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REGULAR ARTICLE

Performance of old and new maize hybrids grown at high plant densities in the tropical Guinea savanna

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ABSTRACT

Genetic improvement of maize hybrids for superior stress tolerance has contributed to increased yield by allowing hybrids to be planted at higher plant populations. This study was conducted to evaluate the response of maize hybrids developed in the Nigerian Savanna from different eras to high plant densities. Field research was conducted in 2002 and 2003 at the experiment station of the Institute of Agricultural Research, Samaru in the northern Guinea savanna zone, Zaria, Nigeria. Six hybrids—two from 1980s, two from 1990s and two from the 2000 eras—were evaluated at three plant densities using a split-plot design with three replications. Plant densities (53,333, 66,666, and 79,999 plants ha^{-1}) constituted the main plots and the six hybrids were assigned to subplots. Plant densities above 53,333 plants ha^{-1} reduced grain yield of hybrids, which might be due to the fact that the hybrids evaluated were selected at low plant densities and were therefore not tolerant to plant-density stress. It might also be due to the low yield potential in the experimental area, which did not allow yield increases at high plant densities. There were significant differences among the tested hybrids. The hybrids released in 2000 out-yielded the hybrids released in 1980 and 1990s at all plant densities. To improve maize grain yield at high plant densities, we recommend that the hybrids be selected at high plant densities.

Key Words: *maize hybrids; plant densities; maize grain yield.*

INTRODUCTION

Grain yield of maize (*Zea mays* L.) is more affected by variations in plant population density than of other members of the grass family because of low tillering ability, monoecious floral organization, and the presence of a relatively short flowering period (Sangoi et al., 2002). The ideal plant population depends on several factors, e.g., water availability, soil fertility, hybrid maturity, and row spacing (Argenta et al., 2001). The use of lower plant densities delays canopy closure and decreases light interception, leading to high grain production per plant but low grain production per unit area (Andrade et al., 1999). On the other hand, higher plant densities enhance interplant competition for assimilates, water and nutrients (Edmeades et al., 2000). High plant densities also stimulate barrenness and increase the anthesis-silking interval (ASI) (Sangoi et al., 2001), thereby reducing kernel number per unit area - the main yield component of maize.

According to Duvick and Cassman (1999), average maize grain yield per unit area increased dramatically during the second half of the 20th century. This yield gain was attributed to genetic improvement, climate change, improvement in crop management practices, and greater tolerance of modern hybrids to low soil-moisture stress (Dwyer et al., 1992) and weed interference (Tollenaar et al., 1997). Yield gain has also been attributed to tolerance of maize to high plant densities (Duvick and Cassman, 1999; Tollenaar and Wu, 1999). The optimal row width and plant density in field maize-production systems continue to intensify in the USA as maize genetic technologies evolve (Duvick and Cassman, 1999).

Maize hybrids differ in their response to plant density (Echarte et al., 2000; Maddonni et al., 2001). Hybrids developed recently could withstand higher plant density levels than the older hybrids (Tollenaar, 1989). The more recent hybrids were found to have decreased lodging at higher plant populations, and also they were better able to withstand environmental stress, resulting in production of fewer barren plants (Tollenaar, 1991).

Research on the use of hybrids in Nigeria started in the early 1970s (Fajemesin, 1978; Fakorede et al., 1993) and became an integral part of the Maize Improvement Program at the International Institute of Tropical Agriculture (IITA) in 1979 (Kim, 1997). Experimental hybrids were tested on farmers' fields located all across the country in 1984 (Fakorede et al., 1999) and were found to yield considerably higher than the widely grown open-pollinated varieties. Since then, many commercial hybrids have been developed and marketed by seed companies. Despite the yield advantage, there is widespread belief in Nigeria that hybrids are less stress tolerant and therefore require higher inputs than open-pollinated varieties. Traditionally both hybrids and open-pollinated varieties are selected at 53,333 plants ha^{-1} with a row width of 0.75 m and within a row distance of 0.25 m. There is no information on the response of maize hybrids developed in the Nigerian savannas to higher plant densities. The objective of this study was to evaluate the performance of maize hybrids, developed in Nigerian Savannas during the past 20 years, at plant densities higher than 53,333 plants ha^{-1}.

MATERIAL AND METHODS

STUDY SITE AND CULTURAL PRACTICES

Field research was conducted in 2002 and 2003 on the experiment station of the Institute of Agricultural Research, Samaru in the northern Guinea savanna zone, Zaria, Nigeria (7.38° E, 11.11° N, 686 m asl). The soil type was a fine-loamy, Isohyperthermic Plinthustalf. The total rainfall received at this site was 1009.5 mm in 2002 and 1139 mm in 2003, and the average temperature was 25° C in 2002 and 26° C in 2003.

Six hybrids developed and widely tested in the Nigerian savanna from 1982 to 2000 were used in this study; two hybrids were from the 1980s (8321-21 and 8425-8), two from the 1990s (9801-11 and 9803-2), and two from 2000s (0103-11 and 0103-15). Trials were planted on 30 June 2002 and 1 July 2003. In both years, the trial was laid out in a split-plot design with three replications. Three plant densities—53,333, 66,666, and 79,999 plants ha^{-1}—were the main plots, whereas the six hybrids were the subplots within each main plot. There were four rows in each sub-plot; the rows were 5 m in length and spaced 0.75 m apart. Plots were over-planted and hand-thinned to achieve the desired target density at two weeks after planting. The previous crop at the test site was soybean (*Glycine max* (L.) Merrill), followed by two years of fallow. At planting, fertilizer was applied at the rate of 40 kg/ha each of N, P, and K. Additional N fertilizer, in the form of urea, was applied at the rate of 60 kg N/ha five weeks after planting (WAP). Weeds were controlled using glyphosate (N-(phosphonomethyl) glycine) two weeks before land preparation, and paraquat (1:1-dimethly-4, 4'-bipyridinium dichloride) at seven WAP.

Days from sowing to 50% pollen shed (anthesis date) and 50% silk extrusion (silking date) were determined using 30 plants in the middle two rows of each plot. Anthesis-silking interval (ASI) was calculated as the difference between days to anthesis and silking. The percent root lodging was recorded from the two central rows. Grain yield was recorded from the two central rows of each plot, excluding the end plants in each row. The total number of plants and ears were counted in each plot at harvest. The number of ears/plant was then calculated as the total number of ears at harvest divided by the total number of plants harvested. Ears harvested from each plot were shelled and the percent grain moisture was determined using a Dickey-John moisture tester (Model 14998, Dickey-John Corporation, Auburn, Alabama). Grain yield, adjusted to 12% moisture, was computed from the shelled grain.

Data were subjected to analysis of variance (ANOVA) using the GLM procedure in SAS (SAS Institute, 1990). Data for the two years with the exception of % root lodging, which was collected only in 2003, were analyzed according to a split-split-plot model with years as the first factor, and plant density as the second factor, and hybrids as the third factor. Data on % root lodging for 2003 were also analyzed using a split plot approach. Means' separation among treatments was conducted using the LSD at $P \leq 0.05$.

RESULTS AND DISCUSSION

Hybrids and plant densities influenced significantly days to 50% silking, ASI, % root lodging, ears per plant, and grain yield. Hybrid × plant density interaction was significant for all traits measured except % root lodging (Table 1).

REPRODUCTIVE RESPONSE TO PLANT DENSITY

Days to mid silking increased with increases in plant population for all hybrids. Averaged across genotypes, silking was delayed by three days as plant population increased from 53,333 to 66,666. In relation to plant population of 53,333, days to silking was delayed by five days at 79,999 plants ha^{-1} (Table 2). Silk delay due to high plant population varied with hybrids and was not consistent between the old and new hybrids. High plant population increased ASI for all hybrids evaluated. There were no significant differences among hybrids at plant populations of 53,333 and 66,666, except that the older hybrid of the year 1980, 8321-21, and the year 1990 hybrid, 9801-11, recorded significantly higher ASI than the other hybrids at 66,666 plants ha^{-1}. At plant population of 79,999 plants ha^{-1}, the year 2000 hybrids had significantly lower ASI than those from the older eras. ASI for year 1980 hybrids did not significantly differ from those of the year 1990 hybrids.

ROOT LODGING, NUMBER OF EARS PER PLANT AND GRAIN YIELD

Plant densities above 53,333 increased root lodging (Table 3). Differences among hybrids were the largest at 79,999 plants ha^{-1}. The year 1980 and 1990 hybrids recorded higher percentage of root lodging than the year 2000 hybrids. High plant populations stimulated barrenness in all the hybrids evaluated. Older hybrids recorded lower number of ears per plant than the newer ones. Nevertheless, on average, the year 1990 hybrids had lower number of ears per plant than those of the year 1980 (Table 4).

Table 1. ANOVA of response to plant density of flowering time, anthesis, ears per plant, lodging, and grain yield of six maize hybrids.

		Mean Square				
Source	Df	Days to silking	Days to anthesis	ASI	Ears per plant	Grain yield
Replicate	2	2.918	2.218	1.155	0.01531	5491029*
Years	1	3.226	1.190	0.4388	0.009946	57935
Error A	2	3.955	0.9082	1.2369	0.01783	1651244
Density	2	306.4**	14.74**	186.8**	2.019**	41109981**
Years × Density	2	1.030	1.482	0.6473	0.003808	775800
Error B	8	0.3728	0.8127	0.5982	0.007616	2433270
Hybrids	5	28.74**	6.252**	9.844**	0.1420**	8078008**
Years × Hybrids	5	3.543	1.305	0.5386	0.006097	136050
Density × Hybrids	10	4.253*	2.935*	2.177**	0.08553**	2495884**
Years × Density × Hybrids	10	1.210	1.369	0.6846	0.006490	163561
Error C	60	2.088	1.322	0.6344	0.017836	714003
	Df	Lodging				
Replicate	2	41.19*				
Density	2	171.2**				
Error A	4	36.13				
Hybrids	5	26.06*				
Density × Hybrids	10	15.97				
Error B	30	8.770				

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

Table 2. Effect of plant population on agronomic performance of maize hybrids from different eras of breeding.

		Days to silking				Days to anthesis				ASI			
		Plants ha^{-1}											
Treatment	Era	53,333	66,666	79,999	Mean	53,333	66,666	79,999	Mean	53,333	66,666	79,999	Mean
Years													
2002		62	65	68	65	61	62	63	62.0	1	3	5	3
2003		62	65	68	65	62	62	63	62.3	1	3	5	3
Hybrids													
0103-11	2000	62	66	68	65.0	61	63	63	62.5	1	3	4	2.6
0103-15	2000	59	63	66	62.9	59	62	62	61.1	0	2	4	2.0
9801-11	1990	63	66	68	65.7	62	62	62	62.2	1	4	6	3.7
9803-2	1990	64	65	70	66.3	62	62	64	62.7	1	3	7	3.6
8321-21	1980	63	66	68	65.9	62	62	63	62.4	1	4	6	3.6
8425-8	1980	62	64	67	64.2	61	61	62	61.6	0	3	4	2.6
Mean		62.1	65.1	67.9		61.4	62.1	62.7		1	3	5	

LSD(0.05) Years [Y] for Days to silking = 0.56, for Days to anthesis = 0.44, for ASI = 0.31
LSD(0.05) Density [D] for Days to silking = 0.68, for Days to anthesis = 0.54, for ASI = 0.38
LSD(0.05) Hybrids [H] for Days to silking = 0.96, for Days to anthesis = 0.77, for ASI = 0.53
LSD(0.05) LSD(0.05) H × D for Days to silking = 1.55, for Days to anthesis = 1.28, for ASI = 0.91

Plant densities above 53,333 plants ha^{-1} reduced grain yield by 22% for plant population of 66,666 and by 56% for plant population of 79,999. Grain yields of the year 2000 hybrids were usually higher than those of 1980 and 1990 hybrids at all plant densities (Table 4). The year 1990 hybrids recorded the highest grain yield reduction at higher plant densities.

Table 3. Effect of plant population on lodging of maize hybrids from different eras of breeding.

		Plants ha^{-1}			
Hybrids	Era	53.333	66.666	79.999	Mean
0103-11	2000	14.3	12.6	16.0	14.3
0103-15	2000	11.3	18.6	18.0	16.1
9801-11	1990	12.0	16.6	21.6	16.8
9803-2	1990	12.6	16.6	23.0	17.4
8321-21	1980	16.6	17.6	18.0	17.4
8425-8	1980	15.6	19.6	23.0	19.4
Mean		13.8	17.0	19.9	

LSD(0.05) Density [D] = 0.68
LSD(0.05) Hybrids [H] = 0.96
LSD(0.05) H × D =1.55

Table 4. Effect of plant population on number of ears per plant and grain yield of maize hybrids from different eras of breeding.

		Ears plant^{-1}				Yield (kg ha^{-1})			
		Plant ha^{-1}							
Treatment	Era	53,333	66,666	79,999	Mean	53,333	66,666	79,999	Mean
Years									
2002		1.06	0.82	0.60	0.83	3838	3405	2001	3081
2003		1.05	0.81	0.56	0.81	4223	3290	1869	3127
Hybrids									
0103-11	2000	1.07	0.85	0.68	0.87	4683	3620	2526	3610
0103-15	2000	1.09	0.96	0.83	0.96	4326	5050	3247	4208
9801-11	1990	1.06	0.60	0.56	0.74	3988	1907	1601	2499
9803-2	1990	1.10	0.85	0.28	0.73	3506	3624	773	2634
8321-21	1980	1.01	0.76	0.51	0.76	4199	2680	1200	2693
8425-8	1980	1.01	0.90	0.64	0.85	3482	3203	2264	2983
Mean		1.06	0.82	0.58		4031	3347	1935	

LSD(0.05) Years [Y] for Ears per plant = 0.05, for Yield = 325.3
LSD(0.05) Density [D] for Ears per plant = 0.06, for Yield = 398.4
LSD(0.05) Hybrids [H] for Ears per plant = 0.09, for Yield = 563.4
LSD(0.05) Y × D for Ears per plant = 0.09, for Yield = 1097.4
LSD(0.05) Y × H for Ears per plant = 0.13, for Yield = 926.6
LSD(0.05) H × D for Ears per plant = 0.15, for Yield = 1169.3

There was a differential response of the maize hybrids to high plant densities, although high plant densities generally reduced grain yield of all the hybrids that were evaluated during this study. Generally, newer hybrids of the year 2000 were more tolerant to high plant population than those of the years 1980 and 1990. At high plant densities, days to silking and ASI were fewer in the year 2000 hybrids than in the year 1980 and 1990 hybrids. The fewer days to silking and shorter ASI among the 2000-era hybrids demonstrate that loss of synchrony between male and female inflorescence was less pronounced in the modern hybrids at dense stands. This suggests greater tolerance of modern hybrids than the older hybrids. Sangoi et al. (2002) reported similar results for Brazilian hybrids. They found that increase in plant population lengthened the ASI more drastically for the older hybrids than the modern hybrids. An increase in ASI is characteristic of maize under environmental stress, such as N-deficiency, drought and higher plant density (Bolanos and Edmeades, 1996). Increase in ASI reduces number of kernels per ear (Sangoi et al., 2002). An asynchronous flowering can limit grain production per ear due to lack of pollen, loss of silk receptivity or early kernel abortion (Carcovas and Otegui, 2001). Although kernel number was not determined in this study, it is speculated that increased ASI at high plant densities particularly for the older hybrids might have reduced kernel number, leading to lower grain yields. Higher plant densities increased root lodging. This was more pronounced in older than newer hybrids. This result agrees with Sangoi et al., (2002) who reported increased stalk and root lodging in older hybrids when grown at supra high densities. Paszkiewicz and Butzen (2005) reported that newer hybrids were more tolerant of high plant population for root and stalk lodging than older hybrids in areas highly prone to lodging in the USA.

Ears per plant, which is a measure of barrenness, were very strongly related to grain yield. This suggests that reduced barrenness at high plant densities is linked to tolerance of maize hybrids to high plant densities. Ears per plant were reduced by 23% at 66,666 plants ha^{-1} and by 43% at 79,999 plants ha^{-1}. Three hybrids (2 from the year 1980 hybrids and 1 from year 1990) recorded reductions ranging from 45%-82%. Sangoi et al. (2002) found that high plant densities above 50,000 plants ha^{-1} stimulated barrenness in Brazilian maize hybrids. They, however, found older hybrids to have fewer ears per plant than the modern hybrids at high plant densities. Similarly, modern cultivars of the year 2000 hybrids were found in our study to produce more ears per plant than the older hybrids at high plant densities.

There was significant grain yield reduction at plant densities above the optimum population in the Nigerian savannas. Other studies conducted elsewhere had reported a curvilinear response of maize hybrids to plant density (Tollenaar and Wu, 1999; Sangoi et al., 2002; Echarte et al., 2000). Most studies found modern hybrids to yield higher than older hybrids at high plant densities. The results presented herein showed that all hybrids studied were not tolerant of high plant densities above 53,333 plants ha^{-1}. This is contrary to the results from other studies. In the USA for example, Miller et al. (1995) found maize hybrids to perform better at higher densities. Widdicombe and Thelen (2002) also found maize hybrids to give higher yields at 90,000 plants ha^{-1} in the northern U.S. Corn Belt. The authors also suggested that 90,000 plants ha^{-1} was not the optimal plant population for the hybrids evaluated. The poor performance of maize hybrids in this study may be due to the fact that selection of maize in the Nigerian savannas is generally done at low plant densities of 53,333 plants ha^{-1}. This may have caused hybrids selected at this population density to be intolerant to high plant populations. Enhancements in maize tolerance to intense competition for incident photosynthetic photon flux density, soil nutrients and soil water, have been obtained by selecting the best yielding inbred lines under high plant population densities across a wide testing area (Sangoi and Salvador, 1998). Consequently, changes in plant density stress tolerance are mostly the result of indirect rather than direct responses to selection (Tollenaar and Wu, 1999). To make progress in selection for tolerance to environmental stress such as high plant density or drought, there is a need to develop/select the maize lines at high plant densities.

The environment may also influence grain yields of maize at higher densities. Research by Pioneer Hi-Bred International from 1999-2000 in locations across the USA and Canada has shown that maize hybrid response to plant population was affected by yield potential of the growing environment (Paszkiewicz and Butzen, 2005). If yield potential in an environment is low, higher plant densities may reduce grain yield of maize. This may be true for the Guinea savanna ecology of northern Nigeria. Soils there are generally poor due to land degradation arising from cropping intensification (Oikeh et al., 2003).

CONCLUSIONS

High plant densities above 53,333 plants ha^{-1} reduced grain yield in maize hybrids in the Nigerian Savanna. This is contrary to results obtained elsewhere where high grain yields were obtained at plant populations far above 53,333. This may be due to the fact that the maize hybrids evaluated were selected at low plant densities and were therefore not tolerant to plant density stress. It may also be due to the low yield potential of the experimental area, which does not allow yield increases at high plant densities. There were significant differences among the maize hybrids evaluated. Hybrids released in 2000 out-yielded the hybrids released in 1980s and 1990s at all plant densities. To improve maize grain yield at high plant densities, we recommend that the hybrids be selected at high plant densities.

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REFERENCES

Andrade, F.H., Vega, C., Uhart, S., Cirilo, A. Canterro, M., Valentnuz, O. (1999). Kernel number determination in maize. *Crop Sci*. 39, 453–459.

Argenta, G., Silva, P.R.F., Sangoi, L. (2001). Maize plant arrangement: analysis of the state of the art. *Ciência Rural* 31, 1075–1084.

Bolanos, J., Edmeades, G.O., (1996). The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize. *Field Crops Res.* 31, 233–252.

Carcova, J., Otegui, M.E. (2001). Ear temperature and pollination timing effects on maize kernel set. *Crop Sci.* 49, 1816–1822.

Duvick, D.N., Cassman, K.G. (1999). Post-green revolution trends in yield potential of temperate maize in the north-Central United States. *Crop Sci.* 39, 1622–1630.

Dwyer, L.M., Stewart, D.W., Tollenaar, M. (1992). Analysis of maize leaf photosynthesis under drought stress. *Can. J. Plant Sci.* 72, 477–481.

Echarte, L., Luque, S., Andrade, F.H., Sadras, V.O., Cirilo, A., Otegui, M.E., Vega, C.R.C. (2000). Response of maize kernel number to plant density in Argentinean hybrids released between 1965 and 1993. *Field Crops Res*. 68, 1–8.

Edmeades, G.O., Bolanos, J., Elings, A., Ribaut, J.M., Baenziger, M. (2000). The role and regulation of the anthesis-silking interval in maize. In: Westgate, M.E., Boote, K.J. (Eds.). *Physiology and modelling kernel set in maize*. CSSA. Madison, WI, 43–73.

Fajemesin, J.M. (1978). An overview of the maize improvement program of the National Cereals Institute. In: Ojomo, O.A., Fajemisin, J.M., Reminsin, S.U. (Eds.). *Prospects of hybrid maize production in Nigeria*. IITA, Ibadan, Nigeria, 7–11.

Fakorede, M.A.B., Fajemisin, J.M., Ajala, S.O., Kling, J.G., Menkir, A. (1999). Hybrid maize and hybrid seed production in Nigeria: Lessons for other West and Central African countries. In: Badu-Apraku, B., Fakorede, M.A.B., Ouedraogo, M., Carsky, R.J. (Eds.). *Impact challenges and prospects of maize research and development in West and Central Africa.* Proceedings of a regional maize workshop, IITA-Cotonou, Benin Republic, 4-7 May, 1999. WECAMAN/IITA. 174–182.

Fakorede, M.A.B., Fajemisin, J.M., Kim, S.K., Ikem, J.E. (1993). Maize improvement in Nigeria—past, present, future. In: Fakorede, M.A.B., Alofe, C.O., Kim, S.K. (Eds.). *Maize* *improvement and utilization in Nigeria*. Maize Association of Nigeria, Ibadan, Nigeria, 15–39.

Kim, S.K. (1997). Achievements, challenges, and future direction of hybrid maize research and production in West and Central Africa. In: Badu-Apraku, B., Akoroda, M.O., Ouedrago, M., Quin, F.M. (Eds.). *Contributing to food self-sufficiency: Maize Research and Development in West and Central Africa*. Proceedings of a regional maize workshop, 29 May-2 June 1995, Cotonou, Benin Republic, 42–82.

Maddonni, G.A., Otegui, M.E., Cirilo, A.G. (2001). Plant population density, row spacing, and hybrid effects on maize canopy architecture and light attenuation. *Field Crops Res.* 71, 183–191.

Miller, L.C., Vasilas, B.L. Taylor, R.W. Evans, T.A., Gempesaw, C.M. (1995). Plant population and hybrid considerations for dryland corn production on drought-susceptible soils. *Can. J. Plant Sci*. 75, 87–91.

Oikeh, S.O., Carsky, R.J., Kling, J.G., Chude, V.O., Horst, W.J. (2003). Differential N uptake by maize cultivars and soil nitrate dynamics under N fertilization in West Africa. *Agr. Ecosyst. Environ.* 100, 181–191.

Paszkiewicz, S., Butzen, S. (2005). Corn hybrid response to plant population. *Crop Insights* 11 (6), 1–9.

Sangoi, L., Graceietti, M.A., Rampazzo, C., Bianchetti, P. (2002). Response of Brazilian maize hybrids from different eras to changes in plant density. *Field Crops Res.* 79, 39–51.

Sangoi, L., (2001). Understanding plant density effects on maize growth and development: an important issue to maximise grain yield. *Ciência Rural* 31, 159–168.

Sangoi, L., Salvador, R.J. (1998). Influence of plant height and leaf number on maize production at high plant densities. *Pesq. Agrop. Bras.* 33, 297-306.

SAS Institute Inc. (1990). *SAS/STAT User's Guide, Version 6. 4th ed*. Cary, USA: SAS Institute Inc.

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

Tollenaar, M. (1989). Genetic improvement in grain yield of commercial hybrids grown in Ontario from 1959-1988. *Crop Sci.* 35, 1074–1080.

Tollenaar, M. (1991). The physiological basis of the genetic improvement of maize hybrids in Ontario from 1959-1988. *Crop Sci.* 29, 119–124.

Tollenaar, M., Aguilera, A., Nissanka, S.P. (1997). Grain yield is reduced more by weed interference in an old than in a new maize hybrid. *Agron J.* 89 (2), 239–246.

Widdicombe, W.D., Thelen, K.D. (2002). Row width and plant density effects on corn grain production in the northern Corn Belt. *Agron. J.* 94, 1020–1023.