Effects of row spacing on soil water and water consumption of winter wheat under irrigated and rainfed conditions

X.B. Zhou[1,2], Y.H. Chen[1], Z. Ouyang[2]

[1]State Key Laboratory of Crop Biology, Shandong Key Laboratory of Crop Biology, Shandong Agricultural University, Taian, P.R. China
[2]Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, P.R. China

ABSTRACT

The results of two seasons' work on soil water content (SWC), evapotranspiration (ET), total dry matter (TDM), and harvest index (HI) of crops under different row spacing (RS), as well as possible ways to improve water utilization, have been reported. Field experiments were carried out at the Experimental Farm of Shandong Agricultural University (36°09'N, 117°09'E) in 2006–2007 and 2007–2008. Four types of RS were treated under two different water conditions (rainfed and irrigated) and set up in a randomized plot design. RS did not exhibit any obvious effects on SWC during the study period. SWC was enhanced evidently by irrigation, especially in the 10–60 cm soil layer. Irrigation increased the ET of crop. At the seeding-jointing stage, the ET of RS14 was significantly higher than those during other treatments ($P < 0.05$). Irrigation increased yields, ET, and TDM, while it decreased water use efficiency and HI. There were significantly negative correlations between TDM and RS ($P < 0.05$). The HI of the rainfed crop was higher than that of the irrigated crop. Results showed that high yields of wheat could be achieved in northern China by reducing RS under uniform planting density conditions.

Keywords: evapotranspiration; harvest index; crop yield; dry matter; water use efficiency

Row widths are known to influence crop population structure and yield (Eberbach and Pala 2005, Zhou et al. 2010). The main competition factors are light, water, nutrients, and weed (Brant et al. 2009). Lower yields are associated with increasing soil water deficits (Mishra et al. 1999). Several attempts, including deep tillage, subsoiling, and chiseling, were implemented to improve the physical environment of the profile in favor of root growth and to increase wheat yield (Gajri et al. 1991, Oussible et al. 1992, Unger 1993).

Irrigation management affects production costs and leaching of nutrients to groundwater (Steele et al. 2000, Liao et al. 2008). Improving water use efficiency (WUE) to optimize the benefits of irrigation is of paramount importance to farmers (Mishra et al. 1995, Ritchie and Basso 2008). Management practices to maintain yields while minimizing external input requirements is necessary in ensuring economic and environmental sustainability (Hill et al. 2006). Wheat-legume rotation systems with additional N input in the wheat phase not only maintain sustainable production systems, they are also more efficient in utilizing limited rainfall (Pala et al. 2007).

Huanghuaihai Plain is one of the most important grain production bases in China. It is an alluvial-flood plain and sub-humid continental monsoon zone that lies in north China, with an annual accumulated temperature (≥ 0°C) of 4800°C, annual average rainfall of 600 mm, cumulative radiation doses of more than 5200 MJ/m^2, and non-frost

Supported by the Special Fund for Agro-scientific Research in the Public Interest, Projects No. 200903040 and 201103001, by the Major State Basic Research Development Program of China, Project No. 2005CB121106, and by the Colleges and Universities Outstanding Young Teacher Domestic Visiting Scholar of Shandong Province Project (2009).

period of more than 200 days. In most years, from October to May, in the winter wheat growing season, rainfall is about 200 mm (20–30% of annual precipitation). The water requirement of winter wheat (~ 400–500 mm) in spring exceeds precipitation; monthly rainfall data shows that water supply from rainfall is inadequate to match crop ontogeny (Zhou et al. 2007).

Previous work on WUE primarily dealt with crops grown under water limited conditions and usually did not consider the relationship between crop row spacing (RS) and WUE (Lehrsch et al. 1994, Bowers et al. 2000). As a consequence, winter wheat yields reflect the amount of stored soil water, rainfall, and water applied through irrigation. Therefore, a schedule should be developed for different ecological regions, as plant water consumption during vegetation periods depend mostly on plant growth, as well as on soil and climatic conditions (Uçana et al. 2007, Zhang et al. 2008). The objective of this study is to derive information on soil water and water consumption, which can vary with RS of wheat under rainfed and irrigated agriculture.

MATERIALS AND METHODS

Site description. This research was conducted at the Experimental Farm of Shandong Agricultural University, Taian (36°09'N, 117°09'E) in northern China. The site is representative of the main winter wheat growing region of Huanghuaihai Plain. Long-term average (years 1971 to 2008) rainfall and temperature were 696.6 mm and 12.8°C, while rainfall was about 200 mm from October to May. The soil is characterized as silt loam with average SOM of 16.3 g/kg, N 92.98 mg/kg, P 34.77 mg/kg, K 95.45 mg/kg, and pH of 6.9.

Experimental design. Experiments were conducted during the growing seasons of October to June in 2006–2007 and 2007–2008. As a part of the continuous winter wheat (*Triticum aestivum*)-summer soybean [*Glycine max* (L.) Merr.] rotation experiment, after post-summer soybean plants were hand-harvested and their stubbles removed. Winter wheat (cv. Shannong 919) was hand-planted according to plant density (4.08×10^6 plant/ha) on October 6, 2006 and October 10, 2007. The experiment consisted of four planting patterns under irrigation and rainfed conditions. Row spacing × plant spacing was 7 × 7 cm (RS7, a uniform grid pattern), 14 × 3.5 cm (RS14), 24.5 × 2 cm (RS24.5) and 49 × 1 cm (RS49). Each experiment plot was 3 m × 3 m in size and replicated thrice in randomized block designs. Concrete slabs were inserted to a depth of 2.0 m and width of 15 cm on four sides of each plot. Plastic films (0.1 mm thick) were also placed along the wall of concrete. Hence, lateral flow of soil water was prevented. Basin irrigation was used and water was conveyed from the outlet of a pump to the pool cultures using plastic pipes. The schedules and amounts of irrigation are given in Table 1. Seedlings thinning were adopted by hand 5 days after wheat emergence to obtain the same final population density (2.04×10^6 plant/ha). The crops were harvested on June 5, 2007 and June 13, 2008. Yields were measured on 2 m^2 per plot. Weather data were collected from Taian Agrometerological Experimental Station located 500 m from the experimental site. Data on monthly rainfall during the winter wheat growing seasons (October to June) are given in Table 2.

Table 1. The timing and amount of irrigation for different treatments to winter wheat

Growth stages	2007	2008	Irrigated (mm)	Rainfed
Jointing	March 31	April 2	60	–
Heading	April 25	May 2	60	–
Milk	May 14	May 18	60	–

Neutron moisture meter access-tubes (one per treatment-replicate) were installed between rows at each location to a depth of 1.3 m prior sowing. Soil water content (SWC) was monitored every 7–10 days throughout the winter wheat growing season at 10 cm intervals from 20 to 120 cm depths using the locally field calibrated CNC503B (DR) Neutron Moisture Probe (Super Energy Nuclear Technology Ltd., Beijing, China). Water content of the top 20 cm soil profile was determined using a portable time domain reflectometry CS620

Table 2. Monthly rainfall (mm) for the winter wheat growth seasons

Season	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
2006–2007	5.3	14.2	9.5	0.0	2.1	46.7	15.2	118.8	0.7	212.5
2007–2008	17.3	8.0	16.5	4.0	4.8	17.7	57.7	44.7	6.4	169.9

(TDR) system (Campbell Scientific Australia Pty. Ltd., Townsville).

Computation and statistical analyses. Evapotranspiration (ET) for each treatment was computed from planting patterns and climate data obtained from the Taian Agrometeorological Experimental Station using the following equation:

$$ET = \Delta W + I + R - SI - Q \quad (1)$$

Where: ΔW is the change of soil water stored (mm), I is the amount of irrigation water (mm), R is the rainfall (mm), SI is the deep percolation (mm), and Q is the surface run-off (mm). Based on observations for the 2006–2007 and 2007–2008 cropping seasons, that surface run-off and deep percolation below the 1.20 m soil depth were negligible, and hence, ET was calculated using ΔW, I, and R.

$$\Delta W = \Sigma(\Delta Ø_i \times Z_i) \quad (2)$$

Where: $\Delta Ø_i$ is the change in soil volumetric water content (m^3/m^3) and Z_i is the depth of soil layer (mm). Then,

$$WUE = Y/ET \quad (3)$$

Where: Y is the grain yield (kg/ha) of winter wheat and ET denotes evapotranspiration.

All data were analyzed by SPSS 16.0 Statistical Software Package, and least significant difference (*LSD*) tests were used. Effects were considered significant in all statistical calculations if *P*-values were ≤ 0.05 (Mishra et al. 2001).

RESULTS AND DISCUSSION

Irrigation exhibited a greater effect on SWC. After irrigation, SWC was evidently enhanced, especially in the 10–60 cm soil layer, and SWC increased by 10.5–55.7% during the jointing and heading stages. Later in the winter wheat growing season (May 24, 2007 and May 31, 2008), after irrigation water was applied during the milk stage, the order of SWC was RS14 < RS7 < RS24.5 ≈ RS49. However, no significant differences were recorded ($P < 0.05$). The SWC of the RS14 was the lowest whereas RS7 was at the mid-range, and there was no evident difference in the SWC between RS24.5 and RS49, especially as days after irrigation increased (Figure 1).

Results showed that the SWC of different treatments had a 'Z' curve trend in the growing season, especially at the milk stage. The inflection point of the curve could be observed in the 40 cm and 60–80 cm soil layers (Figure 1). Clearly, high value could be observed at the 30–60 cm soil layer in 2007 and the 30–50 cm soil layer in 2008. The SWC value of 2008 was higher than that of 2007 at the jointing stage, which could be attributed to the amount of rainfall on April 8–9, 2008 (11.3 mm). There was a reverse trend at the milk stage, possibly due to the amount of rainfall on May 20–23, 2007 (104.7 mm). SWC average values at the 0–20 and 30–60 cm levels were 16.0% and 23.1% in 2007 and 17.0% and 23.3% in 2008, respectively. More rainfall occurred in 2006–2007, but there was no corresponding increase in the SWCs of the jointing and heading stages.

In 2006–2007 and 2007–2008, from jointing to maturity stage, the ET of irrigated crops was significantly higher than that of rainfed crops ($P < 0.05$). The difference in rainfed crops was higher than those for irrigated crops (Table 3). During seeding-jointing, the ET of RS14 was significantly higher than that of other treatments ($P < 0.05$). In 2006–2007, the relatively low ET during heading-filling might have resulted from lesser amounts of rainfall. During filling-maturity, the ET of RS49 was significantly lower than that of other treatments for rainfed crops ($P < 0.05$), and was the reverse for irrigated crops. In 2007–2008, under the same irrigation amount, the ET of RS49 was relatively high during jointing-heading and filling-maturity, and the lowest during heading-filling. For irrigated crops, water consumption per day (WCD) was at the maximum during filling-maturity. From jointing to maturity stage in 2006–2007, the WCDs of RS7, RS14, RS24.5, and RS49 were 2.79, 2.69, 2.51, and 2.45 mm/day for rainfed crops, and 4.65, 4.82, 4.41, and 4.87 mm/day for irrigated crops. In 2007–2008, the corresponding values were 3.00, 2.88, 2.73, and 2.83 mm/day for rainfed crops, and 4.34, 4.40, 4.13, 4.20 mm/day for irrigated crops.

To investigate further the irrigated and rainfed crops, ET versus grain yield in 2006–2007 and 2007–2008 was plotted for all treatments (Figure 2). Based on overall yield trend, more water resulted in higher yields. For rainfed crops, the R^2 values were 0.885 (2006–2007) and 0.8891 (2007–2008), whereas for irrigated crops, the values were 0.9878 (2006–2007) and 0.9699 (2007–2008), respectively. In 2006–2007 and 2007–2008, the yields, ET, and total dry matter (TDM) of irrigated crops were higher than those of rainfed crops, whereas the values for WUE and harvest index (HI) were lower. The yields and ET of RS14 were the highest among the treatments. The order of yields was RS14 > RS7 > RS24.5 > RS49. The yield for RS49 was significantly lower than those of other treatments ($P < 0.05$). The ET average for the two growing seasons of RS7, RS14, RS24.5, and RS49 were 332.3, 333.9, 314.2, and 308.1 mm (rainfed)

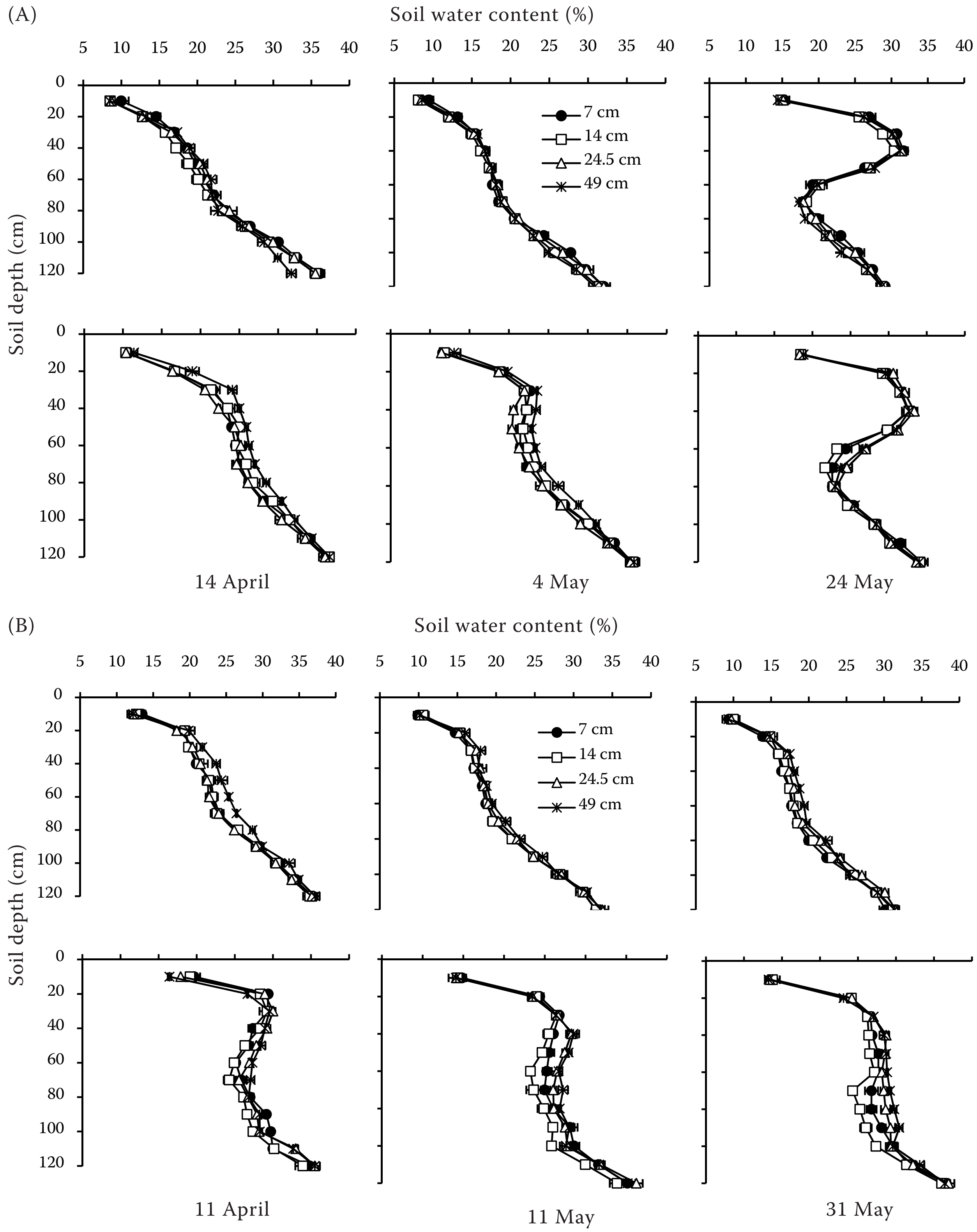

Figure 1. Average soil water content under different RS in (A) 2006–2007 and (B) 2007–2008. Error bars are standard error

and 446.4, 463.8, 431.6, and 443.6 mm (irrigated), respectively. The WUE of RS24.5 was higher than those of other treatments (Table 4). The high WUE of 2007–2008 might have been affected by the lesser amount of rainfall during this season. In this study, there were significantly negative correlations between TDM and RS. For the rainfed crops, the correlation coefficient (*r*) was –0.9298 (2006–2007) and –9831 (2007–2008), whereas for irrigated crops, it was –0.8916 (2006–2007) and

Table 3. Effects of row spacing and irrigation treatments on water consumption of crop in different growth stages

Growth season	RS	Seeding–jointing		Jointing–heading		Heading–filling		Filling–maturity	
		ET/WCD	R	ET/WCD	I + R	ET/WCD	I + R	ET/WCD	I + R
2006–2007	7	126.7/0.75[b]	78	92.1/2.97[bc]	15	32.4/1.62[b]	9	78.9/3.59[d]	111
	14	138.1/0.82[a]	78	88.2/2.85[c]	15	32.5/1.63[b]	9	76.0/3.46[d]	111
	24.5	128.5/0.76[b]	78	79.8/2.57[c]	15	29.9/1.50[b]	9	73.6/3.35[d]	111
	49	126.5/0.75[b]	78	84.3/2.72[c]	15	36.5/1.83[b]	9	58.0/2.63[e]	111
	7	126.7/0.75[b]	78	117.8/3.80[a]	75	92.5/4.62[a]	69	128.9/5.89[b]	171
	14	138.1/0.82[a]	78	123.5/3.98[a]	75	89.8/4.49[a]	69	138.3/6.26[b]	171
	24.5	128.5/0.76[b]	78	118.0/3.81[a]	75	87.3/4.36[a]	69	116.3/5.28[c]	171
	49	126.5/0.75[b]	78	111.7/3.60[ab]	75	93.6/4.68[a]	69	149.9/6.81[a]	171
2007–2008	7	127.6/0.74[b]	58	75.4/3.43[cd]	58	69.2/3.64[c]	14	62.4/3.12[c]	40
	14	134.5/0.78[a]	58	72.4/3.29[d]	58	66.0/3.47[cd]	14	60.2/3.01[c]	40
	24.5	128.3/0.75[b]	58	74.8/3.40[cd]	58	59.6/3.14[de]	14	53.9/2.70[d]	40
	49	115.9/0.67[c]	58	77.1/3.51[c]	58	55.0/2.90[e]	14	62.9/3.15[c]	40
	7	127.6/0.74[b]	58	92.0/4.18[ab]	118	96.8/5.10[a]	74	110.5/5.53[ab]	100
	14	134.5/0.78[a]	58	90.7/4.12[ab]	118	96.3/5.07[a]	74	116.5/5.82[a]	100
	24.5	128.3/0.75[b]	58	87.8/3.99[b]	118	91.4/4.81[ab]	74	105.5/5.27[b]	100
	49	115.9/0.67[c]	58	92.5/4.20[a]	118	87.8/4.62[b]	74	109.3/5.46[b]	100

RS – row spacing; ET – evapotranspiration (mm); WCD – water consumption per day (mm/day); I + R – irrigation + rainfall (mm). Values followed by different small letters within a column are significantly different at level of 0.05.

–0.9474 (2007–2008), respectively ($P < 0.05$). The TDM of RS49 was significantly lower than those of other treatments ($P < 0.05$). For the rainfed crops, the HI of RS49 was significantly higher than those of RS7 and RS14. For irrigated crops, the HIs of RS14 (2006–2007) and RS49 (2007–2008) were significantly higher than those of other treatments ($P < 0.05$).

RS did not exhibit any obvious effects on SWC during the course of this study. The differences in SWC over the growth period were caused by irrigation and rainfall. The SWC of the RS14 was low, which might have been due to ET. Soil profile water status greatly affected the density and depth of root penetration, and often restricted the full utilization of available soil water (Angadi and Entz 2002, Zuo et al. 2006). An upward hydraulic gradient was observed in the root zone, and upward capillary flux might have occurred from deeper soil layers, similar to those reported by Bandyopadhyay et al. (2005). Therefore, although there was a slight decline in SWC at the 60–80 cm soil layer, there was no SWC scarcity for roots at the 90–120 cm soil layer.

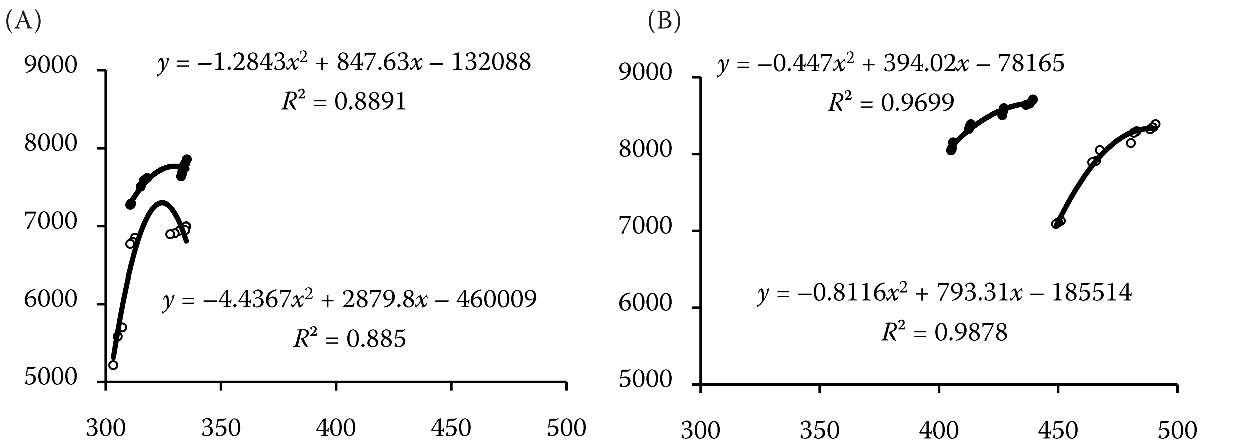

Figure 2. Regression of evapotranspiration vs. grain yield for the irrigated and rainfed wheat in 2006–2007 (A) and 2007–2008 (B)

Table 4. Effects of RS on yield, ET, WUE, TDM, and HI in field over the growth period

Treatments		Yield (kg/ha)		ET (mm)		WUE (kg/ha/mm)		TDM (kg/ha)		HI	
		06/07	07/08	06/07	07/08	06/07	07/08	06/07	07/08	06/07	07/08
Rainfed	RS7	6961^{cd}	7705^{e}	330.1^{f}	334.6^{e}	21.09^{b}	23.03^{c}	17219^{e}	19581^{c}	0.40^{c}	0.39^{c}
	RS14	7081^{c}	7761^{e}	334.8^{e}	333.1^{e}	21.15^{b}	23.30^{bc}	16914^{e}	19461^{c}	0.42^{c}	0.40^{c}
	RS24.5	6820^{d}	7587^{f}	311.8^{g}	316.6^{f}	21.87^{a}	23.96^{a}	13504^{f}	18902^{d}	0.51^{a}	0.40^{bc}
	RS49	5502^{e}	7280^{g}	305.3^{h}	310.9^{g}	18.02^{c}	23.42^{b}	12168^{g}	16818^{e}	0.45^{b}	0.43^{a}
Irrigation	RS7	8241^{a}	8553^{b}	465.9^{c}	426.9^{b}	17.69^{c}	20.04^{de}	22363^{a}	22677^{ab}	0.37^{d}	0.38^{d}
	RS14	8355^{a}	8671^{a}	489.7^{a}	438.0^{a}	17.06^{d}	19.80^{e}	20127^{c}	23097^{a}	0.42^{c}	0.38^{d}
	RS24.5	7954^{b}	8362^{c}	450.1^{d}	413.0^{c}	17.67^{c}	20.25^{d}	20842^{b}	22288^{b}	0.38^{d}	0.38^{d}
	RS49	6949^{cd}	8093^{d}	481.7^{b}	405.5^{d}	14.42^{e}	19.96^{de}	18297^{d}	19721^{c}	0.38^{d}	0.41^{b}

RS – row spacing; ET – evapotranspiration; TDM – total dry matter; HI – harvest index. Values followed by different small letters within a column are significantly different at level of 0.05

Irrigation increased the ETs of different RSs. In our previous work, we demonstrated that the seeding-jointing stage was a critical period for amount of population (Zhou et al. 2007). RS14 exhibited the highest amount of population and RS49 had the lowest; in effect, the ET of RS14 was significantly higher than those of other treatments ($P < 0.05$). In 2006–2007, during filling-maturity, there was low ET for RS49 due to lesser amounts of population for the rainfed crops, but it was high due to high soil evaporation for irrigated crops. Results showed that the WCD of the filling-maturity stage was intense under irrigation.

In this study, irrigation increased yields, ET, and TDM, but it decreased WUE and HI. Our results are similar to previous findings that grain yield is related to ET (Schneider and Howell 1997, Huang et al. 2004). There were significantly negative correlations between TDM and RS, and the correlation coefficient of rainfed crops was significantly higher than that of irrigated crops. The TDM of RS49 was significantly lower than those of other treatments ($P < 0.05$). The narrow RS often increased crop competitiveness. RS at 12 cm resulted in more even spatial plant distribution; it also increased crop ground cover, leaf area index (LAI), dry matter, and light interception (Drews et al. 2009). Consequently, relative uniform-distribution (RS14) promoted crop yield even if ET was high. Previous studies in wheat showed that relatively deep root systems in rainfed crops affect HI and higher water uptake rates during grain filling (Xue et al. 2003). According to our results, the HI of rainfed crops was higher than that of irrigated crops.

The study over two years demonstrated that the yields of irrigated crops were obviously higher than that of rainfed crops. Thus, the production of winter wheat in Taian could not be achieved without irrigation, given the scarce precipitation during growing seasons. Moreover, RS affected yields, ET, and TDM of winter wheat. High yields of wheat could be achieved in northern China by reducing RS under uniform planting density conditions. It is difficult to practice in the agricultural production for RS7 despite its high yields. Given these findings, based on yield and WUE, both RS14 and RS24.5 were of high optimum.

REFERENCES

Angadi S.V., Entz M. (2002): Root system and water use patterns of different height sunflower cultivars. Agronomy Journal, *94*: 136–145.

Bandyopadhyay P.K., Mallick S., Rana S.K. (2005): Water balance and crop coefficients of summer-grown peanut (*Arachis hypogaea* L.) in a humid tropical region of India. Irrigation Science, *23*: 161–169.

Bowers G.R., Rabb J.L., Ashlock L.O., Santin J.B. (2000): Row spacing in the early soybean production system. Agronomy Journal, *92*: 524–531.

Brant V., Neckář K., Pivec J., Duchoslav M., Holec J., Fuksa P., Venclová V. (2009): Competition of some summer catch crops and volunteer cereals in the areas with limited precipitation. Plant, Soil and Environment, *55*: 17–24.

Drews S., Neuhoff D., Köpke U. (2009): Weed suppression ability of three winter wheat varieties at different row spacing under organic farming conditions. Weed Research, *49*: 526–533.

Eberbach P., Pala M. (2005): Crop row spacing and its influence on the partitioning of evapotranspiration by winter-grown wheat in Northern Syria. Plant and Soil, *268*: 195–208.

Gajri P.R., Prihar S.S., Cheema S.S., Kapoor A. (1991): Irrigation and tillage effect on root development, water use and yield of wheat on coarse texture soils. Irrigation Science, *12*: 161–168.

Hill J., Nelson E., Tilman D., Polasky S., Tiffany D. (2006): Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences of the United States of America, *103*: 11206–11210.

Huang M., Gallichand J., Zhong L. (2004): Water-yield relationships and optimal water management for winter wheat in the Loess Plateau of China. Irrigation Science, *23*: 47–54.

Lehrsch G.A., Whisler F.D., Buehring N.W. (1994): Cropping system influences on extractable water for mono-and double-cropped soybean. Agricultural Water Management, *26*: 13–25.

Liao L., Zhang L., Bengtsson L. (2008): Soil moisture variation and water consumption of spring wheat and their effects on crop yield under drip irrigation. Irrigation and Drainage Systems, *22*: 253–270.

Mishra H.S., Rathore T.R., Savita U.S. (2001): Water-use efficiency of irrigated winter maize under cool weather conditions of India. Irrigation Science, *21*: 27–33.

Mishra H.S., Rathore T.R., Tomar V.S. (1995): Water use efficiency of irrigated wheat in the Tarai region of India. Irrigation Science, *16*: 75–80.

Mishra H.S., Rathore T.R., Tomar V.S. (1999): Root growth, water potential and yield of irrigated wheat. Irrigation Science, *18*: 117–123.

Oussible M., Crookstone R.K., Larson W.E. (1992): Sub-surface compaction reduces the root and shoot growth and grain yield of wheat. Agronomy Journal, *84*: 34–38.

Pala M., Ryan J., Zhang H., Singh M., Harris H.C. (2007): Water-use efficiency of wheat-based rotation systems in a Mediterranean environment. Agricultural Water Management, *93*: 136–144.

Ritchie J.T., Basso B. (2008): Water use efficiency is not constant when crop water supply is adequate or fixed: The role of agronomic management. European Journal of Agronomy, *28*: 273–281.

Schneider A.D., Howell T.A. (1997): Methods, amount, and timing of sprinkler irrigation for winter wheat. Transactions of the American Society of Agricultural Engineers, *40*: 137–142.

Steele D.D., Stegman E.C., Knighton R.E. (2000): Irrigation management for corn in the northern Great Plains, USA. Irrigation Science, *19*: 107–114.

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 Research, *101*: 249–258.

Unger P.W. (1993): Residual effects of soil profile modification on water infiltration, bulk density and wheat yield. Agronomy Journal, *85*: 656–659.

Xue Q., Zhu Z., Musick J.T., Stewart B.A., Dusek D.A. (2003): Root growth and water uptake in winter wheat under deficit irrigation. Plant and Soil, *257*: 151–161.

Zhang X., Chen S., Sun H., Pei D., Wang Y. (2008): Dry matter, harvest index, grain yield and water use efficiency as affected by water supply in winter wheat. Irrigation Science, *27*: 1–10.

Zhou X.B., Yang G.M., Sun S.J., Chen Y.H. (2010): Plant and row spacing effects on soil water and yield of rainfed summer soybean in the northern China. Plant, Soil and Environment, *56*: 1–7.

Zhou X.B., Li Q.Q., Yu S.Z., Wu W., Chen Y.H. (2007): Row spacing and irrigation effects on water consumption of winter wheat in Taian, China. Canadian Journal of Plant Science, *87*: 471–477.

Zuo Q., Shi J., Li Y., Zhang R. (2006): Root length density and water uptake distributions of winter wheat under sub-irrigation. Plant and Soil, *285*: 45–55.

Received on May 28, 2010

Corresponding authors:

Dr. Yu Hai Chen, Shandong Agricultural University, State Key Laboratory of Crop Biology, Taian 271018, P.R. China
e-mail: yhchen@sdau.edu.cn

Dr. Zhu Ouyang, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, P.R. China
e-mail: ouyz@igsnrr.ac.cn