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Response of grain yield to plant density and nitrogen rate in spring maize hybrids released from 1970 to 2010 in Northeast China

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The objective of this study was to identify the response of grain yield to plant density and nitrogen rate in spring maize hybrids released from 1970 to 2010 and grown extensively in Northeast China. Twenty-one hybrids were grown for 2 years in Northeast China at densities of 30,000, 52,500, 75,000, and 97,500 plants ha^{-1} and N application levels of 0, 150, 300, and 450 kg N ha^{-1}. Irrespective of density or nitrogen application rate, grain yields both per plant and per unit area were significantly higher for newer than older hybrids. As plant density increased from 30,000 to 97,500 plant ha^{-1}, yield per plant of 1970s, 1980s, 1990s, and 2000s hybrids decreased by 50%, 45%, 46%, and 52%, respectively. The response of grain yield per unit area to plant density was curvilinear. The estimated optimum plant densities were about 58,000, 49,000, 65,000, and 65,000 plants ha^{-1} for hybrids released in the 1970s, 1980s, 1990s, and 2000s, respectively. The theoretical optimum densities for the hybrids released from the 1970s to the 2000s increased by 1750 plants ha^{-1} $decade^{-1}$. Nitrogen fertilization significantly increased grain yields per plant and per unit area for all hybrids. The theoretical optimum N application rates for high yield for hybrids released in the 1970s and 1980s were about 280 and 360 kg ha^{-1}, and the hybrids from the 1990s and 2000s showed highest yield at 330 kg ha^{-1} N. No significant difference in the grain yields of 2000s hybrids between the N levels of 150 to 450 kg ha^{-1} was found. Significant yield gains per plant and per unit area were found, with average increases of 17.9 g $plant^{-1}$ $decade^{-1}$ and 936 kg ha^{-1} $decade^{-1}$ over the period 1970–2010, respectively. Yield gains were attributed mainly to increased yield per plant, contributed by increases in kernel number per ear and 1000-kernel weight. The rates of lodging and barren plants of newer hybrids were significantly lower than those of older ones, especially at high plant density.

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1. Introduction

Globally, maize (*Zea mays* L.) yield and total production increased by 168.5% and 311.8% during the period 1961–2010 [1]. The yield gain can be attributed mainly to variety improvement and cropping technique innovations, such as increases in plant density and fertilizer application [2]. Cardwell [3] reported that increased plant density contributed 21% of the gain in maize yield in Minnesota from 1930 to 1970. Wu et al. [4] stated that fertilizer inputs contributed 50% of the gain in maize yield in China during the period 1985–1994. Thus, the yield superiority of newer over older varieties is attributed to their productivity improvement and their better adaptation to changes in cropping techniques, such as dense cropping and nitrogen (N) fertilization [2,5]. Characterizing trends in yield change and response to plant density and N application among maize hybrids released in different eras can guide future breeding of new varieties and cropping technique innovation [6,7].

Many experiments have been conducted to study the changes in maize hybrids during the past decades [8–11]. Most have focused on changes in plant productivity and morphological characteristics among different eras [12–14], and have greatly advanced our understanding of the improvement potential of maize hybrid productivity and accelerated the progress of new variety breeding [15–17]. With respect to response to density and N rate, some studies have confirmed that older hybrids gave their highest yields at lower densities typical of their era of release, whereas newer hybrids yielded most at higher densities typical of recent years [2,18–20]. N application rates with the highest yields were lower for newer than for older hybrids [21] and older hybrids were more sensitive than newer ones to low soil N [22,23]. However, fewer studies have focused on plant density × N rate × decade interaction. Moreover, most previous studies have been conducted in the European and American continents, with few conducted in Asia. Although it is well known that increased plant density and N application have contributed much to the yield gains of maize hybrids during the past eras [2,21,24], this knowledge is not well documented. It is desirable to investigate further the response of grain yield to plant density and N application in maize hybrids released from different eras, especially in Asia.

Northeast China is the major maize cropping area in Asia and accounts for more than one third of the total maize-sown area in China. Approximately 1200 maize cultivars were released during the period 1970–2010; however, few studies of the change of these cultivars, especially with respect to their responses to plant density and N application under field conditions, have been performed. This lack of knowledge hinders the progress of new variety breeding and cropping technique innovation in Northeast China. We accordingly conducted a field experiment to investigate the responses of grain yield, morphological characteristics, and yield components to plant density and N application, using 21 leading hybrids released during 1970–2010 in Northeast China.

2. Materials and methods

2.1. Study site

This study was conducted in three locations: Shuangcheng (45°25′ N, 126°24′ E), Heilongjiang province; Liuhe (42°05′ N, 125°50′ E), Jilin province; and Tai'an (41°24′ N, 122°26′ E), Liaoning province, China in 2009 and 2010. The rainfall and mean daily air temperature during the growing season in 2009 and 2010 and the soil chemical characteristics at the experimental sites are described in Tables 1 and 2.

2.2. Plant materials and experimental design

Twenty-one maize hybrids, spanning four decades from the 1970s to 2000s and representing the most popular hybrids of their time in the main maize-growing areas in Northeast China, were used. All tested cultivars were the top 10 cultivars in their era of approval with a sown area of more than one million hectares per year in each province. All the parental seeds of the tested hybrids except for those of the 2000s were obtained from the State Bank of Crop Germplasm Sources in Chinese Academy of Agricultural Sciences, China. The seeds of hybrids from the 1970s to 1990s were reproduced hybridization of their parents in Shanya city, Hainan province, China in 2008 and 2009, respectively. The seeds of the 2000s hybrids were purchased from local seed companies. Detailed information about the hybrids tested at each experimental site is presented in Table 3.

Three treatments (hybrid variety, plant density, and N application rate) with three replicates were applied. In view of the changes in plant density and N application adopted by farmers during 1970–2010 in Northeast China, eight hybrids (Table 3) with three densities (30,000, 52,500, and 75,000 plants ha^{-1}) and three N application rates (0, 150, and 300 kg ha^{-1}) were assigned to each experimental site in 2009. Based on the results in 2009 and considering the density and N rate used in yield contests, a density (97,500 plants ha^{-1}) and N application rate (450 kg ha^{-1}) were added in 2010. The plots were arranged in a split-split design, in which plant density was the main plot, N treatment the split plot, and the hybrid variety the sub-split plot. Each sub-split plot comprised five rows 5 m in length.

Total fertilizer P_2O_5, K_2O and one third of N were applied pre-planting and the remaining N (as urea) was applied at the six-leaf collar stage [25] based on each treatment's

Table 1 – Growing season rainfall and mean daily air temperature in 2009 and 2010 at study sites.

Experimental site	Precipitation (mm)		Mean daily air temperature (°C)	
	2009	2010	2009	2010
Shuangcheng	403.3	371	18.9	21.4
Liuhe	328.9	817	18.8	20.1
Tai'an	323.5	635.9	21.1	21.5

Table 2 – Soil chemical characteristics at the experimental sites.

Experimental site	SOM[†] (g kg^{-1})	Total N (g kg^{-1})	Total P (g kg^{-1})	Total K (g kg^{-1})	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	pH
Shuangcheng	32.36	2.03	1.39	23.06	129.5	32.3	219.2	6.89
Liuhe	31.50	2.28	2.23	20.02	327.6	202.8	177.9	4.63
Tai'an	19.37	1.35	1.46	24.20	87.5	266.9	1014.8	5.69

† SOM, soil organic matter.

requirement. Hybrid seeds were sown on April 26, May 2 and 15 in 2009, and May 18, 20, and 24 in 2010 at the experimental sites of Shuangcheng, Liuhe, and Tai'an, respectively. Subplots were hand-planted with three seeds per hill and thinned to one plant per hill for the desired density at V3 [25]. Other agronomic practices were similar to the local cropping techniques for high yield.

2.3. Plant sampling and measurements

Prior to silking, three randomly selected plants of the second row were tagged. At silking (when silks had emerged for 60% of plants within a subplot), plant and ear height and the area of all green leaves were measured on these three tagged plants. Leaf area was calculated as lamina length × maximum width × 0.75. Stalk lodging and barrenness were assessed on the day when each hybrid was harvested. Plants were considered barren when they did not present a visible ear or produced a rudimentary female inflorescence with fewer than 10 kernels [6]. At physiological maturity, rows 3 and 4 of each subplot were hand-harvested for grain yield corrected to a 140 g kg^{-1} water basis. Three plants were measured for dry matter production and harvest index. Kernels per plant were counted for five plants and kernel weight per plant was recorded.

2.4. Statistical analysis

Statistical analyses were performed for the split-split plot arrangement for data combined from three sites and each year was analyzed separately. Means of the three sites were used for three-way ANOVA analysis and LSD multiple

Table 3 – Hybrids used in the present study at three experimental sites.

Experimental site	Hybrid	Pedigree	Breeding institute	Year of release	Decade approved
Shuangcheng, Heilongjiang	Longdan 1	Dian 11 × Bup 44	HLJAAS	1978	1970s
	Nendan 3	Dian 11 × Zaodahuang	HLJAAS	1975	1970s
	Nendan 4	Dian 11 × 7010	HLJAAS	1982	1980s
	Longdan 5	Dian 11 A × Red corn	HLJAAS	1984	1980s
	Dongnong 428	Dong 46 × Dong 237	Northeast Agricultural University	1987	1990s
	Sidan 19	444 × Mo17	SPAAS	1992	1990s
	Xingken 3	167–1 × improved Mo17	Xingan Agricultural Seed Co., Ltd.	2002	2000s
	Jidan 27	Si 287 × Si144	SPAAS	2002	2000s
Liuhe, Jilin	Danyu 6	Lv 28 × Zi 330	DDAAS	1979	1970s
	Sidan 10	Xi 14 × Ji 63	SPAAS	1980	1970s
	Danyu 13	$MO17^{Ht}$ × E28	DDAAS	1985	1980s
	Tiedan 4	Ji 63 × Zi 330	TLAAS	1981	1980s
	Jidan 180	Ji 853 × Mo17	JLAAS	1995	1990s
	Sidan 19	444 × Mo17	SPAAS	1992	1990s
	Jidan 261	W9706 × Ji 853	Jinong High-tech Development Co., Ltd.	2004	2000s
	Xianyu 335	PH6WC × PH4CV	Pioneer Co., Ltd.	2005	2000s
Tai'an, Liaoning	Danyu 6	Lv 28 × Zi 330	DDAAS	1979	1970s
	Danyu 9	334–1 × Lv28	DDAAS	1975	1970s
	Danyu 13	$MO17^{Ht}$ × E28	DDAAS	1985	1980s
	Shendan 7	5003 × E28	SYAAS	1988	1980s
	Tiedan 10	C8605 × Dan 340	TLAAS	1994	1990s
	Yedan 13	Ye 478 × Dan340	LZAAS	1994	1990s
	Danyu 39	C8605–2 × Dan598	DDAAS	2001	2000s
	Zhengdan 958	Zheng 58 × Chang 7–2	HNAAS	2005	2000s

HLJAAS, Heilongjiang Academy of Agricultural Sciences. SPAAS, Siping Academy of Agricultural Sciences in Jilin Province. DDAAS, Dandong Academy of Agricultural Sciences in Liaoning Province. TLAAS, Tieling Academy of Agricultural Sciences in Liaoning Province. SYAAS, Shenyang Academy of Agricultural Sciences in Liaoning Province. JLAAS, Jilin Academy of Agricultural Sciences. LZAAS, Laizhou Academy of Agricultural Sciences in Shandong Province. HNAAS, Henan Academy of Agricultural Sciences.

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comparison using SPSS 11.5. Sums of squares for cultivars and interactions involving cultivars were partitioned among eras.

3. Results and discussion

3.1. *Response of grain yield to plant density*

Similar trends of grain yield were found in the experimental years 2009 and 2010, and grain yields both per plant and per unit area of the hybrids at different plant densities in the 2010 experiment are presented in Fig. 1. Grain yield per plant decreased significantly with increase in plant density, and as plant density increased from 30,000 to 97,500 plant ha^{-1}, the per plant yields of the 1970s, 1980s, 1990s, and 2000s decreased by 50%, 45%, 46%, and 52%, respectively (Fig. 1-a). The decreasing trend of per plant yield with increasing density in each decade was in accord with the results of Niu et al. [26]. Irrespective of density, grain yields both per plant and per unit area of newer hybrids were significantly higher than those of older ones (Fig. 1 and Table 4), in agreement with results of experiments conducted in China by Ci et al. [27] and Niu et al. [26]. The response of grain yield per unit area to plant density differed for all the tested hybrids (Fig. 1-b). The grain yields of hybrids released in the 1980s and 1990s did not differ at the planting density of 30,000 plants ha^{-1}; however, with increasing density, the yield difference between them expanded significantly. According to the response to planting density, the hybrids from the four decades could be divided into two groups: the 1970s and the 1980s into a group that was intolerant of dense planting and the 1990s and the 2000s into a group that was adapted to dense planting. The newer hybrids showed clear increases in tolerance of dense planting.

According to the parabolic relationships, estimated optimum plant densities were about 58,000, 49,000, 65,000, and 65,000 plants ha^{-1} for hybrids released in Northeast China in the 1970s, 1980s, 1990s, and 2000s, respectively. The estimated ideal densities are greater than the planting densities actually used by farmers in Northeast China, ranging from 30,000 to 52,500 plants ha^{-1}, but they are still lower than the ideal densities of hybrids released in Brazil during the 1970s, 1980s, and 1990s, which were about 71,000, 79,000, and 85,000 plants ha^{-1}, respectively [6]. The estimated optimum densities in the present study are also significantly lower than the present planting density in U.S., which averages about 80,000 plants ha^{-1} [17]. During the past 50 years, maize plant density in the central U.S. corn belt has increased at an average rate of about 1000 plants ha^{-1} year^{-1} [2]. However, based on our study, the estimated optimum density for the hybrids released in Northeast China has increased by only 175 plants ha^{-1} year^{-1} from 1970 to 2010. Thus, in comparison with other countries, there is still a substantial margin for increasing corn yield by increasing plant density in Northeast China by improving tolerance to dense cropping [6].

3.2. *Responses of grain yield to nitrogen application*

Nitrogen fertilization significantly increased grain yield per plant and per unit area for all hybrids. Irrespective of N application rate, newer hybrids outyielded older ones (Fig. 2, Table 4), suggesting that modern hybrids have higher resource use efficiency than older ones [28,30]. Without nitrogen application, the grain yield per hectare of hybrids released in the 2000s was superior to those of the hybrids from the other three decades, indicating that the 2000s hybrids could tolerate infertile soil. As applied nitrogen increased from 0 to 150 kg ha^{-1}, the mean yield of hybrids released in the 1970s, 1980s, 1990s, and 2000s increased by 15.20%, 19.37%, 26.54%, and 19.29%, respectively. As nitrogen application increased from 150 to 300 kg ha^{-1}, yields increased by 7.07%, 2.74%, 6.65%, and 1.78%, respectively. When nitrogen application increased from 300 to 450 kg ha^{-1}, the yields of hybrids released in the 1980s and 2000s increased by 3.81% and 0.16%, respectively, but the yields of hybrids released in the 1970s and 1990s decreased by 6.80% and 2.85%, respectively. According to the relationship between grain yield per unit area and N application rate, the theoretical optimal fertilization rates for the highest yield were 280, 360, 330, and

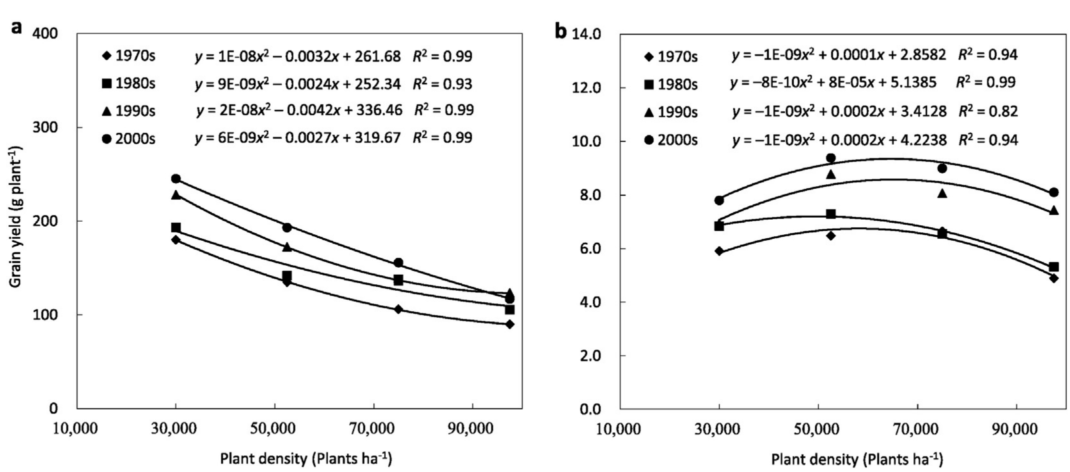

Fig. 1 – Responses of grain yields per plant (a) and per unit area (b) to plant density for maize hybrids released in different eras from the 1970s to 2000s. Calculated from means of three locations and four N rates per location in 2010.

Table 4 – *F*-values of ANOVA of yield and agronomic traits for maize hybrids released in different eras from the 1970s to 2000s.

Source of variation	*df*	Grain yield per unit area	Grain yield per plant	Kernel number per ear	Weight of 1000-kernels	Harvest index	Plant height	Ear insertion	Leaf area per plant
2009									
Density (D)	2	**	**	**	**	ns†	ns	**	**
Nitrogen (N)	2	**	**	**	**	*	**	**	**
Era (E)	3	**	**	**	**	ns	**	**	**
D × N	4	**	ns	**	ns	ns	ns	ns	**
E × D	6	*	*	**	ns	ns	ns	ns	ns
E × N	6	ns	ns	ns	ns	ns	ns	ns	ns
E × D × N	12	ns	ns	**	ns	ns	ns	ns	ns
Error	107								
2010									
Density (D)	3	**	**	**	**	**	ns	**	**
Nitrogen (N)	3	**	**	**	**	**	**	**	**
Era (E)	3	**	**	ns	**	ns	**	**	**
D × N	9	ns	*	ns	ns	**	ns	ns	ns
E × D	9	ns	**	**	**	**	ns	**	ns
E × N	9	ns	ns	**	**	**	ns	ns	ns
E × D × N	27	ns	**	ns	ns	**	ns	*	*
Error	191								

* Significant at the 0.05 probability level. ** Significant at the 0.01 probability level. † ns, not significant at the 0.05 probability level.

330 kg N ha^{-1} for hybrids released in the 1970s, 1980s, 1990s, and 2000s, respectively. At present, the practical N application rate used by farmers in Northeast China ranges from 350 to 400 kg ha^{-1}, which is higher than the theoretical optimum N level estimated in this study. During the last decades, commercial N application to maize plantings has stabilized at approximately 145–150 kg ha^{-1} in the United States [31], which is half of the amount presently used in Northeast China. The present study also showed that there were no significant differences in grain yields for hybrids released in the 2000s between fertilization levels of 150 to 450 kg N ha^{-1} (Fig. 2), indicating that further addition of N fertilizer will not confer yield gain in Northeast China. Our results demonstrate that it is possible and necessary to further improve N use efficiency for maize production via breeding and cropping innovation in Northeast China. Future increases in maize yield can be achieved with an unchanged or even reduced N application rate so as to conserve environmental health and reduce production costs [5].

The nitrogen application rate that resulted in the highest and lowest yields of the maize hybrids differed at different planting densities. At 30,000 and 52,500 plants ha^{-1}, the 2000s hybrids showed the highest yields (7421 and 10,780 kg ha^{-1}, respectively) under a nitrogen application of 450 kg ha^{-1}, and the 1970s hybrids showed the lowest yields (5318 and 5804 kg ha^{-1}, respectively) under no nitrogen application. At 75,000 and 97,500 plants ha^{-1}, the 2000s hybrids showed the highest yields (9582 and 9271 kg ha^{-1}) under a nitrogen application of 300 kg ha^{-1}, and the 1980s showed the lowest yield (5858 kg ha^{-1}, at a planting density of 75,000 plants ha^{-1}) with no nitrogen, and the 1970s hybrids showed the lowest yield (4419.53 kg ha^{-1}, at a planting density of 97,500 plants ha^{-1})

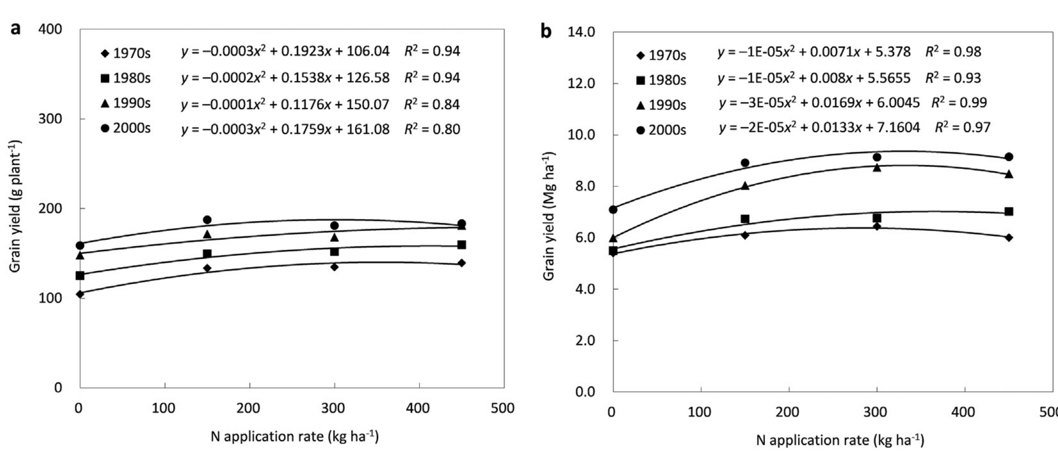

Fig. 2 – Responses of grain yields per plant (a) and per unit area (b) to N application rate for maize hybrids released in different eras from the 1970s to 2000s. Calculated from means of three locations and four densities per location in 2010.

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at the nitrogen rate of 450 kg ha^{-1}. When the effects of hybrids, plant density and nitrogen application on the grain yield were compared, nitrogen application, density and hybrid accounted for 51.78%, 25.21%, and 17.71% of the contributions, respectively.

3.3. Maize yield trends over the period 1970–2010 in Northeast China

Significant yield gains per plant and per unit area were found, with average increases over the period 1970–2010 of 17.9 g plant^{-1} decade^{-1} and 936 kg ha^{-1} decade^{-1}, respectively. Wang et al. [11] also reported that the yield gain of maize hybrids released in China between 1964 and 2001 was 600 kg ha^{-1} decade^{-1}, owing mainly to the increase in grain yield per plant. However, Duvick [20] found that the yield potential per plant did not change over the period from 1930 to 1990 in the U.S.A., although there was a large yield gain per unit area over the eras. Tokatlidis and Koutroubas [28] verified that modern hybrids did not exceed older ones in yield potential per plant. Some studies have shown that modern hybrids lack yield superiority in small plant populations, owing to progress in the U.S.A. in maize breeding at high density [29]. Our results indicate that there are great differences in maize breeding strategies between China and other countries. Chinese breeding scientists have invested more effort in increasing maize yield per plant than in tolerance to dense cropping. However, maize breeders in other countries, such as on the American and European continents, have focused on population productivity because of the requirements of mechanized cropping and the new objectives of high yield and high resource use efficiency [28,30]. At present, similar development trends of mechanized dense cropping and higher yield with higher efficiency are occurring in China, especially in the northeastern maize cropping areas. Increasing maize resistance to dense cropping without changing grain yield per plant will be the future breeding strategy in Northeast China.

3.4. Rates of lodging and barren plants

Both lodging and barren plant rates increased significantly with increasing plant density for all hybrids from different eras (Table 5). Lodging and barren plants represent two of the most serious constraints to dense planting of maize worldwide [32]. Our results showed that lodging and barren plant rates of the newer hybrids were significantly lower than those of the older ones, especially at high plant density ($P < 0.05$). Sangoi et al. [6] also reported that stands above 50,000 plants ha^{-1} showed greater lodging and more barrenness in older hybrids than in newer ones. There were no significant effects of N application on the rates of lodging and barren plants (Table 5). Our results indicate that resistance to lodging and barrenness has improved significantly in the series of hybrids grown in Northeast China from the 1970s to the 2000s.

3.5. Morphological characteristics and yield components

There was no clear trend in plant height with increasing plant population density, whereas ear height increased significantly (Table 6). The increases in ear height were 1.76, 1.45, 1.67, and 2.74 cm per 10,000 additional plants ha^{-1} for hybrids released in the 1970s, 1980s, 1990s, and 2000s, respectively, leading to an upward trend in plant center of gravity. Plant and ear height increased by approximately 5.5 and 4.5 cm decade^{-1}, respectively, on average for all the hybrids over the period 1970–2010 (Tables 6 and 7). A previous study indicated that plant height of hybrids adapted to central Iowa remained unchanged over years but that ear height showed a weak decreasing trend of approximately 3 cm decade^{-1} from 1930 to

Table 5 – Responses of lodging and barren plant rates to plant density and N application rate for maize hybrids released in different eras over the 1970s–2000s.

Era	Plant density			N application rate		
	Plant density (plants ha^{-1})	Lodging plant rate (%)	Barren plant rate (%)	N application rate (kg ha^{-1})	Lodging plant rate (%)	Barren plant rate (%)
1970s	30,000	0 d †	6.0 d	0	18.6 b	17.6 d
	52,500	4.2 c	13.1 c	150	16.7 c	24.0 a
	75,000	26.0 b	16.4 b	300	15.9 d	18.1 c
	97,500	44.1 a	44.4 a	450	22.8 a	20.1 a
1980s	30,000	0.3 d	10.0 d	0	20.7 a	28.3 c
	52,500	4.2 c	21.9 c	150	5.6 c	29.9 b
	75,000	13.9 b	31.0 b	300	9.8 b	30.2 a
	97,500	38.7 a	52.9 a	450	20.6 a	26.8 d
1990s	30,000	0 d	5.5 d	0	14.4 b	18.9 c
	52,500	0 c	15.8 c	150	2.0 d	17.0 d
	75,000	16.7 b	28.2 b	300	10.6 c	20.1 b
	97,500	29.3 a	29.5 a	450	18.7 a	23.1 a
2000s	30,000	0 a	3.9 d	0	2.8 a	12.8 b
	52,500	0 a	9.9 c	150	2.3 c	12.4 c
	75,000	0 a	16.5 b	300	2.3 c	11.5 d
	97,500	10.0 a	20.6 a	450	2.6 b	14.2 a

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05). Since the rates of lodging plant and barren plant were determined in 2010, data are not available for 2009.

Table 6 – Responses of agronomic traits to plant density for maize hybrids released in different eras over the 1970s–2000s and grown in 2009 and 2010.

Year	Era	Plant density (plants ha^{-1})	Plant height (cm)	Ear insertion (cm)	Ratio of ear insertion to plant height	Leaf area (cm^2)	Kernel number per ear	Weight of 1000 kernels (g)	Harvest index (%)
2009	1970s	30,000	223 a[†]	89 b	0.40 b	6988 a	585 a	264.7 a	49.5 ab
		52,500	229 a	94 a	0.41 ab	6483 b	549 b	253.8 a	51.8 a
		75,000	226 a	94 a	0.42 a	5730 c	494 c	233.7 b	48.0 b
	1980s	30,000	233 a	95 b	0.41 b	8278 a	652 a	302.8 a	50.0 a
		52,500	239 a	102 a	0.42 a	8071 a	578 b	288.5 b	51.7 a
		75,000	235 a	99 ab	0.42 a	7483 b	549 c	282.1 b	50.7 a
	1990s	30,000	260 a	110 b	0.43 a	8134 a	653 a	333.8 a	50.5 a
		52,500	262 a	112 ab	0.43 a	7943 a	626 b	320.6 b	50.3 a
		75,000	264 a	116 a	0.44 a	7431 b	574 c	312.4 b	51.2 a
	2000s	30,000	252 a	107 c	0.43 b	8928 a	694 a	350.2 a	48.9 a
		52,500	260 a	113 b	0.43 b	8164 b	608 b	326.1 b	48.9 a
		75,000	259 a	119 a	0.46 a	8010 b	595 b	328.9 b	49.3 a
2010	1970s	30,000	257 b	104 c	0.41 c	7482 a	601 a	329.1 a	47.3 a
		52,500	259 ab	111 b	0.43 b	6684 b	523 b	295.7 b	46.0 ab
		75,000	265 a	120 a	0.45 a	6246 c	496 c	290.3 b	43.8 bc
		97,500	255 b	119 a	0.46 a	5722 d	452 d	272.6 c	42.4 c
	1980s	30,000	259 a	107 c	0.41 c	7585 a	617 a	357.0 a	46.4 a
		52,500	262 a	111 b	0.42 c	7095 b	542 b	317.1 b	43.4 b
		75,000	261 a	117 a	0.45 b	6484 c	476 c	302.7 bc	42.4 b
		97,500	255 a	120 a	0.47 a	5949 d	466 d	289.3 c	42.7 b
	1990s	30,000	271 ab	115 c	0.42 c	7412 a	605 a	393.3 a	49.1 a
		52,500	276 a	125 b	0.45 b	7005 b	497 b	364.8 b	47.2 ab
		75,000	277 a	132 a	0.48 a	6363 c	507 b	329.4 c	41.6 c
		97,500	266 b	128 ab	0.48 a	5802 d	453 c	326.2 c	42.2 c
	2000s	30,000	270 a	117 c	0.43 c	7932 a	611 a	417.5 a	46.7 a
		52,500	276 a	127 b	0.46 b	7216 b	545 b	366.2 b	46.0 a
		75,000	273 a	133 a	0.49 a	6737 c	502 c	361.2 b	45.8 a
		97,500	272 a	136 a	0.50 a	6216 d	449 d	331.0 c	42.0 b

[†] Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

2001 [17]. Sangoi et al. [6] reported that older hybrids plants were taller and had a higher ear insertion to plant height ratio than newer ones. In the present study, significant increases in 1000-kernel weight (19.6 g $decade^{-1}$) and kernel number per ear (10 kernels $decade^{-1}$) with the year of hybrid release were found (Tables 6 and 7). Tollenaar et al. [33] and Echarte et al. [34] concluded that kernel number contributed most to the yield increase in Canada and Argentina, but no clear trend in kernel weight with year was found [34]. Our results indicate that increases in both kernel weight and number have contributed to yield gain over time in Northeast China, and that there are large differences between Northeast China and other cropping areas in the responses of morphological characteristics and yield components to plant density.

A clear increasing trend in morphological traits was found with increasing N application rate (Table 7). For example, with an increase of N fertilizer by 100 kg ha^{-1}, the kernel number per ear increased by 10, 4, 5, and 13, and 1000-kernel weight increased by 6.32, 5.79, 9.67, and 5.43 g from the 1970s to the 2000s. These findings suggest that added N fertilizer simultaneously increases kernel number and weight.

There were significant differences between Northeast China and other countries with respect to the morphological characteristics and grain components of the hybrids. These differences could be attributed to the difference in breeding strategies. In Northeast China, new hybrids are selected at a low population density of about 45,000 plants ha^{-1}, much lower than those used abroad for selection, with densities greater than 75,000 plants ha^{-1}. Most focus is still on the improvement of morphological traits for higher productivity per plant, rather than to increasing tolerance to high population density.

4. Conclusions

Irrespective of planting density and nitrogen application rate, grain yields both per plant and per unit area of newer hybrids were significantly higher than those of older ones. The theoretical optimum densities for the hybrids released from the 1970s to 2000s increased by 1750 plants ha^{-1} $decade^{-1}$. No significant difference was found in the grain yield for the 2000s hybrids between the N levels of 150 to 450 kg ha^{-1}. Significant yield gains per plant and per unit area were found, with average increases of 17.9 g $plant^{-1}$ $decade^{-1}$ and 936 kg ha^{-1} $decade^{-1}$ over the period 1970–2010, respectively. Yield gains were attributed mainly to the increase of yield per plant, which was contributed by increases in kernel number per ear and 1000-kernel weight. Our results indicate that maize yield in Northeast China can be further increased by dense cropping with an unchanged or even lower N application rate.

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Table 7 – Responses of agronomic traits to nitrogen application level for maize hybrids released in different eras over the 1970s–2000s and grown in 2009 and 2010.

Year	Era	N rate (kg ha^{-1})	Plant height (cm)	Ear insertion (cm)	Ear insertion to plant height ratio	Leaf area (cm^2)	Kernel number per ear	Weight of 1000 kernels (g)	Harvest index (%)
2009	1970s	0	214 b†	88 b	0.41 a	5790 b	519 b	236.0 c	50.5 a
		150	230 a	92 ab	0.40 a	6543 a	551 a	251.1 b	50.2 a
		300	233 a	97 a	0.41 a	6868 a	558 a	265.1 a	48.7 a
	1980s	0	225 b	93 b	0.41 a	7401 b	570 b	280.5 b	52.0 a
		150	240 a	100 a	0.41 a	8125 a	611 a	296.4 a	50.2 a
		300	241 a	103 a	0.43 a	8306 a	598 a	296.4 a	50.1 a
	1990s	0	253 b	106 b	0.42 a	7027 b	599 b	303.9 c	51.4 a
		150	267 a	116 a	0.44 a	8081 a	624 a	324.5 b	49.9 a
		300	266 a	117 a	0.44 a	8401 a	629 a	338.3 a	50.7 a
	2000s	0	245 c	104 b	0.42 b	7531 c	600 b	325.1 b	50.7 a
		150	258 b	116 a	0.45 a	8597 b	649 a	339.7 a	48.1 b
		300	268 a	118 a	0.44 a	8973 a	649 a	340.3 a	48.4 ab
2010	1970s	0	247 c	106 c	0.43 a	6136 b	492 b	292.2 ab	43.9 a
		150	258 b	112 b	0.43 a	6372 b	521 a	289.9 b	46.0 a
		300	264 a	117 a	0.44 a	6680 a	530 a	303.1 a	44.6 a
		450	268 a	118 a	0.44 a	6945 a	528 a	302.5 a	45.1 a
	1980s	0	241 b	107 c	0.44 a	6331 b	527 ab	297.5 c	44.8 a
		150	262 a	113 b	0.43 a	6825 a	508 b	322.1 ab	42.0 b
		300	267 a	118 a	0.44 a	6881 a	544 a	315.8 b	42.3 b
		450	268 a	116 ab	0.43 a	7076 a	522 ab	330.7 a	45.9 a
	1990s	0	256 c	115 b	0.45 a	5969 d	510 ab	330.5 c	45.3 ab
		150	275 b	126 a	0.46 a	6619 c	531 a	352.1 b	44.9 ab
		300	280 a	129 a	0.46 a	6844 b	498 b	365.7 a	43.4 b
		450	279 a	130 a	0.46 a	7149 a	522 a	365.3 a	46.4 a
	2000s	0	256 c	118 c	0.46 b	6610 c	497 b	353.3 c	45.8 ab
		150	272 b	128 b	0.47 b	6968 b	526 a	371.6 b	46.5 a
		300	279 a	135 a	0.49 a	7214 ab	540 a	367.5 b	43.9 b
		450	283 a	132 b	0.47 b	7310 a	545 a	383.5 a	44.3 b

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

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REFERENCES

[1] Food and Agricultural Organization of the United Nations, FAO statistical databases[Online]. Available at: http://faostat.fao.org (accessed: 23 Feb. 2012).
[2] D.N. Duvick, The contribution of breeding to yield advances in maize (*Zea mays* L.), Adv. Agron. 86 (2005) 83–145.
[3] V.B. Cardwell, Fifty years of Minnesota corn production: sources of yield increase, Agron. J. 74 (1982) 984–990.
[4] Y.C. Wu, Z.Y. Ma, D.Y. Wang, J. Jiang, Analyses of contribution of maize improvement to yield increment in China, Acta Agron. Sin. 24 (1998) 593–600 (in Chinese with English abstract).
[5] B.L. Ma, K.D. Soubedi, A. Liu, Variations in grain nitrogen removal associated with management practices in maize production, Nutr. Cycl. Agroecosyst. 76 (2006) 67–80.
[6] L. Sangoi, M.A. Gracietti, C. Rampazzo, P. Bianchetti, Response of Brazilian maize hybrids from different eras to changes in plant density, Field Crop Res. 79 (2002) 39–51.
[7] X.K. Ci, M.S. Li, J.S. Xu, Z.Y. Lu, P.F. Bai, G.L. Ru, X.L. Liang, D.G. Zhang, X.H. Li, L. Bai, C.X. Xie, Z.F. Hao, S.H. Zhang, S.T. Dong, Trends of grain yield and plant traits in Chinese maize cultivars from the 1950s to the 2000s, Euphytica 185 (2012) 395–406.
[8] M. Tollenaar, Genetic improvement in grain yield of commercial maize hybrids grown in Ontario from 1959 to 1988, Crop Sci. 29 (1989) 1365–1371.
[9] G.H. Eyhérabide, A.L. Damilano, J.C. Colazo, Genetic gain for grain yield of maize in Argentina, Maydica 39 (1994) 207–211.
[10] T.W. Bruulsema, M. Tollenaar, J.R. Heckman, Boosting crop yields in the next century, Better Crops 84 (2000) 9–13.
[11] T.Y. Wang, X.L. Ma, L. Yu, D.P. Bai, C. Liu, Z.Z. Liu, X.J. Tan, Y.S. Shi, Y.C. Song, M. Carlone, D. Bubeck, H. Bhardwaj, E. Jones, K. Wright, S. Smith, Changes in yield and yield components of single-cross maize hybrids released in China between 1964 and 2001, Crop Sci. 51 (2011) 512–525.
[12] L.M. Dwyer, M. Tollenaar, Genetic improvement in photosynthetic response of hybrid maize cultivars, 1959 to 1988, Can. J. Plant Sci. 69 (1989) 81–91.
[13] O.M. Frei, Changes in yield physiology of corn as a result of breeding in northern Europe, Maydica 45 (2000) 173–183.
[14] G.H. Eyhérabide, A.L. Damilano, Comparison of genetic gain for grain yield of maize between the 1980s and 1990s in Argentina, Maydica 46 (2001) 277–281.
[15] J.F. Crow, 90 years ago: the beginning of hybrid maize, Genetics 148 (1998) 923–928.
[16] J.S. Cunha Fernandes, J.F. Franzon, Thirty years of genetic progress in maize (*Zea mays* L.) in a tropical environment, Maydica 42 (1997) 21–27.

[17] D.N. Duvick, J.S.C. Smith, M. Cooper, Long-term selection in a commercial hybrid maize breeding program, Plant Breed. Rev. 24 (2004) 109–151.
[18] W.A. Russell, Genetic improvement of maize yields, Adv. Agron. 46 (1991) 245–298.
[19] M. Tollenaar, D.E. McCullough, L.M. Dwyer, Physiological basis of the genetic improvement of corn, in: G.A. Slafer (Ed.), Genetic Improvement of Field Crops, Taylor & Francis Inc., New York 1994, pp. 183–236.
[20] D.N. Duvick, What Is Yield? in: G.O. Edmeades, M. Bänziger, H.R. Mickelson, C.B. Pena-Valdivia (Eds.), Developing Drought and Low N-tolerant Maize, Proceedings of a Symposium, March 25–29, 1996, CIMMYT, El Batan, Mexico 1997, pp. 332–335.
[21] M.R. Carlone, W.A. Russell, Response to plant densities and nitrogen levels for four maize cultivars from different eras of breeding, Crop Sci. 27 (1987) 465–470.
[22] D.E. McCullough, A. Aguilera, M. Tollenaar, N uptake, N partitioning, and photosynthetic N-use efficiency of an old and a new maize hybrid, Can. J. Plant Sci. 74 (1994) 479–484.
[23] D.E. McCullough, P. Giradin, M. Mihajlovic, A. Aguilera, M. Tollenaar, Influence of N supply on development and dry matter accumulation of an old and a new maize hybrid, Can. J. Plant Sci. 74 (1994) 471–477.
[24] M. Tollenaar, E.A. Lee, Yield potential, yield stability and stress tolerance in maize, Field Crop Res. 75 (2002) 161–169.
[25] S.W. Ritchie, J.J. Hanway, How a corn plant develops, Special Report No. 48, Iowa State University of Science and Technology, Cooperative Extension Service, Ames, Iowa, 1993.
[26] X.K. Niu, R.Z. Xie, X. Liu, F.L. Zhang, S.K. Li, S.J. Gao, Maize yield gains in Northeast China in the last six decades, J. Integr. Agric. 12 (2013) 630–637.
[27] X.K. Ci, M.S. Li, X.L. Liang, Z.J. Xie, D.G. Zhang, X.H. Li, Z.Y. Lu, G.L. Ru, L. Bai, C.X. Xie, Z.F. Hao, S.H. Zhang, Genetic contribution to advanced yield for maize hybrids released from 1970 to 2000 in China, Crop Sci. 51 (2011) 13–20.
[28] I.S. Tokatlidis, S.D. Koutroubas, A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability, Field Crop Res. 88 (2004) 103–114.
[29] D.N. Duvick, K.G. Cassman, Post-green revolution trends in yield potential of temperate maize in the North-Central United States, Crop Sci. 39 (1999) 1622–1630.
[30] M. Tollenaar, J. Wu, Yield improvement in temperate maize is attributable to greater stress tolerance, Crop Sci. 39 (1999) 1597–1604.
[31] S. Daberkow, H. Taylor, W.Y. Huang, Agricultural Resources and Environmental Indicators: Nutrient Use and Management, Report No. AH722, USDA/ERS, Washington D.C.
[32] G. Argenta, P.R.F. Silva, L. Sangoi, Arranjo de plantas em milho: análise do estado-da-arte, Cienc. Rural 31 (2001) 1075–1084 (in Portuguese with English abstract).
[33] M. Tollenaar, L.M. Dwyer, D.W. Stewart, Ear and kernel formation in maize hybrids representing three decades of grain yield improvement in Ontario, Crop Sci. 32 (1992) 432–438.
[34] L. Echarte, S. Luque, F.H. Andrade, V.O. Sadras, A. Cirilo, M.E. Otegui, C.R.C. Vega, Response of maize kernel number to plant density in Argentinean hybrids released between 1965 and 1993, Field Crop Res. 68 (2000) 1–8.