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Full Length Research Paper

Row spacing effect on leaf area development, light interception, crop growth and grain yield of summer soybean crops in Northern China

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We investigated the effect of row spacing on the structure and radiation utilization efficiency of summer soybean crops in Northern China during the 2006 and 2007 growing seasons. The experiment consisted of 5 planting patterns resulting in the same plant population density (3.09 × 10^5 plant/ha), where row spacing was 18, 27, 36, 45 and 54 cm. We observed a significant negative correlation between DM weight and row spacing in both years. Dry matter was mainly allocated to the middle-lower strata of the canopy. The LAI of all treatments decreased with row spacing increments. At podding stage, PAR interception ratio showed a minimum at 12:00 and decreased with row spacing between 11:00 to 13:00. The RUE of row spacing 18 and 27 cm was significantly higher than those of other treatments. There was a significant positive correlation between seed number and plant growth rate. The yield of row spacing 18 and 27 cm were significantly higher than those of row spacing 45 and 54 cm. The results indicate that summer soybean population of relatively uniform distribution could improve population structure, increases the PAR interception and RUE under rainfed agriculture in Northern China.

Key words: *Glycine max*, dry matter, radiation utilization efficiency, growth, development.

INTRODUCTION

Soybean yield differences between wide and narrow row widths have often been reported for crops in the southern United States and the northeast China (Board et al., 1992; Frederick et al., 1998; Robinson and Wilcox, 1998; Liu, 2002). Row width affects soybean population structure and yield (Mathew et al., 2000; Eberbach and Pala, 2005; Zhou et al., 2010). Soybean grown with narrow row spacing (generally 50 cm or less) produces higher yield than soybean grown with wide row spacing (75 to 100 cm) in the southern USA (Beatty et al., 1982; Ethredge et al., 1989; Oriade et al., 1997). The main competition factors can be identified as light, water, nutrients and weed. A number of production practices (choice of relative maturity for cultivars at a location, suitable planting dates, row spacings, and plant populations) that can influence the attainment of the desired LAI have been investigated extensively. A LAI of 3.5 to 4.0 established by early reproduction is necessary to achieve 95% light interception and this level of light interception is necessary to optimize yield (Board and Harville, 1992).

Huanghuaihai Plain, an alluvial-flood plain and sub-humid continental monsoon zone, lies in north China, including 372 counties in Shandong, Hebei, Henan, Anhui and Jiangsu Province, Beijing and Tianjin municipality. The annual accumulated temperature (≥ 0℃) of 4800℃, annual average rainfall of 600 mm, cumulative radiation doses of more than 5200 MJ/m^2, and non-frost period of more than 200 days.

The cultural practices were generally used for non-irrigated summer soybean, from June to September, and

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Abbreviations: DM, Dry matter; **SOM,** soil organic matter; **PAR,** photosynthetically active radiation; **LAI,** leaf area index; **RUE,** radiation utilization efficiency; **SNP,** seed number per plant; **PGRc,** plant growth rate of the critical period for seed set.

Table 1. Soil 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

accounts for 70 to 80% of annual precipitation, enable water supply from rainfall to be matched with crop ontogeny (Zhou et al., 2010). It is one of China's important grain production bases, with the farming system of main food crops (that is, winter wheat and summer maize or winter wheat and summer soybean for two-season crop in one year) (Ren et al., 2006).

Soybean is produced in double-crop (following winter wheat) production systems using both conventional tillage and no-till practices in the Huanghuaihai Plain of China.

The commonly used row spacing is 40 to 50 cm, reflecting farmers' use of either grain drills or splitter-mounted planting units on row crop planters, for planting soybean. The adoption of narrower row planting has been based upon numerous, favorable reports concerning reduced row spacing for soybean production (Board and Harville, 1994; Bowers et al., 2000; Purcell et al., 2002; Holshouser and Whittaker, 2002; Lambert and Lowenberg-DeBoer, 2003). One limitation to these findings regarding row spacing is that all the studies were done with no considering soil or atmospheric environment of the Huanghuaihai Plain in China (Zhu and Lu, 1993; An et al., 2003; Huang et al., 2003). Therefore, the objective of this study was to evaluate the distribution of seed yield, yield components and PAR interception of soybean grown in wide and narrow rows at recommended plant population density under rainfed agriculture.

MATERIALS AND METHODS

This research was conducted at the Experimental Farm of Shandong Agricultural University, Tai'an (36º09´N, 117º09´E) in northern China. This site is representative of the main summer soybean growing region of Huanghuaihai Plain in China. The long-term average (from 1971 to 2007) rainfall and temperature were 698.5 mm and 12.8℃, and rainfall was about 520 mm from June to September. The soil was a silt loam with the 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. Additionally, some physical properties of the soil are given in Table 1.

The experiments were established during the growing seasons of 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, determinate summer soybean (cv. Ludou 4) was hand-sowed according to a plant density of 6.18 × 10^5 plant/ha on June 12, 2006 and June 13, 2007. The experiment consisted of 5 planting patterns at the same plant population density, and row spacing (cm) was 18, 27, 36, 45 and 54 cm. All plots were thinned to one plant per hill at 5 days after soybean emergence in order to obtain the same final populations density (3.09 × 10^5 plant/ha). Each experiment plot was 3.5 × 6 m in size, with three replications in 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 no-irrigated summer soybean in the Huanghuaihai Plain and pests and weeds were adequately controlled. Monthly rainfall during the summer soybean growing seasons (June to September) was 130.5, 142.1, 152.0, 15.3 mm in 2006, and 203.4, 120.4, 186.0, 29.3 mm in 2007.

Three plants per plot were sampled from 20 days after sowing to maturity stage every ten days to determine DM weight; at graining stage, from cotyledon node upward per 10 cm to measure DM of different height. LAI was measured one time per 10 days at 20 days after sowing by weighing method (Zhang, 1992).

Light interception was measured at the podding stage, placing the sensor bar along the diagonal between the rows (Board and Harville, 1992). All measurements were made in full-sun conditions, from 8:00 to 17:00, one time per one hour, during 2 days. A 1-m long Delta-T Devices Ltd SunScan Probe (Cambridge, England) was used to measure light interception of PAR below the canopy and a beam fraction sensor on a tripod was used to simultaneously measure incident light above the canopy. The intercepted radiation was calculated as the ratio of the difference between the incident and transmitted radiation to the incident radiation.

Ten plants per replicate were randomly sampled at harvest to determine morphometric variables (plant height and stem diameter). Immediately after sampling, plants were harvested and oven dried at 65℃. Reproductive structures included pod, seed number, DM per plant and one hundred seed weight were determined. Yields were measured 2 m^2 per plot.

All data were analyzed with the SPSS 12.0 Statistical Software Package. The experimental data were analyzed by analysis of variance (ANOVA) to determine if significant differences existed among means of the different treatments. Effects were considered significant in all statistical calculations if P-values were ≤ 0.05 by the least significant difference (LSD) tests. The RUE was calculated by the following equation (Ple´net and Pellerin, 2000):

$$RUE = \frac{W_n - W_{n-1}}{cPARa_n - cPARa_{n-1}}$$

where: W is the above-ground biomass measured at dates n and n-1; $cPARa_n$ and $cPARa_{n-1}$ are the cumulated amounts of PAR absorbed by the canopy at dates n and n-1.

RESULTS

DM accumulation and vertical dry matter distribution

The DM accumulation for the different row spacing is shown in Figure 1. The higher DM values in 2007 might have been related to higher rainfall of this season. From seedling stage to physiological maturity, there were significantly negative correlations (R) between DM and row spacing in 2006 and 2007 (LSD, $P < 0.05$). The correlation coefficients (R^2) in 2006 were higher than those in 2007. From podding stage to physiological maturity, the DM of both 18 and 27 cm row width were significantly higher than those of the other treatments (LSD, $P < 0.05$). With the exception of 18 cm row spacing, at physiological maturity, the DM of the other treatments were lower than those at the graining stage, may be due to fall of leaves and petioles.

Row spacing had a significant effect on the vertical distribution of DM among canopy layers at graining stage (Figure 2). In 2006 and 2007, DM was mainly distributed in the aboveground 20 to 50 cm and 30 to 60 cm, respectively. The canopy layer height with the highest DM varied among row spacings. Thus, crops in the narrowest row spacing exhibited the highest DM at the 20 to 30 cm. Contrary for the 27 cm, 36 and 45 cm, DM was maximized at 30 to 40 cm layer, and in rows 54 cm apart, aboveground DM was maximum at the 40 to 50 cm canopy layer (Figure 2).

Leaf area index development

From seedling stage to physiological maturity, LAI were negative correlated with row spacing, and correlation coefficient values were higher in 2007 than in 2006 (Figure 3). Maximum LAI values were 3.5 for the 18, 27 c and 36 cm row spacings and 3.0 for the 45 and 54 cm row spacings. These maximum LAI values were attained at the podding and graining stages. From podding stage to physiological maturity, the LAI of crops in rows 18 cm apart was significantly higher than those of 36, 45 and 54 cm row width (LSD, $P < 0.05$). These results indicated that there was a negative trend between LAI and inter row distance.

PAR interception

The diurnal evolution of PAR interception at the pod stage of soybean crops exhibited ‘V’ curve trend with the minimum value close to the noon (Figure 4). Maximum PAR interception ratios in 2006 (mean 89.9%) resulted lower than those in 2007 (mean 92.8%), and differences among row spacings resulted higher in 2006 than in 2007. In 2006, maximum PAR interception ratios were 93.9, 92.4, 89.9, 89.5 and 82.9% for the 18, 27, 36, 45 and 54 cm row spacings, respectively. Mentioned PAR values of 45 and 54 cm row spacings were the lowest attained by soybean crops in 2006 (LSD, $P < 0.05$). Contrary, in 2007 the lowest PAR interception was only recorded in crops at 54 cm apart (91.9%), and the other row spacings exhibited PAR values above 92% (LSD, $P < 0.05$) (Figure 4).

RUE

RUE in 2007 was higher than that in 2006 (Figure 5). There was an overall trend of higher RUE values with narrow rows during both grown seasons. In 2006 and 2007, the linear regression coefficient was −0.0037 and −0.0046/cm, and R^2 value was 0.9543 and 0.8643 respectively. From the analysis, the R^2 value increased under less rainfall. In 2006, the RUE there was significant difference between treatments (LSD, $P < 0.05$); in 2007, crops in rows 18 and 27 cm apart exhibited the highest RUE values (LSD, $P < 0.05$).

Yield components

In 2006 and 2007, final plant height, stem diameter, productive pod number, seed number per plant (SNP) and 100 seed weight decreased in response to increased row spacing. For example, plants of soybean crops in rows 18 cm were taller (LSD, $P < 0.05$), than those in wide rows (54 cm in 2007 and 45cm in 2006). Similarly, the SNP of 18 and 27 cm were significantly higher than those of 54 cm (in 2006) and 45 cm and 54 cm (in 2007), respectively (LSD, $P < 0.05$). The SNP variability among row spacings was significantly related to plant growth rate around the critical period for seed set (PGRc). A linear function was fitted to each season data set (Figure 6 and Table 2). The SNP linearly varied in responses to PGRc. The slope of fitted function differed among years (value of b parameter in 2006 was lower than in 2007). In 2006, row spacing significantly affected PGRc; in 2007, PGRc of row spacing 18 cm and 27 cm were significantly higher than those of the other row spacings (LSD, $P < 0.05$).

Correlation analysis showed that there was a significant positive correlation (LSD, $P < 0.05$) among SNP and (i) biomass per plant (0.941 to 0.995), (ii) 100 seed weight (0.904 to 0.994) and (iii) grain yield (0.892 to 0.926). Grain yields in 2007 were higher than those in 2006 (Figure 7). In 2006 and 2007, grain yields of crops with a row spacing of 18 cm and 27 cm were significantly higher than those of 45 cm and 54 cm (LSD, $P < 0.05$).

DISCUSSION AND CONCLUSION

At the same plant population density, a square planting pattern may improve the use of resources per unit land area (Han et al., 2003). Under wide row spacings, competition among plants within the row may be increased and capture of environmental resources, example, PAR, may not be maximized. In our experiments, competition among plants inferred from LAI values and PARs, took place from pod stage onwards,

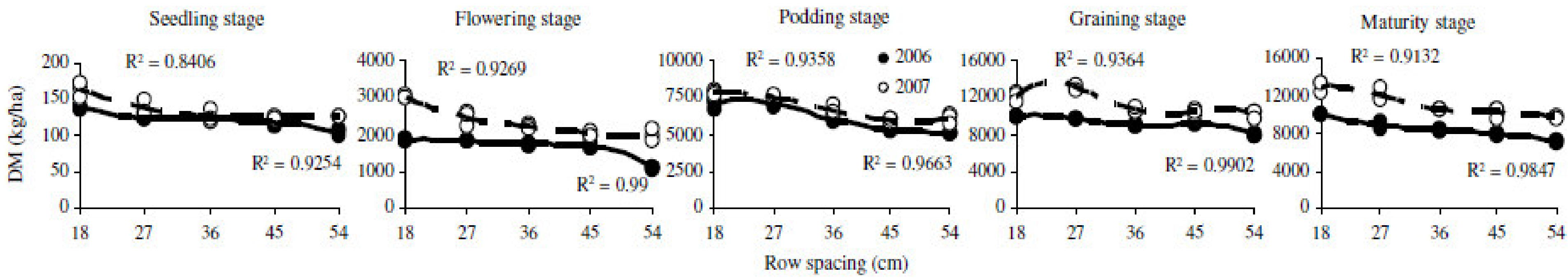

Figure 1. Dry matter production at different ontogenic stages of soybean crops cultivated at contrasting row spacings. Dotted line 2006 experiment, solid line 2007 experiment.

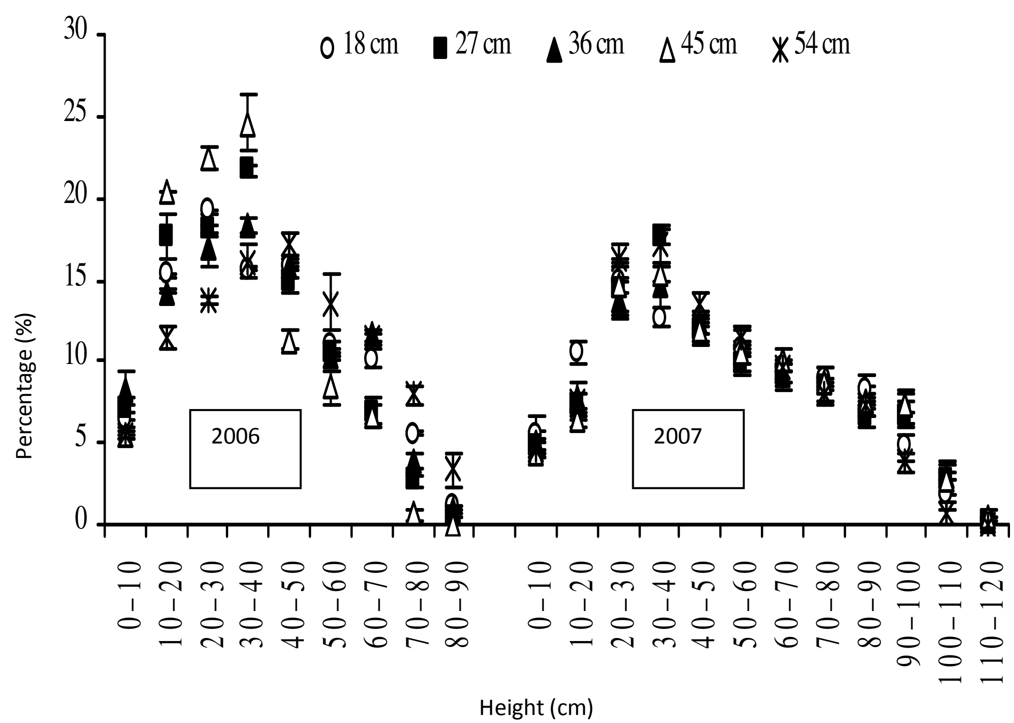

Figure 2. Dry matter distribution (%) among canopy layers (10 cm) of soybean crops cultivated at constraint row spacing.

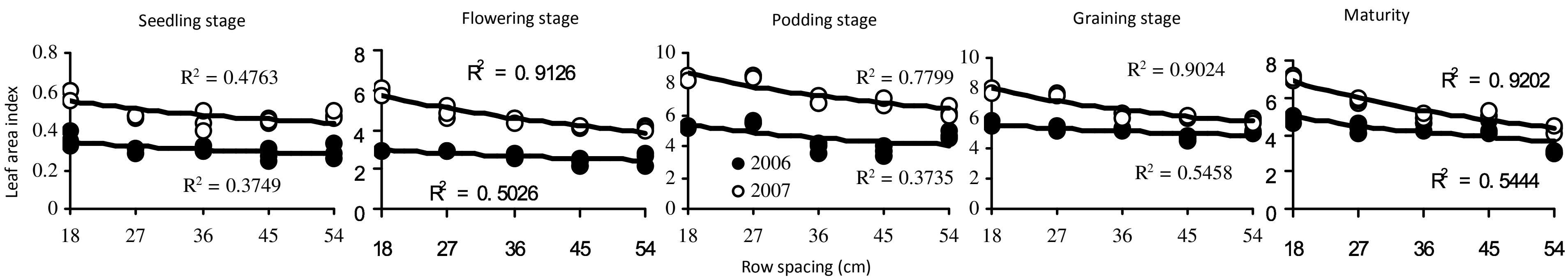

Figure 3. Leaf area index at different ontogenic stages of soybean crops cultivated with contrasting row spacings. Dotted line 2006 experiment, solid line 2007 experiment.

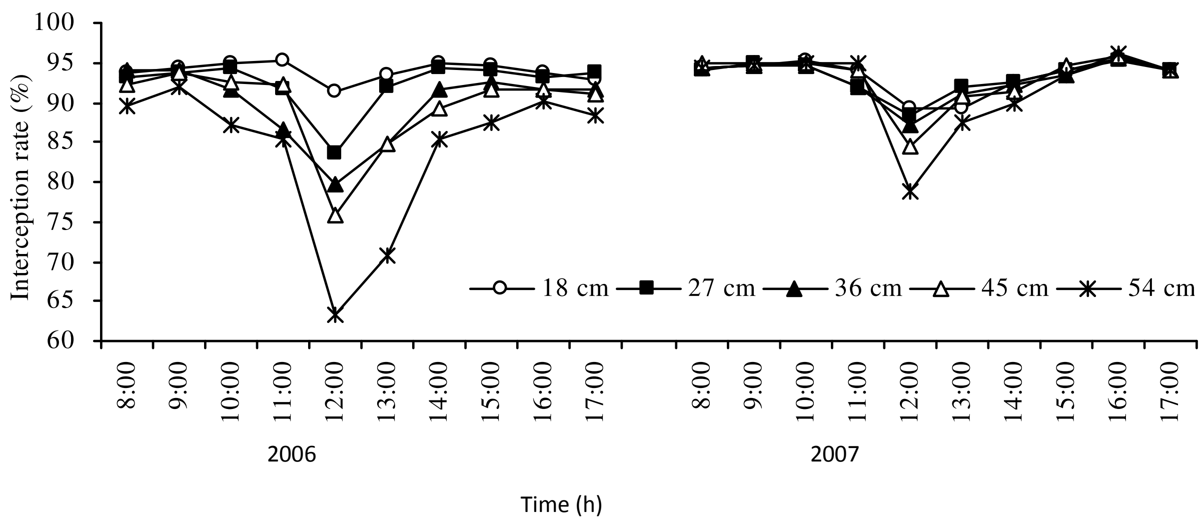

Figure 4. Diurnal change in the rates of PAR interception at the pod-setting stage of soybean crop cultivatedwith different row spacings in 2006 to 2007.

when plants in narrow rows attained higher light capture than in wide rows. Moreover, decreased RUE values at mid-later stage of soybean crops in wide row crops (Liu, 2002), also contributed to the lower canopy growth.

Light capture is highly affected by canopy size, and the amount of PAR intercepted by crops along the season is commonly related to crop growth and grain yield (Ethredge et al., 1989; Board and Harville, 1992; Singer, 2001). Above ground biomass is generally considered to describe variation of grain yield, root-shoot ratio, however, is less considered (Yang et al., 2002). The 18 cm was favorable to DM accumulation and 54 cm was adverse, may be relative to PAR

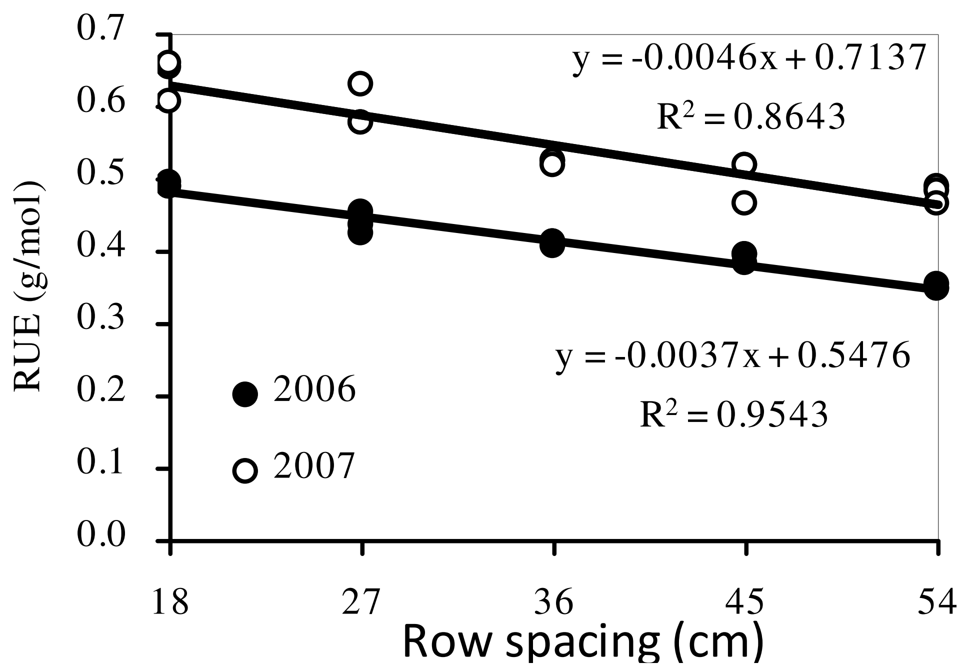

Figure 5. Change in RUE with different row spacings for summer soybean crops in 2006 to 2007.

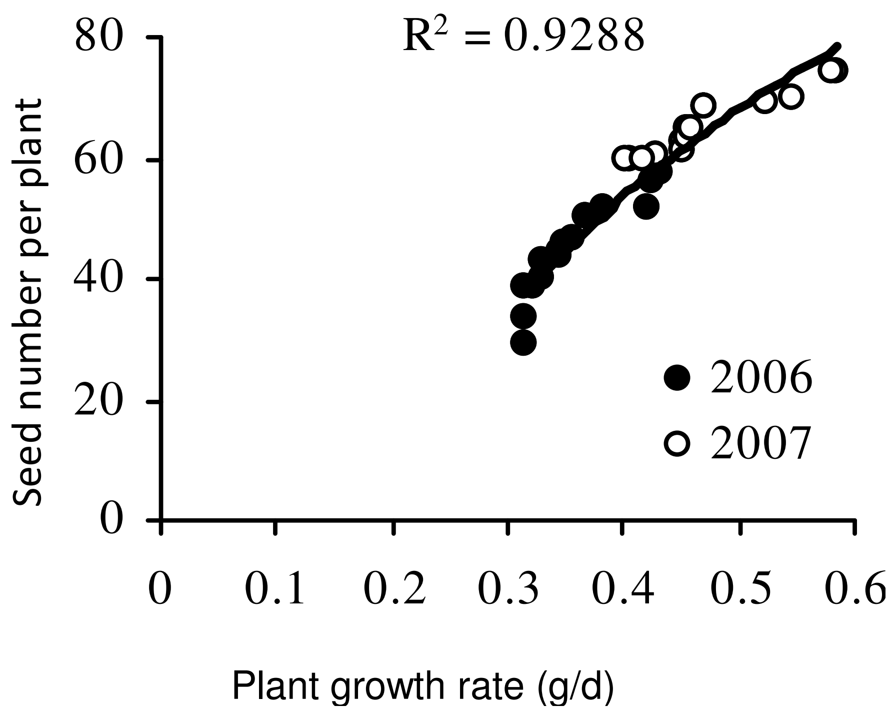

Figure 6. Relationship between seed number per plant (SNP) and plant growth rate (PGRc).

interception. Based on our results, the plant morphological index deteriorated, LAI, DM weight, PAR interception and RUE decreased with row spacing increments.

The SNP is linearly related to plant growth rate during the critical period (PGRc) for seed set (Vega et al., 2001). Narrow rows planting pattern could have increased root

Table 2. Parameters (S.E.) of the linear model (y = α + bx) fitted to SNP and PGRc for individual plants of soybean.

Season	α	b	R^2
2006	-19.1 ± 7.62	178.4 ± 21.21	0.84
2007	26.7 ± 3.77	81.4 ± 7.90	0.89

Regressions and parameter b were significant at p < 0.0001. Parameter α was significant at p < 0.05.

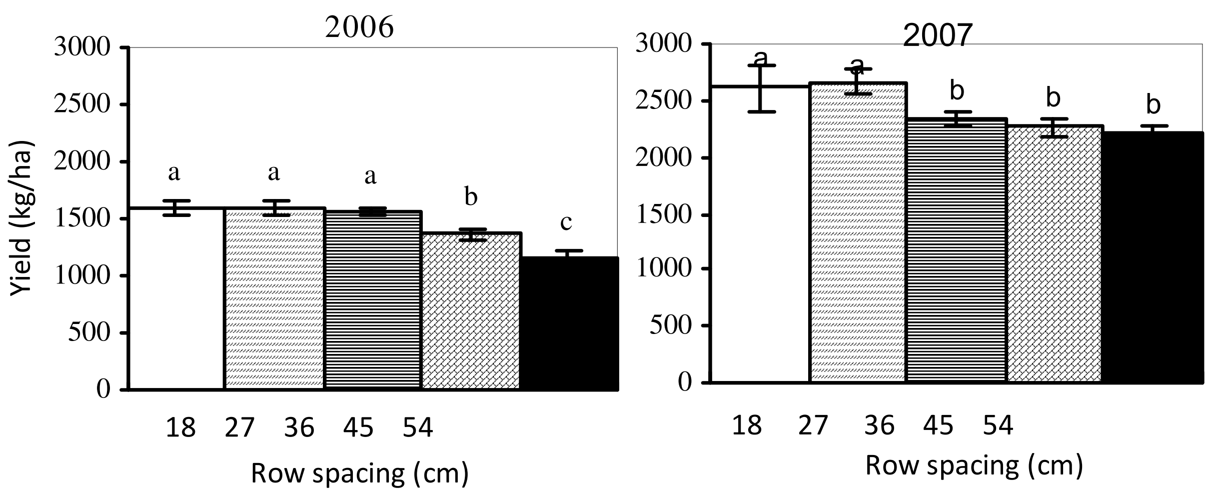

Figure 7. The yield comparison of different row spacings in 2006 to 2007 (±SE). Different small letters within a column are significantly different at P ≤ 0.05.

activity, and vertical distribution of light, enhancing potential productivity of individuals and that of the canopy (Liu, 2002; Zhang and Li, 2007).

The study over 2 years has shown that high LAI, PAR interception, RUE and yields of summer soybean can be achieved in the northern China by reducing row spacing and widening plant spacing within the row, that is, under more uniform planting pattern.

The study found that morphological index and yield components were statistically better in narrow rows (row spacing ≤ 27 cm), which approximated equidistant plant spacing, relative to wider rows (row spacing ≥ 36 cm). The seed number, biomass of single plant, 100 seed weight were key factors to increase yield. With the row spacing widening and plant spacing narrowing, there was a high intraspecies competition, wasted resource and decreased yield; especially in lack of rainfall, individual of uniform distribution was able to resist drought stress. Therefore, the 18 and 27 cm row spacings are high optimum.

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