Plant and row spacing effects on soil water and yield of rainfed summer soybean in the northern China

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ABSTRACT

Productivity and water resource-use efficiency are crucial issues in sustainable agriculture, especially in high-demand water resource crops such as soybean [*Glycine max* (L.) Merr.]. The aims of this research were to compare planting pattern in soybean, evaluating soil moisture content (SMC), yield and water use efficiency (WUE). A 2-year field experiment (2006–2007) was carried out in the north of China. The summer soybean (cv. Ludou 4) experiment consisted of 5 planting patterns under the same plant population density (3.09×10^5 plant/ha), and row spacing (cm) × plant spacing (cm) was 18 × 18 cm (A), 27 × 12 cm (B), 36 × 9 cm (C), 45 × 7.2 cm (D), 54 × 6 cm (E). The results showed that SMC and soil storage water (SSW) decreased with evapotranspiration (ETa) increments after reproductive growth stage, and there were remarkable differences between treatments with decreasing rainfall. SMC curve characteristics in the 0–90 cm soil profile were related to rain; the scope changes of shallow SMC were higher than those of deep SMC. The study revealed that yield and WUE had a negative correlation with row spacing, and they were statistically greater in narrow rows, which approximated equidistant plant spacings, compared to wider rows ($P < 0.05$). The study also indicates that enhanced productivity and WUE of rainfed summer soybean can be achieved via row spacing reduction and plant spacing widening under uniform planting density.

Keywords: summer soybean; planting pattern; soil water content; yield; water use efficiency

Growing plants in crop communities introduces competition. The competition arises when the immediate supply of a single necessary factor falls bellow the combined demands of all plants. One plant was sufficiently close to another to modify its soil or atmospheric environment and thereby decrease its rate of growth. The main competition factors can be identified as light, water, nutrients and weed (Brant et al. 2009). Gaseous exchange between the crop and atmosphere may also be affected by changes in the canopy structure. Soybean grown in narrow row spacing (generally 50 cm or less) produces higher yield than soybean grown in wide row spacing (75 to 100 cm) in the southern USA (Ethredge et al. 1989, Oriade et al. 1997). Board et al. (1990) reported that the yield increases associated with narrow rows may be greater due to late planting dates rather than optimum dates.

Demand for fresh water is globally steadily increasing as the demand for industrial and domestic water supplies increases with population. This growing demand for fresh water necessitates that the agricultural sector should move from a scenario of water supply management to water demand management. An adequate water supply is the major factor limiting soybean [*Glycine max* (L.) Merr.] yield throughout the world. Rainfall and soil moisture mediated the effect of row spacing on soybean yield, and yield tended to increase as row spacing decreased in years of average rainfall, the differences being not significant. Water loss, due to evapotranspiration, was also significantly greater in the row position than in the interrow position (Timlin et al. 2001). Crop management can strongly influence yields when water is not limited (Ritchie and Basso 2008). Wheat-legume rotation systems with additional N input in the wheat phase not only can maintain sustainable production system, but also are more efficient in utilizing limited rainfall (Pala et al. 2007).

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Table 1. Some selected physical properties of the experimental site

Soil depth (cm)	Bulk density (g/cm^3)	Field capacity (V. %)	Wilting coefficient (V. %)	Available water (mm)
0–20	1.48	36.4	7.2	34.80
20–40	1.49	38.3	7.5	36.44
40–60	1.53	41.2	8.2	37.22
Average	1.50	38.6	7.7	36.15

Previous work on WUE (water use efficiency) primarily dealt with crops grown under water limited conditions and usually did not consider relationship between crop row spacing and WUE (Lehrsch et al. 1994, Graterol et al. 1996, Bowers et al. 2000, Lobato et al. 2009). Increase of WUE is imperative for supplying adequate crop in an environment where future water supplies are expected to decrease. The objective of this study was to derive information on WUE and soil water, which can vary greatly with row spacing of soybean under rainfed agriculture.

MATERIALS AND METHODS

Experimental design and weather data collection. This research was conducted at the Experimental Farm of Shandong Agricultural University, Tai'an (36°09'N, 117°09'E) in northern China. This site is a representative of the main summer soybean growing region of Huanghuaihai Plain in China. The soil samples at the experimental site were obtained using a 50 mm diameter core from the depths of 0 to 60 cm in each treatment. The soil was a silt loam with the average soil organic matter (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. Additionally, some physical properties of the soil are given in Table 1. The experiments were established during the growing seasons (from June to September) in 2006 and 2007. As a part of the continuous winter wheat-summer soybean [*Glycine max* (L.) Merr.] rotation experiment, after winter wheat plants were hand harvested and the stubble removed, summer soybean (cv. Ludou 4) was hand planted on June 12, 2006 and June 13, 2007. The experiment consisted of 5 planting patterns under the same plant population density (3.09×10^5 plant/ha), and row spacing (cm) × plant spacing (cm) was 18 × 18 cm (A), 27 × 12 cm (B), 36 × 9 cm (C), 45 × 7.2 cm (D), 54 × 6 cm (E). Each experiment plot was 3.5 × 6 m in size, and every two plots were separated by a buffer zone 2.0 m wide to reduce mutual effects. Each combination had three replications with a randomized block design. The crops were harvested on September 26, 2006 and September 25, 2007. Other cultural practices were similar to those generally used for non-irrigated summer soybean in the Huanghuaihai Plain, although monthly rainfall data (Table 2) were inadequate to enable water supply from rainfall to be matched with crop ontogeny.

Weather data were collected at the Taian Agrometeorological Experimental Station, 500 m from the experimental site. Monthly rainfall during the summer soybean growing seasons (June–September) is given in Table 2. The long-term average (from 1971 to 2005) rainfall and temperature were 700.5 mm and 12.8°C, and rainfall was about 520 mm from June to September. The frost-free period was 192 days. Soil water depletion by soybeans was generally confined to soil profile in a depth less than 90 cm (Alessi and Power 1982); therefore, neutron moisture meter access-tubes (one per treatment-replicate) were installed between the rows at each location to a depth of 1.2 m prior to sowing. Soil volumetric water content (SWC) was monitored every 10 days throughout the summer soybean growing season at 10-cm depth intervals from 20 to 90 cm using a local field-calibrated CNC503B (DR) Neutron Moisture Probe (Super Energy Nuclear Technology Ltd., Beijing). Water content of the top 20 cm profile of the soil was also determined with portable time domain reflectometry CS620 (TDR) system (Campbell Scientific Australia Pty. Ltd., Townsville), which was used to correct neutron probe data at this depth for all the tubes.

Table 2. Monthly rainfall during 2006–2007 growth seasons of summer soybean (mm)

Growth season	Month				Total
	6	7	8	9	
2006	130.5	142.1	152.0	15.3	439.9
2007	203.4	120.4	186.0	29.3	539.1

Computation and statistical analyses. The ETa for each treatment was computed from planting patterns and climate data from Tai'an Agrometeorological Experimental Station in the area using the following equations:

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

where: ΔW is change of soil water stored (mm), R is rainfall (mm), SI is deep percolation (mm), Q is surface run-off (mm). SI was estimated using the approach proposed by Gong and Li (1995).

$$SI = \Delta W - FK \quad (2)$$

where: FK is field capacity.

$$\Delta W = \sum(\Delta \O i \times Zi) \quad (3)$$

where: $\Delta \O i$ is change in soil volumetric water content (m^3/m^3) and Zi is depth of the soil layer (mm).

$$Q = (R - 0.2S)^2/(R + 0.8S) \quad (4)$$

where: S is potential maximum retention after runoff begins (mm) (Bosznay 1989).

$$S = (25400/CN) - 254 \quad (5)$$

where: CN is runoff curve number.

$$WUE = Y/ETa \quad (6)$$

where: Y is grain yield (kg/ha) of summer soybean, ETa is total seasonal evapotranspiration.

The statistical significance of different plant and row spacing on yield and water related data was inferred from significance difference tests using analysis of variance accounting for block effects. The least significant difference (LSD, $P = 0.05$) was used to test for differences in planting patterns (Mishra et al. 2001).

RESULTS AND DISCUSSION

The soil water content (SWC) for different plant and row spacing is shown in Figure 1. Although little difference is shown between treatments within years, there are striking differences between the years themselves. The high SWC average value at the 0–90 cm soil layer in the 2007 growing season might have been affected with 99.2 mm of rainfall, higher than that in the 2006 growing season; similarly, in 2007, there were similar changes in different soil layers, and the range of SWC fluctuations in the upper layer (0–30 cm) was greater compared to deeper layer (60–90 cm) following each row spacing. In the 2006 growing season, there were low SWC values of different soil lay-

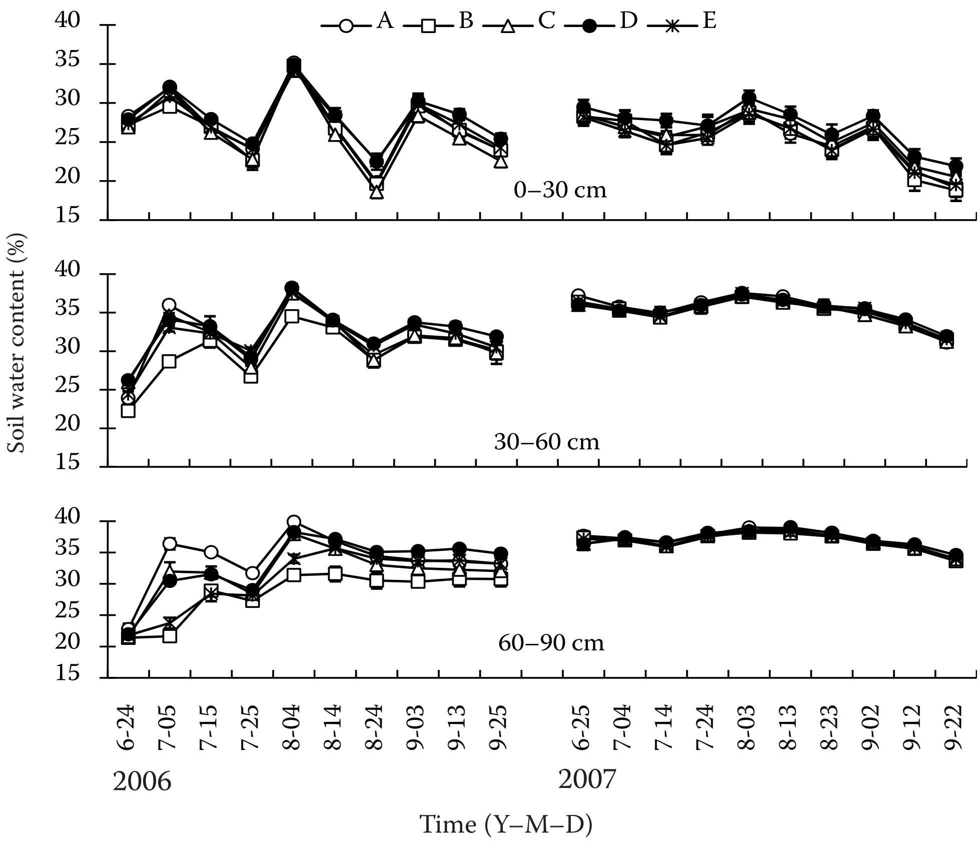

Figure 1. Dynamic change of soil water content (0–90 cm) under different plant and row spacings of summer soybean in 2006 and 2007 growing seasons. Error bars are standard deviation

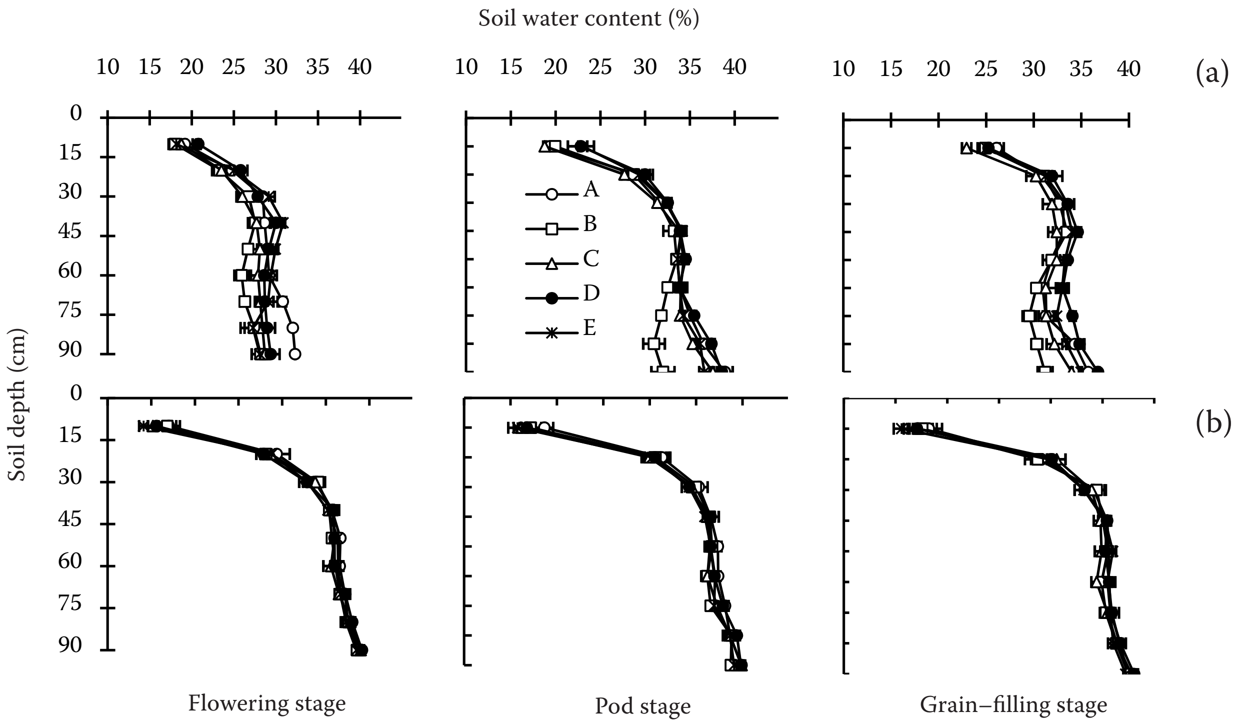

Figure 2. Dynamic changes of soil water in different growth stages under different plant and row spacings in (a) 2006 and (b) 2007. Error bars are standard deviation

ers on June 24; the SWC of treatments decreased with an increase in the soil depth. However, it increased with a decrease in the soil depth since August 14, and reached peak values on July 5, August 4 and September 3. In the 2007 growing season, the high SWC of treatments on June 25 may have been caused by 66.2 mm of rainfall on June 18–23; subsequently, the SWC decreased with decreasing rainfall; the peak values of the SWC in 0–30 cm soil layer on August 3 and September 2 were related to the rainfall of 124.7 and 28.1 mm of from July 14 to August 2 and from 30 to 31 August, respectively.

In the 2006–2007 growing seasons, the SWC average value of D treatment was the highest at 0–30 cm soil layer. In low rainfall period, there were evident differences in SWC of different treatments; in the 2006 growing season, the SWC of D treatment was by 20.7% higher than that of C treatment on August 24; in the 2007 growing season, the SWC of D treatment was by 12.8% higher than that of E treatment on July 14. In the 2006 growing season, the maximum differences of the SWC in 30–60 cm and 60–90 cm soil layers appeared on July 5. A treatment was by 25.5% and 68.1% higher than B treatment, respectively; the SWC of 60–90 cm soil layer had a gradually stable trend after August 14. In the 2007 growing season, the SWC of different treatments in 30–90 cm soil layer was similar.

The SWC of different growth stages under different planting patterns in 2006 and 2007 growing seasons is shown in Figure 2. The results show that in the 2006 growing season, the SWC of different treatments had a 'Z' curve trend at the flowering stage (on July 25), pod stage (on August 14) and grain-filling stage (on September 3), and the inflection point of the curve appeared in 40 cm soil layer and 60–80 cm soil layer (Figure 2a). In the same soil layers, the SWC of the flowering stage was lower than that of the pod stage and grain-filling stage. The SWC at the 30–60 cm level was 35–40% in 2007 vs. only 25–30% in 2006, and it appeared that the plants were more drought-stressed in 2006 than in 2007. At different growth stages, there were no evident differences in the SWC in 0–60 cm soil layer between A treatment and other treatments. At the flowering stage, the SWC of A treatment was the highest in 60–90 cm soil layer. At the pod stage, the SWC of B was by 17.8% lower than that of A treatment in the depth of 90 cm. The SWC of C treatment was medium at reproductive phase. At the flowering stage, the SWC of D and E treatments was high in 0–40 cm soil layer, but it decreased in 40–60 cm soil layer; in 70–90 cm soil layer, the SWC of D and E treatments at the grain-filling stage were by 21.4% and 19.4% higher compared to flowering stage, respectively. In the 2007 growing season, the SWC of 10–20 cm soil layer at pod stage (on August 13) and grain-filling stage (on

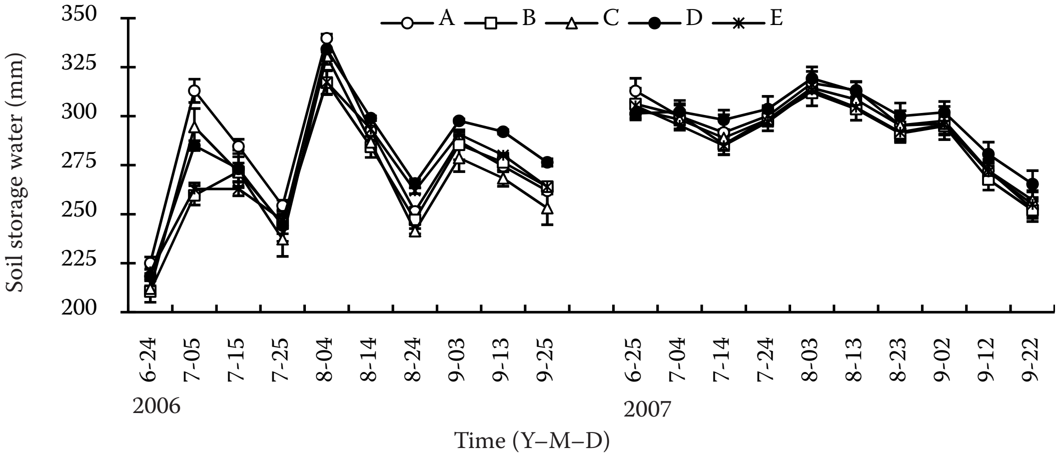

Figure 3. Changes of soil storage water (0–90 cm) in summer soybean field during whole stages of 2006 and 2007. Error bars are standard deviation

September 2) was higher than that of the flowering stage (on July 24) (Figure 2b). During whole stages, the order of the SWC average values at the 0–90 cm was A > B ≈ C ≈ D > E, but there were no significant differences recorded ($P < 0.05$). Especially the SWC profiles during flowering and pod formation stages (the most drought-prone periods for soybean) look very similar across treatments, suggesting that the differences in plant arrangement had little effect on water uptake patterns.

Changes of soil storage water (SSW) in summer soybean field during 2006 and 2007 are given in Figure 3. In the 2006–2007 growing seasons, the order of the SSW average values for different treatments were D > A > C > E > B, and were 278.6, 278.4, 270.1, 267.4, 266.2 mm (in 2006) and 298.5, 295.3, 293.3, 291.5, 291.2 mm (in 2007), respectively; yet, there were no significant differences ($P < 0.05$). In the 2006 growing seasons, the SSW showed obvious pre- and post-rainfall changes; before pod stage, the SSW of A treatment was the highest, of C and D treatments were medium, of B and E treatments were lower; from grain-filling stage to mature stage (after August 14), the SSW of D treatment was the highest, of A and E treatments were medium, of B and C treatments were lower. The maximum difference of the SWW appeared on July 5; A treatment was by 20.6% higher than that of B treatment. In the 2007 growing seasons, the SSW of D treatment was comparatively high since July 4, and those of the other treatments showed no evident differences during the stages; the SSW of different treatments showed a descending trend with the advance of the growth stages, which may be relative to less rainfall in September and increased water consumption in the middle and late period of crop growth.

Plant and row spacing had obvious effects on yield and WUE in the course of this study on summer soybean (Table 3). There were negligible (and in most cases, non-significant) differences in evapotranspiration (ETa) among the treatments. Yields in 2007 were about 50% greater than in 2006. In this study, significantly negative correlation between yield and row spacing was observed; the correlation coefficient in 2006 and 2007 (r) was –0.9257 and –0.9251, respectively ($P < 0.05$). Yields of A and B treatments were significantly higher than that of E treatment, but no significant differences were recorded among C, D and E treatments ($P < 0.05$). Yields of the A and B treatments were higher by 36.9% and 35.4% in 2006, and by 19.1% and 21.5% in 2007 than that of E treatment, respectively.

Table 3. ETa, yield, WUE, TDM and HI in field under different plant and row spacings of summer soybean

Treatment	ETa (mm)		Yield (kg/ha)		WUE (kg/ha/mm)		TDM (kg/ha)		HI	
	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007
A	312.59[a]*	428.55[b]	1600[a]	2615[a]	5.12[a]	5.90[a]	6377[a]	7756[a]	0.25[a]	0.34[a]
B	309.55[a]	435.29[a]	1583[a]	2668[a]	5.12[a]	5.92[a]	5681[ab]	7752[a]	0.28[a]	0.34[a]
C	301.31[a]	437.16[a]	1551[ab]	2340[ab]	5.15[a]	5.17[ab]	6235[a]	7169[ab]	0.25[a]	0.33[ab]
D	319.65[a]	435.15[a]	1362[ab]	2265[b]	4.26[b]	5.03[b]	5638[ab]	7111[b]	0.24[a]	0.32[ab]
E	306.12[a]	436.07[a]	1169[b]	2196[b]	3.82[c]	4.87[b]	4837[b]	7504[ab]	0.24[a]	0.29[b]

*values followed by the letter in the same column do not differ significantly using $LSD_{0.05}$

There was a significantly negative correlation between WUE and row spacing; the correlation coefficient (*r*) in 2006 and 2007 was –0.8874 and –0.9382, respectively ($P < 0.05$). WUE of A and B treatments were significantly higher than those of D and E treatments, respectively ($P < 0.05$). The total dry matter (TDM) was the highest at A treatment. In the 2007 growing seasons, crop harvest index (HI) of A and B treatments were significantly higher than that of E treatment ($P < 0.05$). There was a positive correlation between HI and yield, and the correlation coefficient (*r*) was 0.6288 in 2006 and 0.8434 in 2007 ($P < 0.05$). The study indicated that enhanced productivity and WUE of rainfed summer soybean can be achieved by reducing row spacing and widening plant spacing under uniform planting density.

In the 2006 growing season, the SWC values were low at early stage of growth (on June 24) and decreased with an increase in the soil depth; it was affected by 149.8 mm of rainfall during the winter wheat growing seasons (October–June in 2005/2006), out of which 55.2 mm fell between June 1–24, and most of it on June 13–14 then. With less rainfall, the differences in the SWC of shallow (0–30 cm) and deep layer (60–90 cm) were stable. However, similar SWC profiles across treatments within the years indicated that changes in plant arrangement were of no benefit for extracting more water under drought conditions. At the same growing season, the SSW showed a descending trend with ETa increasing after August.

Due to annual and seasonal rainfall differences, changes of the SWC curve of different growth stages differed from related reports (Yu et al. 2006). In the 2006 growing season, the SWC of the flowering stage was low and the results showed that soil evaporation was the main way of ETa at early stage of growth; the SWC of deep layer was reduced with the increase of crop ETa since pod stage. In the 2007 growing season, the SWC average value of A treatment was high; the results showed that uniform distribution could effectively inhibit soil water evaporation when rainfall was able to meet the water requirements of crop. In the 2006–2007 growing seasons, the SSW of D treatment was comparatively high in the middle and late period of soybean growth, which was probably a result of the effect of plants spacing within rows on reducing soil evaporation; it decreased water requirement of a single plant at late growth stage as inter-plant competition inhibited plant growth at early stage of growth.

Increased pod number resulting from greater light interception and crop growth rate during the early reproductive period is mainly responsible for narrow-row yield increases (Board and Harville 1996). Grain yield increase in response to narrow rows was closely related to the improvement in light interception during the critical period for grain set (Andrade et al. 2002). Generally, soybean yield declined as clipping timing was delayed and as clipping frequency increased in narrow rows (Singer 2001). The objective of our study was to study the effect of plant and row spacing on soil water and yield of rainfed summer soybean under the same planting density. WUE of D and E treatments were significantly lower than those of A and B treatments, respectively ($P < 0.05$). It is more likely that the greater WUE of A and B were caused by the narrow-row treatments; they had greater early-season light interception which accelerated crop growth rate resulting in higher yields. Greater yields with equivalent levels of water extraction consequently resulted in greater WUE. The differences in WUE were therefore almost entirely related to differences in seed yield, and it is likely that the observed differences in seed yield were caused by differences in HI (Lawn 1982, 1983). Thus greater WUE in narrow rows was a symptom. The differences in HI may have reflected treatment differences in the timing of water stress relative to crop ontogeny. The results indicated that D and E treatments showed obvious inter-plant competition. There were significantly negative correlations between WUE and row spacing, and significantly positive correlations between WUE and yield ($P < 0.05$), which is similar to Ethredge et al. (1989) and Holshouser and Whittaker (2002). The narrow rows (≤ 40 cm) should be used to optimize yields from the Early Soybean Production System plantings in the midsouthern USA (Bowers et al. 2000). The study found that seed yield and WUE were statistically greater in narrow rows (row spacing ≤ 27 cm), with approximate equidistant plant spacing, compared to wider rows (row spacing ≥ 36 cm).

The study over 2 years has shown that high yields and WUE of summer soybean can be achieved in the northern China by reducing row spacing and widening plant spacing under uniform planting density. Similar SWC values across treatments within years indicate that changes in plant arrangement of summer soybean are of no benefit for extracting more water under rainfed agriculture. During whole stages, the SWC average value at the 0–90 cm had no significant differences ($P < 0.05$), suggesting that differences in plant arrangement have little effect on water uptake patterns. The conclusion of the study is that row spacing ≤ 27 cm is high optimum.

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