grain yield and WUE, and the limited water resource was utilized effectively in the condition of less irrigation.

Table 2. Grain yield and water use efficiency (WUE) of winter wheat under different water treatment in the two growth seasons.

Year	Treatment	Grain Yield (kg ha^{-1})	WUE (kg m^{-3})
2007-2008	W_1	$6293^{b\dagger}$	2.15^{b}
	W_2	7325^{a}	2.26^{a}
	W_4	7147^{a}	2.13^{b}
2008-2009	W_1	5214^{c}	1.50^{c}
	W_2	7547^{a}	2.14^{a}
	W_3	7179^{ab}	1.93^{ab}
	W_4	6768^{b}	1.76^{b}

† Within a column for a given dependent variable, means followed by the same letter in the same growth season are not significantly different at P<0.05.

Seasonal evapotranspiration (SET) and its components

Various studies showed that SET increased linearly as irrigation frequency and amount increased (Sun et al., 2006; Xue et al., 2006), and the component of ΔSWS was negatively related to irrigation amount (Ju et al., 2000; Li et al., 2005). From the results in Table 3, SET from wheat sowing to maturity increased as water amount increased. The highest water treatment gave the maximum SET, and the lowest water treatment W_1 had the minimum SET. SET of W_2 decreased 15-33 mm compared with that on excessive irrigation treatment (W_4). A significant linear relationship existed between water amount and SET (r=0.525, P<0.05). Conversely, ΔSWS of 2 m soil body decreased as applied water amount increased. Comparing with that on W_4, ΔSWS increased 115 mm (W_2), and 163 mm (W_1) in 2007-2008, 16 mm (W_3), 102 mm (W_2), and 167 mm (W_1) in 2008-2009, respectively. A significantly negative correlative relationship (r=-0.913, P<0.01) was found between irrigation and ΔSWS. The regression equation suggested that applying 750 m^3 ha^{-1} water would reduce ΔSWS by 46 mm. The components of rainfall and irrigation accounted for 53.9% (W_1), 72.8% (W_2) and 124.8% (W_4) of SET in 2007-2008, and 41.4% (W_1), 60.6% (W_2), 87.6% (W_3) and 106.0% (W_4) of SET in 2008-2009. It means that the consumed water by wheat on excessive water treatments mainly comes from the water of irrigation and precipitation in NCP.

Drainage was calculated by dividing winter wheat growth period as five in 2007-2008 (sowing-raising, raising-jointing, jointing-booting, booting-20 DAA, 20 DAA-maturity) and six in 2008-2009 (sowing-raising, raising-jointing, jointing-booting, booting-anthesis, anthesis-20 DAA, 20 DAA-maturity). Drainage was observed on excessive water treatments but not on limited water treatments during the two growth seasons. 55 mm water on the treatment of W_4 percolated out of 2 m soil body in 2007-2008, and 9 mm and 61 mm water on the treatments of W_3 and W_4, respectively in 2008-2009, respectively. The drainage in 2007-2008 happened after irrigation at booting stage (27 mm) and 20 DAA (28 mm), and the drainage in 2008-2009 happened during anthesis-20 DAA in which heavy rainfall occurred at the third day after the anthesis irrigation. The drainage in 2008-2009 should be slightly higher than the actrual value because the consumed water of the two days from wheat anthesis to the date of precipitation did not include in the equation (3), however the water consumption of wheat during heading-maturity was around 3.5-5.3 mm d^{-1} (Hu and Li, 1995). The drainage data suggested that farmers spend high energy pumping cost to make the water return to groundwater again on the excessive treatments.

Table 3. The seasonal evapotranspiration (SET) and its components on different water treatments during winter wheat growth seasons. Δ SWS, apparent change of soil water storage in 2 m soil body; R, rainfall; I, irrigation; D, drainage percolated out of 2 m soil profile.

Year	Treatment	SET	Components of SET			
			Δ SWS	R	I	D
			mm			
2007-2008	W_1	$293^{b\dagger}$	136	158	0	0
	W_2	320^{a}	87	158	75	0
	W_4	336^{a}	-27	158	260	55
2008-2009	W_1	347^{b}	203	144	0	0
	W_2	353^{b}	139	144	70	0
	W_3	363^{b}	53	144	175	9
	W_4	385^{a}	37	144	265	61

† Within a column, means followed by the same letter in the same growth season are not significantly different at P<0.05.

Soil water storage (SWS)

For making clear soil water change in quantity, the SWS in each soil layer in 2 m soil body also was calculated (Figure 2). Compared with that before sowing, SWS in 2 m soil profile decreased clearly on lower water treatments during wheat growing period, even if in the deeper soil layers. Many soil layers were determined in which the SWS had a significant decrease (P<0.05) compared with that before sowing, but it was obvious that the number on excessive water treatments was less than that on lower water treatments. On excessive water treatments (W_3, W_4), there was no obvious change of SWS in most soil layers or the change was smaller, and the SWS at maturity in all determined soil layers in 2007-2008 and most soil layers (60-200 cm) in 2008-2009 were not obviously changed compared with that before sowing. It means that the water consumption on W_4 mainly depended on irrigation and precipitation water.

Compared with that before sowing, the total apparent change amount of SWS in 2 m soil body at wheat harvest was 136 mm (W_1), 87 mm (W_2), and -27 mm (W_4) in 2007-2008, and 203 mm (W_1), 139 mm (W_2), 53 mm (W_3), and 37 mm (W_4) in 2008-2009, respectively. The total apparent change amount of SWS in upper layers (0-120 cm) was 124 mm (W_1), 77 mm (W_2), and -25 mm (W_4) in 2007-2008, and 186 mm (W_1), 128 mm (W_2), 48 mm (W_3), and 29 mm (W_4) in 2008-2009, and it accounted for 93.2% (W_1) and 88.5% (W_2) of total apparent change amount in 2 m soil body in 2007-2008 (the total apparent change amount of SWS on W_4 was minus), and 90.3% (W_1), 90.8% (W_2), 87.3% (W_3), and 76.3% (W_4) in 2008-2009, respectively. The water stored in lower soil layers (120-200 cm) only provided 6.8%-23.7% for wheat growth. The apparent change amount of SWS in different soil layers should be also related to the root distribution, since the root distribution of winter wheat in soil was 71.1% in 0-0.6 m depth, 25.0% in 0.6-1.2 m, and 3.9% in the 1.2-2.0 m depth (Zhou et al., 2008). These data indicated that the consumed water from soil by winter wheat in NCP mainly came from 0-120 cm soil body.

In this study, the maximum field water holding capacity in 2 m soil body was 690 mm. The vacated storage space for water after wheat harvest (the difference between maximum field water holding capacity and total SWS in 2 m soil body) was 196 mm (W_1), 150 mm (W_2), and 34 mm (W_4) in 2007-2008, and 275 mm (W_1), 210 mm (W_2), 124 mm (W_3), and 107 mm (W_4) in 2008-2009, respectively. Compared with that on W_4, the vacated storage space increased 116 mm (W_2), and 162 mm (W_1) in 2007-2008, 17 mm (W_3), 103 mm (W_2) and 168 mm (W_1) in 2008-2009, respectively. As a consequence, limited irrigation enhanced water consumption from soil and vacated more storage space for water in 2 m soil body, so it make more rainfall during following rainy season stored in 2 m soil body, and this would be benefit to improve rainfall use efficiency.

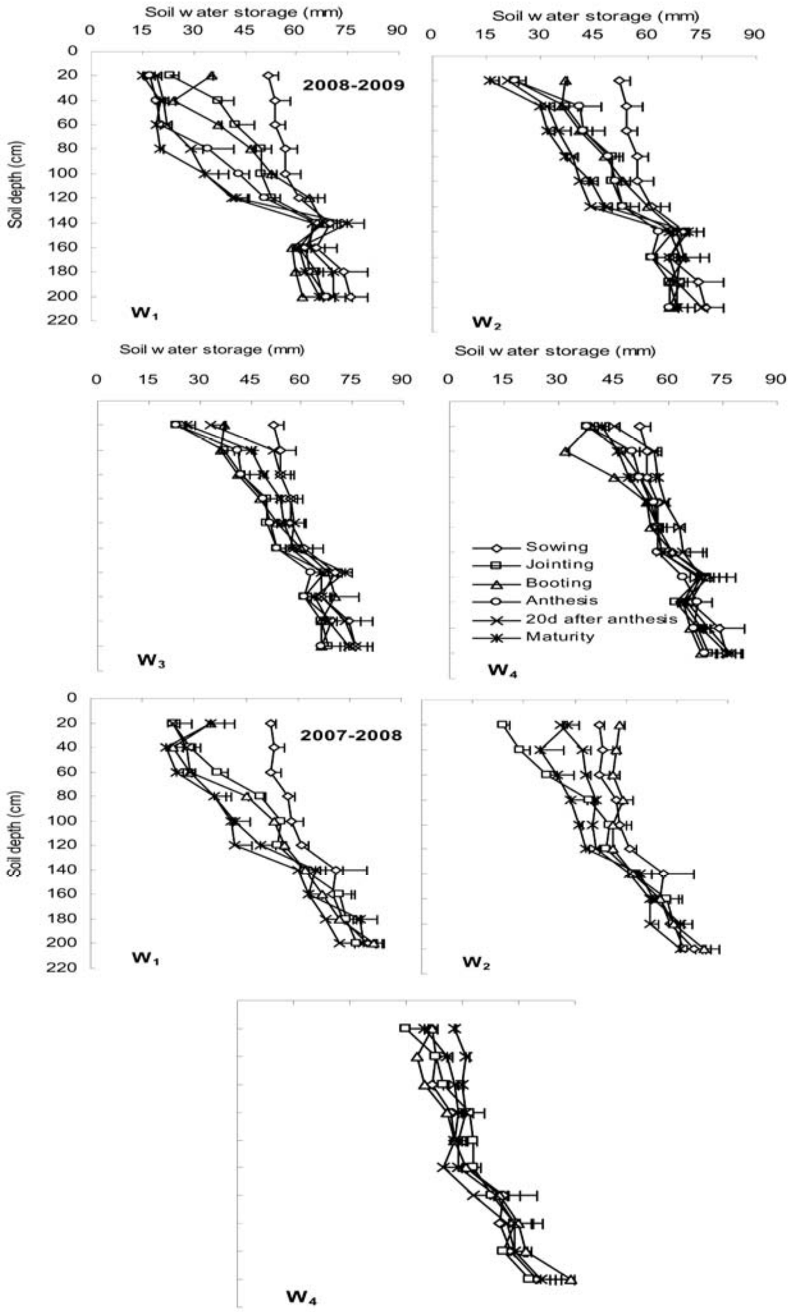

Figure 2. The soil water storage in different soil layers of 2 m soil body at different winter wheat growth stages in 2007-2008 and 2008-2009. The soil sampling at anthesis in 2007-2008 was cancelled due to the accident of heavy precipitation 2 d before anthesis, so there was no data at this stage.

Effects of water-saving winter wheat on rainfall use and water percolating loss during subsequent summer maize

For evaluating the aftereffects of winter wheat under different water regimes on rainfall storage during subsequent summer maize period, SWC at maize early stage was determined (Table 4). The SWC at wheat harvest in upper soil layers (0-120 cm) had significant difference among water treatments, but no significant difference in deeper soil layers (120-200 cm). Summer maize was planted after winter wheat harvested, and several precipitation incidents occurred from maize sowing to elongation (Seven in 2007-2008; five in 2008-2009). After two precipitations (87 mm in total) in 2008-2009, the SWC (7 d after maize sowing) on W_1 and W_2 gave a trends of “high-low-high” following soil depth increased, because the rainfall was not enough to complement the middle soil water consumed in wheat although the upper soil water was complemented in some extent. The SWC (at maize elongation stage) for all water treatments gave the same distribution trend after another heavy rainfall (91 mm) in 2008-2009, and had the same trend in 2007-2008. The SWC at maize elongation stage increased with a different increasing degree according to water treatment and soil depth. Obvious increase of SWC was observed on lower water treatments and in upper soil layers. The SWC at maize elongation stage for most soil layers in 2 m soil profile had no significant difference among water treatments, and from now on, the aftereffects derived from water-saving winter wheat on subsequent water utilization disappeared (no differences between water treatments).

The increase of SWC means rainfall stored in soil and more rainfall stored in soil in limited water treatments. Compared with that at wheat harvest, the water storage in 2 m soil body increased 76 mm (W_1), 57 mm (W_2), and 28 mm (W_4) in 2007-2008, and 57 mm (W_1), 43 mm (W_2), 18 mm (W_3), and 10 mm (W_4) in 2008-2009, respectively.

The drainage from wheat harvest to maize elongation was calculated. Drainage was observed on excessive water treatments but not on limited water treatments during the two growing seasons. 40 mm water on the treatment of W_4 percolated out of 2 m soil body in 2007-2008. There was no drainage loss before 7d after maize sowing in 2008-2009 although two precipitations occurred, but water percolating loss happened after another heavy rainfall, and 18 mm and 36 mm water on the treatments of W_3 and W_4, respectively. The drainage water accounted for 30% (W_4) of total rainfall amount during the period in 2007-2008, and 9.2% (W_3), and 18.5% (W_4) in 2008-2009, respectively. The same reason as in winter wheat, the drainage in 2007-2008 should be slightly higher than the actrual value because the consumed water of summer maize seedling was around 2-3.1 mm d^{-1} (Hu and Li, 1995) and the consumed water of 2-3 days did not include in the equation (3). Considering the drainage and the increment of soil water from wheat harvest to maize elongation, the rainfall stored in 2 m soil body increased more 88 mm (W_1), 69 mm (W_2) in 2007-2008, and 83 mm (W_1), 69 mm (W_2) in 2008-2009 than that on the treatment of W_4, respectively. It is obvious that winter wheat under water-saving condition make more rainfall store in soil, and avoid water percolating loss by drainage during subsequent summer maize growing period in the winter wheat-summer maize rotation system in NCP.

Table 4. The variations of soil water content (Gravimetric, %) from winter wheat harvest to summer maize elongation stage.

Soil layer (cm)	2007-2008						2008-2009											
	Wheat maturity			Maize elongation			Wheat maturity				7d after maize sowing				Maize elongation			
	W_1[†]	W_2	W_4	W_1	W_2	W_4	W_1	W_2	W_3	W_4	W_1	W_2	W_3	W_4	W_1	W_2	W_3	W_4
0-20	$12.3^{c‡}$	15.9^{b}	20.3^{a}	22.0^{a}	22.4^{a}	23.2^{a}	5.4^{c}	5.6^{c}	9.3^{b}	14.7^{a}	21.0^{c}	21.0^{bc}	22.9^{ab}	23.7^{a}	16.1^{a}	15.7^{a}	15.7^{a}	16.6^{a}
20-40	8.3^{c}	13.3^{b}	20.7^{a}	22.1^{a}	22.6^{a}	23.0^{a}	6.8^{c}	10.4^{b}	15.3^{a}	15.5^{a}	18.7^{b}	18.4^{b}	20.2^{a}	20.4^{a}	16.9^{a}	17.3^{a}	17.4^{a}	17.7^{a}
40-60	8.7^{c}	14.7^{b}	20.5^{a}	22.3^{a}	22.1^{a}	23.6^{a}	6.6^{c}	11.0^{b}	16.8^{a}	16.7^{a}	7.7^{c}	14.9^{b}	20.1^{a}	21.5^{a}	18.5^{b}	18.9^{ab}	19.0^{ab}	19.3^{a}
60-80	12.0^{c}	15.7^{b}	20.3^{a}	22.3^{a}	21.9^{a}	22.6^{a}	6.8^{c}	12.5^{b}	18.1^{a}	18.2^{a}	8.0^{c}	11.3^{b}	19.1^{a}	20.5^{a}	19.0^{a}	19.1^{a}	19.3^{a}	19.0^{a}
80-100	14.1^{b}	15.7^{b}	19.8^{a}	22.6^{a}	21.7^{a}	23.0^{a}	11.3^{c}	14.8^{b}	18.5^{a}	19.2^{a}	12.2^{b}	12.6^{b}	18.2^{a}	19.1^{a}	18.9^{a}	18.6^{a}	19.8^{a}	19.7^{a}
100-120	16.8^{b}	16.4^{b}	20.2^{a}	23.0^{a}	22.3^{a}	23.6^{a}	14.4^{c}	16.6^{b}	20.0^{a}	20.1^{a}	15.8^{b}	15.4^{b}	17.4^{ab}	19.3^{a}	20.9^{a}	19.6^{a}	21.4^{a}	21.4^{a}
120-140	20.6^{a}	21.9^{a}	23.7^{a}	27.0^{a}	26.0^{a}	26.5^{a}	25.6^{a}	24.4^{ab}	24.9^{ab}	23.3^{b}	22.0^{a}	20.6^{a}	20.9^{a}	22.2^{a}	20.7^{b}	24.1^{a}	23.9^{a}	24.2^{a}
140-160	21.9^{a}	23.5^{a}	25.8^{a}	26.0^{b}	27.4^{ab}	28.3^{a}	21.3^{a}	22.8^{a}	22.3^{a}	22.1^{a}	21.8^{a}	23.4^{a}	23.3^{a}	21.9^{a}	22.5^{ab}	23.8^{a}	22.6^{ab}	21.3^{b}
160-180	27.6^{a}	25.9^{a}	25.5^{a}	29.2^{a}	29.4^{a}	28.4^{a}	21.4^{a}	23.3^{a}	23.4^{a}	23.8^{a}	22.6^{a}	22.4^{a}	24.5^{a}	22.9^{a}	22.8^{b}	24.9^{a}	25.8^{a}	24.3^{ab}
180-200	27.2^{a}	26.3^{a}	27.9^{a}	29.3^{b}	30.3^{ab}	30.8^{a}	23.2^{b}	23.4^{b}	25.4^{a}	26.1^{a}	21.9^{b}	23.4^{ab}	24.9^{a}	26.1^{a}	23.9^{b}	25.4^{ab}	26.8^{a}	26.2^{a}

† W_1, W_2, W_3, and W_4 denote the four water treatments in winter wheat.

‡ Within a row, means followed by the same letter in the same stage are not significantly different at $P<0.05$.

Conclusions

Conserving limited water resources is an important management practice for maintaining sustainable development in the NCP. As the results in this study, not only the highest yield but also maximum WUE were obtained on limited water treatment (W_2), and the limited irrigation practice during winter wheat growing period enhanced soil water consumption, avoided water percolating loss by drainage, and made more rainfall during following rainy season store in 2 m soil body. Therefore, limited irrigation schedule for winter wheat is considered as an effective practice to save water and improve WUE in the winter wheat-summer maize cropping system in NCP.

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