The Journal of Agricultural Sciences - Sri Lanka
Vol 15, No. 3, September, 2020. Pp 387-394
http://doi.org/10.4038/jas.v15i3.9030

Varietal Response to Double Plant Population Density in Maize: Implications for Breeding

Q.O. Oloyede-Kamiyo[1*] and A.B. Olaniyan[2]

Date Received: 1st November 2019 / Date Accepted: 29th June 2020

ABSTRACT

Purpose : *Suboptimal plant population has been identified as one of the causes of low yield of maize in Nigeria, hence the need for increased plant population per hectare. Maize varieties respond differently to increased plant population density. There is need to identify maize varieties that respond well to increased plant population density towards developing maize for tolerance to population stress.*

Research Method : *Four new maize varieties were tested under population density of 53,333 (ND) and 106,666 plants/ha (DD). The trials were conducted at two locations in two seasons. The experimental design was split plot in three replications. The DD plots received additional 50% of fertilizer. Data were collected on agronomic and yield traits.*

Findings : *Mean squares due to density were significant for grain yield and the number of ears per plant. Mean squares due to variety was significant for all traits except the number of ears per plant. Yield and plant appeal under DD were generally lower than under ND except in few instances. For instance, grain yield under DD was higher (4.96tons/ha) than under ND (4.61tons/ha) for BR9943DMRSR at Ile-Ife, and for BR9928DMRSR (2.47tons/ha under DD, 2.09tons/ha under ND) at Ilora. Only BR9928DMRSR had an increased grain yield from ND (2.41tons/ha) to DD (2.48tons/ha) across locations.*

Originality / Value : *The variety, BR9928DMRSR, with increased yield and reduced plant height from ND to DD seemed promising for improvement for tolerance to plant population stress.*

Keywords: *Maize (Zea mays L), Plant population density, Population stress, Varietal response*

INTRODUCTION

Maize yield in Nigeria has been low when compared to some other countries in Africa. The reason adduced to this yield disparity has been low soil nitrogen, problem of pests and diseases as well as poor access to quality seeds. Apart from these factors, one other major cause of poor yield of maize in Nigeria is suboptimal plant population. When adequate plant population is not maintained, low yield results. The recommended plant population for maize is 53,333 plants/ha at spacing of 25cm within row and 75cm between rows at one plant per hill and a population density of 80,000 plants ha^{-1} was found to be optimal for hybrids (Olaniyan, 2014).

During the Presidential Initiative on Doubling Maize project (PIDOM), an attempt was made to double the recommended maize plant population of 53,333 plants per hectare with the aim of doubling maize yield in Nigeria and success was recorded at on-station trial. Although weed emergence may be low under high population density, weed control is a bit difficult especially at the early stage due to clumsiness of the plants. The advent of selective post-emergence herbicide for maize helps to solve this problem. Several population densities have been used by different workers to increase maize yield. Murányi (2015)

[1] *Institute of Agricultural Research and Training, Obafemi Awolowo University, Nigeria*

qudratkamiyo@gmail.com

[2] *Department of Agronomy, University of Ibadan, Ibadan, Nigeria*

ORCID http://orcid.org/0000-0002-9409-0259

and Sangoi, (2000) used 30,000-90,000 plants/ha; Yada (2011) used 50,000 – 150,000 plants/ha; Kondombo *et al.,* (2017) used 62,500 - 93,750 plants/ha; Al-Naggar *et al.,* (2015) used 47,600-95,200 plants/ha; Novacek (2011) used 69,136-106,173 plants/ha. However, the ideal plant number per area depends on several factors such as water availability, soil fertility, hybrid maturity and row spacing (Staggenborg *et al.,* 1999). Ipsilandis and Vafias (2005) reported that the graph of maize yield under increased density is curvelinear. Tollenaar *et al.,* (1997) and Kgasago (2006) reported that maize grain yield declines when plant population density is increased beyond the optimum plant population density, primarily because of intense interplant competition for incident photosynthetic photon flux density, nutrients and water.

High-density has been reported to delay stalk biomass accumulation in maize variety, BSCB1, but not in variety, BSSS. High density also delayed ear shoot and tassel biomass accumulation in BSSS but not BSCB1 (Stein *et al.,* 2016), indicating that maize varieties vary in their response to high plant population density. Ability of maize variety to increase in yield with increased density shows it level of tolerance to population stress. Organic farmers require effective alternative weed control methods, including crops bred to tolerate higher planting densities and thus competitively suppress weeds. Duvick (1997), suggested that the best way to effect future gains in yielding ability may be to make further improvement in tolerance to high plant population density in combination with improvement in potential yield per plant under low stress environments. Tollenaar and Wu (1999) suggested that increased stress tolerance, combined with increased crop uniformity under stress condition, will probably continue to provide high potential for yield improvement in maize. Apart from increase in yield, high plant population density reduces the direct impact of tropical sunlight onto the soil, thereby reducing excessive heat and conserve soil moisture through canopy formation. The objectives of this study were therefore, to (i) determine the effect of double plant population density on performance of four maize varieties (ii) identify the promising variety for tolerance to population stress.

MATERIALS AND METHODS

The study was carried out at Ilora and Ile-Ife out-stations of the Institute of Agricultural Research and Training (IAR&T), Nigeria in 2017 and 2018 cropping season. However, the trial was carried out in Ile-Ife only in 2017. Ilora is located in the derived savannah (7^o 48’ N and 3^o 54’ E), while Ile-Ife is located in the rain forest zone of Nigeria (7^o 31ˋN and 4^o 31ˋE).

The experimental site was ploughed twice before planting. Four new maize varieties were tested under recommended population density (ND) of 53,333 plants/ha and double plant population density (DD) of 106,666 plants/ha. Similar plant spacing of 75cm inter-row and 25cm intra-row was used for both ND and DD. However, ND had one plant per hill, while the DD plots had two plants per hill. To test for the better planting geometry under double density, another DD plot was established (DDp) which also had one plant per hill as in ND, but there was also planting at the inter-row spaces. The four maize varieties used were LNTP-W, BR9943-DMRSR, LNTP-Y and BR9928-DMRSR. The first two are white, while the remaining two are yellow -grained varieties. The varieties were sourced from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria and the Institute of Agricultural Research and Training (IAR&T). The experiment was laid out in a split plot design with three replications. The main plot was plant population density, while the sub plot was the maize varieties. Plot size was 3m by 3m.

Pre-emergence herbicide (Atrazine and paraquat) was applied a day after planting, while post emergence herbicide (Nicosulforon) was applied four weeks after planting. NPK fertilizer was applied within fourteen days after planting, followed by urea at six weeks after planting. However, double density plots received additional fifty percent of fertilizer. Ampligo (100g/l Chlorantraniliprole, 50g/l- Lambda cyhalothrin) was used to control insects mainly fall armyworm on the field.

Data collection

Data were collected on agronomic and yield parameters. The number of plants per plot was counted three weeks after planting as plant stands. Days to 50% anthesis was recorded as the number of days from sowing to when half of the plants in a plot shed pollen. Anthesis-silking interval (ASI) computed as the interval in days between silking and pollen shed. Plant height was measured in centimeter from five randomly selected plants within each plot after flowering as the distance from the base of the plant to the base of the tassel. Average of the five plants was recorded. Ear-plant height ratio was estimated as the ratio of ear height to plant height. Root lodging was taken at maturity as the number of plants that made angle 45^o to the ground level or laid flat on the ground in a plot expressed as percentage of plant stands per plot. Plant aspect was rated per plot on scale of 1-9, on how appealing and strong the plants are. 1 was excellent, while 9 was poor. The number of ears per plant (EPP) was estimated as proportion of the total number of harvested ears per plot divided by the number of harvested plants per plot. Few ears were shelled from each plot to determine percentage moisture using moisture meter. Grain yield adjusted to 14% moisture was estimated from field weight at 80% shelling percentage. Ear diameter was measured in centimeter using vernier caliper. Average of five randomly selected cobs from each plot was used.

Statistical Analyses

Mean, standard error and CV were estimated. Combined analyses of variance (ANOVA) was performed using SAS version 9.2 (SAS Institute, 2009). Means were separated using Duncan Multiple Range Test.

RESULTS AND DISCUSSION

Combined analysis of variance for the traits studied

Combined analysis of variance for the traits studied is presented in Table 01. Mean square of environment was significant for all traits except ASI and root lodging. Mean squares due to density and mean square due to environment by density was significant for only grain yield and the number of ears per plant. Mean squares due to variety were significant for all traits except the number of ear per plant. Mean squares due to environment by variety was significant for the number of days to 50% pollen shed, plant height grain yield and ear diameter. Mean squares due to other interactions were not significant for any of the traits. The significant mean square for environment and non-significant mean squares of environment by density interaction for most of the traits indicated that irrespective of the environment, the varieties will respond differently under different population density. The significant mean square of variety was expected because the varieties are distinct in morphological and other agronomic traits. LNTP-W and LNTP-Y are medium in height, while BR9943DMRSR and BR9928DMRSR are naturally taller plants.

Effects of population density and variety on the traits studied

Effects of population density and variety on the traits studied are shown in Table 02. LNTP-Y flower faster with mean days to 50% pollen shed of 57days followed by LNTP-W. BR9928DMRSR flowered late with longer ASI. It was also the tallest with mean height of 159.9cm, highest percentage lodging (19%) and poor plant appeal, although the grain yield was moderate (2.23tons/ha). LNTP-W was the shortest in height (145cm) with low ASI of about 3 days. It had a good ear-plant ratio (0.47) with better plant appeal and the highest grain yield (3.0tons/ha). Usually tall plants are prone to lodging, and lodging leads to poor plant appeal. Density did not have effect on most of the traits. However, the plant appeal was better in normal density (ND) and worst in DDp. Poor plant appeal under DDp could be due to overcrowding of plants at the inter-row spaces.

Grain yield was also better in ND (3.14tons/ha) followed by DD (2.72tons/ha) and least in DDp (1.82tons/ha). The number of ears per plant and ear diameter were also least in DDp. One area of concern when increasing crop density is the effect on ear characteristics as reported by Shelton and Tracy (2013). When the number of individuals per area is increased beyond the optimum plant population density, there is a series of consequences that are detrimental to ear ontogeny and result in barrenness (Sangoi, 2000). This reflected in the present study as grain yield and ear diameter reduced from normal density of 53,333 plants/ha to double density of 106,666 plants/ha. Yada (2011) reported that narrowing rows spacing from 0.45 to 0.225 m and plant densities above 100 000 plants ha-1 led to formation of smaller ears, a shorter ear length and diameter, favored plant lodging and development of barren plants with an obvious negative impact on grain yield.

Table 01: Mean squares from combined analysis of variance for the traits studied in the four maize varieties under varied plant population densities in Ile-Ife and Ilora in 2017 and 2018.

Source	df	Days to 50% pollen shed	ASI	Plant height (cm)	Ear-Plant height ratio	Root lodging (%)	Plant aspect (1-9)	Grain yield (t/ha)	Ears per plant	Ear diameter (cm)
Env	2	87.65**	12.42	12527.01**	0.02*	0.03	160.72**	24.32**	0.88**	25.52**
Rep (Env)	6	0.78	1.06	1520.99**	0.01**	0.09**	4.00**	2.28**	0.11**	2.81**
Density	1	0.12	0.97	22.69	0.00	0.02	2.96	8.95**	0.30*	0.06
Env*Density	2	0.76	0.60	231.46*	0.00	0.03	0.54	2.25**	0.13**	0.02
Rep*Density	2	5.90**	2.33	177.21	0.00	0.01	2.29**	1.01	0.04	0.03
Variety	3	10.69**	10.63**	1814.04**	0.01**	0.04*	4.47**	3.48**	0.04	0.52**
Env*Variety	6	3.97**	2.53	317.27**	0.00	0.01	0.88	1.89**	0.05	0.13**
Density*Variety	3	2.77	3.79	151.60	0.00	0.02	0.33	0.51	0.02	0.01
Env*Density*Variety	6	1.37	1.38	105.50	0.00	0.00	0.26	0.78	0.05	0.01
Error	18	1.29	2.47	90.74	0.00	0.02	0.61	0.56	0.03	0.03

*Env: Environment (year and locations); ASI: Anthesis-Silking Interval; df: degree of freedom; *, **: significant at P = 0.05 and 0.01 respectively.*

Table 02: Effect of population density and variety on the traits studied.

Treatment	Days to 50% pollen shed	ASI	Plant height (cm)	Ear-Plant height ratio	Root lodging (%)	Plant aspect (1-9)	Grain yield (t/ha)	Ears per plant	Ear diameter (cm)
Variety									
LNTP-W	57.83b	2.58b	145.0c	0.47a	12.02b	3.63b	3.0a	0.82a	3.55b
LNTP-Y	57.00c	2.76b	142.00c	0.48a	9.92b	4.41a	2.15b	0.72a	3.71a
BR9928DMRSR	58.88a	4.17a	159.90a	0.43b	18.98a	4.38a	2.23b	0.78a	3.21c
BR9943DMRSR	58.10b	3.52ab	154.00b	0.47a	11.96b	3.57b	2.84a	0.82a	3.72a
Density									
ND	58.1a	3.33a	151.0a	0.45a	15.9a	3.73b	3.14a	0.87a	3.61a
DD	58.00a	3.00a	150.30a	0.46a	12.12a	3.95ab	2.72b	0.84a	3.51b
DDp	57.83a	3.47a	149.80a	0.47a	12.10a	4.30a	1.82c	0.64b	3.48b

ND: Recommended density of 53,333 plants/ha with one plant per hill at 25cm x 75cm spacing; DD: Double plant population density of 106,666 plants/ha with two plants per hill at 25cm x 75cm spacing; DDp: Double density with one plant/hill and interrow planting (at 25cm x 37.5cm spacing). Values with the same alphabet are not significantly different from each other.

Yield performance of varieties under different densities in each location

Yield performance of the varieties at Ile-Ife and Ilora is presented in Table 03. Yield performance was better in Ile-Ife for all the varieties. LNTP-W yielded the highest at Ile-Ife with grain yield of 5.26tons/ha under ND. This yield was comparable to its yield under DD in Ile-Ife (5.18tons/ha). LNTP-W had the least yield under DDp at Ile-Ife (2.19tons/ha). BR9943DMRSR followed LNTP-W in yield performance at Ife with grain yield of 4.61tons/ha under ND, but it had a better yield of 4.96 under DD at Ile-Ife, and the worst yield under DDp (2.39tons/ha). LNTP-W also yielded the highest under ND and DD at Ilora with grain yield of 2.73tons/ha and 2.43tons/ha respectively, followed by BR9943DMRSR with yield of 2.6tons/ha under ND, but the yield was much lower in DD (2tons/ha). Mean yield performance across locations for LNTP-W and BR9928DMRSR under ND was comparable to their respective performance under DD. However, the difference in yield between ND and DD across locations was the lowest in BR9928DMRSR (3.1%).

Generally, at both locations, LNTP-W performed best under ND and DD. This was so due to the yield potential of each maize variety, however, this did not translate to high level of tolerance to population stress. Yield under DD was a bit lower than under ND except in few instances. For instance, grain yield under DD was higher than under ND for BR9943DMRSR at Ile-Ife and for BR9928DMRSR at Ilora. Novacek (2011) working on population density of 69,136 to 106,173 plants ha-1 also reported that varying maize hybrids, plant population, and row configuration had inconsistent effects on grain yield, yield components, plant morphology and leaf area, interception of solar radiation, and stalk lodging. However, for bt maize hybrids, yield increased linearly and the highest target population resulted in the greatest grain yield. Bt hybrids lodged less in three of five environments. Shelton and Tracy (2013) working on hybrids reported that increase in yield results from the ability of the newest hybrids to continue to produce an ear on every plant, while the older hybrids tend to have barren plants, or plants with few kernels, at the highest densities. Kondombo *et al.,* (2017) working on sorghum reported that plant densities of 83,500 and 93,750 plants/ha gave the highest grain yield compared with population density 62,500 plants/ha. Plant population for maize maximum economic grain yield varies from 30,000 to over 90,000plant/ha, depending on water availability, soil fertility, maturity rating, planting date and row spacing.

Overall performance of the varieties under varied densities

Overall performance of the varieties under varied density is presented in Table 04. Flowering, ASI and ear-plant ratio did not differ significantly under any of the densities. Grain yield and ear diameter reduced from ND to DD. Sher *et al.,* (2017) reported that at higher plant populations, reduced grain yield resulted from increased anthesis-silking interval (ASI) and this is followed by barrenness. The ear-plant height ratio recorded at high density in this study was similar to that reported by Tang *et al.,* (2018). Height of LNTP-W reduced slightly from 148.8cm in ND to 141cm in DD and DDp. The plant appeal seemed better in ND than in DD and DDp. Poor plant appeal under DDp was due to overcrowding from close canopy which may lead to a higher risk of lodging, hence causing significant yield loss of the crop as also reported by Sher *et al.,* (2017). LNTP-W was the highest in yield under all density levels followed by BR9943DMRSR. Their yield and ear diameter however, reduced from ND to DD with the worst yield in DDp. All varieties performed worst under DDp. It is however worth noting that among all the varieties, only BR9928DMRSR had its grain yield increased from ND (2.41tons/ha) to DD (2.48tons/ha). Its height also reduced slightly from 159cm under ND to 157cm under DD and DDp.

Despite the relative increase in supply of nitrogen fertilizer at double plant population density, the yield and performance of most of the varieties were still low. This is an indication that plant population of as high as 106,666 plants/ha for open-pollinated maize varieties could be detrimental and not economical.

Overcrowding from high plant population could lead to competition for air and water which will eventually affect grain yield. Shi *et al.,* (2016) reported that taking into account the need for high grain yield and resource use efficiency, a 30% reduction in N supply, and an increase in plant population density to 5.25 plants m–2, would lead to an optimal balance between yield and resource use efficiency. Al-Naggar *et al.,* (2015) reported that maize response to elevated plant population density combined with lowered N-fertilizer rate is genotype dependent.

Table 03: Yield (tons/ha) performance of the varieties under varied densities at Ilora and Ile-Ife in 2017 and 2018.

Variety	ND			DD			DDp		
	Ile-Ife	Ilora	Mean	Ile-Ife	Ilora	Mean	Ile-Ife	Ilora	Mean
LNTP-W	5.26	2.73	3.995	5.18	2.43	3.805	2.19	2.42	2.305
LNTP-Y	4.25	2.34	3.295	2.35	1.64	1.995	1.98	1.58	1.78
BR9928DMRSR	3.05	2.09	2.57	2.51	2.47	2.49	1.86	1.44	1.65
BR9943DMRSR	4.61	2.61	3.61	4.96	2.0	3.48	2.39	1.87	2.13

ND: Recommended density of 53,333 plants/ha with one plant per hill at 25cm x 75cm spacing; DD: Double plant population density of 106,666 plants/ha with two plants per hill at 25cm x 75cm spacing; DDp: Double density with one plant/hill and interrow planting (at 25cm x 37.5cm spacing).

Table 04: Overall performance of the maize varieties under varied density at both locations in 2017 and 2018.

Density	Variety	Days to 50% pollen shed	ASI	Plant height (cm)	Ear-Plant height ratio	Root lodging (%)	Plant aspect (1-9)	Ears per plant	Grain yield (t/ha)	Ear diameter (cm)
ND	LNTP-W	58.44	2.00	148.80	0.46	16.26	3.56	0.89	3.58	4.12
ND	LNTP-Y	57.67	3.00	133.60	0.47	8.30	4.33	0.86	2.98	4.13
ND	BR9928DMRSR	59.11	4.78	159.06	0.43	24.79	4.44	0.86	2.41	3.70
ND	BR9943DMRSR	59.00	3.11	143.40	0.43	11.91	3.56	0.92	3.28	4.10
DD	LNTP-W	57.56	3.67	140.68	0.46	8.58	3.78	0.91	3.34	4.05
DD	LNTP-Y	57.89	2.56	136.54	0.47	9.18	4.72	0.76	1.88	3.99
DD	BR9928DMRSR	60.11	3.78	157.89	0.42	12.26	4.78	0.85	2.48	3.57
DD	BR9943DMRSR	58.67	3.33	148.23	0.45	13.47	3.67	0.91	2.99	3.95
DDp	LNTP-W	58.89	1.89	141.26	0.49	10.48	4.11	0.71	2.35	4.05
DDp	LNTP-Y	57.44	3.11	139.89	0.48	9.70	5.11	0.71	1.72	3.85
DDp	BR9928DMRSR	58.56	3.33	157.79	0.43	16.60	4.78	0.63	1.58	3.55
DDp	BR9943DMRSR	58.89	3.22	148.07	0.46	8.76	4.33	0.69	2.04	3.97
Mean		57.98	3.27	150.4	0.46	13.37	3.99	0.78	2.56	3.54
SE (P=0.05)		1.14	1.57	9.53	0.04	8.70	0.78	0.17	0.75	0.17
CV (%)		1.96	48.07	6.34	7.97	35.0	19.51	21.4	29.23	4.92

ND: Recommended density of 53,333 plants/ha with one plant per hill at 25cm x 75cm spacing; DD: Double plant population density of 106,666 plants/ha with two plants per hill at 25cm x 75cm spacing; DDp: Double density with one plant/hill and interrow planting (at 25cm x 37.5cm spacing).

While not directly breeding for weed suppression, one of the effects of the increased density tolerance of field corn is a rapidly closing canopy, which greatly reduces sunlight in the understory (Shelton and Tracy, 2013).

CONCLUSION

It can be concluded that plant population density of as high as 106,666 plants/ha is detrimental to open populated maize and additional 50% fertilizer at this population density is not economical. However, only BR9928DMRSR recorded high yield under high plant population density. This variety is a promising variety for improvement for tolerance to plant population stress.

Statement of conflict of interest

The authors declared that there is no conflict of interest on this manuscript.

REFERENCES

Al-Naggar, A.M.M., Shabana, R.A., Atta, M.M.M. & Al-Khalil, T.H. (2015). Maize response to elevated plant population density combined with lowered N-fertilizer rate is genotype-dependent. *The Crop Journal.* 3, 96-109. DOI: http://dx.doi.org/10.1016/j.cj.2015.01.002.

Duvick, D.N. (1997). What is Yield? In Developing drought and low N-tolerant maize. Proceedings of Symposium (Eds. G.O. Edmeades, B. Banzinger, H.R. Mickelson and C.B. Pena-Valdivia). March 25-29, 1996, CIMMYT, El Batan, Mexico.

Ipsilandis, C.G. & Vafias, B.N. (2005). Plant population density effects on grain yield per plant in maize: Breeding implications. *Asian Journal of Plant Science*. 4(1), 31- 39.

Kgasago, H. (2006). Effect of planting dates and densities on yield and yield components of short and ultra-short growth period maize (*Zea mays L*.). M.Sc. Thesis. Faculty of Natural and Agricultural Sciences Department of Plant Production and Soil Science. University of Pretoria pp 120.

Kondombo, C.P., Tamini, M., Barro, A. & Chantereau, J. (2017). Plant population density effects on agro-morphological traits and the yield of grain sorghum varieties in rainfed conditions in Burkina Faso. *Agricultural Science Research Journal*. 7(6), 221 – 229.

Murányi, E. (2015). Effect of plant population density and row spacing on maize (*Zea mays* L.) grain yield in different crop year. Columella - *Journal of Agricultural and Environmental Sciences.* 2 (1), 57-63. DOI: 10.18380/szie.colum.2015.1.57.

Novacek, M.J. (2011). Twin-Row Production and Optimal Plant Population for Modern Maize Hybrids. MSc Thesis. Agronomy and Horticulture. University of Nebraska-Lincoln.

Olaniyan, A.B. (2014). Maize: Panacea for hunger in Nigeria. *African Journal of Plant Science*. 9(3), 156.

SAS Institute Inc., (2003). SAS/STAT user's guide, version 9.1.3. SAS Institute Inc., Cary, NC, USA.

Sangoi, L. (2000). Understanding plant population density effects on maize growth and development: an important issue to maximize grain yield. *Ciência Rural, Santa Maria*, 31(1), 159-168.

Sher, A., Khan, A., Cai, L.J., Ahmad, M.I., Asharf, U., *et al.,* (2017). Response of maize grown under high plant population density; Performance, Issues and Management - A Critical Review. *Advances in Crop Science and Technology.* 5(3), 275 page 1-8. DOI: 10.4172/2329-8863.1000275.

Shelton, A.C. & Tracy, W.F. (2013). Genetic variation and phenotypic response of 15 Sweet Corn (*Zea mays* L.) hybrids to population density. *Sustainability.* 5, 2442-2456. DOI:10.3390/su5062442

Shi, D., Li, Y., Zhang, J., Liu, P., Zhao, B., & Dong S. (2016). Increased plant population density and reduced N rate lead to more grain yield and higher resource utilization in summer maize. *Journal of Integrative Agriculture*. 15(11), 2515–2528. DOI: 10.1016/S2095-3119(16)61355-2.

Staggenborg, S.A., Fjell, D.L., Delvin, D.L., Gordon, W.B., Maddux, L.D. & Marsh, B.H. (1999). Selecting optimum planting dates and plant populations for dryland corn in Kansas. *Journal of Prod*uction *Agriculture*. 12, 85-90.

Stein, M., Miguez, F. & Edwards, J. (2016). Effects of plant population density on plant growth before and after recurrent selection in maize. *Crop Science.* 56, 2882–2894. DOI: 10.2135/cropsci2015.09.0599.

Tang, L., Ma, W., Noor, M.A. Li, L., Hou, H., Zhang, X. & Zhao, M. (2018). Density resistance evaluation of maize varieties through new “Density–Yield Model” and quantification of varietal response to gradual planting density pressure. *Scientific Reports.* 8,17281. DOI:10.1038/s41598-018-35275-w

Tollenaar, A., Aguilera, A. & Nissank, S.P. (1997). Grain yield is reduced more by weed interference in an old than in a new maize hybrid. *Agronomy Journal.* 89, 239-246.

Tollenaar, M. & Wu, J. (1999). Yield improvement in temperate maize is attributable to greater stress tolerance. *Crop Science*. 39, 1597- 1604.

Yada, G.L. (2011). Establishing optimum plant populations and water use of an ultra-fast maize hybrid (*Zea mays* L.) under irrigation. PhD Thesis. Department of Soil, Crop and Climate Sciences, Faculty of Natural and Agricultural Sciences, University of the Free State BLOEMFONTEIN viii +151pg.