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Full Length Article

Waxy Maize Yield in Response to a Novel Plant Growth Regulator and Plant Density

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Abstract

High crop density often weakens plants, thereby leading to an increased risk of lodging and reductions in crop yield. In this study, the effects of a novel plant growth regulator, DHEAP [*N*, *N*-diethyl-2-hexanoyl oxygen radicals-ethyl amine (2-ethyl chloride) phosphoric acid salt], on waxy maize yield and lodging was evaluated. The field experiment was conducted at two locations (Changping and Wuqiao, China), four plant densities (4.5, 6.0, 7.5 and 9.0 plants m^{-2}) and three cultivars (JHN 2008, JKN 2000 and JKN 928) in 2015. After foliar spraying with DHEAP during the 8-leaf stage, fresh ear and grain yield, yield components, and lodging percentage were determined for all cultivars. Grain yield showed a significant increase (3.47%), thousand-kernel weight and kernel number per ear increased by 6.10 and 3.21%, respectively after DHEAP treatment. The optimal plant density ranged from 6.0 to 7.5 plants m^{-2}. DHEAP significantly decreased waxy maize lodging percentage for all cultivars. Among the maize cultivars, the yield of the compact short plant cultivar JKN 928 was higher than that of JKN 2000 and JHN 2008. It is concluded that optimized plant density might enhance waxy maize yield with a single application of DHEAP before jointing stage.

Keywords: Lodging percentage; Plant and ear height; Residue ratio; Waxy maize; Yield components; Plant growth regulator

Introduction

Crop yield potential is normally affected by multiple factors, including genetic basis of the cultivar, the growth environment and management factors (Tokatlidis *et al.*, 2011; Wang *et al.*, 2011; Ndhlela *et al.*, 2014; Li *et al.*, 2016; Mehmood *et al.*, 2018). Worldwide, it is an important measure to enhance maize yield potential by planting closely (Li *et al.*, 2015; Xue *et al.*, 2016); however, lodging might be a consequence of increased plant density (Tokatlidis *et al.*, 2010; Novacek *et al.*, 2013; Xue *et al.*, 2016), which can lead to maize grain yield losses of up to 30% (Ma *et al.*, 2014a). As an important cultivation technique, the application of plant growth regulators is an effective measure for reducing plant height and preventing lodging in maize (Esechie *et al.*, 2004; Shekoofa and Emam, 2008; Zhang *et al.*, 2014). In recent years, some scholars reported the interactive effects of plant growth regulators, or other agronomic measures and genotypes in different environments, which have shown the practical significance of these regulators in terms of crop yield improvement and lodging control (Esechie *et al.*, 2004; Shekoofa and Emam, 2008; Tokatlidis *et al.*, 2011; Tokatlidis, 2013; Mao *et al.*, 2014; Lindsey *et al.*, 2015).

Waxy maize (*Zea mays* L. var. *ceratina* Kulesh), containing almost 100% amylopectin in starch composition and high economic value, is becoming an important source of maize for fresh consumption, food industries, feedstuff, and so on (Fan *et al.*, 2008; Yang *et al.*, 2017). With improvements in living standards, Chinese people have been increasing its planting area rapidly, and large quantities of maize are sold as cooked, frozen or in cans on market (Lertrat and Thongnarin, 2008; Kang *et al.*, 2010). A favorable characteristic of fresh waxy maize is its specific superior eating quality (*e.g.*, a lower residue ratio of the

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pericarp), which is related to a greater flexibility in harvesting time (the grain develops over 20 days after pollination) (Lu *et al*., 2015; Yang *et al.*, 2017). However, its economic characteristics also depend on a high yield of fresh ears and grains. Therefore, investigations of the effects of genetics, growth environment, and management on eating quality of waxy maize by increasing its fresh ear and grain yield are needed (Zulfiqar *et al*., 2017).

Agronomists have applied several commercially available plant growth regulators for reducing lodging and increasing yield in maize, *e.g*., ethephon applied for increasing stalk strength (Ye *et al.*, 2015), DA-6 applied for accelerating leaf photosynthesis (Nie *et al*., 2010), EDAH applied for regulating plant density as a mixture (Zhang *et al*., 2014) and chlormequat chloride applied for plant height and disease control (Clark and Fedak, 1977). However, the wide-scale application of ethephon and its mixtures is limited because of its corrosiveness to professional workers and low stability under neutral pH conditions. We recently reported the use of DHEAP, a newly synthesized plant growth regulator, which showed a synergistic effect of yield increase and reduced lodging when applied to maize crops and represents a safer product and technology for maize farmers (Zhang *et al*., 2017). Examining the field efficacy of this growth regulator is now of significance in terms of the yield and lodging of fresh waxy maize.

The present study aims at (1) quantifying how the interaction between DHEAP treatment and plant density effects on fresh ear yield, fresh grain yield, components of yield and lodging in waxy maize cultivars and (2) explore the optimal management strategies for further improvements in the yield of waxy maize.

Materials and Methods

Field Experiments

Field trial was conducted at the Wuqiao experimental station of China Agricultural University at Wuqiao (37° 41′ N, 116° 37′ E) and the National Modern Agricultural Science and Technology Park at Changping (40.19°N, 116.45°E) in 2015. Table 1 and 2 showed the weather data recorded during the growth period of maize and the soil characteristics at each location, respectively. At Wuqiao, the 0 20 cm soil layer contains 17.40 g kg^{-1} organic matter, 1.16 g kg^{-1} total nitrogen, 41.20 mg kg^{-1} available phosphorus and 123.40 mg kg^{-1} available potassium, and had pH 8.6. At Changping, the content of organic matter, total nitrogen, available phosphorus and available potassium in the 0–20 cm soil layer was 10.91 g kg^{-1}, 0.76 g kg^{-1}, 25.30 mg kg^{-1} and 150.6 mg kg^{-1}, respectively and the soil pH was 8.2.

Three hybrid waxy maize cultivars Jinghuanuo 2008 (JHN 2008, flat-type tall plant), Jingkenuo 2000 (JKN 2000, semi-compact tall plant) and Jingkenuo 928 (JKN 928, semi-compact short plant) were selected as experimental crops. Four plant densities were 4.5, 6.0, 7.5 and 9.0 plants m^{-2}. Maize sowing was conducted manually with 5 cm depth on 6 May and on 5 May at Changping and Wuqiao respectively.

DHEAP treatment was conducted with foliar spraying at a concentration of 360 mL ha^{-1} in late afternoon (4 to 7 p.m.) during the 8-leaf stage. For the control group, the same amount of water was sprayed. The experiment was conducted under randomized block design with three replicates, cultivar as the main block, plant density and DHEAP application as the randomized sub-blocks. Eight rows of maize were grown in each plot of 48 m^2 (10 m × 4.8 m). At Changping, the base fertilizer with 95 kg ha^{-1} nitrogen, 25.3 kg ha^{-1} P_2O_5, 152.4 kg ha^{-1} K_2O and was applied before sowing. A further 95 kg ha^{-1} nitrogen applied as a top dressing at the tassel stage (VT). Each plot was irrigated with 70 mm of water so that the moisture was adequate for maize growth. In Wuqiao, the base fertilizer consists of 110 kg ha^{-1} nitrogen, 120 kg ha^{-1} P_2O_5 and 120 kg ha^{-1} K_2O was applied before sowing. Further 130 kg ha^{-1} nitrogen applied as a top dressing at the tassel stage. Immediately after sowing each plot was irrigated with 60 mm of water. Other agronomic practices were carried out by referring to local farmers. The maize was harvested on 7 August at Changping and 10 August at Wuqiao respectively.

Measurements

In each plot, the inner two rows were hand harvested to calculate fresh ear and grain yield (the area is 12 m^2). Each harvested area was protected by single guard rows. Ear density (as the number of ears per unit ground area), ear weight and ear size (length and diameter) for all plants in the sampling area of each plot at the time of harvest were measured. To measure kernel number per ear and thousand-kernel weight, 10 ears were randomly selected from the sampling area. The residue ratio of grain pericarp was calculated following Zhang (2008).

At the dough stage (R3) (Changping: July 16; Wuqiao: July 18), morphological trait data were collected for plant and ear height of six plants in each plot. The minimum distance from the harvest sampling area to this 6 m^2 area was 0.6 m. The lodging percentage at dough-stage was calculated. A less than 60° angle of stalk and ground level was used as the identification of lodged plants.

Statistical Analysis

Analysis of Variance (ANOVA) was applied in S.P.S.S. 21 for determining how DHEAP treatment affects yield and morphological traits. The general linear model procedure was used for analysis. Location, cultivar, plant density and DHEAP treatment were set as fixed factors, including all interactions. Replicate was considered a random factor. Duncan's multiple range test was used for the difference significance at $P < 0.05$ and Origin 8.6 was used for the figure's preparation.

Table 1: Weather data of experimental locations during maize growing season in 2015

Monthly	Temperature (°C)		Precipitation (mm)		Sunshine hours (h)		wind speed (m s^{-1})	
	Changping	Wuqiao	Changping	Wuqiao	Changping	Wuqiao	Changping	Wuqiao
5-May	20.8	20.5	1.2	50.0	309	294	1.1	2.8
6-Jun	24.4	25.6	4.0	35.5	221	207	0.9	2.5
7-Jnly	25.8	27.2	126	118	209	209	0.5	1.3
8-Aug	28.4	25.5	81.2	176	248	227	0.3	1.5
Total [a]	24.9	24.7	212	380	986	937	0.7	2.0

[a] Precipitation and sunshine are monthly sums, while air temperatures and wind speed are monthly mean in maize growing season

Table 2: Soil type, original fertility in the top 0-20 cm soil layer and fertilization, irrigation application of each plot in the two locations

Location	Soil type	pH	Original fertility				Fertilizer application				Irrigation
			Organic matter	Total N	Available P	Available K	Before sowing			Vasseling stage	
			(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	N kg ha^{-1}	kg P_2O_5 ha^{-1}	kg K_2O ha^{-1}	N kg ha^{-1}	mm (date)
Changping	Fluvo-aquic soil	8.2	10.91	0.76	25.30	150.6	95	25.3	152.4	95	70 (May 10)
Wuqiao	Fluvo-aquic soil	8.6	17.40	1.16	41.20	123.4	110	120	120	130	60 (May 8)

Table 3: Results of ANOVA analysis for the effects of location (Loc), plant density (PD), cultivar (Cul) and plant growth regulator (DHEAP) on fresh ear yield, fresh grain yield, yield components, morphological traits and residue ratio in waxy maize

Effect	Fresh ear yield	Fresh grain yield	Ear density	Thousand kernels weight	Kernel numbers per ear	Lodging percentage	Plant height	Ear height	Residue ratio
Loc	43.41**	91.84**	5.15ns	155.25**	3.63ns	36.98**	26.26**	6.73**	-
DHEAP	64.63**	115.85**	24.71**	128.76**	51.44**	282.14**	171.05**	321.57**	2.03ns
Cul	67.63**	36.96**	2.66ns	436.82**	403.71**	173.63**	477.82**	313.19**	17.32**
PD	81.47**	86.85**	195.75**	126.54**	122.02**	731.83**	66.58**	18.85**	7.29*
Replicate	2.09ns	1.35ns	0.64ns	0.61ns	0.87ns	1.94ns	0.95ns	1.92ns	2.63ns
DHEAP × PD	2.37ns	1.76ns	0.27ns	0.87ns	0.77ns	61.02**	0.54ns	1.18ns	2.96*
DHEAP × Cul	1.29ns	5.87**	0.72ns	1.06ns	0.05ns	13.43**	7.08**	1.34ns	0.80ns
Cul × PD	6.77**	2.46*	8.76**	0.40ns	2.64*	24.92**	0.36ns	0.15ns	7.91**
Cul × DHEAP × PD	0.23ns	0.78ns	0.35ns	0.33ns	0.41ns	2.57*	0.18ns	0.16ns	3.73**
Cul × DHEAP ×PD × Loc	10.01**	3.83**	1.16ns	2.26**	0.72ns	2.30**	1.21ns	2.02*	-

F values and significance levels (* $P < 0.05$, ** $P < 0.01$ and ns $P \geqq 0.05$) are given. Analyses were made using a split block design with plant density as main plot factor and DHEAP and cultivar as subplot factors. DHEAP indicates compound was synthesized from ethephon and diethyl aminoethyl hexanoate, which was applied at a rate of 360 ml ha^{-1} at the stage of 8 expanded leaves

Results

Fresh Ear Yield

Variability in location, plant density, cultivars and DHEAP treatment contributed to significant difference in fresh ear yield ($P < 0.01$) (Table 3). Cultivars in Changping had a higher average fresh ear yield (14.22 ton ha^{-1}) than in Wuqiao (13.80 tons ha^{-1}) (Table 4). Fresh ear yield showed a significantly increase by 3.16% across all cultivars, plant densities and locations with the application of DHEAP. The average fresh ear yields across both locations for JKN 2000 (14.32 ton ha^{-1}) and JHN 2008 (14.03 ton ha^{-1}) were significantly higher than that for JKN 928 (13.68 ton ha^{-1}); however, the yield of JKN 2000 did not differ significantly to that of JHN 2008 (Table 4).

There were significant interactions ($P < 0.01$) in plant density and cultivar, and between interactions among all the four fixed factors (Table 3). At Changping, the highest yield of maize was obtained from JHN 2008 with DHEAP application when planted at 7.5 plants m^{-2}, whereas the best performing cultivar at Wuqiao was JKN 2000, of which the optimal plant density was also 7.5 plants m^{-2}, indicating significant interaction between cultivar (*e.g.*, plant type) and management (*e.g.*, DHEAP application and plant density).

Fresh Grain Yield

Fresh grain yield showed significant difference with the four fixed factors ($P < 0.01$) (Table 3). Cultivars in Changping showed a higher average fresh grain yield (9.54 ton ha^{-1}) than in Wuqiao (9.21 ton ha^{-1}) (Table 5). A significant higher average fresh ear yields were also present across both locations for JKN 2000 (9.52 ton ha^{-1}) and JKN 928 (9.40 ton ha^{-1}) than that of JHN 2008 (9.21 ton ha^{-1}); however, the yield for JKN 2000 did not differ significantly than JKN 928 (Table 5). After DHEAP treatment, fresh grain yield was largely increased by 3.67% across all cultivars, plant densities and locations.

The application of DHEAP showed significant interaction with cultivar ($P < 0.01$), but non-significant interaction with plant density. Cultivar showed significant interaction with plant density ($P < 0.05$) (Table 3). There was also significant interaction among the four fixed factors ($P < 0.01$) (Table 3). In Changping, JKN 2000 treated with DHEAP showed the highest yield when planted at 6.0 plants m^{-2}, whereas JKN 928 showed the best performance at Wuqiao, with the same value of optimal plant density, indicating that the interaction effect of cultivar (*e.g.*, plant type) and managements (*e.g.*, DHEAP application and plant density) on fresh ear yield was also significant.

Table 4: Fresh ear yield (ton ha^{-1}) of waxy maize affected by cultivar, plant density (plants m^{-2}) and plant growth regulator (DHEAP) at the two locations

Location	Plant density	Cultivar					
		JHN2008		JKN2000		JKN928	
		No DHEAP	DHEAP	No DHEAP	DHEAP	No DHEAP	DHEAP
CP	4.5	13.35 ± 0.08 C a	13.30 ± 0.17 C a	13.38 ± 0.07 C b	13.77 ± 0.11 C a	12.50 ± 0.22 A a	12.78 ± 0.38 D a
	6.0	13.75 ± 0.06 B a	14.05 ± 0.12 B a	14.58 ± 0.13 B b	15.29 ± 0.20 AB a	13.56 ± 0.06 B b	14.22 ± 0.06 AB a
	7.5	15.49 ± 0.11 A b	16.28 ± 0.17 A a	15.63 ± 0.36 A a	16.15 ± 0.42 A a	13.77 ± 0.05 B b	14.56 ± 0.25 A a
	9.0	13.87 ± 0.03 B b	14.22 ± 0.09 B a	14.68 ± 0.27 B a	15.09 ± 0.32 B a	13.38 ± 0.16 B a	13.77 ± 0.05 C a
WQ	4.5	13.55 ± 0.07 B b	13.87 ± 0.08 AB a	13.39 ± 0.12 B a	13.55 ± 0.16 B a	13.34 ± 0.05 C b	13.60 ± 0.04 B a
	6.0	14.01 ± 0.11 A a	14.09 ± 0.12 A a	13.72 ± 0.20 AB a	13.89 ± 0.20 B a	14.13 ± 0.18 A a	14.17 ± 0.17 AB a
	7.5	13.70 ± 0.06 B a	13.93 ± 0.06 A a	13.93 ± 0.08 A b	14.47 ± 0.17 A a	13.85 ± 0.13 AB b	14.28 ± 0.07 A a
	9.0	13.50 ± 0.11 B a	13.56 ± 0.11 B a	13.51 ± 0.07 AB b	14.08 ± 0.13 AB a	13.46 ± 0.05 BC a	13.63 ± 0.20 B a

Same capital letters indicate no significant difference between plant densities within same year at *a* =0.05. Same small letters indicate no significance between DHEAP treatments in same year, plant density, cultivar and location at *a* =0.05. The mean and standard error are reported
CP, Changping; WQ, Wuqiao

Table 5: Fresh grain yield (ton ha^{-1}) of waxy maize affected by cultivar, plant density (plants m^{-2}) and plant growth regulator (DHEAP) at the two locations

Location	Plant density	Cultivar					
		JHN2008		JKN2000		JKN928	
		No DHEAP	DHEAP	No DHEAP	DHEAP	No DHEAP	DHEAP
CP	4.5	9.18 ± 0.02 B b	9.68 ± 0.04 AB a	9.69 ± 0.07 A b	9.95 ± 0.08 AB a	9.05 ± 0.04 B b	9.50 ± 0.11 B a
	6.0	9.54 ± 0.17 A a	9.93 ± 0.13 A a	9.88 ± 0.13 A b	10.44 ± 0.14 A a	9.84 ± 0.07 A b	10.21 ± 0.11A a
	7.5	9.19 ± 0.06 B b	9.52 ± 0.05 BC a	9.57 ± 0.22 AB a	9.81 ± 0.27 B a	9.23 ± 0.12 B a	9.59 ± 0.09 B a
	9.0	9.07 ± 0.03 B a	9.35 ± 0.11 C a	9.17 ± 0.09 B a	9.22 ± 0.11 C a	9.03 ± 0.07 B b	9.32 ± 0.05 B a
WQ	4.5	8.98 ± 0.04 B b	9.25 ± 0.06 A a	9.27 ± 0.03 AB a	9.26 ± 0.09 B a	8.99 ± 0.12 BC b	9.59 ± 0.07 AB a
	6.0	9.27 ± 0.06 A b	9.44 ± 0.03 A a	9.40 ± 0.05 A b	9.64 ± 0.06 A a	9.19 ± 0.06 AB b	9.94 ± 0.09 A a
	7.5	8.83 ± 0.12 B a	8.90 ± 0.11 B a	9.17 ± 0.02 AB b	9.35 ± 0.04 B a	9.4 ± 0.13 A a	9.69 ± 0.15 AB a
	9.0	8.55 ± 0.09 C a	8.66 ± 0.12 B a	9.01 ± 0.15 B a	9.28 ± 0.11 B a	8.78 ± 0.09 C b	9.32 ± 0.1 B a

Same capital letters indicate no significant difference between plant densities within same year at *a* =0.05. Same small letters indicate no significance between DHEAP treatments in same year, plant density, cultivar and location at *a* =0.05. The mean and standard error are reported
CP, Changping; WQ, Wuqiao

Yield Components

Plant density and DHEAP, rather than location or cultivar, has significant effects on ear density (P < 0.01). The increase of ear density showed a linear relationship with the increase of plant density. Although neither plant density nor cultivar showed significant interaction with DHEAP treatment, the two factors showed significant interactions (P < 0.01) (Table 3).

DHEAP, location, cultivar and plant density showed significant effects on thousand-kernel weight (P < 0.01) (Table 2). Although the thousand-kernel weight showed a significant increase after DHEAP treatment (P < 0.01), there was no interaction between DHEAP treatment and other factors (Table 3). The decrease of thousand-kernel weight showed a linear relationship with the increase in plant density across both locations and all cultivars (Fig. 1). The interaction among the four factors was significant (P < 0.01).

The fixed factors also have significant effects on kernel number per ear (P < 0.01) (Table 3). This parameter showed a significant increase (P < 0.01) after DHEAP application, but was significantly decreased by an increase in plant density (P < 0.01) across all cultivars and both locations (Fig. 2). Interactions between DHEAP and other factors were not significantly different, but showed significance in terms of plant density × cultivar (P < 0.01) (Table 3).

Lodging

The fixed factors also significantly affect lodging percentage (Table 3). The mean lodging percentage across cultivars and over all plant densities was higher in Wuqiao (4.91%) than that in Changping (3.53%). This result might be due to increased wind speed during the latter part of the crop season (Table 1). The average lodging percentage across both locations was higher for JHN 2008 (6.31%) than for JKN 2000 (3.55%) and JKN 928 (2.79%) (Fig. 5), which was mainly attributable to plant type (Table 1). There was a significant increase in lodging for all cultivars induced by plant density, whereas lodging percentage showed a significant decrease (48.92%) after DHEAP treatment. However, in terms of averaged plant densities and cultivars, JHN 2008 showed the highest effect by DHEAP treatment (Fig. 3), which indicates that flat-type tall plants are more susceptible to lodging. When the lodging percentage was higher than 5%, the lodging could largely be reduced by applying DHEAP, particularly at high plant density; however, compared with crops with low lodging percentage, the effect on increasing maize yield was considerably smaller. Significant interactions include DHEAP × plant density (P < 0.01), DHEAP × cultivar (P < 0.01), plant density × cultivar (P < 0.01) and among all the four fixed factors (P < 0.01).

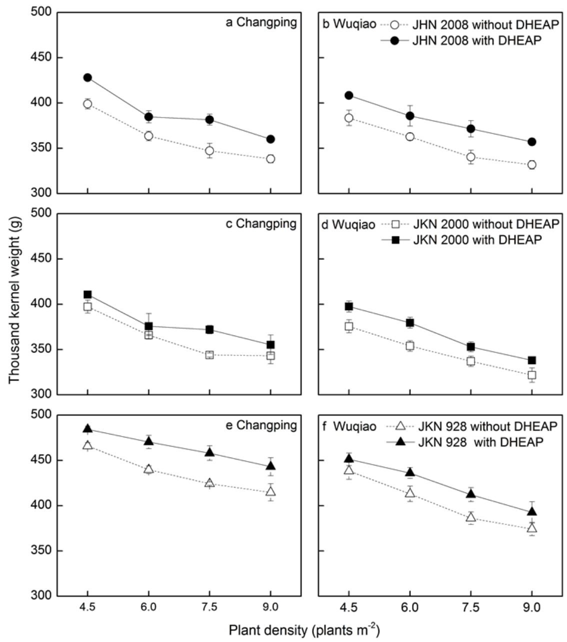

Fig. 1: The effects of DHEAP on the thousand-grain weight of three maize cultivars planted at four densities in two locations

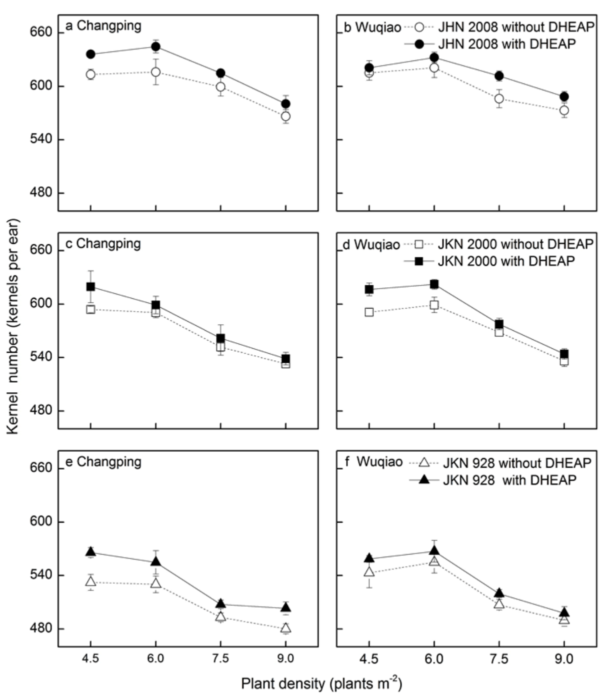

Fig. 2: The effects of DHEAP on kernel number per ear of three maize cultivars planted at four densities in two locations

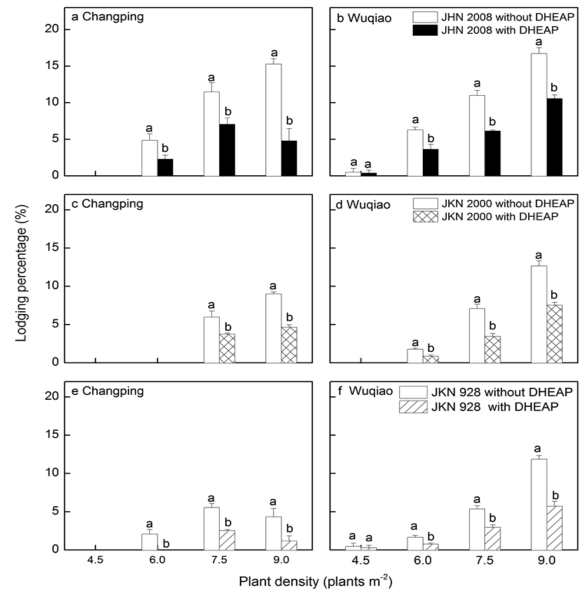

Fig. 3: The effects of cultivar, location, DHEAP treatment and plant density on lodging percentage. The same lower-case letter indicates no significant difference between DHEAP treatments for each combination of location and plant density

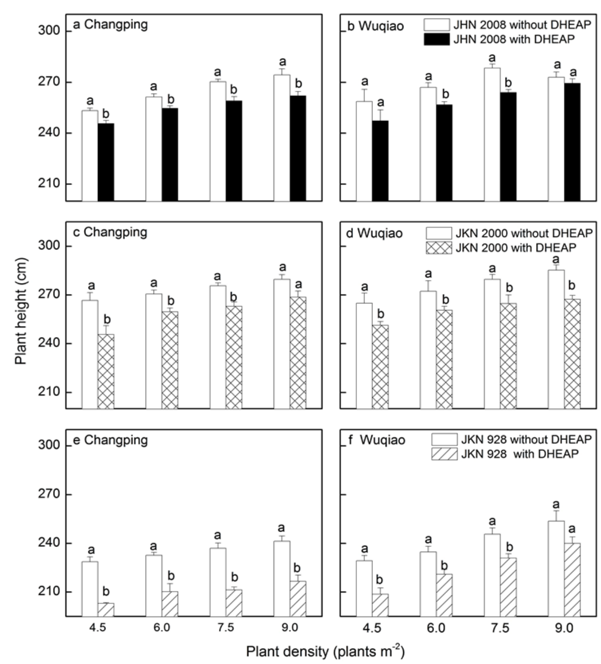

Fig. 4: The effects of cultivar, location, plant density, and DHEAP treatment on maize plant height. The same lower-case letter indicates no significant difference between DHEAP treatments for each combination of location and plant density

Plant and Ear Height

The fixed factors also significantly affect plant height (Table 3). Plant density increased plant height (Fig. 4), with that of JKN 2000 (268 cm) being significantly higher than that of JHN 2008 (261 cm) and JKN 928 (228 cm), across all plant densities and in both locations. Plant height showed a significant ($P < 0.01$) decrease across all plant densities and

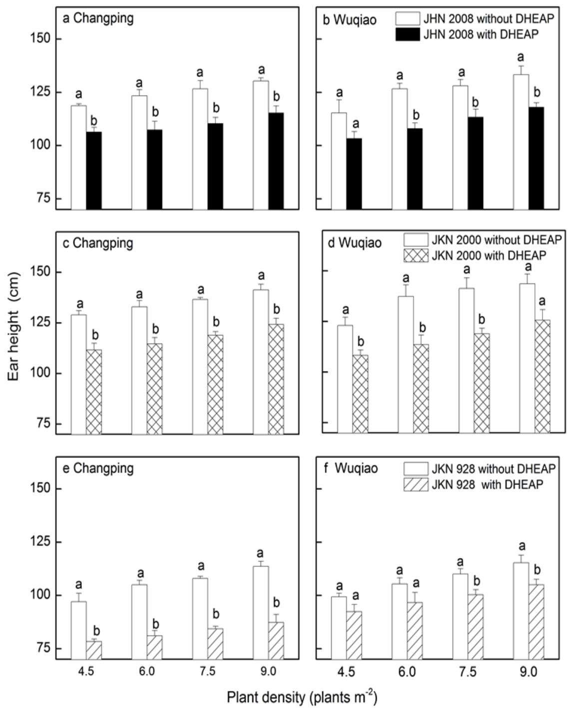

Fig. 5: The effects of cultivar, location, plant density, and DHEAP treatment on the maize ear height. The same lower-case letter indicates no significant difference between DHEAP treatments for each combination of location and plant density

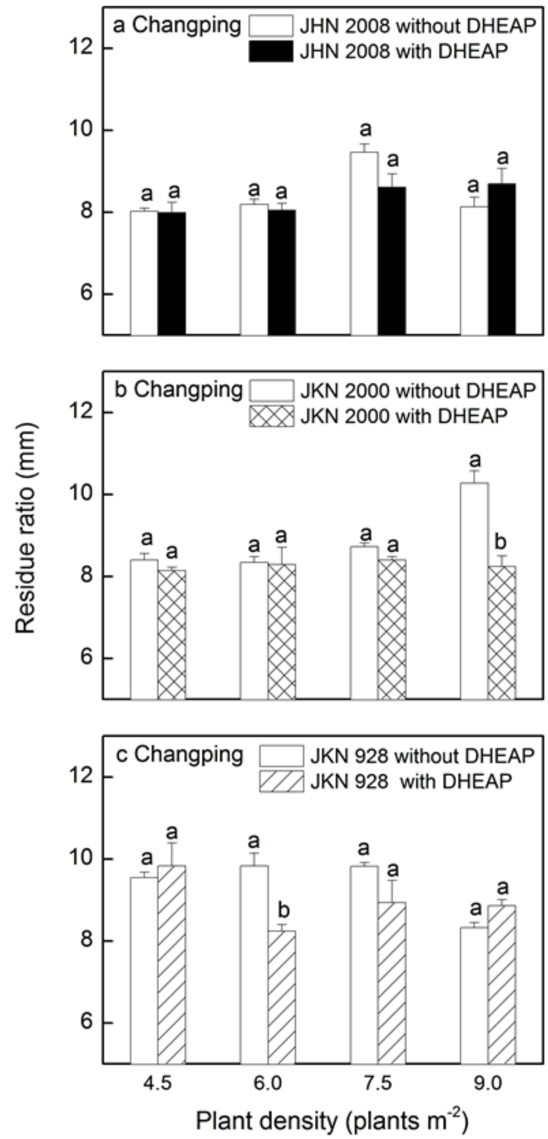

Fig. 6: The effects of cultivar, location, plant density, and DHEAP treatment on the residue ratio of maize. The same lower-case letter indicates no significant difference between DHEAP treatments for each combination of location and plant density

cultivars after DHEAP application, and showed a significant interaction with cultivar ($P < 0.01$) (Table 2).

DHEAP, location, plant density and cultivar, also significantly affects ear height (Table 3). JKN 928 had a significantly lower ear height (98 cm) than JKN 2000 (126 cm) and JKN 928 (118 cm) (Fig. 5). After DHEAP application, ear height was significantly decreased ($P < 0.01$) and ear position was lowered in JKN 2000 when the plant density was low.

Residue Ratio

Cultivar and plant density also significantly affected the residue ratio, whereas DHEAP application didn't (Table 3). Plant density significantly increased residue ratio (Fig. 6), particularly among the tall cultivars JKN 2000 and JHN 2008. Across all treatments, the residue ratio of JKN 928 (9.17%) was significantly higher than that of JHN 2008 (8.39%) and JKN 2000 (8.64%). Significant interactions were shown for plant density with DHEAP treatment ($P < 0.05$) and with cultivar ($P < 0.01$). There was also significant cultivar × DHEAP × plant density interaction ($P < 0.01$) (Table 2).

Discussion

Compared to traditional enhancement of grain yield in maize hybrids, which is measured per plant, an increase in optimal plant density has greatly enhanced grain yield per unit area (Tokatlidis and Koutroubas, 2004; Tokatlidis, 2013; Liu *et al.*, 2013), therefore, we speculate that fresh maize yield has a similar increase in optimal plant density. However, the percentage lodging increases from 6% to 18% as a result of increased plant density, which results in variability among plants and higher potential for maize yield loss at harvest (Stanger and Lauer, 2007). Application of DHEAP can effectively reduce this negative effect, particularly at high plant density (Zhang *et al.*, 2014, 2017). As shown in our study, DHEAP treatment increased the optimal density for fresh maize from 4.5 to 7.5 plants m^{-2}, and at the latter plant density the fresh ear yield was increased by 3.52% on average across the two experimental locations. In contrast, DHEAP treatment increased the optimal density for fresh grain yield to 6.0 plants m^{-2}, and fresh grain yield was increased by 4.21% on average across the two experimental locations. Further, the optimal plant density for greater fresh ear yield in waxy maize was higher than that for fresh grain yield, largely because fresh ear weight consists of waxy maize kernel and cob. Taking commercial value into consideration, waxy maize fresh ear and grain yields could be optimized by applying DHEAP before blooming, with plant density further increased to 7.5 plants m^{-2}.

Residue ratio has been shown to be affected by the cultivar, DHEAP application and plant density, and is positively related to plant density (Zhang, 2008). In the present study, there were significant interactions between cultivar (G) and managements (M, *e.g*., plant density & DHEAP) for residue ratio in waxy maize. The interactions with genotypes may related to ear height and compact plant structure. In depth study on the mechanism of plant morphology structure, *e.g.*, plant height, ear height, and radiation responses in residue ratio between cultivar, DHEAP and plant density in waxy maize.

Application of DHEAP significantly increased waxy maize fresh ear (3.16%) and grain yield (3.47%). The yield increase ascribed to DHEAP treatment was principally attributable to a decrease of lodging by 48.92% as a consequence of reduced plant and ear height, which resulted in significant increases in thousand-kernel weight by 6.10%, and kernel number per ear 3.21%, respectively. The positive effect of DHEAP on waxy maize can probably be caused by reduced lodging due to the function of ethephon and also the promotion of crop growth due to the function of DA-6 (Zhang *et al*., 2014, 2017). Ethephon inhibited internode elongation of maize stalks and promoted stem thickness, thus enhancing resistance to lodging in maize as plant height is lowered and ear position goes down (Norberg *et al*., 1988; Rajala, 2004). The effects of ethephon have been shown to be more beneficial in terms of grain yield at higher plant densities and under water stress conditions (Shekoofa and Emam, 2008). The effects of DHEAP on maize morphological traits (ear position and plant height) observed in the present study indicated that the positive function of ethephon has been retained in the new synthetic DHEAP.

Reducing lodging can increase kernel weight (Zhang *et al*., 2014) and the increase in kernel weight attained with DHEAP treatment might be a result of reducing lodging; however, an increase in kernel number, which is determined prior to the application of DHEAP, is probably due to the promotion of crop growth by the DA-6 function of DHEAP. Application of DA-6 has previously been shown to increase yield by 8.01%–10.1%, as the enhanced leaf antioxidant defense system increased kernel numbers and thousand-kernel weight (Nie *et al*., 2010). DA-6 contributes to increase in contents of chlorophyll, proteins, and nucleic acids and accelerates plant photosynthetic activity (Jiang *et al*., 2012). The significant effects of DHEAP on maize morphological traits, lodging, and yield indicated that this new synthetic plant growth regulator retains the positive effects of both ethephon and DA-6, while minimizing the negative effects of these two chemicals, *e.g*., yield decreases resulting from the suppression of crop growth by ethephon and excessive promotion of vegetative growth by DA-6. However, the physiological mechanisms by which this new chemical functions need to be more comprehensively assessed in field experiments.

New maize cultivar yields have risen at high plant densities owing to the cultivation of new varieties in which plant height has remained essentially unchanged, but for which ear height has shown a weak trend for light capture (Duvick, 2005; Tokatlidis, 2013). In China, scientists have slightly increased plant height and decreased ear height for maize hybrids, so that closer planting is enhanced (Ma *et al*., 2014a, b). In this study, DHEAP significantly reduced plant and ear height, and the semi-compact short plant cultivar JKN 928 performed considerably better in terms of increases in optimal plant density and yield, despite of its lowest ear height. This can probably be attributed to the low ear position, which contributes to better balance and stability of the centre of gravity and the higher rind penetration strength of maize plants, thereby reducing lodging and enhancing grain yield (Ma *et al*., 2014b; Xu *et al*., 2017).

Variability in maize yield is highly related to the diversity of genotypes, management (*e.g*., higher plant density) and environmental factors (Ndhlela *et al*., 2014; Qin *et al*., 2016; Shuai *et al*., 2016; Trachsel *et al*., 2016). Therefore, interactions among location, genotype and plant density give rise to the importance of managing crops based on hybrid characteristics and location (Esechie *et al*., 2004; Shekoofa and Emam, 2008; Ma *et al*., 2014a). Nonetheless, high variability in yield potential and management (*e.g*., higher plant density) across environments (locations and/or years) makes it more difficult to predict the best-fit plant population and to apply appropriate field cropping practices (Tollenaar and Lee, 2002; Tokatlidis, 2013; Lindsey *et al*., 2015). Because of the environmental factors might attribute to precipitation, wind speed or radiation, and also related to varietal characteristic, *e.g*., plant morphology structure, canopy transmittance (Remison and Akinleye, 1978; Xue *et al*., 2016). Spraying DHEAP can play an important role as a new technological measure in agronomical field management for enhancing the stability of high yield and stress tolerance in waxy maize at high plant densities. In the present study, we observed significant interactions among cultivar, DHEAP, plant density, and location for waxy maize yield and lodging percentage ($P < 0.01$), which constitutes important information for waxy maize management, for example, the optimization of plant density, and selection of semi-compact and short plant waxy maize cultivars.

Conclusion

In general, the application of DHEAP significantly reduced waxy maize lodging and increased grain yield. As a new synthetic plant growth regulator, DHEAP not only enhances waxy maize yield by increasing lodging resistance but is also an environmental friendly technology in maize cultivation because of its safety in use and low cost. Our results will assist farmers with regards to optimizing plant density, plant growth regulator and cultivar in waxy maize cultivation.

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