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EFFECTS OF SPATIAL DISTRIBUTION ON PHOTOSYNTHESIS AND YIELD OF SUMMER MAIZE

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Abstract

The experiment was aimed to determinate reasonable group structure for maintaining stable and higher grain yield by adjusting row spacing. High leaf area index, chlorophyll content index, photosynthetic rate (Pn) and radiation use efficiency of row spacing 50 cm was observed in this study. Pn of row spacing 40 cm and 80 cm were lower than those of other treatments. Three-year average values of the daily increase in dry matter of row spacing 40, 50, 60, 70 and 80 cm were 199, 198, 182, 185 and 184 kg/ha/d, respectively. Grain yield of row spacing 50 cm was significantly different as compared to row spacing of only 80 cm. Therefore, row spacing 80 cm was minimal spatial structure whereas 50 cm spatial structure found to be optimal compared to rest of the row spacings that positively affect summer maize grain yield under rain-fed condition.

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops and plays an important role in expanding overall grain production capacity, especially in the North China Plain, which is main producing areas in China. However, lack of surface water sources has led to long-term and massive exploitation of groundwater resources for development of irrigated agriculture in the region (Sun *et al*. 2010), which has caused the water level to fall and created several environmental problems (Wang *et al*. 2016). Therefore, water-saving agricultural practices system is necessary. Cultivation practices could affect maize population significantly and break these restrictions on yield (Guan *et al*. 2014). Row spacing determines the spatial distribution of the plants, which affects canopy structure, light interception and radiation use efficiency (RUE) (Mattera *et al.* 2013); row spacing is expected to be an economical method for enhancing grain yield by utilizing increased radiation capture (Caviglia and Andrade 2010).

Different spatial arrangements can affect resource competition relationships (Brant *et al.* 2009), and the reasonable row spacing is necessary to improve the relation between group and individual plants (Norsworthy and Shipe 2005). The bilinear response of dry matter (DM) accumulation to plant spatial distribution was determined by RUE (Mattera *et al.* 2013). Cropping systems are also proposed as a better method to enhance crop yields (Caviglia and Andrade 2010). A leaf area index (LAI) of 3.5 - 4.0 in early reproduction is necessary to increasing crop yield (Liu *et al*. 2016). Zarate-Valdez *et al*. (2012) predicted that LAI and chlorophyll content should be determined in early stages to enhance distribution and utilization of crop resources. Therefore, the hypothesis was that reduced row spacing generates reasonable spatial arrangements that minimize interspecific competition, and favorable utilization of crop resources likely maintain higher grain yield of summer maize under rain-fed condition in the North China Plain.

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Materials and Methods

The experiment was carried out at the Agronomy Experiment Stations of Shandong Agricultural University (36°09′ N, 117°09′ E) at Tai'an, China from 2011 to 2013. The soil was silt loam (from surface 0 to 20 cm depth; pH 6.9) with the following average contents: soil organic matter 16.3 mg/g, total nitrogen 1.3 mg/g, available P 35 mg/kg, and available K 95 mg/kg. The long-term (from 1971 to 2010) annual average rainfall and temperature were 693.5 mm and 13.1°C, respectively. Total solar radiation data in 2011, 2012, and 2013 summer maize growing season were 4747, 4951, and 4980 MJ/m^2, respectively. The weather data were collected from the Tai'an Agrometerological Experimental Station.

The experiment consisted of five row spacings as 40 cm (RS40), 50 cm (RS50), 60 cm (RS60), 70 cm (RS70), 80 cm (RS80) under the same plant density (62500 /ha). The experiments had three replications with a randomized plot design. Summer maize (cv. Luyu14) was planted in plots (4 m × 4 m) on June 18, 2011, June 17, 2012, and June 19, 2013 and harvested on September 24, 2011, October 2, 2012, and October 2, 2013, respectively. The experimental plot was applied with 202.5 g diammonium phosphate, 202.5 g urea, and 152.1 g kalium chloratum before sowing. Summer maize is a rain-fed crop thus the experiment conducted without irrigation during growth period.

The photosynthetic rate (Pn), LAI, chlorophyll content index (CCI), and DM were measured at V6, R0, R2, R3, R4, and R5 growth stages following Wang *et al*. 2015. Plants were dried in an oven at 105°C for 30 min followed by at 80°C until reach to a constant weight to determine DM.

The Pn was measured using a LI-6400XT (LI-COR Inc., Lincoln, USA) with an artificial light source (1400 $\mu mol/m^2/s$); CCI was measured using chlorophyll content meter 200 (Optic-Sciences Inc., Tyngsboro, USA). LAI was measured with the following formulae:

LAI = Leaf length × leaf width × 0.75 (Amanullah *et al*. 2007).

Where leaf length is the distance between the leaf pillow and leaf tip, and leaf width is the widest part of the leaf. Use of radiation efficiency was calculated as:

RUE = $\Delta W \times H/\Sigma S \times 100\%$ (Zhang *et al*. 2016), where ΔW is the aboveground biomass of sample (g/m^2), H is the product value of heat (summer maize kernel is 16.5 KJ/g; both stem and leaf are 14.4 KJ/g), it is same for all treatments, ΣS is the total radiation of the unit area (MJ/m^2).

Ten plants with similar growth vigour were harvested as samples by using a sickle in each plot for measuring per-plant kernel number (KNP), kernel weight (KW). A total of 2 m^2 summer maize was harvested to measure grain yield and harvest index (HI).

The data were statistically analyzed by SAS 9.2 software. All graphs were drawn using Sigma Plot 10.0 (SPSS Inc., Chicago, IL). Effects were considered significant with the least significant difference (LSD) test at $p \leq 0.05$.

Results and Discussion

The three-year experiment showed Pn more or less decreasing tendency with growth stage development (Fig. 1). A significant linear regression was also noted between Pn and growth stage. The linear correlation equation was y (Pn, $\mu mol\ CO_2/m^2/s$) = $-6.201\ x$ (growth stage) + 49.944, $R^2 = 0.803$ (2011, $p \leq 0.001$); $y = -2.441x + 38.088$, $R^2 = 0.544$ (2012, $p \leq 0.001$); and $y = -4.393x + 42.95$, $R^2 = 0.624$ (2013, $p \leq 0.001$). At V6 to R4, the three-year average values of row spacing for 40, 50, 60, 70, 80 cm were 29.9, 31.0, 32.1, 31.3, and 28.8 $\mu mol\ CO_2/m^2/s$, respectively. At V6 and R3, no significant difference was noted among the Pn of the treatments ($p > 0.05$). At R0 and R2, the Pn of RS80 was significantly lower than that of the other row spacing; at R4, the Pn of RS50, RS60, RS70 was higher than that of RS40. The photosynthesis in narrow spacings (40 and 50 cm) was better than those of wide spacing (60, 70 and 80 cm), suggesting reasonable canopy closure and plants distribution in narrow spacing was an indicator of more favorable growing condition (Caviglia and Andrade 2010).

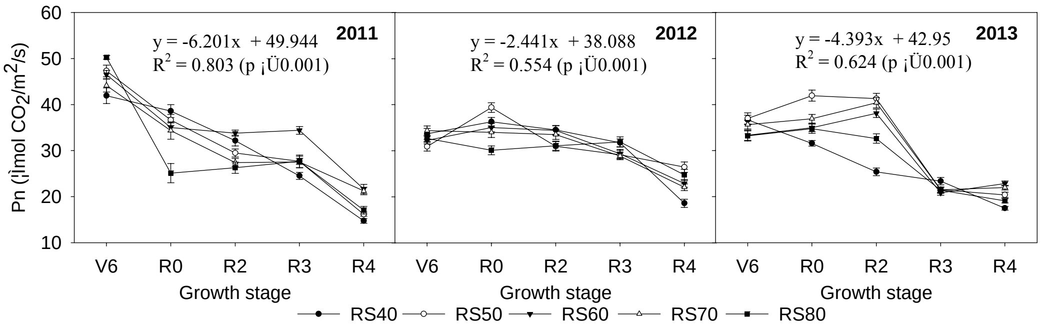

Fig. 1. Net photosynthetic rate (Pn) of different row spacings and growth stages. The bars are the SE.

Different treatments showed similar trend of inverted-U shaped ('∩') curve in LAI during the growing season, especially in 2012 (Fig. 2). Three regression equations in 2011, 2012, and 2013 were: y (LAI) = $-0.1731x^2 + 0.9669x$ (growing stage) + 3.5087, $R^2 = 0.6931$ ($p \leq 0.001$); $y = -0.450x^2 + 3.055x - 0.281$, $R^2 = 0.935$ ($p \leq 0.001$); and $y = -0.167x^2 + 0.800x + 3.082$, $R^2 = 0.877$ ($p \leq 0.001$), respectively. In V6 to R4, the LAIs of row spacing 40, 50, 60, 70, 80 cm were listed as follows: 4.49, 4.38, 4.60, 4.44, and 4.62 in 2011; 3.76, 4.06, 3.99, 3.95, and 3.92 in 2012; and 3.52, 3.83, 3.62, 3.54, and 3.68 in 2013, respectively. Han *et al.* (2016) reported that seedling phase to physiological maturity, LAI were negative correlated with row spacing for winter wheat under deficit irrigation.

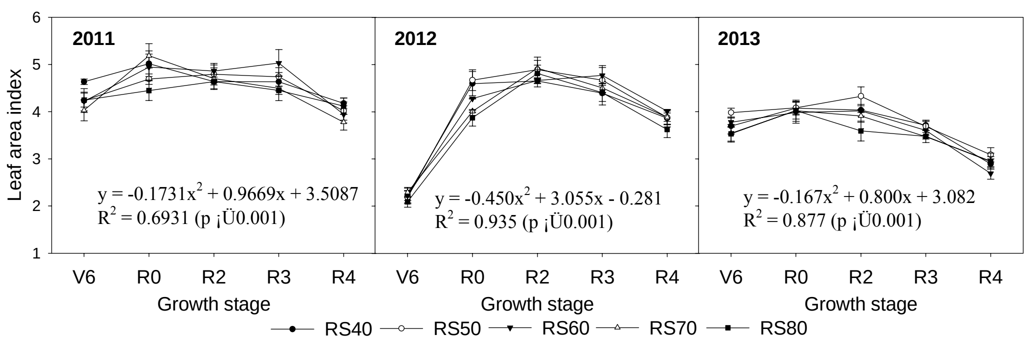

Fig. 2. Leaf area index of different row spacing and growth stages. The bars are the SE.

In 2011, the CCI of RS40 at V6 was significantly higher than that of other treatments in contrast, the CCI of RS80 was $p < 0.05$. The CCIs of all treatments were relatively low because of low amount of solar radiation. A relatively high CCI in R0 to R4 was attributed to high amount of precipitation. At R2, the CCI of RS50 was the highest in all treatments. At V6 to R4, the CCIs of row spacing 40, 50, 60, 70, 80 cm were 43.5, 43.3, 41.5, 40.7 and 41.5, respectively. The CCI of RS40 11.1% was higher than that of RS80. At V6, the CCI of 2012 was higher than that of 2011 and 2013. Whereas the CCI mean of RS40, RS50, RS60 was 7.4% higher than that of RS70 and RS80 (Fig. 3).

The three-year CCI average of row spacing 40, 50, 60, 70, 80 cm were 43.0, 44.4, 41.9, 41.7, and 41.0, respectively. The pattern of CCIs observed as: RS50 > RS40 > RS60 > RS70 > RS80. The CCI of RS80 was the lowest, but CCI of RS50 was the highest among all treatments. The discrepancy may contribute to optimum spatial distribution and improve light distribution. CCI and LAI for RS40 and RS50, resulted in high intercept and capture of solar radiation in rain-fed condition. Photosynthesis was significantly affected by plant spatial distribution (Hamzei and Soltani 2012).

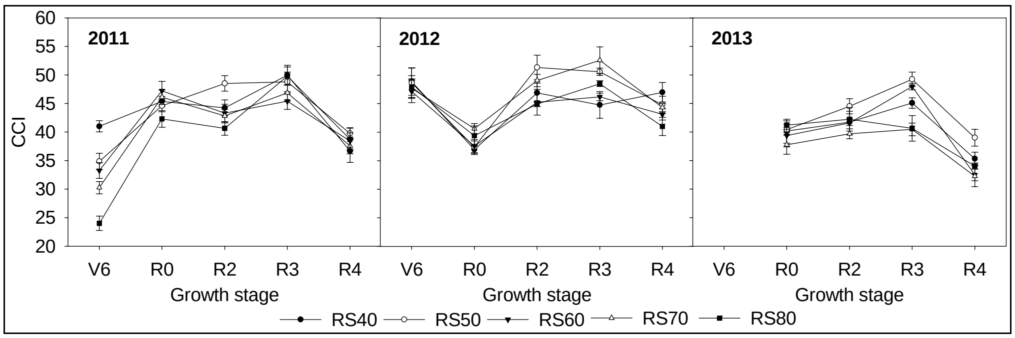

Fig. 3. Chlorophyll content index (CCI) of different row spacings and growth stages. The bars are the SE.

DM was positively correlated with growing stage (Fig. 4). The linear equation was y (DM, kg/ha) = 3896.1 x (growth stage) + 853.88, $R^2 = 0.902$ (2011, $p \leq 0.001$); $y = 5230.9x - 3580.3$, $R^2 = 0.989$ (2012, $p \leq 0.001$), $y = 3664.5\,x + 509.01$, $R^2 = 0.906$ (2013, $p \leq 0.001$), respectively. In 2011, the DM of RS60 was lower than that of other treatments at R0; the DM of RS40 increased daily by 13.9% higher than that of RS50. In 2012, DM slightly differed among the treatments; the average DM values of RS40 and RS50 were 10.3% higher than those of other treatments. In 2013, the average DM was relatively high. The three-year average values of daily increase in DM of row spacing 40, 50, 60, 70, 80 cm were 199, 198, 182, 185, and 184 kg/ha/d. Narrow spacings improved spatial distribution and increased Pn, hence, crop plants produced high DM (Gonias and Oosterhuis 2011).

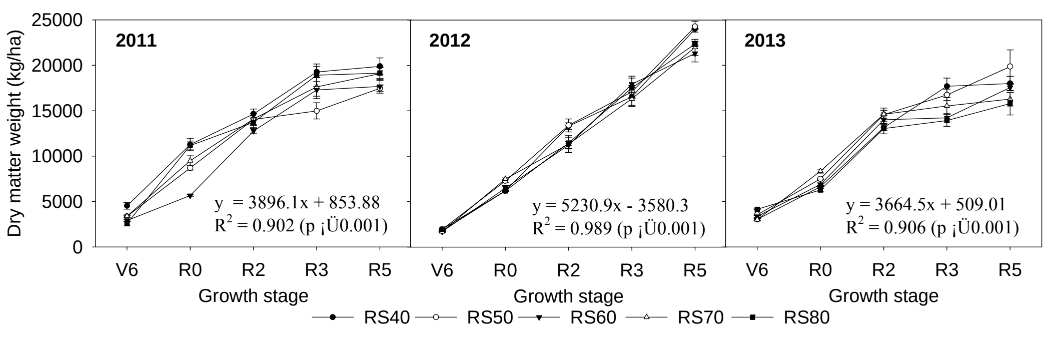

Fig. 4. Dry matter weight of different row spacings and growth stages. The bars are the SE.

The RUE of crops are determined by environmental factors, such as canopy structures, LAI, radiation regimes (diffuse or direct), temperatures, water contents, and cropping systems (Brodrick *et al.* 2013). In 2011, row spacing did not significantly affect KNP and KW (p > 0.05). The yield and RUE of RS40 were the highest among all of the treatments. The HI of RS80 was also significantly lower than that of RS50 and RS60 ($p \leq 0.05$). In 2012, the KNP of RS70 and RS80 was significantly lower than that of RS50 ($p \leq 0.05$). The yield, DM, and RUE of RS60 were significantly lower than that of RS50 ($p \leq 0.05$).

Table 1. Row spacing effects on summer maize per-plant kernel number (KNP), kernel weight (KW), yield, dry matter (DM), harvest index (HI) and radiation use efficiency (RUE) in 2011-2013.

Row spacing (cm)	KNP	KW (mg)	Yield (kg/ha)	DM (kg/ha)	HI	RUE (%)
2011						
40	538a	348a	10415a	19878a	0.53a	1.81a
50	506a	332a	9288ab	17458b	0.53a	1.59b
60	500a	338a	9569ab	17679b	0.54a	1.62b
70	510a	330a	9551ab	19080ab	0.50ab	1.73ab
80	496a	336a	9152b	19142ab	0.48b	1.73ab
LSD (0.05)	50	20	941	1888	0.05	0.17
2012						
40	536ab	371a	9948ab	24008a	0.41ab	1.87ab
50	572a	356a	10779a	24269a	0.44ab	1.90a
60	529ab	378a	9660b	21314b	0.45a	1.67b
70	515bc	366a	9035b	21992ab	0.41ab	1.71ab
80	475c	366a	9011b	22367ab	0.40b	1.74ab
LSD (0.05)	40	39	993	2668	0.05	0.20
2013						
40	552ab	314b	8352b	18003ab	0.46b	1.37ab
50	572a	351a	9443a	19853a	0.48ab	1.51a
60	519b	332ab	8693ab	17536ab	0.50ab	1.34ab
70	539ab	313b	8238b	16278b	0.51a	1.25b
80	535ab	313b	8099b	15778b	0.51a	1.21b
LSD (0.05)	39	33	1586	3509	0.04	0.26
Mean						
40	543a	344a	9572ab	20629a	0.47bc	1.68a
50	550a	347a	9837a	20503ab	0.48ab	1.67a
60	515ab	349a	9307bc	18843c	0.50a	1.54bc
70	521ab	336a	8956cd	18995c	0.47bc	1.56b
80	502b	338a	8754d	19076bc	0.46c	1.56b
LSD (0.05)	39	17	520	1445	0.02	0.12

Values in a column with different letters are significantly different ($p \leq 0.05$).

The average of the three-year experiments showed that row spacing did not significantly affect KW. In addition, the KNP of RS40 and RS50 were significantly higher than that of RS80. The order of yield from high to low was recorded as RS50, RS40, RS60, RS70, and RS80, respectively. The DMs of RS40 were significantly higher than those of RS60 and RS70 ($p \leq 0.05$). The HI of RS60 was 7.1% higher than that of RS80 (Table 1). Although DM accumulation and RUE of RS40 were higher than those of RS50, uniform distribution was not advisable to maintain high Pn in the late growth stage. Yield also slightly decreased. Therefore, RS50 is an optimal pattern for summer maize cultivation. In all treatments the RUE of RS40 was the highest in 2011; whereas RUE of RS50 was relatively higher in 2012 and 2013. Three years study demonstrated that there was no difference in row spacings regarding KW, KNP was significantly higher in RS50 than that in RS80, correspondingly, plants in RS50 had the highest grain yield, while that in RS80 had the lowest. These indicate that RS50 had significantly increased grain yield when compared to other row spacings and positively related with the increase of KNP. This finding shows similarity to the result of mungbean crop reported by Rachaputi *et al.* (2015).

The values of each variable decreased with the increase of row spacing and significantly negatively correlated with yield and LAI ($p < 0.05$). Yield was highly significantly and positively correlated with LAI ($p < 0.01$). Pn increased with other variables and there was no significant differences between them. CCI significantly and positively correlated with LAI ($p < 0.05$) (Table 2). The change in row spacing would have changed of the canopy structure, and as spacing reduced, leaves may had been exposed to lower irradiance resulting higher LAI, and thus showed increase RUE (Mattera *et al.* 2013). High KNP in RS50 and its positive association with RUE, suggested that different row spacings changed the responses of RUE to KNP, and grain yield.

Table 2. Correlation matrix of row spacing-related variables, grain yield, and photosynthetic rate (Pn), chlorophyll content index (CCI) and leaf area index (LAI) in summer maize grown in 2011-2013.

Variable	Row spacing	Yield	Pn	CCI	LAI
Row spacing	1.0000	–0.9020*	–0.2212	–0.8004	–0.8893*
Yield		1.0000	0.3217	0.9556**	0.9580**
Pn			1.0000	0.2460	0.5606
CCI				1.0000	0.8787*
LAI					1.0000

*Presented at $p < 0.05$; ** presented at $p < 0.01$.

This study showed that plant spatial distribution had significant effect on Pn, CCI, LAI, HI, grain yield, yield components and RUE. The results suggested that RS50 is an optimal spatial structure that positively improves CCI, LAI and RUE of summer maize and consequently is relatively high KNP and plant grain yield in rain-fed condition.

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