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Research Article

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Linear and quadratic regression of maize (*Zea mays* L.) crop yield on elevated plant density

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Abstract Growing density-tolerant genotypes under the optimum plant density would lead to maximize maize (*Zea mays* L.) grain productivity per unit land area. The objective of this investigation was to match the functions of optimum plant density with the greatest maize genotype efficiency to produce the highest possible grain yield per unit area. Six maize inbred lines differing in tolerance to high density (D) [three tolerant (T); L-20, L-53, Sk-5, and three sensitive (S); L-18, L-28, Sd-7] were inter-crossed in a diallel fashion. Parents and F_1 crosses were evaluated in the 2013 and 2014 seasons under three plant densities: low (47,600), medium (71,400), and high (95,200) plants ha^{-1}. The T × T crosses were superior to the S × S and T × S crosses under the high D environment in most studied traits across seasons. Linear and quadratic regression functions between grain yield/ha (GYPH) and plant densities indicated that the inbred L20 showed a quadratic response of increase to elevated plant density, with an optimum GYPH at plant density of ca 83,300 plants/ha. The four inbreds L53, Sk5, L28 and Sd7 showed near linear or completely linear response of increase to density levels, with a maximum GYPH at 95,200 plants/ha. By contrast, the inbred L18 showed near linear response towards decrease in GYPH due to increasing plant density, with a maximum GYPH at 47,600 plants/ha. Three F_1 crosses (L20 x L53, L53 x Sk5 and L53 x Sd7) that belong to the group efficient responsive and classified as density tolerant showed clear curvilinear (quadratic) regression of GYPH increase up to more than 16 ton/ha with an optimum density of about 83,300 plants/ha. The rest of crosses (12 F_1's) showed near linear or completely linear regression of increase with an optimum density of 95,200 plants/ha.

Keywords Slope, Corn, Unit area productivity, Optimum plant density

Introduction

At present, approximately all maize acreage in Egypt (0.725 million ha) is grown mostly by single and three-way cross hybrids, developed mainly by the National Maize Breeding Program (NMBP), Agricultural Research Center (ARC) of the Egyptian Ministry of Agriculture, with a total production of about 6 million tons of grains and an average yield of about 8.3 tons ha^{-1}. According to FAO [1], Egypt ranks sixth in the world with respect to average productivity after Germany, France, Canada, Italy and USA, where average yield for these countries reached > 12 ton ha^{-1}. Hybrid varieties currently released in Egypt by NMBP are bred and grown at low plant density (ca. 57,000 plants ha^{-1}), *i.e.* much less than that used in the developed countries, because such Egyptian hybrids cannot withstand higher plant densities. This may be one of the important reasons of getting lower maize productivity in Egypt from unit land area than that in the developed countries, which use high-density tolerant varieties. One of the potential methods to maximize maize productivity per unit land area in Egypt is through growing high-density tolerant hybrids density under higher plant density than that currently used in Egypt.

Grain yield per land unit area is the product of grain yield per plant and number of plants per unit area [2]. Maximum yield per unit area may be obtained by growing maize hybrids that can withstand high plant density up to 100,000 plants ha^{-1} [3]. Average maize grain yield per unit area in the USA increased dramatically during the second half of the 20th century, owing to improvements in crop management practices and greater tolerance by modern hybrids of high plant densities [4,5]. Modern hybrids have shown tendencies to withstand higher levels of stress (*i.e.* high plant densities), which allow them to better sustain suitable photosynthetic rates, appropriate assimilate supplies, and maintain plant growth rates under such stress [6].

Modern maize hybrids in developed countries are characterized with high yielding ability from unit area under high plant densities, due to their morphological and phenological adaptability traits, such as early silking, short anthesis silking interval (ASI), less barren stalks and prolificacy [7-11]. Radenovic *et al.* [8] and Al-Naggar *et al*. [10, 11] pointed out that maize genotypes with erect leaves are very desirable for increasing the population density due to better light interception. Although high plant density results in interplant competition (especially for light, water and nutrients), which affects vegetative and reproductive growth of maize[12, 13], the use of high-density tolerant hybrids would overcome the negative impacts of such competition and lead to maximizing maize productivity from the same unit area.

Maize grain yield per plant decreases as the density per unit area increases [2]. The yield decreases as a response to decreasing light and other environmental resources available to each plant [14]. Reduction in yield is due mainly to fewer cobs (barrenness) [15], fewer grains per cob [12], lower grain weight [16], or a combination of these components [17]. At high densities, many kernels may not develop, an event that occurs in some hybrids following poor pollination resulting from a silking period that is delayed relative to tassel emergence [18] and/or owing to a limitation in assimilate supply that causes grain and cob abortion [19]. However, under optimum water and nutrient supply, high plant density can result in an increased number of cobs per unit area, with an eventual increase in grain yield [20]. Liu *et al.* [21] reported that maize yield differed significantly at varying plant density levels, owing to differences in genetic potential. In general, significant stressed environment and genotype × stress interaction effects are detected for agronomic and yield characteristics in maize [22-29]. Differential responses of maize genotypes to elevated plant density were reported by several investigators [25-29]. Knowledge about differential responses of maize genotypes to elevated plant densities could be an invaluable aid in maize improvement strategies. Therefore, the objectives of the present investigation were (*i*) to evaluate the effects of stress resulting from elevating plant density on traits of six inbreds and their diallel F_1 crosses, and (*ii*) to match the functions of appropriate plant density with greatest maize inbred or hybrid efficiency to produce the highest possible yields per land unit area.

Materials And Methods

This study was carried out at the Agricultural Experiment and Research Station of the Faculty of Agriculture, Cairo University, Giza, Egypt (30° 02'N latitude and 31° 13'E longitude with an altitude of 22.50 meters above sea level), in 2012, 2013 and 2014 seasons.

Plant material

Based on the results of previous experiments [30], six maize (*Zea mays* L.) inbred lines in the 8^{th} selfed generation (S_8), showing clear differences in performance and general combining ability for grain yield under high plant density, were chosen in this study as parents of diallel crosses (Table 1).

Table 1: Designation, origin and most important traits of 6 inbred lines (L) used for making diallel crosses in this study.

Inbred designation	Origin	Institution (country)	Prolificacy	Productivity under high density	Leaf angle
L20-Y	SC 30N11	Pion. Int. Co.	Prolific	High	Erect
L53-W	SC 30K8	Pion. Int. Co.	Prolific	High	Erect
Sk5-W	Teplacinco # 5 (Tep-5)	ARC-Egypt	Prolific	High	Erect
L18-Y	SC 30N11	Pion. Int. Co.	Prolific	Low	Wide
L28-Y	Pop. 59	ARC-Thailand	Non-Prolific	Low	Wide
Sd 7-W	A.E.D. (old local OPV)	ARC- Egypt	Non-Prolific	Low	Erect

ARC = Agricultural Research Center, Pion. Int. Co. = Pioneer International Company in Egypt, SC = Single cross, W = White grains, Y = Yellow grains, A.E.D. = American Early Dent, Pop = Population, OPV=Open pollinated variety.

Making F_1 diallel crosses

In 2012 season, all possible diallel crosses (except reciprocals) were made among the six parents, so seeds of 15 direct F_1 crosses were obtained. Seeds of the 6 parents were also increased by selfing in the same season (2012) to obtain enough seeds of the inbreds in the 9^{th} selfed generation (S_9 seed).

Evaluation of parents and F_1`s

Two field evaluation experiments were carried out in 2013 and 2014 seasons. Each experiment included 15 F_1 crosses, their 6 parents and 2 check cultivars, namely SC 130 (white), obtained from the Agricultural Research Center (ARC) and SC 2055 (yellow) obtained from Hi-Tech Company-Egypt. Evaluation in each season was carried out three plant densities, namely low-, medium- and high-plant density (D) (47,600, 71,400 and 95,200 plants/ha, respectively).

A split plot design in randomized complete blocks (RCB) arrangement with three replications was used. Main plots were devoted to plant density (high-D, medium-D and low-D). Sub plots were devoted to 23 maize genotypes (6 parents, 15 F_1`s and 2 checks). Each sub plot consisted of one ridge of 4 m long and 0.7 m width, *i.e.* the experimental plot area was 2.8 m^2. Seeds were sown in hills at 15, 20 and 30 cm apart, thereafter (before the 1st irrigation) were thinned to one plant/hill to achieve the 3 plant densities, *i.e.*, 47,600, 71,400 and 95,200 plants/ha, respectively. Sowing date was on May 5 and May 8 in 2013 and 2014 seasons, respectively.

The soil analysis of the experimental soil as an average of the two growing seasons 2013 and 2014, indicated that the soil is clay loam (4.00% coarse sand, 30.90% fine sand, 31.20% silt, and 33.90% clay), the pH (paste extract) is 7.73, the EC is 1.91 dSm-1, soil bulk density is 1.2 g cm-3, calcium carbonate is 3.47%, organic matter is 2.09%, the available nutrient in mg kg-1are Nitrogen (34.20), Phosphorous (8.86), Potassium (242), hot water extractable B (0.49), DTPA - extractable Zn (0.52), DTPA - extractable Mn (0.75) and DTPA - extractable Fe (3.17). Meteorological variables in the 2013 and 2014 growing seasons of maize were obtained from Agro-meteorological Station at Giza, Egypt. For May, June, July and August, mean temperature was 27.87, 29.49, 28.47 and 30.33°C, maximum temperature was 35.7, 35.97, 34.93 and 37.07°C and relative humidity was 47.0, 53.0, 60.33 and 60.67%, respectively, in 2013 season. In 2014 season, mean temperature was 26.1, 28.5, 29.1 and 29.9°C, maximum temperature was 38.8, 35.2, 35.6 and 36.4°C and relative humidity was 32.8, 35.2, 35.6 and 36.4%, respectively. Precipitation was nil in all months of maize growing season for both seasons. All other agricultural practices were followed according to the recommendations of ARC, Egypt.

Sowing dates were May 5 and 8 in the 2013 and 2014 seasons, respectively. The soil analysis of the experimental soil at the Agricultural Experiment and Research Station of the Faculty of Agriculture, Cairo University, Giza, Egypt, as an average of the two growing seasons 2013 and 2014, indicated that the soil is clay loam (4.00% coarse sand, 30.90% fine sand, 31.20% silt, and 33.90% clay), the pH (paste extract) is 7.73, the EC is 1.91 dSm-1, soil bulk density is 1.2 g cm-3, calcium carbonate is 3.47%, organic matter is 2.09%, the available nutrient in mg kg-1are Nitrogen (34.20), Phosphorous (8.86), Potassium (242), hot water extractable B (0.49), DTPA - extractable Zn (0.52), DTPA - extractable Mn (0.75) and DTPA - extractable Fe (3.17).

Data recorded

1. **Days to 50% anthesis (DTA)** (as number of days from planting to anthesis of50% of plants per plot).
2. **Days to 50% silking (DTS)** (as number of days from planting to silking of 50% of plants/plot).
3. **Anthesis-silking interval (ASI)** (as number of days between 50% silking and 50% anthesis of plants per plot).
4. **Plant height (PH)** (cm) (measured from ground surface to the point of flag leaf insertion for five plants per plots).
5. **Ear height (EH)** (cm) measured from ground surface to the base of the top most ear relative to the plant height for five plants per plots.
6. **Barren stalks (BS)** (%) measured as percentage of plants bearing no ears relative to the total number of plants in the plot (an ear was considered fertile if it had one or more grains on the rachis).
7. **Leaf angle (LANG)** (^{o}) measured as the angle between stem and blade of the leaf just above ear leaf according to Zadoks *et al*. [31]. The following grain yield traits were measured at harvest.
8. **Number of ears per plant (EPP)** calculated by dividing number of ears per plot on number of plants per plot.
9. **Number of rows per ear (RPE)** using 10 random ears/plot at harvest.
10. **Number of kernels per row (KPR)** using the same 10 random ears/plot.
11. **Number of kernels per plant (KPP)** calculated as: number of ears per plant × number of rows per ear × number of kernels per row**.**
12. **100-kernel weight (100-KW)** (g) adjusted at 15.5% grain moisture, using shelled grains of each plot.
13. **Grain yield per plant (GYPP)**(g) estimated by dividing the grain yield per plot (adjusted at 15.5% grain moisture) on number of plants/plot at harvest.
14. **Grain yield per hectare (GYPH)** in ton (t), by adjusting grain yield/plot to grain yield per hectare. **Stress tolerance index (STI):** Stress tolerance index (STI) modified from equation suggested by Fageria [32] was used to classify genotypes for tolerance to stress (water stress and/or high density stress). The formula used is as follows: STI= (Y_1/AY_1) X (Y_2/AY_2), Where, Y_1 = grain yield mean of a genotype at non-stress. AY_1 = average yield of all genotypes at non-stress.Y_2 = grain yield mean of a

genotype at stress. AY_2 = average yield of all genotypes at stress. When STI is ≥ 1.0, it indicates that genotype is tolerant (T), If STI is < 1, it indicates that genotype is sensitive (S).

Biometrical analyses

Analysis of variance of the split-split plot design in RCB arrangement was performed on the basis of individual plot observation using the MIXED procedure of SAS ® [33]. Combined analysis of variance across the two seasons was also performed if the homogeneity test was non-significant. Moreover, each environment (from E1 to E6) separately across seasons as randomized complete block design for the purpose of determining genetic parameters using GENSTAT 10th addition windows software. Least significant differences (LSD) values were calculated to test the significance of differences between means according to Steel *et al*. [34].

Results And Discussion

Analysis of variance

Combined analysis of variance across years (Y) of the split plot design for the studied 23 genotypes (G) of maize (6 inbreds +15 F_1's + 2 check commercial single-cross hybrids) under three plant densities (D) is presented in Table (2). Mean squares due to years were significant or highly significant for all studied 20 traits, except for anthesis-silking interval (ASI), barren stalks (BS), kernels/plant (KPP) and grain yield/ha (GYPH), indicating significant effect of climatic conditions on most studied traits. Mean squares due to plant densities and genotypes were significant or highly significant for all studied traits, except ASI, RPE for plant density, indicating that plant density has a significant effect on most studied traits and that genotype has an obvious and significant effect on all studied traits. Mean squares due to the 1st order interaction, *i.e.* D×Y, G×Y and G×D were significant (P ≤ 0.05 or 0.01) for all studied traits, except for 8 traits for D×Y, and two traits (ASI and BS) for G×D.

Table 2: Combined analysis of variance across 2013 and 2014 years (% sum of squares) of split plot design for studied 23 maize genotypes under three plant densities.

SOV	df	% Sum of squares (SS)						
		DTA	DTS	ASI	PH	EH	BS	LANG
Years (Y)	1	37.06**	24.03**	1.03**	0.36**	0.81**	1.55*	0.00
Densities (D)	2	13.96**	29.82**	59.40**	2.52**	6.81**	4.21**	0.84**
Y x D	2	0.03	0.05	0.07	0.02	0.14**	0.53	0.77**
Error (a)	12	0.17	0.09	0.60	0.09	0.11	3.25	0.27
Genotypes (G)	22	40.48**	38.11**	9.75**	86.47**	79.67**	23.72**	68.35**
Y x G	22	3.58**	3.21**	3.91**	4.96**	5.65**	12.84**	17.34**
D x G	44	1.21**	1.09**	4.61**	3.67**	4.20**	11.70**	4.44**
Y x D x G	44	1.39**	1.31**	3.61	0.57**	1.08**	12.04**	4.03**
Error (b)	264	2.13	2.29	17.02	1.34	1.52	30.17	3.95
Total SS	413	3393	4648	403.79	321878	134320	12991	8115
		EPP	RPE	KPR	KPP	100KW	GYPP	GYPH
Years (Y)	1	3.32**	0.30**	0.90**	0.09*	3.63**	0.26**	0.21**
Densities (D)	2	33.41**	9.48**	4.83**	27.37**	16.54**	11.70**	9.38**
Y x D	2	0.44**	0.10	0.06*	0.07	0.17*	0.06**	0.06*
Error (a)	12	0.33	0.33	0.09	0.15	0.25	0.07	0.06**
Genotypes (G)	22	38.87**	69.87**	85.65	62.44	68.10	82.00	83.55
Y x G	22	10.36**	12.80**	5.30**	5.29**	5.23**	2.89**	2.82**
D x G	44	5.11**	1.42**	0.90**	1.60**	1.91**	1.92**	2.87**
Y x D x G	44	2.87**	0.99	0.46*	0.85**	0.56	0.53**	0.58**
Error (b)	264	5.30	4.72	1.80	2.13	3.60	0.59	0.48
Total SS	413	5.54	659.8	22186	10255377	8040	1888599	8228

DTA= Days to 50% anthesis, DTS = days to 50% silking, ASI = anthesis-silking interval, PH = plant height, EH = ear height, BS = barren stalks. LANG = leaf angle, EPP = number of ears per plant, RPE = Number of rows per ear, KPR = Number of kernel per row ,KPP = number of kernels per plant, 100-KW = 100-kernel weight, GYPP = grain yield per plant, GYPH = grain yield per hectare, * and ** indicate significance at 0.05 and 0.01 probability levels, respectively.

Mean squares due to the 2^{nd} order interaction, i.e. G×D×Y were significant or highly significant for all studied traits, except EPP, RPE, KPR and KPP , indicating that the rank of maize genotypes differ from one density to another and from one year to another for most studied traits and the possibility of selection for improved performance under a specific plant density as proposed by several investigators [25, 26,28,29, 35, 36]. It is observed from Table (2) that variance due to genotypes was the largest contributor to the total variance in this experiment for most studied traits, as measured by percentage of sum of squares to total sum of squares. For the three traits ASI and BS, error variance was the largest contributor to the total variance; the reason might be due to the large value of C.V. for these characters (17.36 and 39.48%, respectively).
Combined analysis of variance of a randomized complete blocks design for 14 traits of 23 maize genotypes under three environments (LD, MD and HD); representing 3 plant densities, *i.e.* LD = low density, MD = medium density, HD = high density across two seasons is presented in Table (2). Mean squares due to genotypes, parents and crosses under all environments were highly significant for all studied traits, except ASI under LD and HD, indicating the significance of differences among parents and among F_1 diallel crosses in the majority of cases. Mean squares due to parents *vs.* F_1 crosses were highly significant for all studied traits under all three environments, except for ASI under LD and HD, EPP under HD, BS under LD, suggesting the presence of significant heterosis for most studied cases.
Mean squares due to the interactions parents × years (P × Y) and crosses × years (F_1 × Y) were significant or highly significant for all studied traits under all environments, except DTS under LD and MD for F_1× Y, DTS under LD for F_1 x Y, ASI under LD and HD for P x Y and HD for F_1 x Y, PH under LD and HD for P×Y and MD, HD for F_1×Y, EH under LD, MD and HD for P x Y, BS under MD for P x Y and HD for F_1 x Y, EPP under LD and MD for P×Y and HD for F_1×Y, RPE under MD and HD for P x Y and MD for F_1 x Y, KPP under LD, MD and HD for P x Y and HD for F_1 x Y, KPR under HD for P x Y, 100KW under HD for P x Y, GYPH under LD for P x Y and F_1 x Y.
Mean squares due to parents *vs.* crosses × years were significant or highly significant in most cases (Table 2). Such interaction was expressed in most environments for DTS, BS, LANG, EPP, KPR, KPP, 100KW and GYPH traits. This indicates that heterosis differ from season to season in these cases. Among genotypes components under all three environments, the largest contributor to total variance was parents vs. F_1's (heterosis) variance, followed by F_1 crosses and parents.

Effect of elevated plant density

The effects of elevating plant density on the means of studied traits across all genotypes across the two years are presented in Table (3). The environment LD represents the non-stressed one (47,600 plants/ha), while MD and HD represent higher plant density (stressed) environments (71,400 and 95,200 plants/ha, respectively).

Table 3: Change (%) in means of studied traits from low density to medium (MD) and high density (HD) combined across all studied genotypes and across 2013 and 2014 seasons.

Trait	MD	HD	Trait	MD	HD
DTA (day)	+2.22**	+4.34**	**EPP**	-8.74**	-13.06**
DTS (day)	+3.50**	+7.14**	**RPE**	-3.42**	-6.55**
ASI (day)	+36.25**	+78.96**	**KPR**	-5.13**	-9.18**
PH (cm)	+1.57**	+4.61**	**KPP**	-16.46**	-26.06**
EH (cm)	+5.75**	+11.79**	**100-KW (g)**	-6.57**	-12.79**
BS (%)	+13.07	+28.11**	**GYPP (g)**	-19.22**	-29.98**
LANG (o)	-3.27**	-2.93**	**GYPH(ton)**	+20.59**	+38.48**

DTA= days to 50% anthesis, DTS = days to 50% silking, ASI = anthesis-silking interval, PH = plant height, EH = ear height, BS = barren stalks, LANG = leaf angle, EPP = ears per plant, RPE = rows per ear, KPR = kernel per row , KPP = kernels per plant, 100-KW = 100-kernel weight, - = decrease, + = increase , * and ** indicate significance at 0.05 and 0.01 probability levels, respectively.

Mean grain yield/plant was significantly ($P \leq 0.01$) reduced due to elevating plant density from 47,600 plants/ha (E1) to 71,400 plants/ha (E2) and 95,200 plants/ha (E3), by 19.22 and 29.98%, respectively. This reduction was associated with reductions in all yield components, namely EPP (8.74 and 13.06%), KPP (16.46 and 26.06%)

and 100-KW (6.57 and 12.79%), indicating the importance of number of kernels followed by number of ears/plant as measures of tolerance to high-density. This conclusion was previously reported by El-Lakany and Russell [37] and Al-Naggar *et al.* [25,26,28,29]. It is observed that the reduction in number of kernels/plant was 2.5 and 1.57 fold greater than reduction in 100-kernel weight under high plant density (71,400 and 95,200 plants/ha, respectively), which is consistent with previous investigators on high-density stress in maize [23-29, 38,39].

Considerable evidence indicates that maize plants exposed to high plant density stress have reduced ears/plant, kernels/plant and kernel weight [40-43]. The reductions in yield components are logic and could be attributed to the increase in competition between plants at higher densities for light, nutrients and water. This conclusion was previously reported by several investigators [23,24, 27-29, 44-46]. Elevation of plant density from the low density (47,600 plants/ha) to 71,400 and 95,200 plants/ha also resulted in significant reductions of LANG (3.27 and 2.93%, respectively). A small but significant reduction in leaf angle (erectness) is the result of elevation of plant density in this study, which is in consistency with several investigators [11, 26, 47,48].

On the contrary, higher plant densities (71,400 and 95,200 plants/ha) caused a significant increase in grain yield/ha (GYPH) compared with the low-density by 20.59 and 38.48%, respectively (Table 3). Moreover, higher plant density (71,400 and 95,200 plants/ha) caused a significant increase in plant height (PH) by 3.63 and 10.66 cm, ear height (EP) by 5.60 and 11.50 cm, days to anthesis (DTA) by 1.34 and 2.62 day, days to silking (DTS) by 2.20 and 4.48 day, anthesis-silking interval (ASI) by 0.85 and 1.86 day (36.25 and 78.96%) and barren stalks (BS) by 13.07 and 28.11%, respectively as compared with low plant density (47,600 plants/ha). Elongation of plant stalks and increase of ear position exhibited in this study due to elevating the plant densities could be attributed to lower light level and greater competition between plants for light. This conclusion was previously reported by other investigators [25, 26, 28, 29,49, 50].

In general, the elongation of ASI due to high plant density, in this study was less than that reported by other investigators. Such ASI elongation ranged from 0 to 28 days [51] and from -4 to 10 days [52]. Tokatlis and Koutroubas [45] reported that the time gap between pollen shedding and silking increased from 0 to 9 days by increased plant density from 5 plants m^{-2} to 20 plants m^{-2}. Increased days to silking, days to anthesis and ASI as symptoms of interplant competition were reported by several investigators [10, 28,37,53]. These traits are also considered as indicative of barrenness or high-density intolerance [9-11, 41,52]. Several authors indicated that the separation of reproductive organs in maize may also account for this susceptibility to stress at flowering [40, 54-56]. Delayed silking under conditions of drought or high-density is related to less assimilates being partitioned to growing ears around anthesis, which results in lower ear growth rates, increased ear abortion, and more barren plants [23, 24,27, 40]. When assimilate supply is limited under stress, it is usually preferentially distributed to the stem and tassel at the expense of ear nutrition, leading to poor pollination and partial or complete failure of seed set. This occurs with practically all kinds of stress, including drought, low soil N and P, excess moisture, low soil pH, iron deficiency and high population density [9-11,23,24, 27-29,50,54,].

Genotype × plant density interaction

Mean grain yield/plant was significantly ($P \leq 0.01$) reduced due to elevating plant density from 47,600 (recommended density) to 71,400 and 95,200 plants/ha, by 25.77 and 39.54% for inbreds, 17.99 and 28.20% for F_1 crosses, respectively (Table 4). This reduction was associated with reductions in all yield components, namely EPP (6.40 and 13.14% for parents and 10.13 and 13.59% for crosses, KPP (16.88 and 30.64% for parents and 16.99 and 25.47% for crosses and 100-KW (9.79 and 17.46% for parents and 5.82 and 11.72% for crosses) at plant density of 71,400 and 95,200 plants/ha, respectively as compared with 47,600 plants/ha, indicating that the reduction in number of kernels is the main cause of reduction in GYPP due to high density stress and the GYPP and yield component reduction due to high plant density stress is more pronounced in the inbred lines than F_1 crosses. This means that crosses are more tolerant to high plant density stress than inbred lines, which might be due to the hybrid vigor (heterosis) and that heterozygotes are more adapted to stress conditions than homozygotes. Elevation of plant density from the low density (47,600 plants/ha) to 71,400 and 95,200 plants/ha also resulted in significant reductions of LANG (6.68 and 6.26% for parents and 1.69 and 2.08% for crosses, respectively).

Table 4: Means of studied traits of parents and crosses and percentage change (Ch%) from low density (LD) to medium density (MD) and high density (HD across two seasons.

Genotype	LD Mean	MD Mean	MD Ch%	HD Mean	HD Ch%	LD Mean	MD Mean	MD Ch%	HD Mean	HD Ch%
	Days to 50 % anthises					**Day to 50 % silking**				
Parents	62.11	63.89	-2.86	65.36	-5.23	64.81	67.58	-4.29	70.06	-8.1
Crosses	59.52	60.71	-2.01	61.97	-4.13	61.72	63.71	-3.23	65.99	-6.92

LSD.05	D =0.16 , G =0.36 , G×D×Y= 0.88					D =0.19 , G =0.44 , G×D×Y =1.08				
	Anthesis-silking interval (day)					**Plant height (cm)**				
Parents	2.69	3.69	-37.11	4.69	-74.23	194.33	196.79	-1.27	203.75	-4.85
Crosses	2.2	3	-36.36	4.02	-82.58	244.16	246.82	-1.09	254.86	-4.38
LSD.05	D =0.15 , G =0.28 , G×D×Y =0.70					D =0.97 , G =3.55 G×D×Y =8.70				
	Ear height (cm)					**Barren stalks (%)**				
Parents	75.77	80.7	-6.51	92.42	-21.98	9.94	12.69	-27.7	14.4	-44.9
Crosses	105.54	110.63	-4.82	114.76	-8.73	9.97	10.59	-6.1	12.14	-21.7
LSD.05	D =1.03 , G =1.96 , G×D×Y = 4.80					D = 0.99, G = 2.30 G×D×Y = 5.65				
	Leaf angle (°)					**Number of ears per plant**				
Parents	26.61	24.83	6.68	24.94	6.26	1.234	1.155	6.4	1.072	13.14
Crosses	28.26	27.78	1.69	27.67	2.08	1.237	1.112	10.13	1.069	13.59
LSD.05	D = 0.29, G = 0.76, G×D×Y= 1.87					D = 0.010 , G = 0.041 , G×D×Y= 0.100				
	Number of rows per ear					**Number of kernels per row (KPR)**				
Parents	14.05	13.55	3.52	13.13	6.51	33.61	31.09	7.48	28.8	14.31
Crosses	14.62	14.1	3.57	13.64	6.66	45.81	43.76	4.47	42.21	7.86
LSD.05	D = 0.066 , G = 0.334 , G×D×Y = 0.818					D = 0.19 , G = 0.81, G×D x Y = 1.99				
	Number of kernels per plant					**100-kernel weight (g)**				
Parents	581.02	482.96	16.88	403.02	30.64	30.2	27.24	9.79	24.92	17.46
Crosses	825.05	684.88	16.99	614.92	25.47	36.04	33.94	5.82	31.82	11.72
LSD.05	G = 28.49 , G×D×Y= 69.80					D = 0.19 , G = 0.65 G×D×Y= 1.58				
	Grain yield per plant (g)					**Grain yield per hectare (ton)**				
Parents	77.06	57.2	25.77	46.59	39.54	3.49	4.03	-15.5**	4.33	-24.1**
Crosses	225.1	184.6	17.99	161.62	28.2	10.42	12.75	-21.80**	14.75	-41.55**
LSD.05	D = 2.48 , G = 3.80, G×D×Y = 9.32					D =0.17 , G =0.25 , D × G =0.37				

LD = 47,600 plants/ha **, MD** =71,400 plants/ha**, HD** = 95,200 plants/ha**, Change = 100*(LD–MD or HD)/LD, * and ** significant at 0.05 and 0.01 probability levels, respectively**.

On the contrary, higher plant densities (71,400 and 95,200 plants/ha) caused a significant increase in grain yield/ha (GYPH) compared with the low-density by 10.58 and 21.29% for inbreds, 22.33 and 41.57% for F_1 crosses, respectively (Table 4). The increase in GYPH due to increasing plant density for inbreds was 1.43 and 1.40 fold greater than the increase for F_1 crosses under 71,400 and 95,200 plants/ha, respectively. This conclusion was also reported by Monneveux *et al.* [50], who stated that lines yielded more than open-pollinated varieties and hybrids under high plant population density, probably because of lower vigor and lower competition between plants. On the contrary, several investigators [14,25,26,28,42,43] reported that hybrids were more adapted to high plant density than inbred lines of maize. Differences in conclusions regarding the effects of high density may be attributed to the differences in the genetic background of the plant materials and/or climatic conditions prevailing through the growing seasons of different studies.

Increasing plant density from 47,600 to 71,400 and 95,200 plants/ha caused a significant increase in grain protein yield/ha (PYPH) by 4.11 and 19.83% for inbreds, 20.04 and 39.83% for hybrids, respectively. Moreover, high density (95,200 plants/ha) caused a significant increase in plant height (PH) by 4.85 and 4.38%, ear height (EP) by 21.98 and 8.73 %, anthesis-silking interval (ASI) by 10.31 and 28.23% and barren stalks (BS) by 18.40 and 28.5 % for parents and crosses, respectively as compared with low plant density (47,600 plants/ha). Days to anthesis (DTA) and days to silking (DTS) showed a slight and significant decrease (2.86 and 5.23%) for inbreds and a slight and significant increase (2.01 and 4.13%) for hybrids, respectively due to elevating plant density to 71,400 and 95,200 plants/ha.

Mean grain yield/ha across years under three densities for each inbred, hybrid and check is presented in Table (5). The rank of inbred parents for GYPH was approximately similar in all three environments, indicating less effect of interaction between inbreds and plant density on GYPH. The percent reduction in GYPH due to both stresses relative to LD was smaller for the inbred lines L20, L28 and L53 than the inbreds L18, Sk5 and Sd7 in HD environment, which could be attributed to the higher potential yield of the first group of lines than the second one, under good environmental conditions. The first group of lines was therefore considered tolerant to density stress expressed in GYPH, while the second one was considered sensitive. The best GYPH was obtained from HD for the inbreds L20, Sk5 and L53 followed by MD and LD environment. Regarding GYPH of the F_1 crosses, the rank varied from one environment to another, indicating high effect of interaction between hybrids and plant density on GYPH.

Table 5: Mean grain yield ha^{-1} (ton) of each inbred and cross under three plant densities and change (Ch %) from low density across two seasons.

Genotypes	Low-D	Med-D	Ch%	High-D	Ch%
	Inbred parents (P)				
L20	4.95	6.41	-29.5**	6.64	-34.1**
L53	6.13	6.47	-5.5**	6.66	-8.6**
Sk5	3.60	4.48	-24.5**	4.92	-36.6**
L18	2.16	1.85	14.5**	1.86	13.9**
L28	2.06	2.44	-18.5**	2.83	-37.3**
Sd7	2.01	2.50	-24.1**	3.05	-51.7**
	Crosses (C)				
L20 × L53	12.88	16.45	-27.71**	17.05	-32.42**
L20 ×SK5	10.22	12.59	-23.19**	14.21	-39.11**
L20 × L18	10.15	13.38	-31.77**	16.04	-58.00**
L20 × L28	10.81	12.88	-19.17**	14.51	-34.26**
L20 × Sd7	10.53	12.60	-19.67**	14.85	-41.05**
L 53 × Sk5	11.40	15.50	-35.99**	16.47	-44.48**
L53 × L18	8.99	10.20	-13.38**	12.85	-42.82**
L53 × L28	11.03	11.66	-5.75**	14.99	-35.90**
L53 × Sd7	11.19	15.13	-35.24**	16.30	-45.74**
Sk5 × L18	10.90	13.60	-24.77**	15.18	-39.20**
Sk5 × L28	10.34	13.90	-34.41**	15.45	-49.40**
Sk5 × Sd7	9.58	10.88	-13.59**	13.48	-40.77**
L18 × L28	7.91	8.59	-8.60**	11.42	-44.37**
L18 × Sd7	9.88	11.17	-13.08**	13.80	-39.66**
L28 × Sd7	10.49	12.67	-20.75**	14.67	-39.84**
	Checks				
S.C 130	10.67	11.76	-10.2**	13.59	-27.4**
S.C 2055	10.00	12.58	-25.8**	13.87	-38.7**
LSD 0.05	D =0.17 , G =0.25 , D × G =0.37				

Low density= 47,600, medium density= 71,400, high density= 95,200, Ch% = 100 x (LD– MD or HD)/LD, * and ** significant at 0.05 and 0.01 probability levels.

Comparing to the non-stressed environment (LD), all 15 F_1 crosses showed an increase in their GYPH ranging from 0.4 to 46.6% under MD and from 23.4 to 66.4% under HD. The increase in GYPH of these crosses under MD and HD, over that under LD could be attributed to the elevation of plant density. This indicates that the increase of GYPH due to the increase in plant density could compensate the reduction in GYPP due to competition between plants on light, water and nutrients and even this could happen in some crosses if they have more tolerance to high density stress. The best GYPH in this experiment was obtained under HD (high density) and the best crosses in this environment were L20 x L53 (17.05 t), L53 x Sk5 (16.47 t), L53 × Sd7 (16.30 t), L20× L18 (16.04 t) and Sk5 × L28 (15.45 t), with a significant superiority to SC 2055 (the best check under this experiment) by 27.0, 19.5, 18.3, 15.6 and 11.4%, respectively.

Stress tolerance of inbreds and hybrids

Stress tolerance index (STI) values of studied genotypes estimated using the equation suggested by Fageria [32] under the stressed environments MD and HD are presented in Table (6).According to our scale, when STI is ≥1.0, it indicates that genotype is tolerant (T), If STI is < 1, it indicates that genotype is sensitive (S). The highest STI under medium and high density environments was exhibited by the inbred line L53, followed by inbred L20 and then Sk5. These three inbreds had STI value greater than unity under the two stress environments and therefore could be considered tolerant to medium and high plant density stress.

Table 6: Stress tolerance index (STI) of maize inbreds and hybrids under medium (MD) and high (HD) density stressed environments.

Genotype	MD	HD	Genotype	MD	HD
Inbreds					
L20	2.25	2.12	**L18**	0.29	0.26
L53	2.81	2.64	**L28**	0.36	0.38
Sk5	1.14	1.14	**Sd7**	0.36	0.50
F_1 crosses					

L20 × L53	1.59	1.46	**L53 × Sd7**	1.27	1.21
L20 ×SK5	1.00	1.00	**Sk5 × L18**	1.13	1.14
L20 × L18	0.89	0.92	**Sk5 × L28**	0.94	0.96
L20 × L28	1.08	1.07	**Sk5 × Sd7**	0.79	0.83
L20 × Sd7	0.99	1.00	**L18 × L28**	0.51	0.58
L 53 × Sk5	1.33	1.25	**L18 × Sd7**	0.83	0.87
L53 × L18	0.70	0.75	**L28 × Sd7**	1.01	1.04
L53 × L28	1.22	1.17			

WW = well watering, WS = water stress, LD = low density, MD = medium density, HD = high density, E = environment.

On the contrary, the three inbred lines Sd7, L18 and L28 exhibited STI values less than unity under both stressed environments and therefore could be considered sensitive to medium and high plant density stress; with the most sensitive one was the inbred L18 under MD and HD environments. For F_1 crosses, the highest STI value was recorded by the cross L20 x L53 (TxT), followed by the cross L53 x Sk5 (TxT) and L53 x Sd7 (TxS) under stressed environments. On the other hand, the most sensitive crosses under both stressed environments are L18 x L28 (S x S), L53 x L18 (T x S) and Sk5 x Sd7 (T x S). It is observed that all three T x T crosses (L20 x L53, L20 x Sk5 and L53 x Sk5) were tolerant under both stressed environments, indicating hybrid accumulation of effects of stress tolerance genes from its two parents. Among the three S x S crosses, two (L18 × L28 and L18 × Sd7) were sensitive and one (L28 × Sd7) was tolerant to density stress. The stress tolerance exhibited in the latter S x S hybrid could be attributed to epistasis effects. Among the nine T x S crosses, five (L20 x L28, L20 x Sd7, L53 x L28, L53 x Sd7 and Sk5 x L18) were tolerant, while four (L20 x L18, L53 x L18, Sk5 x L28 and Sk5 x Sd7) were sensitive under both environments. The tolerance of the first five T x S crosses indicated accumulating of more genes of dominance effects of tolerance over sensitivity, while the tolerance of the latter four T x S crosses suggested accumulating less number of dominant tolerance genes.

Superiority of tolerant (T) over sensitive (S) genotypes

To describe the differences between tolerant (T) and sensitive (S) inbreds and hybrids, data of the selected characters were averaged for the two groups of inbreds and hybrids differing in their high density tolerance, namely in grain yield/plant under high density (HD) stress (Table 7). Based on STI index, the high-density tolerant (T) inbred lines were L20, L53 and Sk5 and the high-density sensitive (S) inbred lines were Sd7, L18 and L28. Moreover, the 3 F_1 crosses L20 × L53, L53 × Sk5 and L53× Sd7 were considered the most high density tolerant, while the crosses L18 × L28, L53 × L18 and Sk5× Sd7 were considered as the most high-density sensitive crosses.

Table 7: Superiority (%) of the three most tolerant (T) to the three most sensitive (S) inbreds and crosses for studied characters under the high density (HD) stressed environment combined across 2013 and 2014 seasons.

Trait	Inbreds			Crosses		
	T	S	Superiority%	T	S	Superiority%
DTA (day)	64.67	66.06	-2.10**	60.97	63.28	-3.64**
DTS (day)	69.56	70.56	-1.42**	64.86	67.39	-3.75**
ASI (day)	3.61	3.78	-4.41	3.89	4.11	-5.41*
PH (cm)	221.56	185.94	19.15**	236.94	273	-13.21**
EH (cm)	102.45	82.38	24.37**	102.17	125.11	-18.34**
BS (%)	12.06	13.32	-9.45	7.68	17.85	-56.96**
LANG (°)	21.94	27.94	-21.47**	23.78	32.11	-25.95**
EPP	1.13	1.02	11.05**	1.15	1	14.57**
RPE	14.34	11.92	20.37**	14.94	12.52	19.35**
KPR	33.6	24	40.00**	46.43	38.29	21.27**
KPP	471.74	334.29	41.11**	704.26	526.27	33.82**
100-KW (g)	28.36	21.49	31.95**	34.15	29.26	16.70**
GYPP (g)	65.38	27.8	135.21**	186.07	135.5	37.32**
GYPH(ton)	2.55	1.08	135.21**	6.98	5.29	32.00**

% Superiority = 100 × [(T – S)/S].

Based on STI index, the high-density tolerant (T) inbred lines were L20, L53 and Sk5 and the high-density sensitive (S) inbred lines were Sd7, L18 and L28. Moreover, the 3 F_1 crosses L20 × L53, L53 × Sk5 and L53×

Sd7 were considered the most high density tolerant, while the crosses L18 × L28, L53 × L18 and Sk5× Sd7 were considered as the most high-density sensitive crosses. Data averaged for each of the two groups (T and S) of inbreds and crosses differing in tolerance to high density indicate that grain yield/ha of high density tolerant (T) was greater than that of the sensitive (S) inbreds and crosses by 135.21 and 32.00%, respectively under high density (95,200 plants/ha) conditions. Superiority of high-density tolerant (T) over sensitive (S) inbreds in GYPH under high density was due to their superiority in GYPP (135.21%), EPP (11.05%), RPE (20.37%), KPR (40.00%), KPP (41.11%), 100-KW (31.95%) , *i.e.* in all studied yield component traits. Likewise, under high plant density, the tolerant inbreds showed 9.45% less barren stalk percentage, 2.10% less DTA, 1.42% less DTS, 4.41% shorter ASI and 21.47% smaller leaf angle than the sensitive inbreds. Superiority of T over S hybrids in GYPF under high density (95,200 plants/ha) was due to their superiority in GYPP (37.32%), EPP (14.57%), RPE (19.35%), KPR (21.27), KPP (33.82%), 100-KW (16.70%), BS (-56.96%) and ASI (-5.41%), DTA (-3.64%), DTS (-3.75%), PH (-13.21%) EH (-18.34%) than sensitive F_1 crosses (Table 7).

The superiority of modern maize hybrids tolerant to high plant density was also attributed to decreased barrenness [57], more leaf erectness [8], synchronization of 50% anthesis with 50% silking [40] and increased prolificacy, *i.e.* more ears plant^{-1}[58] (Miller *et al.*, 1995). A shortened ASI was considered as an indication of higher flow of assimilates to the developing ears during the early reproductive stage under conditions of high density stress [40]. High plant density-tolerant genotypes possess shorter ASI than intolerant ones[30, 54]. Al-Naggar *et al.* [30] also reported that under high plant density, the tolerant testcrosses showed 314.4% more GYPP, 115.0% more KPP, 48.4% heavier 100-KW, 42.9 more EPP, 98.2% less BS and 63.3 % shorter ASI than sensitive testcrosses.

Differential response of T×T, T×S and S×S crosses

Mean performance of traits were averaged across three groups of F_1 crosses, *i.e.* T×T, T×S and S×S groups based on grain yield per plant of their parental lines under density stress and non-stress conditions, *i.e.* parental tolerance to high density and presented in Table (8). Number of crosses was 3, 9 and 3 for the T×T, T×S and S×S groups, respectively. In general, high density T×T group of crosses exhibited better values in most studied traits than high density T×S and S×S groups of crosses.

Table 8: Studied trait differences averaged across 2013 and 2014 seasons for T×T, T×S and S×S groups of F_1 crosses under three plant densities (LD = 47,600, MD = 71,400 and HD = 95,200 plants/ha).

Trait	LD			MD			HD		
	T ×T	T ×S	S ×S	T ×T	T ×S	S ×S	T ×T	T ×S	S ×S
DTA (day)	58.67	59.49	60.44	60	60.59	61.78	61.22	61.88	63
DTS (day)	60.78	61.69	62.72	62.89	63.7	64.56	65.22	65.91	67
ASI (day)	2.11	2.2	2.28	2.89	3.11	2.78	4	4.03	4
PH (cm)	227.78	245.28	257.17	236.5	247.04	256.5	240.17	255.74	266.89
EH (cm)	92.37	106.86	114.75	100.43	111.66	117.72	103.23	115.95	122.73
BS (%)	8.36	9.84	11.99	7.67	10.2	14.64	8.73	11.98	16.04
LANG (°)	24.39	28.52	31.33	23.44	28.22	30.78	24.83	27.54	30.89
EPP	1.36	1.22	1.16	1.19	1.1	1.06	1.13	1.06	1.03
RPE	15.74	14.59	13.58	15.3	13.98	13.24	14.73	13.57	12.78
KPR	49.68	45.3	43.46	47.64	43.38	41.02	45.88	41.8	39.76
KPP	918.58	818.1	752.37	771.7	680.74	610.48	688.84	612.29	548.88
100-KW (g)	38.14	35.92	34.3	35.28	34	32.45	33.33	31.81	30.31
GYPP (g)	248.19	224.43	204.01	214.99	183.81	156.55	176.44	161.96	145.77
GYPH (t)	11.49	10.39	9.42	14.84	12.69	10.81	15.90	14.84	13.29

T = tolerant, S = sensitive

Superiority of high density T×T and T x S to S x S crosses was more pronounced under medium density (71,400 plants/ha) than under high (95,200 plants/ha) and low density (47,600 plants/ha). Under high plant density conditions, grain yield/ha of high-density T×T crosses (15.90 t) was significantly greater than that of S×S (13.29 t) and T×S (14.84 t) crosses by 19.65 and 7.13%, respectively. Grain yield per hectare superiority of high-density T×T (19.65%) and T x S (11.68%) to S×S crosses was associated with their superiority in grain yield/plant by 21.04 and 11.11%, KPP by 25.50 and 11.55%, 100KW by 9.96 and 4.95%, KPR by 15.39 and 5.13%, RPE by 15.26 and 6.18% and EPP by 9.71 and 2.91%, respectively. The high T×T and T x S crosses were earlier in DTA by -2.83and -1.78% and DTS by-2.66** and -1.63*%, shorter in PH (-10.01 and -4.18%), lower in EH (-15.89 and -5.52%), lower in BS (-45.57 and -25.31%) and narrower in LANG (-19.62 and -10.84%), than high density S×S, respectively under high-density conditions (95,200 plants/ha) (Table8). The superiority of modern crosses of maize (tolerant to high plant density) over the old ones in countries grow maize under high plant densities is due to their short stature, erect leaves, prolificacy, synchronization between anthesis and silking. Duvick *et al.* [7], O'Neill *et al.* [6] and Radenovic *et al.* [8] reported a similar conclusion. This study concluded that to obtain maximum grain yield from a hybrid under elevated plant density, it is better that both of its two parents to be tolerant to high plant density. This assures that high plant density stress tolerance trait is quantitative in nature, so the tolerant cross accumulates additive genes of high density tolerance from both parents.

Grouping genotypes based on stress efficiency and responsiveness

Mean grain yield per plant or per hectare across years of studied F_1crosses under high density (HD) was plotted against same trait of the same genotypes under low-D (Figs. 1 and 2) where numbers from 1 to 6 refer to parent names No 1 = L20 , No 2 = L53, No 3 = Sk5 , No 4 = 18 , No 5 = L28 and No 6= Sd7andnumbers from 1 to 15 refer to F_1 hybrid names 1 = L20×L53, 2 = L20×Sk5, 3 = L20×L18, 4 = L20×L28, 5 = L20×Sd7, 6 = L53×Sk5, 7 = L53×L18, 8 = L53×L28, 9 = L53×Sd7, 10 = Sk5×L18, 11 = Sk5×L28, 12 = Sk5×Sd7, 13 = L18×L28, 14 = L18×Sd7 and 15 = L28×Sd7, which made it possible to distinguish between efficient and inefficient genotypes on the basis of above-average and below-average grain yield under high-D and responsive and non-responsive genotypes on the basis of above-average and below-average grain yield under low-D according to Sattelmacher *et al.*, [59], Worku *et al.* [60] and Al-Naggar *et al.* [29].

According to efficiency under high density and responsiveness to low density, studied inbreds and crosses were classified into four groups, *i.e.* density efficient and responsive (E-R), density efficient and non-responsive (E-NR), density in-efficient and responsive (IE-R) and density in-efficient and non-responsive (IE-NR) based on GYPH trait. The inbreds No.2 (L20), No.1 (L53) and No.3 (Sk5) were classified as density efficient and responsive, while inbreds No.4, No.5 and No.6 were classified as density in-efficient and non-responsive. The F_1 crosses No. 1 (L20 × L53), No. 6 (L 53 × Sk5), No. 9 (L53 × Sd7), No. 15(L28 × Sd7), No.8 (L53 × L28) and No.10 (Sk5 × L18) had the highest GYPH under high-D and Low-D, *i.e.* they could be considered as the most density efficient and the most responsive genotypes in this study (Fig. 1). On the contrary, the F_1 crosses No.13 (L18× L28), No.7 (L53 × L18), No.12 (Sk5 × Sd7), No.14 (L18 × Sd7) and No.2 (L20 ×Sk5) had the lowest GYPH under both high-D and low-D and therefore could be considered inefficient and non-responsive. The crosses No.3 (L20 × L18) and No.11 (Sk5 × L28) occupied the group of density efficient and non-responsive (high GYPH under high density but low GYPH under low density). The crosses No.4 (L20 × L28) and No.5 (L20 × Sd7) had low GYPH under high density and high GYPH under low density, i.e. density inefficient and responsive.

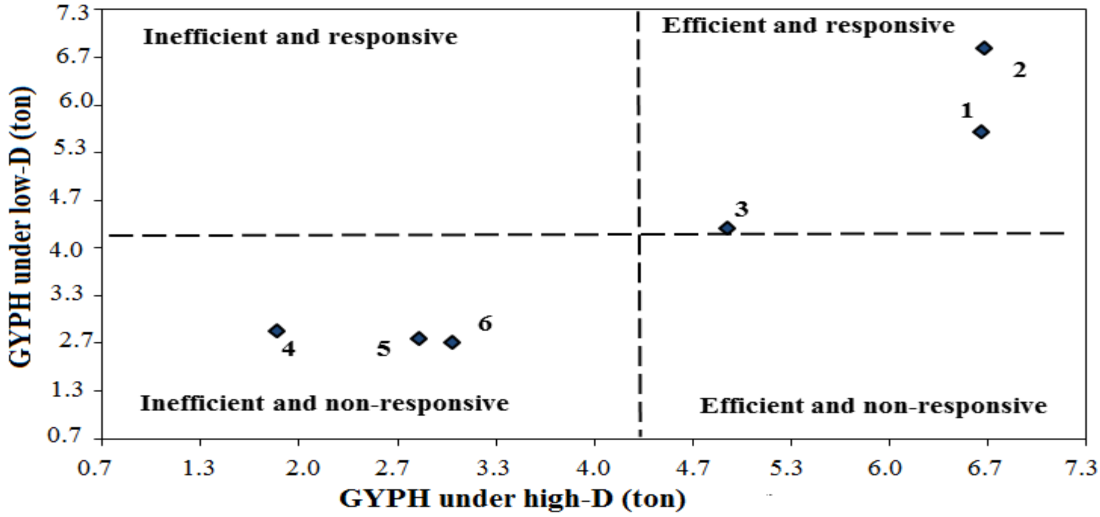


Figure 1: Relationships between grain yield/ha (GYPH) of 6 parental inbreds under high and low density (D) combined across 2013 and 2014 seasons. Broken lines represent mean of GYPH. Numbers from 1 to 6 refer to parental inbreds names.

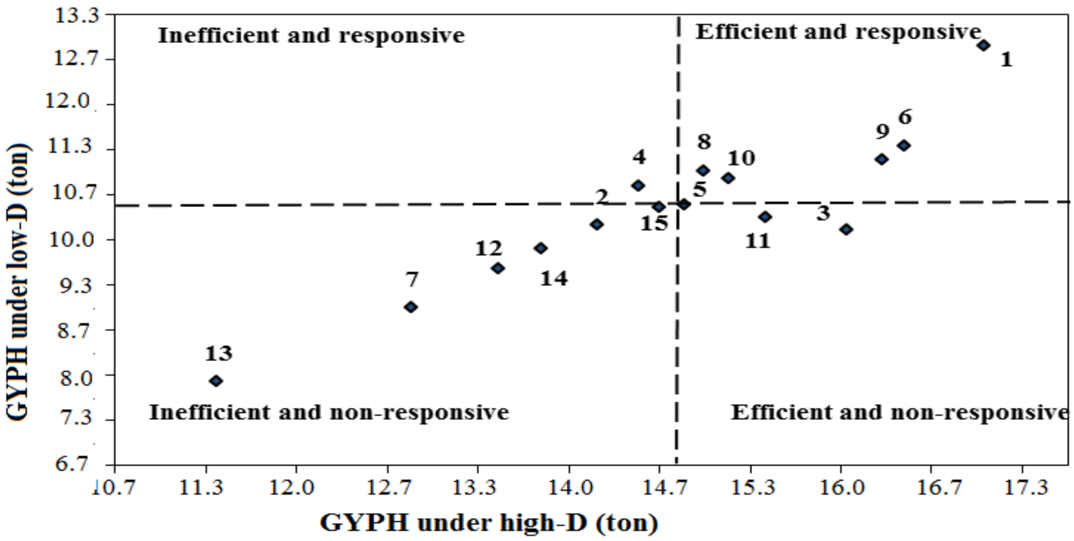


Figure 2: Relationships between grain yield/ha (GYPH) of 15 F_1 maize hybrids under high and low density (D) combined across 2013 and 2014 seasons. Broken lines represent mean of GYPH. Numbers from 1 to 15 refer to F_1 hybrids names).

Summarizing the above-mentioned classifications, it is apparent that the three parents L20, L53 and Sk5 and the F_1 crosses No.1(L20 × L53), No.6(L 53 × Sk5), No.9(L53 × Sd7), No.10(Sk5 × L18) and No.5(L20 × Sd7) occupied the first group; they are the most efficient (tolerant) to high density stresses and responsive to the good environment (low density). According to Fageria and Baligar [61] genotypes (progenies) belonging to the 1st group "efficient and responsive" (above all) and 2nd group "efficient and non-responsive" (to a lesser extent) appear to be the most desirable materials for breeding programs that deal with adaptation to high density stress. On the contrary, the three parents L18, L28 and Sd7 and the crosses No.13 (L18 × L28),No.7 (L53 × L18), No.12 (Sk5 × Sd7), No.14 (L18 × Sd7) and No.2 (L20 ×Sk5) occupied the fourth group in all classification; they are the most inefficient (sensitive to high density) and non-responsive to the good environment.

Quadratic and linear regression of GYPH on elevated plant density

Data were re-analyzed to evaluate GYPH responses of inbreds and hybrids across elevated plant density *via* regression technique. For each genotype or group of genotypes, quadratic and linear regression functions were performed for plant density effects. The regression functions were used to identify which plant density provides maximum GYPH for each genotype (or group of genotypes). The relationship between grain yield/ha of the inbreds across two years and plant densities is illustrated in Fig. (3). It is clear that the inbred L20 showed a quadratic response of increase to elevated plant density, with an optimum GYPH at plant density of ca 83,300 plants/ha. The four inbreds L53, Sk5, L28 and Sd7 showed near linear or completely linear response of increase to density levels, with a maximum GYPH at the highest plant density in this experiment (95,200 plants/ha). By contrast, the inbred L18 showed near linear response towards decrease in GYPH due to increasing plant density, with a maximum GYPH at the lowest plant density in this experiment (47,600 plants/ha). The relationship between plant density and GYPH of the studied F_1 crosses across years is illustrated in Fig. (4). In general, three F_1 crosses (L20 x L53, L53 x Sk5 and L53 x Sd7) that belong to the group E-R and classified as density tolerant showed clear curvilinear (quadratic) regression of GYPH increase up to more than 16 ton/ha with an optimum density of about 83,300 plants/ha. The rest of crosses (12 F_1's) showed near linear or completely linear regression of increase with an optimum density of 95,200 plants/ha. Three of these 12 crosses (L20 x L18, Sk5 x L18 and L20 x Sd7) that belong to the group E-NR, one (Sk5 x L18) that belongs to E-R group and one (L28 x Sd7) that belongs to IE-NR group showed maximum GYPH between 15 and 16 ton/ha. Moreover, five F_1 crosses (L20 x Sk5, L53 x L28, Sk5 x Sd7, L18 x L28 and L18 x L28) that belongs to IE-NR, one (L20 x L28) that belongs to IE-R and one (L53 x L28) that belongs to E-R group showed maximum GYPH between 11 and <15 ton/ha.

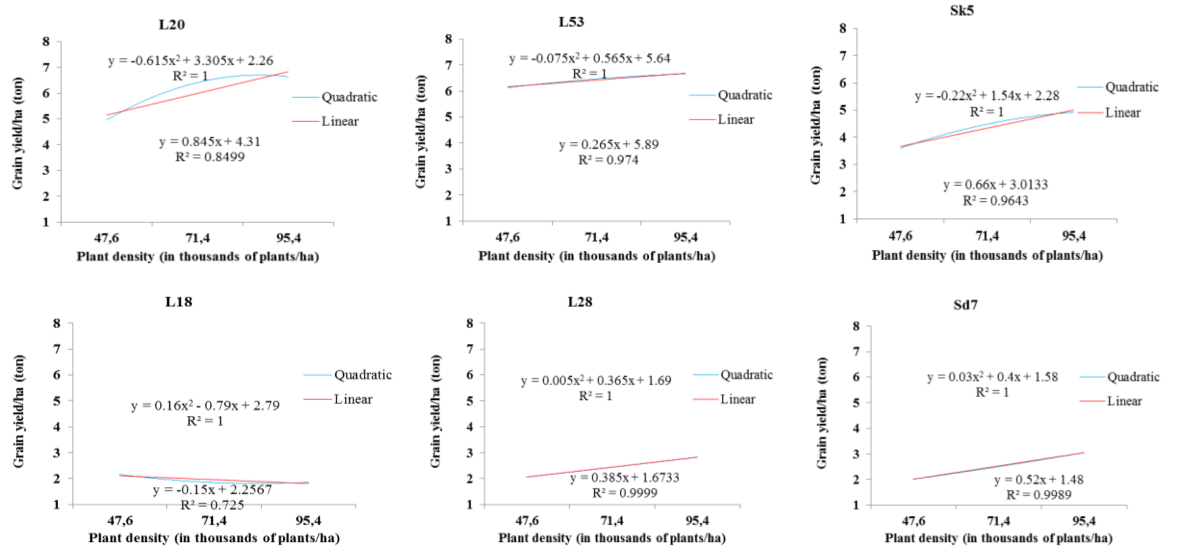
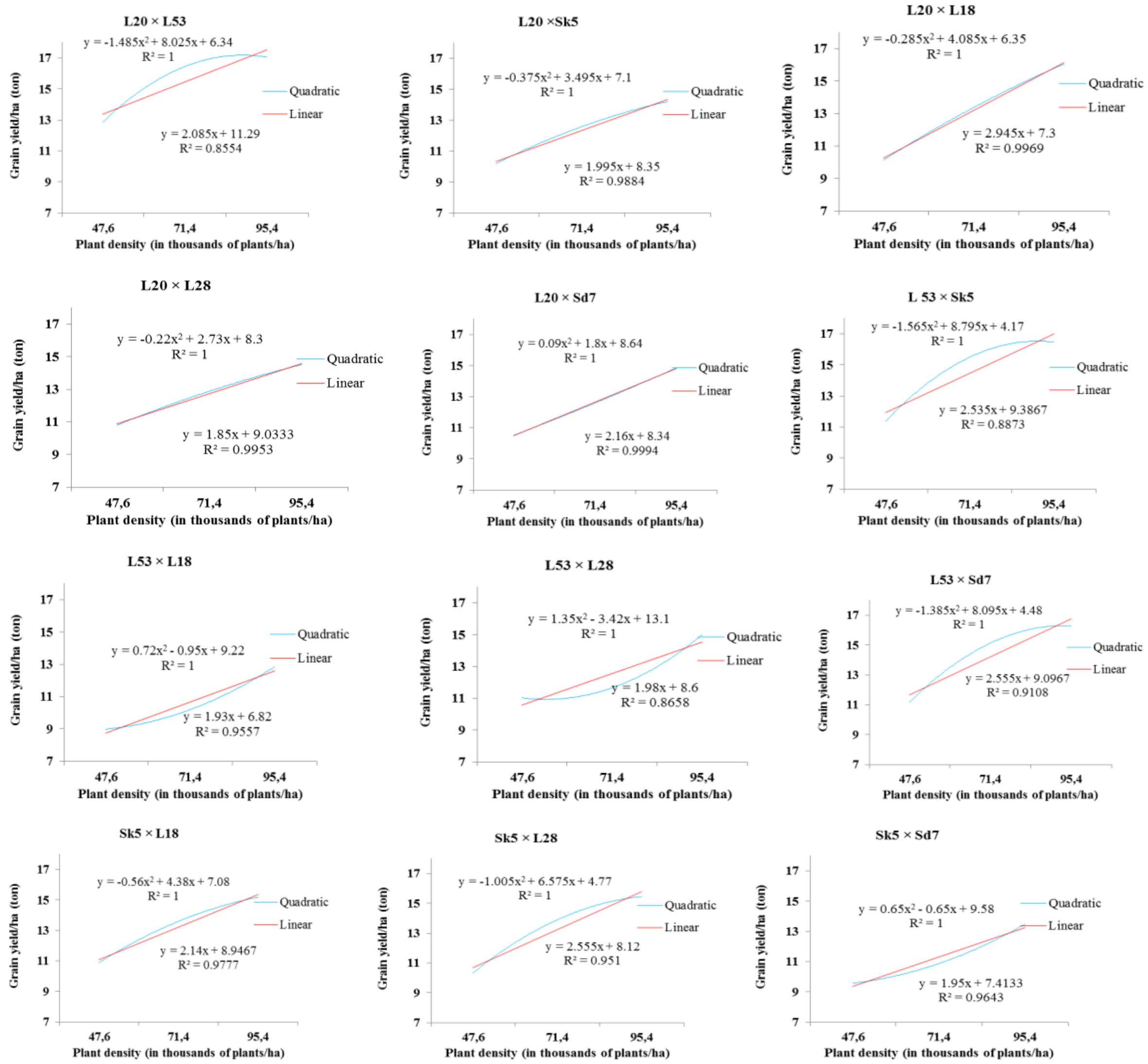


Figure 3: Linear and quadratic relationships between grain yield/ha of 6 inbreds and plant density across two seasons.



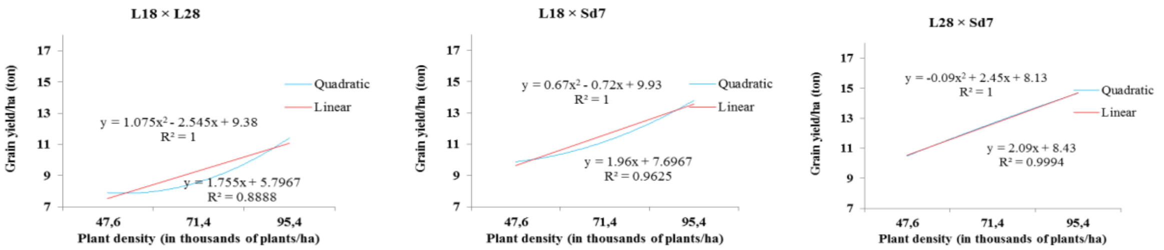


Figure 4: Linear and quadratic relationships between grain yield/ha of **15** *F_1 crosses and plant density across two seasons.*

In this context, Shapiro and Wortmann [62] reported that the corn grain yield typically exhibits a quadratic response to plant density with a near-linear increase across a range of low densities, a gradually decreasing rate of yield increase relative to density increase and finally a yield plateau at some relatively high plant density. Boomsma *et al.* [63] showed that under large ranges of plant density (54,000-104,000 plants/ha), higher densities required more N. Most recently, Clark [64] concluded that no support was found for the idea that increasing corn yield requires increases in both plant density and N rate above rates typically used. Our understanding of the complexities of hybrid interactions with plant density will require additional work.

Conclusion

Some newly developed maize genotypes could maximize maize productivity reaching 17,05 t ha^{-1} in the cross L20 × L53 on the same land unit area, if they are grown at twice the plant population density of 95,200 plants ha^{-1} used in Egypt, with a superiority of 27.0% over the best check in this study (SC 2055). The same cross also gave the highest grain yield (16.45 t ha^{-1}) under medium plant density (71,400 plants ha^{-1}) with a superiority of 30.8% over the same best check. This study concluded that to obtain maximum grain yield from a hybrid under elevated plant density, it is better that both of its two parents to be tolerant to high plant density. This study identified the best plant population density for giving the highest grain yield per unit land area for the studied maize genotypes. The inbred L20 showed a quadratic response to elevated plant density, with an optimum GYPH at plant density of ca 83,300 plants/ha. The two inbreds L53 and Sk5 showed near linear response to density levels, with maximum GYPH at the highest plant density in this experiment (95,200 plants/ha). By contrast, the inbred L18 showed near linear response towards decrease in GYPH due to increasing plant density, with maximum GYPH at the lowest plant density in this experiment (47,600 plants/ha). In general, three F_1 crosses (L20 x L53, L53 x Sk5 and L53 x Sd7) that belong to the group efficient-responsive showed clear curvilinear (quadratic) regression of GYPH increase up to more than 16 ton/ha with an optimum density of about 83,300 plants/ha. The rest of crosses (12 F_1's) showed near linear or completely linear regression with an optimum density of 95,200 plants/ha. Understanding of the complexities of hybrid interactions with plant density will require additional work.

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