The Journal of Animal & Plant Sciences, 26(3): 2016, Page: 697-705
ISSN: 1018-7081

ROW SPACING EFFECTS ON RADIATION DISTRIBUTION, LEAF WATER STATUS AND YIELD OF SUMMER MAIZE

J. Q. Liu, M. D. Li and X. B. Zhou*

Agricultural College of Guangxi University, Nanning 530004, China
*Author for correspondence. E-mail: whyzxb@gmail.com.
J. Q. Liu and M. D. Li are co-first authors

ABSTRACT

Different row spacing can affect the canopy structure, and then affect the environment of crop growth and the yield. The research aimed to investigate the effects of row spacing on light interception ratio and leaf water status of summer maize (*Zea mays* L.), and to select the reasonable planting pattern. The experiment comprised five planting population distribution patterns in the same plant population density (62500 plant/ha) in northern China from 2011 to 2013. The following row spacing × spacing between the plant schemes were used: 40 cm × 40 cm (RS40), 50 cm × 32 cm (RS50), 60 cm × 27 cm (RS60), 70 cm × 23 cm (RS70), and 80 cm × 20 cm (RS80). A significant negative correlation was observed between row spacings and leaf relative water content (LRWC), water potential (Ψ) and yield during 3 years. RS40 and RS50 had the high total photosynthetically active radiation (PAR) capture ratio (CR) and upper CR (>100 cm) than the others. The yield of RS50 was higher than the others during three years study. The narrow row spacing (RS40 and RS50) was beneficial to the CR of PAR, LRWC, and Ψ. However, compared with RS50, the RS40 could increase the evapotranspiration and decrease the lower-CR. So RS50 could be the reasonable row spacing of summer maize in Huang-huai-hai Plain in China.

Keywords: *Zea mays* L.; evapotranspiration; capture ratio; leaf water potential; leaf relative water content.

INTRODUCTION

Different approaches have been used to increase crop yield, such as increasing the amount of fertilizer, application of high-density resistant cultivars, uniformity of row spacing (RS) distribution (Ritchie and Basso, 2008). The field plant distribution, as affected by planting density and row spacing, has drawn a great deal of attention for decades (Farnham, 2001). To attain a suitable canopy structure may be obtained through change of row spacing. For maize sown at high density, wide-narrow row planting can improve the ventilation and light environment effectively (Megowan *et al.*, 1991). For a particular region, as the planting density is generally stable, the reasonable row spacing is crucial (Norsworthy and Shipe, 2005).

The appropriateness of row spacing has been widely studied in different crops. Determinate soybean grown in RS50 or less can produce higher yields than that in RS75 to RS100, and the narrow RS can capture light effectively (Bowers *et al.*, 2000). Similarly, in cotton, 19 cm and 38.1 cm row spacing can capture more light than the traditional wide RS (Jost and Cothren, 2000). Inconsistent results have been produced about the studies of narrow-row maize production systems. The results vary from no yield advantage of planting maize in narrow-row to a 7% increase in yield over wider rows (Johnson *et al.*, 1998).

To build a good canopy structure, row spacing is of great significance (Sharratt and Mcwilliams, 2005). The adjustment of crop population distribution can affect the structure and function of canopy, improve the interception rate of photosynthetically active radiation (PAR), and enhance the population productivity (Maddonni *et al.*, 2001). The competition between individual in the light of crop canopy plays an important role in group productivity. The radiation use efficiency of crops is determined by light interception rate and efficiency of light energy conversion. Leaf water potential (Ψ) is the important factors that affect the leaf net photosynthetic rate (Peri *et al.*, 2011).

The reasonable RS can improve the light, temperature, humidity, and water resource utilization. And then affect the photosynthetic efficiency and yield of crop. Summer maize, as one of the main crops is produced in double-crop (following winter wheat) production systems in Huang-huai-hai Plain, China. Cultural practices are generally used for non-irrigated summer maize from June to October. The precipitation of summer maize growing season accounts for 70%–80% of annual precipitation. The research aimed to investigate the effects of RS on light interception ratio and water status, to select the reasonable planting pattern. For these purposes, the PAR and moisture content of leaves were determined so that proper information could be provided for the selection and management of RS in the region.

MATERIALS AND METHODS

The research was conducted at the Agronomy Experimental Station of Shandong Agricultural University, Tai'an, China (36º09´N, 117º09´E) in 2011, 2012 and 2013. This site represented the main summer maize growing region of Huang-huai-hai Plain in China. The type of soil was loam, which contained SOM (16.3 g/kg), N (1.3 g/kg), P (35 mg/kg), and K (95 mg/kg); the pH was 6.9. The annual average rainfall was 693.5 mm from 1971 to 2010. The rainfall (on July and August) accounted for 52.5% of the annual rainfall. The annual average rainfall was 500 mm during the growing seasons of summer maize from 1971 to 2010; the values were 572.5 mm, 337.1 mm, and 461.8 mm from 2011 to 2013, respectively (Table 1).

The experiments were executed during the growing seasons of June to October from 2011 to 2013. As a part of the continuous winter wheat-summer maize rotation experiment, the previous winter wheat was hand-harvested and their residues were removed. The summer maize seeds (cv. Luyu 14) were sown by hand at a seeding rate of 62500 seeds/ha. The seeding of maize was at 3-4 cm soil depth on18June 2011, 17June 2012, 19June 2013. The experiment involved five plant population distribution patterns under rainfed conditions. The following row spacing × spacing between the plant schemes were used: 40 cm × 40 cm (RS40), 50 cm × 32 cm (RS50), 60 cm × 27 cm (RS60), 70 cm × 23 cm (RS70), and 80 cm × 20 cm (RS80). Each experimental plot possessed dimensions of 4 m × 4 m; three replications were obtained in a randomized block design. The growth stage of V6, R0, R2, R3, and R4 were measured in this experiment (Ritchie *et al*., 1996). Fully expanded leaves were selected at V6 and ear leaves from R0 to R4. Dicot weeds in the summer maize plots were controlled chemically by applying the herbicide 0.84 kg/ha 2-methyl-4-clorophenoxyacetic acid (MCPA), other weeds were removed by hand. The air temperature during the growing seasons of 2011, 2012 and 2013 was showed in Fig. 1.

Canopy radiation, reflection, and underlying radiation were measured. Typical sunny days were selected to measure the data by using the SunScan Canopy Analysis System (Delta T Devices Ltd., Cambridge, UK), where a 1.5 m long linear sensor was placed parallel to the row direction. The PAR capture ratio (CR) was calculated as a ratio of the difference between incident and transmitted radiations to incident radiation, the PAR penetration ratio (PR) was calculated as a ratio of transmitted radiation to incident radiation, and the PAR reflection ratio (RR) was calculated as a ratio of the PAR reflection measured above the canopy to incident radiation (Han *et al*., 2014).

The Ψ was measured by using a PSYPRO Water Potential System (Wescor Inc., Logan, USA) with eight L-51 sample chambers, measuring three leaves for each treatment. During the transfer of each leaf to the sample chamber, water loss was minimized by ice box in a black plastic bag immediately after excision. The leaves were cut approximately 7 mm in diameter by hole puncher and sealed in the sample chamber. Samples were equilibrated for 20 min and then the readings were recorded.

Leaf relative water content (LRWC) was measured on clear-sky days at 08:30. Three leaves per treatment were obtained from different individual plants. LRWC was calculated by the equation RWC (%) = (Fw – Dw)/(Tw – Dw) × 100 (Aydi *et al*., 2008)

Fw is the fresh weight, Dw is the dry weight, and Tw is the turgid weight of the leaf samples. Being excised from the plants, the leaves were weighed Fw and placed in distilled water at 4 °C in the dark to minimize respiration losses until they reached a constant weight typically after 12 h. The leaf Tw was measured, after which the leaves were dried at 80 °C for 48 h and obtained the Dw.

The soil temperatures were recorded from 0 cm, 5 cm, 10 cm, and 15 cm depth with soil thermometers buried at respective soil depths. The temperatures were read at 8:00 a.m. and 14:00 p.m. every 5 d from July 25 to September 28, the average of which was as daily temperature (Fig. 2).

Grain yield was randomly recorded from an area of 2 m^2 in each plot on 24 September 2011, 2 October 2012, 2 October 2013.

All data were analyzed using SAS 9.2 and graphs were drawn using SigmaPlot 10.0. Experimental data were evaluated by ANOVA. The effects were considered significant in all statistical calculations if $p \leq 0.05$ based on least significant difference tests (LSDs).

RESULTS

Photosynthetically available radiation distribution: During 2011–2013, CR at R3 was the highest and V6 was the lowest. CR was the highest proportion, PR was the medium, and RR was the least (Table 2).

In 2011, CR, RR, and PR had significant difference among the treatments at the different growth stage ($p< 0.05$). The CR of RS70 and RS80 was lower than RS40, RS50, and RS60, and PR was reverse. During 2012, CR (R0, R3, and R4) and PR (R0 and R4) among the treatments had no significant difference ($p> 0.05$). While, at V6 in 2012, affected by less rainfall, CR was significantly lower than the other two years ($p< 0.05$). During V6–R2, CR of RS70 and RS80 was lower than RS40, RS50, and RS60. In 2013, CR (R3) and RR (V6 and R3) among the treatments had no significant difference ($p> 0.05$). During V6–R4, CR average of RS40 and RS50 was 11.8% higher than that of RS80; PR of RS80 was significantly higher than those of RS40 and RS50 ($p < 0.05$).

From R0 to R4, CR accounted for 84.1% of the total CR in the summer maize growing season in the 3 years. The upper CR (>100 cm) was 66.6%; the lower (0–100 cm) was 17.6%. The upper of CR accounted for 79.1% of the total CR. The upper CR of RS40, RS50, RS60, RS70, and RS80 were 71.4%, 70.6%, 63.7%, 61.1%, and 66.2%; the lower were 14.2%, 15.4%, 21.4%, 22.2%, and 14.6%, respectively. The upper CR accounted for 83.4%, 82.1%, 74.9%, 73.3%, and 81.9% of the total CR (Fig. 3).

Leaf water potential: The Ψ average in 2011, 2012, and 2013 was -1.54, -1.33, and -1.42 MPa, respectively (Fig. 4). The precipitation of 2011 growing season was apparently higher than the other two years, but the low rainfall of R3 might contribute to the decrease of Ψ. The Ψ average of V6, R0, R2, R3, and R4 were -1.41, -1.36, -1.42, -1.58, and -1.40 MPa in a 3-yr study; R3 was the lowest and R0 was the highest. The Ψ average of RS40, RS50, RS60, RS70, and RS80 were -1.36, -1.39, -1.42, -1.50, and -1.49 MPa from 2011 to 2013. The Ψ average of RS40 and RS50 was 8.8% higher than that of RS70 and RS80.

Leaf relative water content: Generally speaking, the LRWC of 2011 and 2012 were higher than 2013. In 2013, the LRWC decreased with the advance of the growth stage, which associated with low rainfall. The total rainfall of August and September were merely 54 mm in 2013. In the 3 years, the LRWC average of V6, R0, R2, R3, and R4 was 89.7%, 90.0%, 91.4%, 87.1%, and 83.6%; RS40, RS50, RS60, RS70, and RS80 was 88.7%, 88.8%, 88.5%, 87.4%, and 88.3%, respectively. The LRWC decreased at late growth stage, and the LRWC of RS70 and RS80 were lower than others. No significant differences were observed between RS and LRWC ($p > 0.05$) (Fig. 5).

Evapotranspiration: In the growing season, the total evapotranspiration of RS40, RS50, RS60, RS70, and RS80 were 433.4, 479.7, 463.1, 473.6, 475.3 mm (2011); 314.3, 299.2, 316.0, 313.5, 307.6 mm (2012); 494.6, 496.3, 471.1, 486.3, 500.3 mm (2013), respectively.

In 2011, no significant differences were observed between different RSs at R3–R5 ($p > 0.05$). The evapotranspiration of RS40 was the lowest at VE–V6 and R0–R2, which was significantly lower than that of RS70 and RS80 ($p < 0.05$). In 2012, at VE–V6, the evapotranspiration of RS60 and RS70 were significantly higher than that of RS40 and RS50; RS70 were significantly lower than RS40 and RS80 ($p < 0.05$). In 2013, no significant differences were observed between the treatments at R2–R3 and R3–R5 ($p > 0.05$). RS80 was significantly higher than others and RS60 was significantly lower than others at VE–V6. RS40 was significantly higher than RS50, RS70, and RS80 at V6–R0; RS50 was significantly higher than RS60 at VE–V6 and R0–R2 ($p < 0.05$) (Table 3).

Grain yield of summer maize: In 2011, the grain of RS40 was significantly higher than that of RS80. In 2012, RS50 was significantly higher than RS60, RS70 and RS80 ($p < 0.05$), the values were 11.58%, 19.30% and 19.62%, respectively; RS50 was 8.35% higher than RS40. In 2013, RS50 was significantly higher than RS40, RS70 and RS80 ($p < 0.05$); RS50 was 8.63% higher than RS60 (Fig. 6). The yield average of the 3 years, RS50 was significantly higher than RS60, RS70 and RS80 ($p < 0.05$), the values were 5.69%, 9.84% and 12.37%, respectively, and RS50 was 2.77% higher than RS40. The yield of RS40, RS70, and RS80 in different years followed the order of 2011 > 2012 > 2013; RS50 was 2012 > 2013 > 2011; RS60 was 2012 > 2011 > 2013. For the 3 years experiment, yield of 2012 was the highest and 2011 was the lowest.

The grain yield and water potential were significantly negative correlation with RS, correlation coefficients (r) were -0.9020 ($p < 0.05$) and -0.9550 ($p < 0.01$), respectively. The Ψ was significantly positive correlation with grain yield (r = 0.9225, $p < 0.01$). The grain yield and Ψ were positive correlation with LRWC, and r was 0.6761 and 0.8072 respectively. RS was negative correlation with LRWC (r = -0.5894) (Table 4).

Table 1. Monthly rainfall (mm) from 2011 to 2013 during the summer maize growing season

Years	June*	July	August	September	Total
2011	38.7	192.0	165.8	176.0	572.5
2012	11.6	210.5	53.4	61.6	337.1
2013	8.1	399.8	42.9	11.0	461.8

* The rainfall from sowing date to June 30.

Table 2. Effects of row spacing on the capture ratio (CR), reflection ratio (RR) and penetration ratio (PR) of PAR in 2011–2013 (%).

Row spacing	V6			R0			R2			R3			R4		
(cm)	CR	RR	PR	CR	RR	PR	CR	RR	PR	CR	RR	PR	CR	RR	PR
2011															
40	88.9a[*]	3.1c	8.1b	89.6a	3.0c	7.4c	90.5a	2.9c	6.5b	89.1a	3.5a	7.4b	86.1ab	3.9a	10.0bc
50	88.1ab	3.5b	8.4b	88.9a	3.0c	8.2bc	89.3a	3.0c	7.7b	86.8a	2.5b	10.7b	89.2ab	2.8b	8.0bc
60	87.8ab	4.2a	8.0b	85.2bc	4.2a	10.6ab	83.3ab	4.3a	12.4ab	87.6a	3.3a	9.1b	89.6a	3.0b	7.4c
70	82.7c	3.1c	14.2a	82.5c	3.9b	13.6a	85.2ab	3.8b	11.0ab	85.5a	3.4a	11.1b	85.1b	2.9b	12.0ab
80	85.2bc	3.5b	11.3ab	85.7b	2.8d	11.5a	81.4b	2.8c	15.8a	81.3b	2.2b	16.5a	80.4c	4.2a	15.4a
LSD (0.05)	3.16	0.26	3.40	2.98	0.21	3.16	7.39	0.38	7.70	3.72	0.36	3.99	4.31	0.32	4.48
2012															
40	65.1a	1.6ab	33.3b	89.4	2.3	8.3b	89.5b	2.7b	7.9b	89.6	4.4a	6.0ab	82.3	4.6a	13.1
50	61.6ab	1.9a	36.5ab	86.4	2.2	11.4a	88.7ab	3.7ab	7.6b	91.1	3.6c	5.3ab	84.0	2.9cd	13.0
60	60.8ab	1.4b	37.8ab	90.2	2.6	7.2b	90.2a	4.4a	5.4c	88.5	3.7bc	7.8a	83.7	3.9b	12.4
70	59.5ab	1.5ab	39.0ab	87.0	3.7	9.3ab	87.0b	3.2b	9.8a	89.1	3.2d	7.7a	83.0	3.0c	13.9
80	55.8b	1.6ab	42.6a	89.8	2.4	7.8b	88.1ab	3.3ab	8.6ab	91.9	3.9b	4.1b	85.9	2.4d	11.7
LSD (0.05)	9.06	0.52	7.88	6.00	2.08	2.68	7.88	1.18	1.92	6.60	0.30	2.70	9.31	0.61	4.75
2013															
40	81.3a	2.6	16.0c	82.2ab	1.8b	16.0cd	77.9a	3.0a	19.0b	86.2	3.2	10.6bc	74.6ab	4.2a	21.3b
50	81.4a	2.8	15.8c	84.5a	2.4a	13.1d	82.4a	3.0a	14.6c	87.2	3.6	9.2c	73.2ab	3.6abc	23.2b
60	71.8b	2.7	25.4a	79.4abc	1.4c	19.2bc	83.3a	2.8a	13.9c	84.7	3.5	11.8ab	74.9a	3.3bc	21.8b
70	74.4b	2.4	23.2ab	78.0bc	1.6bc	20.4b	81.8a	3.3a	14.9c	83.7	3.5	12.8a	71.3ab	4.1ab	24.7b
80	77.3ab	2.4	20.2b	75.0c	1.2c	23.8a	58.0b	1.6b	40.4a	83.6	3.5	13.0a	68.7b	3.0c	28.3a
LSD (0.05)	5.86	0.49	3.19	6.26	0.40	3.31	7.41	0.52	2.14	5.29	0.58	2.17	6.12	0.79	3.42

[*] Values followed by the same letter in a column are not significantly different according to LSD$_{0.05}$.

Table 3. Effects of row spacing on the evapotranspiration (mm) of summer maize in different growth stages (2011–2013).

Row spacing (cm)	VE–V6	V6–R0	R0–R2	R2–R3	R3–R5
2011					
40	107.1c[*]	56.1ab	78.7b	35.7a	155.8
50	127.4a	59.1a	101.3a	33.7ab	158.2
60	114.4bc	58.1ab	104.2a	29.5b	156.8
70	119.2b	52.8b	108.3a	35.4a	157.9
80	117.5b	57.0ab	107.9a	36.9a	156.1
LSD (0.05)	7.5	5.6	8.1	5.8	5.8
2012					
40	76.2b	66.1	54.6	50.6a	66.8
50	83.7b	57.7	51.7	45.7ab	60.5
60	100.7a	60.8	50.8	40.9ab	62.7
70	98.5a	57.3	57.0	39.0b	61.6
80	87.0ab	57.5	57.2	49.6a	56.3
LSD (0.05)	14.2	9.7	8.9	10.5	13.8
2013					
40	286.4b	65.0a	63.8ab	34.8	44.6
50	290.2b	57.0b	66.5a	34.7	47.9
60	273.7c	63.4ab	56.3b	35.4	42.4
70	290.4b	56.9b	64.3ab	33.3	41.4
80	303.4a	56.0b	65.1ab	34.9	40.9
LSD (0.05)	7.7	7.6	9.6	6.2	11.0

[*] Values followed by the same letter in a column are not significantly different according to LSD$_{0.05}$.

Table 4. Correlation matrix of row spacing-grain yield, leaf relative water content (LRWC) and water potential (Ψ) of summer maize grown in 2011–2013.

	Row spacing	Yield	Ψ	LRWC
Row spacing	1.0000	-0.9020*	-0.9550**	-0.5894
Yield		1.0000	0.9225**	0.6761
Ψ			1.0000	0.8072
LRWC				1.0000

*r values presented at $P< 0.05$; ** r values presented at $P< 0.01$.

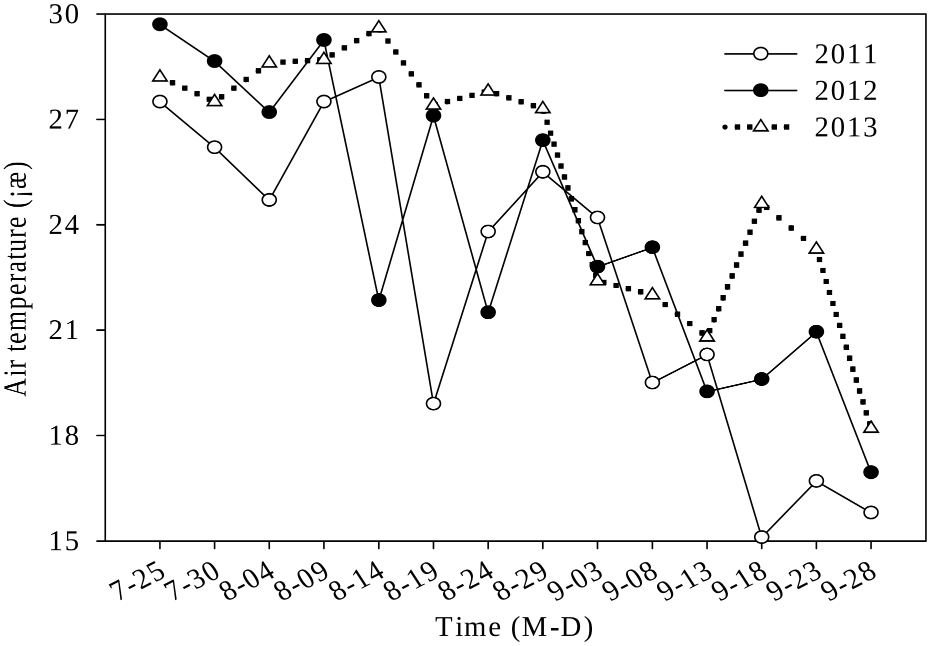

Fig. 1 Air temperature during summer maize growth stage.

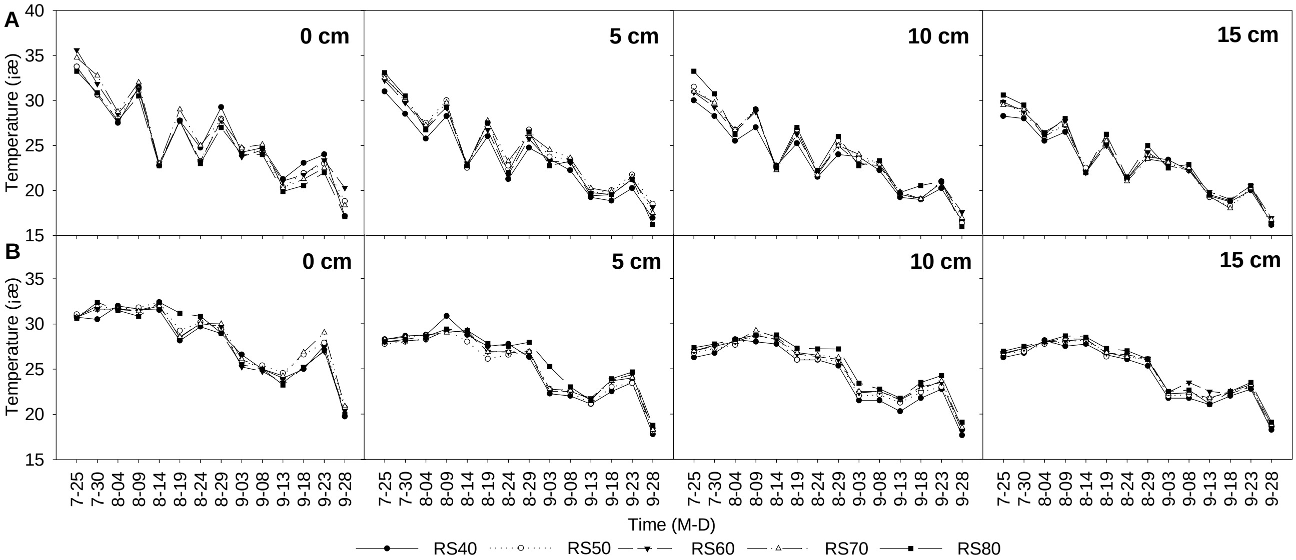

Fig. 2 Soil temperature during summer maize growth season. A, B are 2012 and 2013 respectively.

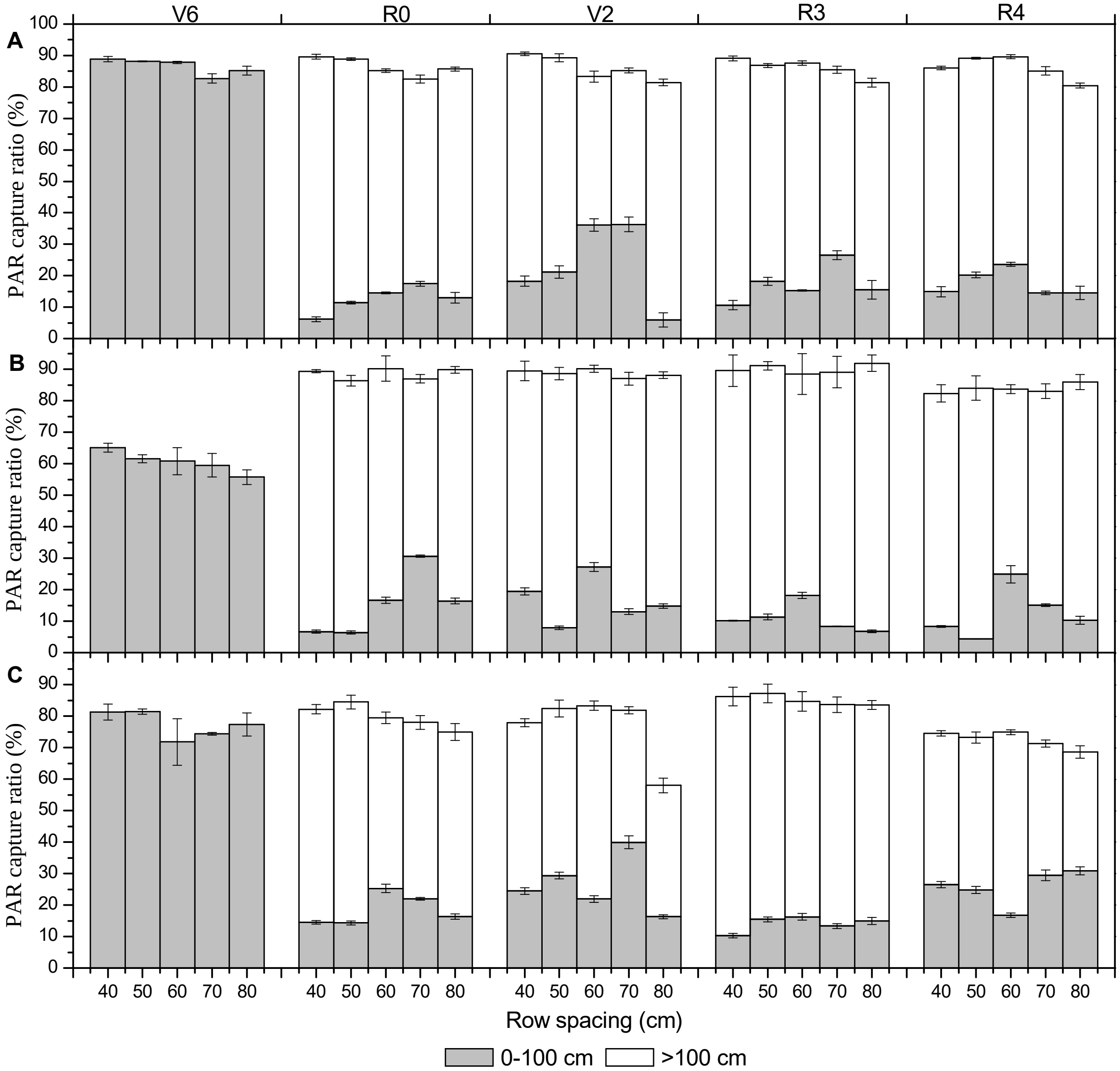

Fig. 3 Effects of row spacing on PAR capture ratio at different growth stages. A, B, C are 2011, 2012 and 2013 respectively; the bars are the SE.

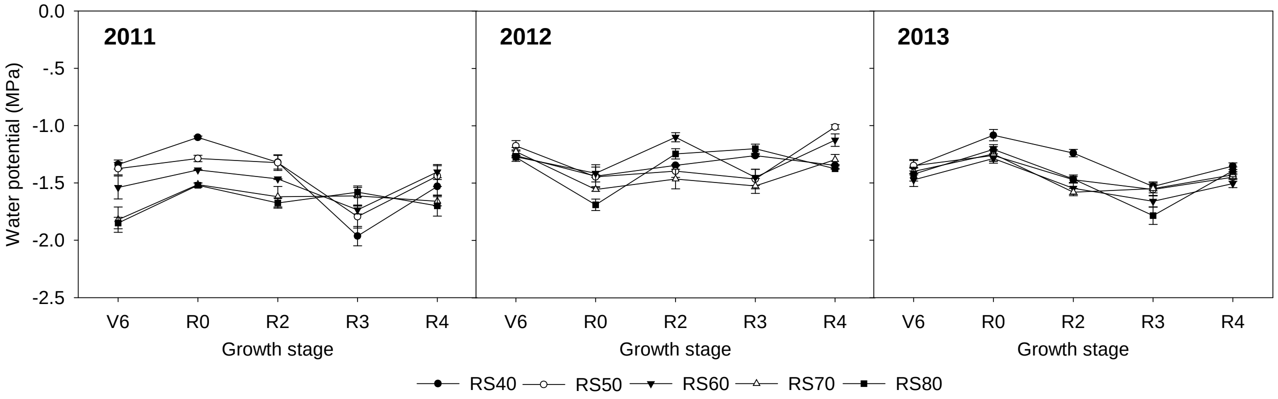

Fig. 4 Effects of row spacing on the leaf water potential. The bars are the SE.

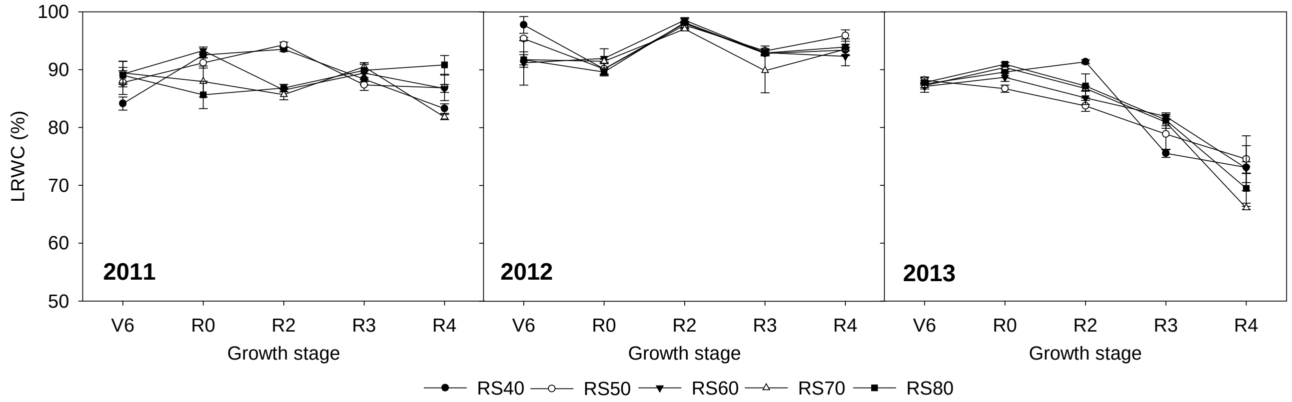

Fig. 5 Effects of row spacing on the leaf relative water content (LRWC). The bars are the SE.

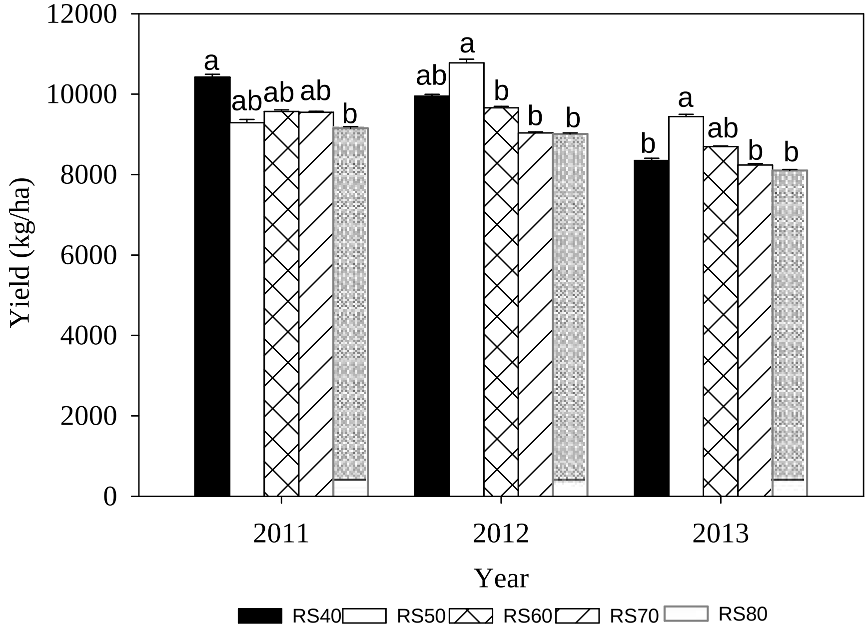

Fig. 6 Effects of row spacing on the yield of summer maize during 2011–2013. The bars are the SE.

DISCUSSION

In the study, the CR of RS70 and RS80, especially the latter, were significantly lower than the other treatments. The narrow RS was beneficial to the CR of PAR, hence, observation of present study was consistent with Lehrsch *et al*. (1994). The upper CR (>100 cm) of different RSs was higher than that of lower. The higher total CR and upper CR (>100 cm) (like RS40 and RS50) were more favorable towards yield (Board *et al*., 1992). The lower CR of RS40 (14.2%) and RS80 (14.6%) were lower than the others. Accompanying with the waste of light, the increasing of RS could affect the light energy utilization rate, thus may impact yield adversely (Maddonni and Otegui, 2006). Our study was consistent with it, the wide RS could decrease the CR and yield.

Water from leaves is usually viewed as important information on living plants (Yu *et al*., 2000). In our study, the LRWC of RS70 and RS80 were lower than the other treatments, which was consistent with the winter wheat studied by Huang *et al*. (2013). No significant differences were observed between RS and LRWC (p> 0.05). The Ψ average of RS40 and RS50 was higher than that of RS70 and RS80. The narrow RS was beneficial to increase Ψ and the yield (Sakamoto and Murata, 2000), which was also found in our research. Uniform distribution of the population (like RS40) could enhance the water consumption through transpiration thus increased the soil water during the growing season (Rahman *et al*., 2005), and the wide RS increased the evapotranspiration (Zhou *et al*., 2015). However, high evapotranspiration did not increase the yield of summer maize. This indicated that there exists a lot waste and low water resource utilization under rainfed conditions.

In a 3 year study, the yield of RS50 was significantly higher than that of RS60, RS70 and RS80 ($p< 0.05$), and RS50 was higher than RS40. The soil temperature gradually decreased with the increasing of soil depth and the decreasing of RS. Row spacing can change farmland microclimate (Wang *et al*., 2015). The close intrarow spacing can weaken the growth of the crop (De Bruin and Pedersen, 2008), which is in row with our result of RS80. The wide RS had a higher soil temperature, which can increase the evapotranspiration and decrease the yield. Ψ is an important factor that affect the leaf net photosynthetic rate (Peri *et al*., 2011), which is the basis of the formation of crop yield. In our study the grain yield and Ψ were significantly negative correlation with RS. The narrow RS is beneficial to the yield of summer maize. For the 3 years, the air temperature of 2011 was the lowest and 2013 was the highest. The suitable air temperature of 2012 and the low air temperature in the late growth stage of 2011 may contribute to the yield.

Conclusion: The wide RS increased the soil temperature hence affected the CR of PAR, LRWC, and Ψ. However, compared with RS50, the RS40 could increase the evapotranspiration and decrease the lower-CR. In conclusion, RS50 planting pattern is a reasonable cultivation approach that could promote the yield of summer maize in Huang-huai-hai Plain in China.

Acknowledgements: The authors especially thank Huang Juan, Feng Zhibo, Wang Guoyun and Han Yuanyuan for his valuable contributions. This research was supported by the National High Technology Research and Development Program of China (2013AA102903), Guangxi Natural Science Foundation (2015GXNSFAA139049) and Starting Foundation for Docotors of Guangxi University (XBZ160072).

REFERENCES

Aydi, S.S., S. Aydi, E. Gonzalez, and C. Abdelly (2008). Osmotic stress affects water relations, growth, and nitrogen fixation in *Phaseolus vulgaris* plants. Acta Physiol. Plant. 30: 441–449.

Board, J.E., M. Kamal, and B.G. Harville (1992). Temporal importance of greater light interception to increase yield in narrow-row soybean. Agron. J. 84: 575–579.

Bowers, G.R., J.L. Rabb, L.O. Ashlock, and J.B. Santini (2000). Row spacing in the early soybean production system. Agron. J. 92: 524–531.

De Bruin, J.L., and P. Pedersen (2008). Effect of row spacing and seeding rate on soybean yield. Agron. J. 100: 704–710.

Farnham, D.E. (2001). Row spacing, plant density, and hybrid effects on corn yield and moisture. Agron. J. 94: 1049–1053.

Han, Y.Y., G.Y. Wang, X.B. Zhou, Y.H. Chen, and P. Liu (2014). Radiation use efficiency and yield response of winter wheat to planting patterns and irrigation in northern China. Agron. J. 106: 168–174.

Huang, J., Y.H. Chen, X.B. Zhou, P. Liu, J.J. Bi, and Z. Ouyang (2013). Spatial arrangement effects on soil and leaf water status of winter wheat. J. Anim. Plant Sci. 23: 1379–1384.

Johnson, G.A., T.R. Hoverstad, and R.E. Greenwald (1998). Integrated weed management using narrow corn row width, herbicides, and cultivation. Agron. J. 90: 40–46.

Jost, P.H., and J.T. Cothren (2000). Growth and yield comparisons of cotton planted in conventional and ultra-narrow row spacings. Crop Sci. 40: 430–435.

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

Maddonni, G.A., and M.E. Otegui (2006). Intra-specific competition in maize: Contribution of extreme plant hierarchies to grain yield, grain yield components and kernel composition. Field Crops Res. 97: 155–166.

Maddonni, G.A., M.E. Otegui, and A.G. Cirilo (2001). Plant population density, row spacing and hybrid effects on maize canopy architecture and light attenuation. Field Crops Res. 71: 183–193.

Megowan, M., H.M. Taylor, and J. Willingham (1991). Influence of row spacing on growth, light and water use by sorghum. J. Agr. Sci. 116: 329–339.

Norsworthy, J.K., and E.R. Shipe (2005). Effect of row spacing and soybean genotype on main stem and branch yield. Agron. J. 97: 919–923.

Peri, P.L., M. Arena, G.M. Pastur, and M.V. Lencinas (2011). Photosynthetic response to different light intensities, water status and leaf age of two *Berberis* species (Berberidaceae) of Patagonian steppe, Argentina. J. Arid Environ. 75: 1218–1222.

Rahman, M.A., J. Chikushi, M. Saifizzaman, and J.G. Lauren (2005). Rice straw mulching and nitrogen response of no-till wheat following rice in Bangladesh. Field Crops Res. 91: 71–81.

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

Ritchie, S.W., J.J. Hanway, and G.O. Benson (1996). How a corn plant develops. Spec. Rep. 48. Rev. ed. Iowa State Univ. Coop. Ext. Serv., Ames.

Sakamoto, A., and N. Murata (2000). Genetic engineering of glycinebetaine synthesis in plants: current status and implication for enhancement of stress tolerance. J. Exp. Bot. 51: 81–88.

Sharratt, B.S., and D.A. Mcwilliams (2005). Microclimatic and rooting characteristics of narrow-row versus conventional-row corn. Agron. J. 97: 1129–1135.

Wang, X.Y., Z. Zhang, X.B. Zhou, P. Liu, and Y.H. Chen (2015). Planting pattern and irrigation effect on farmland microclimate and yield of winter wheat. J. Anim. Plant Sci. 25: 708–715.

Yu, G.R., T. Miwa, K. Nakayama, N. Matsuoka, and H. Kon (2000). A proposal for universal formulas for estimating leaf water status of herbaceous and woody plants based on spectral reflectance properties. Plant Soil 227: 47–58.

Zhou, X.B., Y.H. Chen, and Z. Ouyang (2015). Spacing between rows: effects on water-use efficiency of double-cropped wheat and soybean. J. Agr. Sci. Cambridge 153: 90–101.