Irrig Sci (2008) 27:1–10
DOI 10.1007/s00271-008-0131-2

LETTER TO THE EDITOR

Dry matter, harvest index, grain yield and water use efficiency as affected by water supply in winter wheat

Xiying Zhang · Suying Chen · Hongyong Sun · Dong Pei · Yanmei Wang

Received: 27 December 2007 / Accepted: 8 August 2008 / Published online: 27 August 2008

Abstract Food production and water use are closely linked processes and, as competition for water intensifies, water must be used more efficiently in food production worldwide. A field experiment with wither wheat (*Triticum Aestivum* L.), involving six irrigation treatments (from rain-fed to 5 irrigation applications), was maintained in the North China Plain (NCP) for 6 years. The results revealed that dry matter production, grain yield and water use efficiency (WUE) were each curvilinearly related to evapotranspiration (ET). Maximum dry matter at maturity was achieved by irrigating to 94% and maximum grain yield to 84% of seasonal full ET. A positive relationship was found between harvest index (HI) and dry matter mobilization efficiency (DMME) during grain filling. Moderate water deficit during grain filling increased mobilization of assimilate stored in vegetative tissues to grains, resulting in greater grain yield and WUE. Generally, high WUE corresponded with low ET, being highest at about half potential ET. At this location in NCP, highest WUE and grain yield was obtained at seasonal water consumption in the range 250–420 mm. For that, with average seasonal rainfall of 132 mm, irrigation requirements was in the range of 120–300 mm and due to the deep root system of winter wheat and high water-holding capacity of the soil profile, soil moisture depletion of 100–150 mm constituted the greater part of the ET under limited water supply. The results reveal that WUE was maximized when around 35% ET was obtained from soil moisture depletion. For that, seasonal irrigation was around 60–140 mm in an average season.

Communicated by E. Fereres.

X. Zhang (✉) · S. Chen · H. Sun · D. Pei · Y. Wang
The Center for Agricultural Resources Research,
Institute of Genetics and Developmental Biology,
The Chinese Academy of Sciences,
286 Huaizhong Road, Shijiazhuang 050021, China
e-mail: xyzhang@ms.sjziam.ac.cn; xyzhang@sjziam.ac.cn

Introduction

It is necessary to produce the maximum yield per unit area by using available water efficiently because irrigation water is rapidly diminishing around the world. At present and more so in the future, irrigated agriculture will take place under water scarcity. Irrigation management will shift from emphasizing production per unit area towards maximizing the production per unit of water consumed, the water productivity. It is essential to develop the most suitable irrigation schedule to produce the maximum plant yield. Such schedule should be developed for different ecological regions, as plant water consumption during the vegetation period depends mostly on plant growth, soil and climatic conditions (Uçana et al. 2007).

The biological or primary productivity is normally evaluated in terms of biomass (as dry matter), and the water consumed and not recoverable in this production process is normally assessed in terms of evapotranspiration (ET), the sum of transpiration by the crop (T) and evaporation from the soil (E). The linearity between crop biomass (and often final yield) and water use has been observed since the early 1900 and several hundreds of linear relationships can be found in the literature along with different approaches to link both variables (Steduto et al. 2007). However, Viets (1962) acknowledged that there could be situations in which ET would not result in proportionate yield increases. Recently, a lot of researches showed that more than optimized water supply resulted decreasing both in grain yield and water use efficiency (WUE; Abbate et al. 2004; Zhang et al. 2003, 2005; Sun et al. 2006; Purcella et al. 2007).

To cope with scarce supplies, deficit irrigation, defined as the application of water below full crop-water requirements (ET), is an important tool to achieve the goal of reducing irrigation water use (Fereres and Soriano 2007). Extensive studies have demonstrated that post-anthesis water deficits result in early senescence and more mobilization of pre-anthesis stored assimilates to grains in cereals (e.g. Kobata et al. 1992; Palta et al. 1994; Yang et al. 2001b, 2003). Delayed senescence retards mobilization and can lead to reduced grain weight and much nonstructural carbohydrate left in the straw when growing seasons are terminated (Yang et al. 2001a). A linear genetic gain in grain yield (for different cultivars) has been positively correlated with both harvest index (HI) and above-ground mass (Shearman et al. 2005). It was concluded that optimization of inputs at the farm level would maximise biomass production as well as increasing the HI (Pandey et al. 2000a, b). The North China Plain (NCP) is one of the most important winter wheat growing regions in China. If crop maturation is delayed, dry winds at the end of the growing season can dehydrate wheat very rapidly and reduce yield. Then it is quite important to optimize water supply to improve grain production and WUE in this serious water shortage area in China. The purposes of this study was to investigate the biomass accumulation in vegetative and productive stages of winter wheat under different irrigation scheduling and the effects of water supply on crop water use, grain production, HI and WUE to provide references for irrigation management in NCP.

Materials and methods

Experimental details

The study was conducted during 2000–2006, six growing seasons of winter wheat, at Luancheng Agro-Eco-Experimental Station of the Chinese Academy of Sciences, which is located in the northern part of the NCP at the base of Mt. Taihang (37°53′N, 114°40′E; 50 m above sea level). The area is in a monsoon climatic zone with 70% annual rainfall falling in the summer season. Mean rainfall during the growing season of winter wheat was about 132 mm. Irrigation is quite important for this winter crop. Soil is a moderately well drained loamy soil with a deep profile that is considered highly suitable for crop production. Average water holding capacity is 38% (v/v) and wilting point is 13% (v/v) for the 2 m profile (Table 1). Soil organic matter is 17 g/kg, total N is 1.11 g/kg, available N, P and K are 80, 21 and 120 mg/kg, respectively, for the top tillage soil layer.

Winter wheat was sown in October in small plots in a randomized block design with four replications of six irrigation treatments (Table 2). Each plot was 5 × 8 m^2, and separated by a 2 m wide zone planted with non-irrigated winter wheat in order to minimize the mutual effects of adjacent plots. The six irrigation treatments were rainfed (I0), and one (I1), two (I2), three (I3), four (I4) and five (I5) irrigations based on the stage of the crop development (Table 2). At each irrigation, 60–70 mm of water was applied to the soil by surface irrigation using a low-pressure tube water transportation system with a flow meter to record the irrigation applied to each plot.

Precipitation and others meteorological factors such as radiation, wind speed, humidity and temperature were recorded at a standard weather station about 100 m away from the experimental site. Seasonal rainfall for the six growing seasons of winter wheat were shown in Table 3. Compared with the long-term average, 2000/2001 and 2005/2006 seasons were dry, 2001/2002 and 2004/2005 were normal seasons, and 2002/2003 and 2003/2004 were two wet seasons. The ten-day average of ET without water deficit (potential ET or full ET) was calculated by the Penman–Monteith equation recommended by FAO (Allen et al. 1998) multiplied by a crop coefficient derived from the same station (Liu et al. 2002). The seasonal potential ET (ETp) was listed in Table 3.

Measurements

The date of a certain phenology appearing (at 20, 50 and 80%) was recorded, especially heading and anthesis date for all the irrigation treatments. Dry matter accumulation was monitored at each developing stages using the conventional methods. At maturity, plots were harvested manually and then threshed using a stationary thresher. Grain was air-dried prior to recording weights. Prior to harvest, spike numbers per unit area were counted and 80 plants were collected from each plot to determine kernel numbers per spike, kernel weight and HI.

Dry matter mobilization (DMM) and dry matter mobilization efficiency (DMME) during grain filling were calculated following Arduini et al. (2006):

$$\begin{aligned}\text{DMM} = {} & \text{dry matter of the aerial plant part at heading} \\ & - (\text{dry matter of leaves} + \text{culms} + \text{chaff at maturity})\end{aligned} \quad (1)$$

$$\text{DMME} = \text{DMM}/\text{dry matter of the aerial plant part at heading.} \quad (2)$$

Soil volumetric water contents were monitored weekly in 20 cm increments to a depth of 2 m using the neutron meter (IH-II, Cambridge) with access tubes installed in the

Table 1 Characteristics of soil at Luancheng station

Depth (cm)	Texture	Bulky density (g/cm^3)	Effective porosity (%)	Field capacity (v/v)	Wilting point (v/v)	Saturated hydraulic conductivity (m/d)
0–25	Loam	1.39	49	0.36	0.096	1.1
25–40	Loam	1.5	46	0.35	0.114	0.43
40–60	Loam	1.46	46	0.33	0.139	0.73
60–85	Loam	1.49	46	0.34	0.139	0.71
85–120	Sandy clay loam	1.54	46	0.34	0.129	0.02
120–165	Clay loam	1.63	42	0.39	0.139	0.003
165–210	Sandy clay loam	1.55	44	0.38	0.164	0.016

Table 2 The timing and amount of irrigation for different treatments to winter wheat from 2000 to 2006

Treatment	Irrigation timing and amount (mm)				
	Before-wintering	Jointing	Booting	Heading-anthesis	Grain fill
Rain fed (I0)	–	–	–	–	–
One irrigation (I1)	–	70	–	–	–
Two irrigation (I2)	–	70	–	60	–
Three irrigation (I3)	60	70	–	60	–
Four irrigation (I4)	60	70	60	–	60
Five irrigation (I5)	60	70	60	60	60

Table 3 The monthly precipitation for the growing seasons of 2000–2006 of winter wheat and the long-term average and the calculated seasonal potential evapotranspiration (ETp)

Seasons	Rainfall (mm)										ETp (mm)
	October	November	December	January	February	March	April	May	June (0–10)[a]	Total	
2000/2001	31.9	8.4	0.0	8.1	6.9	0.4	23.3	6.2	0.0	85.2	483.0
2001/2002	9.4	18	0.4	1.2	0.0	5.5	30.1	45.7	19.3	129.6	491.2
2002/2003	16.2	0.0	9.9	1.0	1.1	10.1	51.5	66.6	15.0	171.4	444.1
2003/2004	86.7	44.7	0.0	0.6	8.7	0.0	28.6	41.4	3.2	213.9	547.6
2004/2005	4.2	6.2	11.4	0.5	8.0	0.0	10.6	63.3	10.6	114.8	514.9
2005/2006	7.9	0.0	4.6	1.3	1.5	0.4	10.5	44.2	12.7	83.1	477.3
Average of 1951–2000	26.2	14.3	3.7	2.9	6.5	10.9	18.9	33.9	15.2	132.5	497.5

[a] June (0–10) represents the first 10 days of June. Winter wheat was generally harvested around 10th of June

centre of the plot. ET was identified from initial soil water content minus final soil water content, precipitation, irrigation, runoff, drainage and capillary rise using the following equation:

$$\mathrm{ET} = P + I + \Delta W - R - D + \mathrm{CR} \tag{3}$$

where ET is the total water use during a certain growing period, P precipitation, I irrigation; ΔW soil water content at starting minus that at the ending of a period for the 2 m depth, R runoff, D drainage from the root zone and CR capillary rise to the root zone. Runoff and capillary rise were negligible and were not considered. Drainage from the root zone was calculated based on the relation of unsaturated water conductivity with volumetric soil moisture at the bottom of the soil profile. Thus $\mathrm{ET} = P + I + \Delta W - D$ was used under this experimental conditions. The ET during sowing to heading (vegetative growing period, ETv) and from heading to maturity (the reproductive period, ETr) was separately calculated. WUE was defined as crop yield (Y) divided by total water use during the whole growing time:

$$\mathrm{WUE} = \mathrm{Y}/(\mathrm{ETv} + \mathrm{ETr}). \tag{4}$$

Statistical analysis

All the data collected were statistically analyzed as a completely randomized design with four replications using ANOVA to test the difference in biomass, HI, grain yield

Table 4 Aerial biomass at heading (BH) and maturity (BM) (g/m^2), grain yield (GY) (g/m^2), harvest index (HI) and dry matter mobilization efficiency during grain filling (DMME, %) for all the treatments in 2000–2006

Treatments	2000/2001					2001/2002				
	BH	BM	GY	HI	DMME	BH	BM	GY	HI	DMME
I0	823a	1,304a	508.6a	0.39a	3.4a	719a	808a	432.2a	0.53c	47.7d
I1	1,018b	1,418b	539.1a	0.38a	13.6b	1,069b	1,436b	618.2c	0.43b	23.5c
I2	1,187c	1,580c	663.9b	0.42b	22.8c	1,044b	1,562c	661.4d	0.42b	13.7b
I3	1,118c	1,502c	676.0b	0.45b	26.1d	1,123c	1,605d	646.0d	0.40a	14.5b
I4	1,137c	1,635d	703.2c	0.43b	18.1b	1,161c	1,619d	560.4b	0.37a	8.7a
I5	1,121c	1,526c	641.3b	0.42b	21.0c	1,186c	1,577c	549.4b	0.37a	13.4b
	2002/2003					2003/2004				
I0	775b	1,164a	547.2b	0.47c	20.4c	833a	1,299a	654.2a	0.50b	22.5b
I1	733a	1,168a	525.7b	0.45b	12.4a	888a	1,456b	707.3c	0.49b	15.7a
I2	750b	1,150a	506.3a	0.44b	14.1b	896a	1,436b	702.1c	0.49b	18.1a
I3	816c	1,235b	519.1a	0.42a	12.2a	957b	1,438b	674.3b	0.47a	20.2b
I4	839c	1,237b	519.8a	0.42a	14.5b	951b	1,445b	684.4b	0.47a	19.9a
I5	851c	1,211b	508.7a	0.42a	17.5b	1,042b	1,521c	680.2b	0.45a	19.3a
	2004/2005					2005/2006				
I0	719a	1,208a	616.4a	0.51b	17.8b	388a	480a	158.0a	0.33a	17.1a
I1	792b	1,416c	705.8b	0.50b	10.3a	728b	1,028b	514.0b	0.50c	29.4b
I2	815b	1,468c	730.7c	0.50b	9.5a	939c	1,213c	618.4c	0.51c	36.6c
I3	763b	1,259a	703.3b	0.48a	27.1c	961c	1,483d	667.5d	0.45b	15.1a
I4	733a	1,358b	709.2b	0.45a	11.4a	983c	1,496d	658.3d	0.44b	14.7a
I5	736a	1,348b	702.8b	0.45a	12.4a	997c	1,406d	591.1c	0.44b	18.3a

Under the same categories and the same season, the values marked with the same letter was not significant at $P < 0.01$

and WUE among different treatments. When the *F*-test indicated statistical significance at $P \leq 0.01$, mean comparisons were made by LSD.

Results

Biomass accumulation, yield and HI

Table 4 shows that with the increase in water supply, biomass both at heading and maturity increased accordingly till it reached the maximum value. From then on the increase in water supply did not result further increase in biomass. Treatment I4 generally produced the maximum biomass in five out of the six seasons. While the maximum grain production was generally achieved with I2 and I3. In the wet season of 2002/2003, I0 produced the highest yield. The final grain production was not linearly related to biomass production (Fig. 1). In very dry seasons such as in 2005/2006, the rainfall was small and mostly fell in the later period of grain fill, I0 produced the lowest biomass and grain yield among the six seasons (the lowest point in Fig. 1). With one irrigation application, the increase in biomass and grain yield was enormous. Biomass at maturity was increased by 114% and grain yield by 225% for I0 compared with I1. The increase in biomass and grain yield became smaller with further irrigation application (Fig. 1, Table 4).

Generally, HI decreased with the increase in water supply. However, in very dry seasons of 2000/2001 and 2005/2006 (seasonal rainfall was less than 80 mm), the HI of the rain-fed treatment was reduced. HI gradually increased with the increase in water supply and it reached the highest with either two or three irrigations. Then it decreased again with more irrigation application. Positive linearity between HI and DMME was found (Fig. 2). The results showed that grain production of winter wheat was affected not only by its biomass accumulation during its vegetative growth period, but also by the DMM during its grain filling.

The higher DMME and HI for the less irrigated treatments might be attributed to phenological development. The well-irrigated treatments tended to delay its heading and anthesis by 2–5 days compared with the rain-fed treatment. In NCP, the grain filling duration is limited to one month. The high temperature and dry wind in late May and early June accelerate the maturity and shorten the grain-filling stage. Thus, the grain-filling of well-watered treatments lasted less than that the less watered treatments, resulting lower HI and DMME. The yield potential of

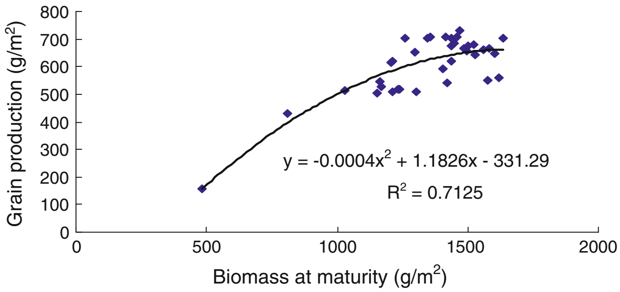


Fig. 1 The relation of biomass at maturity with the final grain production of winter wheat under different water supply during 2002–2006

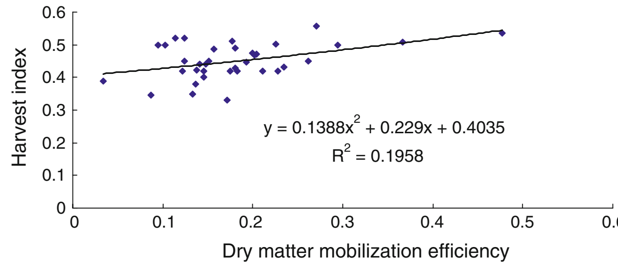


Fig. 2 The relation of dry matter mobilization efficiency during grain filling (DMME) with harvest index of winter wheat under different irrigation conditions from 2000 to 2006 (significant at $P < 0.01$)

the well-watered treatments was restricted under this condition.

Analysis of yield components showed that grain yield linearly increased with the increase in the multiplied value of spike number per area and kernel number per spike (Fig. 3). No significant relationship was found between seed weight and yield. The less irrigated winter wheat tended to have less spikes per area, but its kernel numbers per spike was not significantly affected. The seed weight of less irrigated treatments tended to be greater, except in very dry years. The lowest seed numbers per area of I0 in 2005/2006 resulted the lowest grain yield among the six seasons (Fig. 3).

The relation of ET with biomass accumulation

Results from this experiment showed that biomass at heading and maturity and the dry matter accumulation from heading to maturity (post heading dry matter) were all in a quadric relationship with ET (Fig. 4). When ET was lower, the increase in ET resulted linearly increase in biomass production. When ET reached a certain level, the increase in biomass by ET was slowed down, till the increase in ET did not cause any significant change in biomass. The extreme drought for I0 in 2005/2006 season produced the lowest ET and biomass among the treatments in all the six seasons (Fig. 4). Irrigation application and rainfall distribution all affected crop growth.

The non-linear relationship of ET with biomass was possibly because the soil evaporation was greater for the well-watered treatments. Liu et al. (2002) showed that under well-watered condition at the same site, soil evaporation (E) took up 30% of the total ET and the ratio of E/ET was significantly affected by surface soil moisture and leaf area index. Figure 5 showed the top 0–20 cm soil moisture change during the growing period of winter wheat in one wet season of 2003–2004 and one dry season of 2005–2006 for I0 and I5. It indicated that the top soil moisture was always maintained at a high level for I5, which increased the soil evaporation loss. Figure 6 shows the relationship of relative biomass production (calculated by biomass/maximum biomass in a season) at maturity with the relative ET (calculated by ET/ETp in a season). The maximum biomass could be produced by 94% of the potential ET.

The relation of grain yield and WUE with ET

Figure 7 shows the relationship of grain yield and WUE with seasonal ET. Similar to the relation of biomass with ET, grain yield was also curvilinearly related to ET. From the relationship of the relative grain yield (grain yield/maximum grain yield in a season) and relative evapotranspiration (ET/ETp in a season) (Fig. 8), it was concluded that 84% of the seasonal ETp produced the maximum grain production, 10% less than the maximum biomass which was achieved with 94% of ETp. Thus, for grain production, the optimized water supply was lower than that for the aerial dry matter production. However, WUE was negatively related to ET. For greater WUE, ET should be reduced below the ET for highest grain yield.

The maximum yield was achieved with ET that was 16% less than ETp, which indicated the importance of dry matter accumulation and relocation. Grain production requires not only the higher dry matter production during the vegetative growing period, but also the higher mobilization efficiency to grain, especially for crops that grown under limited grain filling duration. The moderate water deficit that improved HI and reduced excessive soil evaporation was a good strategy to maximum grain production and WUE.

Patterns of soil water use under different water supply

The previous study at the same site showed that winter wheat had a deep root system down to 2 m (Zhang at al. 2002) and the soil has a deep profile with high water holding capacity. Even with less irrigation, winter wheat still produced considerable production by using the stored soil moisture. Taking the example of season 2004/2005, a normal season with rainfall 115 mm, Figure 9 shows the

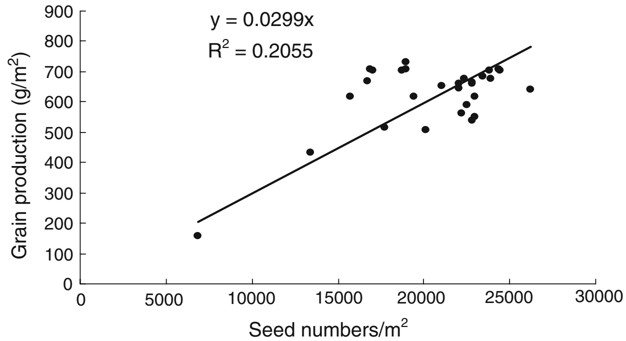


Fig. 3 The relation of kernel numbers per area with grain production under different water supply conditions for winter wheat during 2002–2006 (significant at $P < 0.01$)

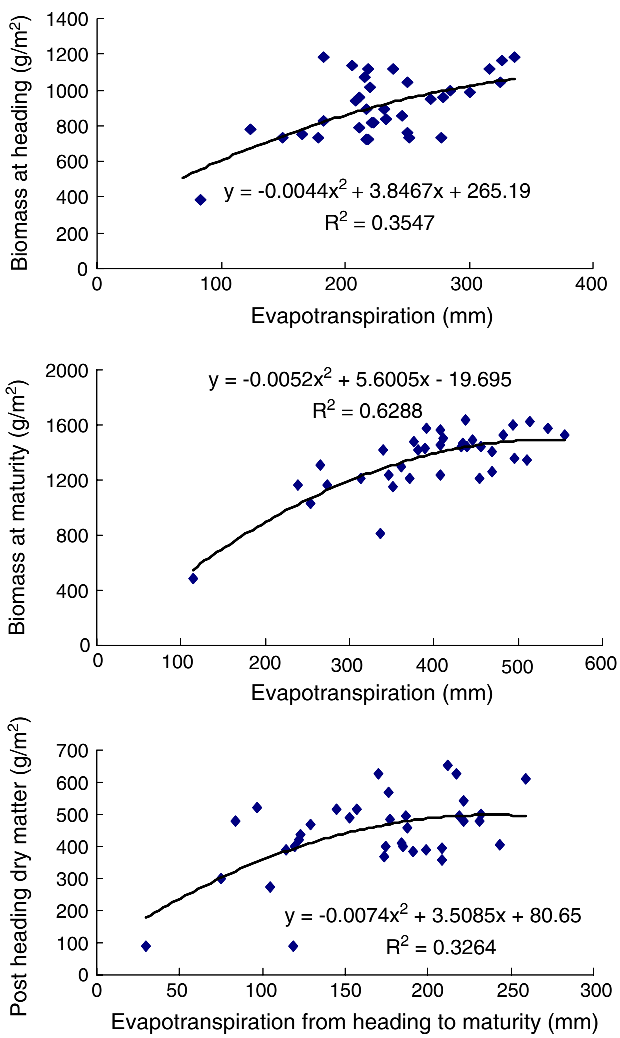


Fig. 4 The relation of aerial dry matter at heading, maturity and post heading accumulation with their corresponding ET for six irrigation treatments of winter wheat during 2000–2006

daily potential ET and soil moisture change at different depth for I0, I2 and I5. Daily ETp before winter was relative constant. During over-wintering, it decreased and remained at the lowest level. After recovery in March, ETp increased significantly. The soil water use by the crop also showed similar pattern. With less water use before winter and during over-wintering, soil moisture along root zone

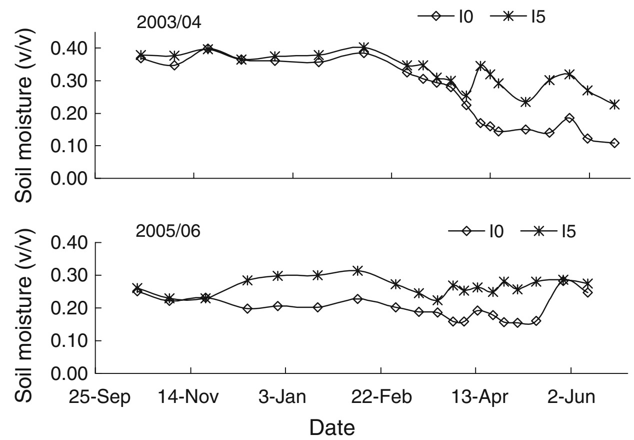


Fig. 5 The top soil moisture (0–20 cm) change in two seasons (2003/2004, a wet season; 2005/2006, a dry season) for the rainfed treatment (I0) and the most frequently irrigated treatment (I5)

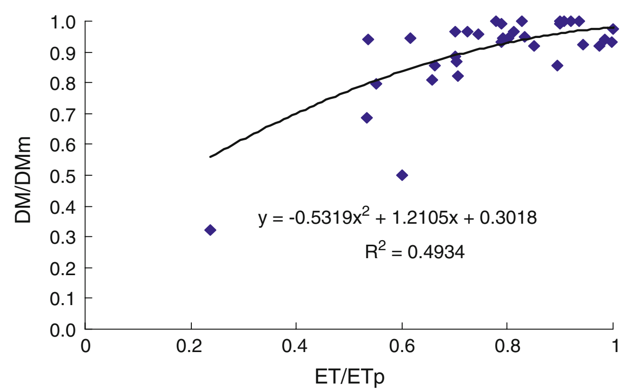


Fig. 6 The relation of the relative aerial dry matter production (dry matter/maximum dry matter in a season, DM/DMm) and relative evapotranspiration (evapotranspiration/potential evapotranspiration in a season, ET/ETp) for different treatments during 2000–2006

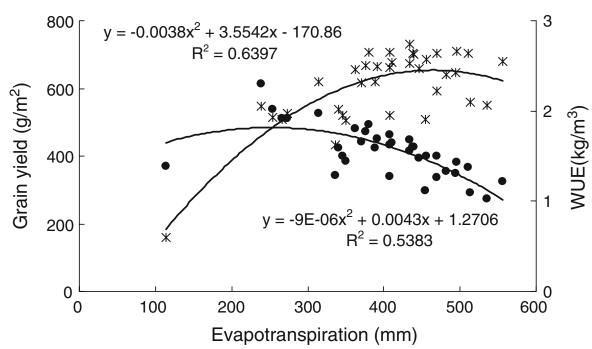


Fig. 7 The relation of grain yield and water use efficiency (WUE) with seasonal evapotranspiration (ET) under different water supply conditions from 2000 to 2006

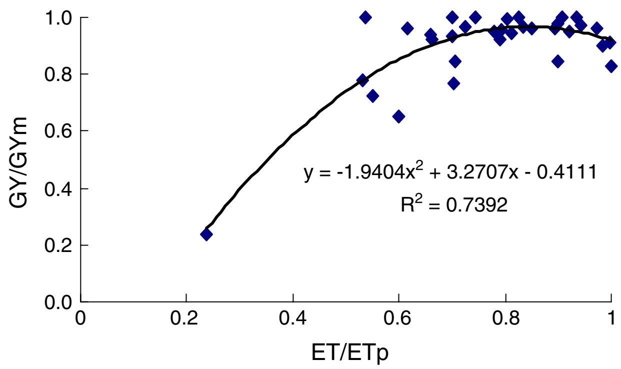
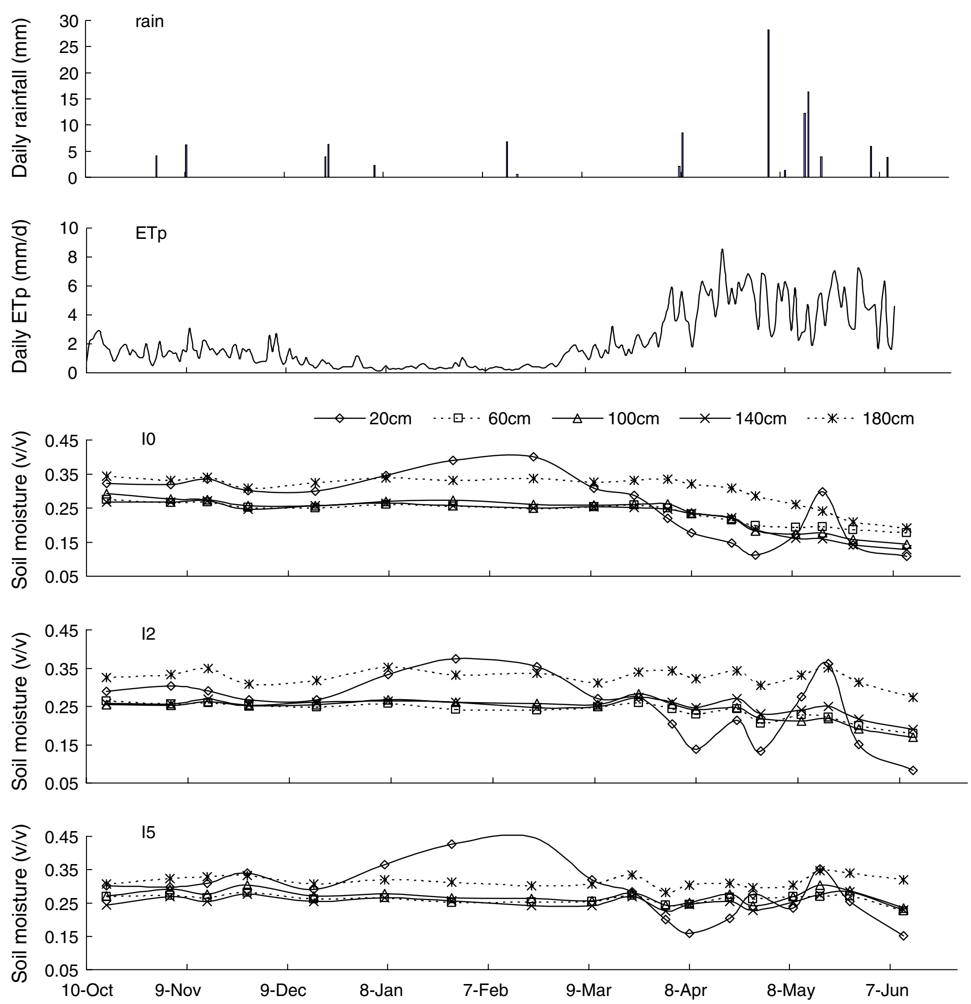


Fig. 8 The relation of relative grain yield (grain yield/maximum grain yield in a season, GY/GYm) and relative seasonal evapotranspiration (evapotranspiration/potential evapotranspiration in a season, ET/ETp) under different water supply conditions from 2000 to 2006

profile was stable for all the treatments. After recovery stage in March, the sharply increase in ET caused the significant decrease in soil moisture down to 180 cm for the rainfed treatment. While the most irrigated treatment I5 did not show soil moisture decrease till the last irrigation at grain-fill stage. The soil water contents of the moderately irrigated treatment I2 also begun to decrease at the end of March, but the amplitude was less than that of the rainfed treatment.

The marked decrease in soil water contents suggested that rainfall was far less than the water requirements of the crop and the stored soil moisture before sowing supplied the larger part of the ET for I0 (Fig. 9). For I2, the first irrigation at the earlier April corresponded with the increase in water use. The soil moisture was not significantly reduced. The second irrigation at anthesis stopped the decreasing trend of soil moisture for some time. Later at grain-fill stage, soil moisture decreased gradually without further irrigation. For the whole growing season, the moderately irrigated wheat maintained slightly lower soil moisture compared with I5 during the vegetative growing period. After anthesis soil moisture of I2 was lower than I5. The water deficit during this time might increased DMME, which resulted the higher yield of I2 compared with I5. The results indicated that without irrigation soil moisture would continuously decrease after

Fig. 9 Rainfall distribution, daily potential evapotranspiration and soil moisture at depths of 20, 60, 100, 140 and 180 cm during 2004/2005 for winter wheat under rainfed (I0), two irrigations (I2) and five irrigations (I5)



winter wheat going into the rapid growing season and water deficit reduced grain production. While with two irrigation applications, soil moisture was maintained at reasonable level before grain-fill and moderate deficit level after grain fill that produced the highest grain yield in a normal season.

Optimizing the water supply

The results showed that maximum grain production of winter wheat was corresponding with 84% of full ET and the highest WUE was achieved with half of full ET. For an average seasonal potential ET of 497 mm, 250–420 mm was the water consumption range either for maximum WUE or maximum yield. With a seasonal average rainfall of 133 mm, irrigation water should be around 120–300 mm. However, the results from this experiment showed that maximum yield was produced with only 60–120 mm irrigation in a normal season. Due to the deep soil profile and high water holding capacity within the root zone (about 2 m), the stored soil moisture extracted by the root system of winter wheat took up 60% of ET in dry seasons for the rain-fed treatment. Even for I1, I2 and I3, soil depletion still took up 30–50% of the total seasonal ET (Table 5). The stored soil moisture before sowing contributed significantly to grain production under limited water supply. For the double cropping system of winter wheat and maize in NCP, the maximum rooting depth for winter wheat was 2 m and for maize was 1.2 m (Zhang et al. 2002). The combination of shallow rooted maize in the wet season with deep rooted wheat in the dry season made the double-cropping system in the NCP more efficient in utilizing soil moisture. Winter wheat extracted soil moisture that was stored in the deep soil profile during rainy season. The shallower root system of maize utilized soil moisture mostly in the top 0.6–0.8 m of the soil profile. Rain in excess of maize water consumption was stored lower in the profile and utilized by the following wheat crop (Zhang et al. 2006). Then irrigation management to winter wheat should consider the soil moisture along the root zone profile.

Based on the analysis of the yield and soil profile depletion, it was concluded that in a normal season, the components of ET for a maximum yield were 150 mm from stored soil moisture before sowing, 130 mm from rainfall and 140 mm from irrigation. Then two numbers of irrigation applications were the optimized irrigation scheduling in a normal year. The timing of irrigation was after the recovery stage, when winter wheat going into the rapid growing season and water use increased. In dry or wet seasons, the irrigation can be increased or reduced accordingly. In a wet season, I0 or I1 gave the maximum production. Irrigation once at jointing stage, combined with fertilizing, will be the best irrigation practice for this region. While in very dry seasons, irrigation numbers can be increased to two or three.

Conclusion and discussion

It is important to improve grain production with less water in water shortage regions. Water stress affects crop growth and productivity in many ways and most of the responses have a negative effect but crops have different and often complex mechanisms to react to shortages of water (Chaves and Oliverira 2004). The results from this experiment showed that 94% of full ET could result maximum dry matter accumulation, and 84% of full ET achieved the maximum grain production of winter wheat. The improved grain production under moderate water deficit was related to the longer grain filling duration and higher DMME that improved HI. Wheat under water stress tended to flower earlier and thus gain several days during the grain filling stage, before high temperature in June limited further grain fill and accelerated crop maturity in NCP. The senescence and mobilization promoted

Table 5 The seasonal evapotranspiration (ET, mm) and the contribution of the soil profile depletion to ET (SWD, %) for different treatments from 2000 to 2006

Treatments	2000/2001		2001/2002		2002/2003		2003/2004		2004/2005		2005/2006	
	ET	SWD	ET	SWD	ET	SWD	ET	SWD	ET	SWD	ET	SWD
I0	266	69	337	62	238	28	362	41	371	69	114	27
I1	340	51	389	49	273	12	407	30	381	51	254	40
I2	392	44	408	36	351	14	439	22	434	44	314	32
I3	410	35	473	35	346	−4	433	7	469	35	376	27
I4	438	26	489	26	408	−4	455	−2	493	26	446	25
I5	482	17	494	18	454	−6	556	−6	511	17	479	16

The negative SWD indicates that the soil moisture along the 2 m profile was increased at maturity compared with that at sowing by water deficits during the grain filling period are coupled processes in wheat. Even with less than maximum biomass accumulation, the higher HI compensated this loss and the final yield was improved.

The stored soil moisture in the root zone profile before sowing played an important role in higher yielding of winter wheat under limited water supply. Other studies also showed the possibility of combining residual soil moisture with limited rainfall in obtaining high yields of crops. The availability of residual soil moisture depended on earlier rainfall, soil texture and the effective root depth (Sharma and Ghildyal 1977; Chaudhary and Bhatnagar 1980; Mishra et al. 1995; Mugabe 1998; Mugabe and Nyakatawa 2000). The high water holding capacity and deep root system of winter wheat under the experimental condition are advantages for reducing irrigation application. The result from this experiment shows that the maximum grain yield was achieved by one third of the ET contributed by residual soil moisture in a normal year. Another beneficial factor for more ET from the stored soil moisture was the reduced soil evaporation. With more water used from soil profile, less irrigation was applied and the top soil surface would be kept drier to reduce soil evaporation. The extracted soil moisture in the profile could be partly compensated during the following rainy season or by an irrigation before sowing (Zhang et al. 2006). Then irrigation scheduling must take account of the stored soil moisture in the root zone profile.

Higher WUE generally corresponded with small ET. The results from this experiment showed that the maximum WUE was achieved with ET at 250 mm, which was 170 mm less than the ET for maximum grain production. With the intensifying in water shortage and the increasing in irrigation cost, the economic ET should be less than the ET for maximum production. Zhang et al. (2002) found that irrigation for maximum profit was 40 mm less than the irrigation for maximum production under water fee of US$0.0588/m^3, now common in NCP. Then for maximum economic return, the irrigation water could be further reduced.

Acknowledgments This research was funded by the National Basic Research Program of China (project no. 2006CB403406) and the Innovation Knowledge Project of Chinese Academy of Sciences (Grant no. KZCX2-YW-N-004).

References

Abbate PE, Dardanelli JL, Cantarero MG, Maturano M, Melchiori RJM, Suero EE (2004) Climatic and water availability effects on water-use efficiency in wheat. Crop Sci 44:474–483

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO. Irrigation and drainage paper no 56, FAO, Rome, 300 pp

Arduini I, Masoni A, Ercoli L, Mariotti M (2006) Grain yield, and dry matter and nitrogen accumulation and remobilization in durum wheat as affected by variety and seeding rate. Eur J Agron 25:309–318

Chaudhary TN, Bhatnagar K (1980) Wheat root distribution, water extraction pattern and grain yield as influenced by time and rate of irrigation. Agric Water Manage 3:115–124

Chaves MM, Oliverira MM (2004) Mechanisms underlying plant resilience to water deficits: Prospects for water-saving agriculture. J Exp Bot 55:2365–2384

Fereres E, Soriano MA (2007) Deficit irrigation for reducing agricultural water use. J Exp Bot 58:147–159

Kobata T, Palta JA, Turner NC (1992) Rate of development of postanthesis water deficits and grain filling of spring wheat. Crop Sci 32:1238–1242

Liu CM, Zhang XY, Zhang YQ (2002) Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agric Fores Meteorol 111:109–120

Mishra HS, Rathore TR, Tonar MS (1995) Water use efficiency of irrigated wheat in the Tarai region of India. Irrig Sci 16: 75–80

Mugabe FT (1998) Effects of soil and rainfall variability on water storage and mazie yields in Zimbabwe. Afr Crop Sci J 6: 39–47

Mugabe FT, Nyakatawa EZ (2000) Effect of deficit irrigation on wheat and opportunities of growing wheat on residual soil moisture in southeast Zimbabwe. Agric Water Manage 46:111–119

Palta JA, Kobata T, Turner NC, Fillery IR (1994) Remobilization of carbon and nitrogen in wheat as influenced by post-anthesis water deficits. Crop Sci 34:118–124

Pandey RK, Maranville JW, Admou A (2000a) Deficit irrigation and nitrogen effects on maize in a Sahelian environment. I. Grain yield and yield components. Agric Water Manage 46:1–13

Pandey RK, Maranville JW, Chetima MM (2000b) Deficit irrigation and nitrogen effects on maize in a Sahelian environment. II. Shoot growth. Agric Water Manage 46:15–27

Purcella LC, Edwardsb JT, Bryea KR (2007) Soybean yield and biomass responses to cumulative transpiration: Questioning widely held beliefs. Field Crops Res 101(1):10–18

Sharma RB, Ghildyal BP (1977) Soil water-root relations in wheat: water extraction rate of wheat roots that developed under dry and moist conditions. Agron J 69:231–233

Shearman VJ, Sylvester-Bradley R, Scott PK, Foulkes MJ (2005) Physiological processes associated with wheat yield progress in the UK. Crop Sci 45:175–185

Steduto P, Hsiao TC, Fereres E (2007) On the conservative behavior of biomass water productivity. Irri Sci 25:189–207

Sun HY, Liu CM, Zhang XY, Shen YJ, Zhang YQ (2006) Effects of irrigation on water balance, yield and WUE of winter wheat in the North China Plain. Agric Water Manage 85:211–218

Uçana K, Killib F, Gençoğlana C, Merduna H (2007) Effect of irrigation frequency and amount on water use efficiency and yield of sesame (Sesamum indicum L.) under field conditions. Field Crops Res 101(3):249–258

Viets FG (1962) Fertilizers and the efficient use of water. Adv Agron 14:223–264

Yang JC, Zhang JH, Wang ZQ, Zhu QS (2001a) Activities of starch hydrolytic enzymes and sucrose-phosphate synthase in the stems of rice subjected to water stress during grain filling. J Exp Bot 52(364):2169–2179

Yang JC, Zhang JH, Wang ZQ, Zhu QS, Liu LJ (2001b) Water deficit-induced senescence and its relationship to the remobilization of pre-stored carbon in wheat during grain filling. Agron J 93:196–206

Yang JC, Zhang JH, Wang ZQ, Liu LJ, Zhu QS (2003) Postanthesis water deficits enhance grain filling in two-line hybrid rice. Crop Sci 43(6):2099–2108

Zhang XY, Pei D, Li Z, LI J, Wang Y (2002) Management of supplemental irrigation of winter wheat for maximum profit. Deficit irrigation practices. Water reports 22, FAO, pp 57–65

Zhang XY, Pei D, Hu CS (2003) Conserving groundwater for irrigation in the North China Plain. Irri Sci 21:159–166

Zhang XY, Chen SY, Pei D, Liu MY, Sun HY (2005) Improved water use efficiency associated with cultivars and agronomic management in the North China Plain. Agron J 97:783–790

Zhang XY, Pei D, Chen SY, Sun HY, Yang YH (2006) Performance of double-cropped winter wheat-summer maize under minimum irrigation in the North China Plain. Agron J 98:1620–1626