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Row Arrangement, Phosphorus Fertility, and Hybrid Contributions to Managing Increased Plant Density of Maize

Jason W. Haegele, Ryan J. Becker, Adam S. Henninger, and Frederick E. Below*

ABSTRACT

Inter-plant competition must be carefully managed to realize the yield potential of increased plant density of maize (*Zea mays* L.). Twin row planting arrangement, P fertility, and hybrid selection may be important components of managing increased plant density. Our hypotheses were (i) that twin row planting arrangement would be superior to traditional 0.76-m rows at ultra-high densities and (ii) that supplemental P fertility would alleviate inter-plant competition. In 2010 and 2011, twin row planting arrangement was compared to single 0.76-m rows across densities ranging from 61,775 to 160,615 plants ha^{-1} and P fertility treatments ranging from 0 to 168 kg P_2O_5 ha^{-1}. Twin rows did not increase yield relative to single rows, and twin rows often yielded significantly less at plant densities greater than 111,195 plants ha^{-1}. Mean responses to supplemental fertility were 1.0 and 0.3 Mg ha^{-1} in 2010 and 2011, respectively. There was no interaction between plant density and P fertility suggesting that extra resource availability does not necessarily overcome inter-plant competition. In 2011, two hybrids of contrasting ear type were included to explore the role of hybrid selection in plant density response. Maximum yields of each hybrid were achieved at contrasting densities, and genetic differences in plant density tolerance appeared to be related to (i) kernel number response on a per-area basis and (ii) stability of individual kernel weight. These results highlight the importance of independently optimizing row spacing and soil fertility while understanding the plant density response characteristics of maize hybrids.

The agronomic and economic responses of maize grain yield to plant densities representative of current agronomic practices have been studied extensively (Farnham, 2001; Bruns and Abbas, 2005; Shapiro and Wortmann, 2006; Coulter et al., 2010, 2011), and these studies along with concurrent university extension research typically recommend economically optimum plant densities for the central U.S. maize growing region that are between 74,000 and 89,000 plants ha^{-1} (Nafziger, 2008; Elmore and Abendroth, 2009; Nielsen, 2012). With the current goal of doubling average maize grain yields in the United States (Edgerton, 2009), increasing plant density becomes a particularly important strategy, because densities in excess of 111,200 plants ha^{-1} may be required to routinely achieve grain yields at or near 16 Mg ha^{-1} (300 bushels acre^{-1}). This prediction assumes that kernel number per plant can be maintained in the range of 500 to 600 kernels that is typically associated with a well managed maize crop (Kiniry and Ritchie, 1985; Andrade et al., 1999; Subedi and Ma, 2005), and that individual kernel weight is not reduced substantially by increased shading of source leaves. Thus, it is imperative to identify maize germplasm that can tolerate an increased level of inter-plant competition under stressful environmental conditions (Tokatlidis and Koutroubas, 2004; Boomsma et al., 2009), while also implementing agronomic practices that allow density tolerant germplasm to respond with additional yield when environmental conditions are favorable. These complementary agronomic practices could include factors such as row spacing or arrangement, and improved fertility, especially for soil immobile nutrients such as P that may become more limiting under intense crowding stress.

Narrow row spacing (<0.76 m) has been proposed as a strategy to increase plant-to-plant spacing within the row, thereby promoting less inter-plant competition and greater yield (Farnham, 2001; Thelen, 2006). Inconsistent responses to narrow row spacing (Lee, 2006; Thelen, 2006; Van Roekel and Coulter, 2012) as well as the large capital investment in narrow row planting and harvesting equipment have led some maize producers to adopt a twin row planting arrangement. This approach uses rows on typical 0.76 m spacing; however, each row is further divided into adjacent subrows spaced approximately 0.20 m apart. Plants are staggered within the twin row resulting in greater plant-to-plant spacing than would be achieved in a single row at the same plant density. Twin row maize production has been compared to traditional 0.76-m rows across a broad range of geographies and few differences have been detected between these row arrangements (Kratochvil and Taylor, 2005; Nelson and Smoot, 2009; Balkcom et al., 2011; Robles et al., 2012; Novacek et al., 2013). In contrast to narrow row spacing or twin row planting arrangement, other approaches have investigated ultra-wide rows or the “Solar Corridor” concept (Deichman, 2000; Nelson, 2013). Regardless of the row spacing employed, past studies highlight the possible need to co-optimize row spacing or arrangement along with plant density. While these studies have examined the interaction between row arrangement and plant density, none

Dep. of Crop Sciences, Univ. of Illinois, 1201 W. Gregory Dr., Urbana, IL 61801. Received 12 Aug. 2013. *Corresponding author (fbelow@illinois.edu).

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have included P fertilizer application as a possible avenue for managing increased plant density of maize.

It is not known if current soil testing methods are adequately calibrated for the yield potential of modern maize hybrids. For example, while average Illinois corn yields for the 2000 to 2010 period increased by nearly 85% compared to yields in the 1960s, the typical P fertilizer application rate has only increased by 26% (USDA-ERS, 2011; USDA-NASS, 2012). Fittingly, a recent survey of soil test levels in the United States showed that the median P level for 12 major Corn Belt states had declined between 2005 and 2010 (Fixen et al., 2010). This decline was especially evident for Illinois, which experienced a 10 mg kg^{-1} decrease in soil test P during the 6-yr period included in the study. A separate analysis showed that this rate of P fertility decline in Illinois would correspond to a negative P balance of approximately 8.8 kg P ha^{-1} yr^{-1} (IPNI, 2010), indicating that more P is being removed with grain than is being replaced by fertilizer or manure application. Collectively, this evidence suggests that fertilizer practices, especially for nutrients like P which are removed at a greater rate with harvested grain (Bender et al., 2013), have been inadequate to support the yield potential of modern germplasm and agronomic systems. In particular, mutual shading associated with denser stands of maize decreases total plant dry matter accumulation (Maddonni and Otegui, 2006; Boomsma et al., 2009). Furthermore, shading alters the shoot/root ratio and increases biomass partitioning to the aboveground shoot (Demotes-Mainard and Pellerin, 1992; Hébert et al., 2001). Fittingly, decreased root biomass might reduce the volume of soil explored, and consequently, decrease uptake of nutrients such as P that are acquired through diffusion. As a result, placement of P fertilizer within the restricted rooting zone of a dense stand of maize might lessen inter-plant competition.

Elevated plant density might not be a successful strategy for increasing grain yield if the hybrids grown are not tolerant of greater competition. Contrasting responses of different germplasm sources to plant density have been documented (Troyer and Rosenbrook, 1983; Cox, 1996; Sarlangue et al., 2007; Brekke et al., 2011; Berzsenyi and Tokatlidis, 2012), yet there is a scarcity of hybrid by plant density interaction data for current commercial maize hybrids. Nonetheless, it is clear that modern hybrids exhibit greater yields relative to older hybrids when inter-plant competition is increased (Tollenaar and Wu, 1999; Duvick et al., 2004; Hammer et al., 2009), and that optimum densities can vary between hybrids (Sarlangue et al., 2007).

A 2-yr research study was designed to understand the possible interactions of plant density, row arrangement, and P fertility on grain yield and yield components of maize. Our hypothesis was that yield improvements might be achieved with elevated plant density only when complementary management practices such as row arrangement, supplemental P fertility, and hybrid selection are used. The primary objectives were to determine (i) if a twin row planting arrangement would be of greater advantage at densities in excess of those currently used by maize producers (≥111,195 plants ha^{-1}) and (ii) if application of supplemental P fertility using subsurface placement might lessen inter-plant competition associated with increased planting density. An additional objective of the second year of the study was to understand how hybrids of contrasting ear types (i.e., a fixed-ear type vs. a flex-ear type) might respond differently to increased plant density and twin-row arrangement.

MATERIALS AND METHODS

Cultural Practices, Experimental Design, and Treatments

Two similar studies were conducted in 2010 and 2011 to investigate the contributions of row arrangement, P fertility, and hybrid to managing supra-optimal plant density of maize. The 2010 study was located at a cooperator's farm near Lewisville, IN (39°46′ N, 85°21′ W), while the 2011 trial was located at the University of Illinois Crop Sciences Research and Education Center in Champaign, IL (40°3′ N, 88°14′ W). Soybean [*Glycine max* (L.) Merr.] was the previous crop at each site. Plant density and hybrid treatments differed between years; however, row arrangement and fertility treatments were consistent across years. Two types of row arrangement were investigated. These included single 0.76-m rows and twin rows spaced 0.19 m apart on 0.76 m centers. The single 0.76-m rows were planted using a research plot planter with variable seeding rate capabilities (SeedPro 360, ALMACO, Nevada, IA) while the twin rows were planted with a prototype twin row planter provided by AGCO Corporation (Duluth, GA). Phosphorus fertility was supplied as MicroEssentials SZ (12–40–0–10S–1Zn) (The Mosaic Company, Plymouth, MN) at rates of 0, 56, 112, and 168 kg P_2O_5 ha^{-1} (0, 24.4, 48.8, and 73.2 kg elemental P ha^{-1}). In 2010, the fertility treatments were banded using the dry fertilizer metering application capability of the prototype twin row planter. Fertilizer treatments were applied first, and then planting occurred for both the single and twin rows using real-time kinematic guidance over the previously placed fertility strips. In 2011, the P fertility treatments were banded (10–15 cm beneath the row) by a toolbar fitted with Dawn Equipment 6000 Series Universal Fertilizer Applicators (Dawn Equipment, Sycamore, IL).

A randomized complete block design in either a split-plot (2010 study) or split-split plot (2011 study) arrangement with four replications was used. The split-plot or split-split plot experimental units consisted of four rows 11.4 m in length. In 2010, the main plot consisted of row arrangement (single row or twin rows) while the split-plots were factorial combinations of plant density and P fertilizer rate. Six levels of plant density were chosen in 2010 to represent "high" (86,485; 98,840; or 111,195 plants ha^{-1}) and "ultra-high" (123,550; 135,905; or 160,615 plants ha^{-1}) densities. While several of these densities are outside the range of those currently used by maize producers, they were chosen to evaluate the possible advantage of twin row arrangement relative to single 0.76-m rows at elevated densities. Plots were over seeded on 26 May 2010 and thinned to within 2500 plants ha^{-1} of the target densities. The soil type at Lewisville was a Westland clay loam soil (Typic Argiaquolls), and the pre-planting soil test values at the 0- to 15-cm depth included 41 g kg^{-1} organic matter, 24 mg kg^{-1} of P, 161 mg kg^{-1} K, 6.7 mg kg^{-1} S, and 2.5 mg kg^{-1} Zn. The minerals were extracted using Mehlich-3 solution (Mehlich, 1984). The experiment received 314 kg ha^{-1} of N in the form of urea (rate and source were chosen by the site cooperator) which was applied 25 Apr. 2010. A single hybrid (DKC61-21 SmartStax, Monsanto Co., St. Louis, MO) of 111-d relative maturity was used in 2010. Although this hybrid possessed transgenic resistance to above- and belowground insect herbivory, a soil applied insecticide, tefluthrin [(2,3,5,6-tetrafluoro-4-methylphenyl) methyl-(1a,3a)-(*Z*)-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate], was applied at planting (0.11 kg of active ingredient per hectare) for additional control of seedling insect pests.

In 2011, an additional hybrid was added to the study to investigate the role of hybrid selection in managing plant density. Hybrids were chosen to represent a "flex-ear" type (DKC61-21 SmartStax) and a "fixed-ear" type (Croplan Genetics 7505 YieldGard VT Triple Pro [Croplan 7505VT3P]; 115-d relative maturity). Hybrid characteristics were initially suggested by the seed providers and experimentally verified by multi-year field trials grown at 79,072 and 111,195 plants ha^{-1} (Haegele and Below, unpublished data, 2010 through 2012). In these hybrid characterization trials, yields of the two hybrids were typically similar at the "standard" density of 79,072 plants ha^{-1}, while the fixed-ear type performed better relative to the flex-ear type at the higher density (data not shown). The main plot in 2011 consisted of hybrid, the split-plot was row arrangement (single rows and twin rows), and the split-split plots were factorial combinations of plant density and P fertilizer rate. Target plant densities were amended in 2011 to represent a range of potentially suboptimal (61,775 plants ha^{-1}), optimal (86,485 and 111,195 plants ha^{-1}), and supra-optimal (135,905 plants ha^{-1}) levels for the Champaign location. Plots at Champaign were planted 20 May 2011 on a Drummer–Flanagan soil association (fine-silty, mixed, superactive, mesic Typic Endoaquolls). The pre-planting soil test values at the 0- to 15-cm depth were 48 g kg^{-1} organic matter, 43 mg kg^{-1} P, 131 mg kg^{-1} K, 10 mg kg^{-1} S and 2 mg kg^{-1} of Zn (Mehlich-3 method). The experimental area at Champaign received 202 kg ha^{-1} of N applied as urea ammonium nitrate in the spring with a further 67 kg ha^{-1} of N applied as a side-dress treatment when the plants had achieved six fully collared leaves. Soil insecticide application was identical to that previously described for the 2010 study. Final densities achieved at harvest in 2011 averaged 65,726; 89,772; 110,785; and 130,831 plants ha^{-1} for the 61,775; 86,485; 111,195; and 135,905 target densities, respectively.

Yield and Yield Component Measurements

The center two rows of each four row plot were mechanically harvested using a plot combine to determine grain yield. Grain yields are expressed as megagrams per hectare at 0 g kg^{-1} moisture concentration. Individual kernel weights were estimated by bulk weighing 300 kernels from a representative grain subsample using an electronic seed counter with the resultant data expressed as milligrams per kernel at 0 g kg^{-1} moisture. Kernel number (m^{-2}) was algebraically derived from the total plot grain weight and the estimate of individual kernel weight.

Statistical Analysis

Yield and yield component data were analyzed separately for each year using PROC MIXED in SAS (SAS Institute, 2009). Row arrangement, P fertilizer rate, target plant density, and hybrid were included as fixed effects while replication was included as a random effect. Main effects and interactions were deemed significant at $\alpha = 0.05$. The assumption of homogeneous error variances was not valid for the 2010 data. As such, a heterogeneous variance model was used for the 2010 data in which different residual variances were specified for row arrangement. Least-square means were computed for significant treatment effects.

RESULTS

Temperature and Precipitation

Daily weather conditions (temperature and precipitation) for Lewisville, IN, (2010 study) were obtained from publicly available climate data (39°49′ N, 85°19′ W; NOAA-NCDC, 2013) (Fig. 1). Weather conditions following planting in 2010 were generally characterized by precipitation and temperatures that were greater than the 10-yr average. In particular, the period from 26 May 2010 through 31 Aug. 2010 was warmer than usual, with recorded maximum and minimum daily temperatures exceeding the 10-yr average by approximately 2°C. Total precipitation at the Lewisville site in 2010 between planting and physiological maturity was approximately 444 mm; however, 395 mm or 89% of the total occurred before flowering.

Daily weather conditions for Champaign, IL, in 2011 were obtained from a state climate water and atmospheric monitoring program (40°5′ N, 88°14′ W; Illinois Climate Network, 2013) (Fig. 1). Temperature and rainfall were similar to the long-term average for much of the early part of the growing season. Toward the latter part of vegetative growth and for much of the reproductive phase (July through August), however, daily maximum temperatures exceeded the 10-yr average by approximately 2.3°C. Total precipitation from planting to physiological maturity was

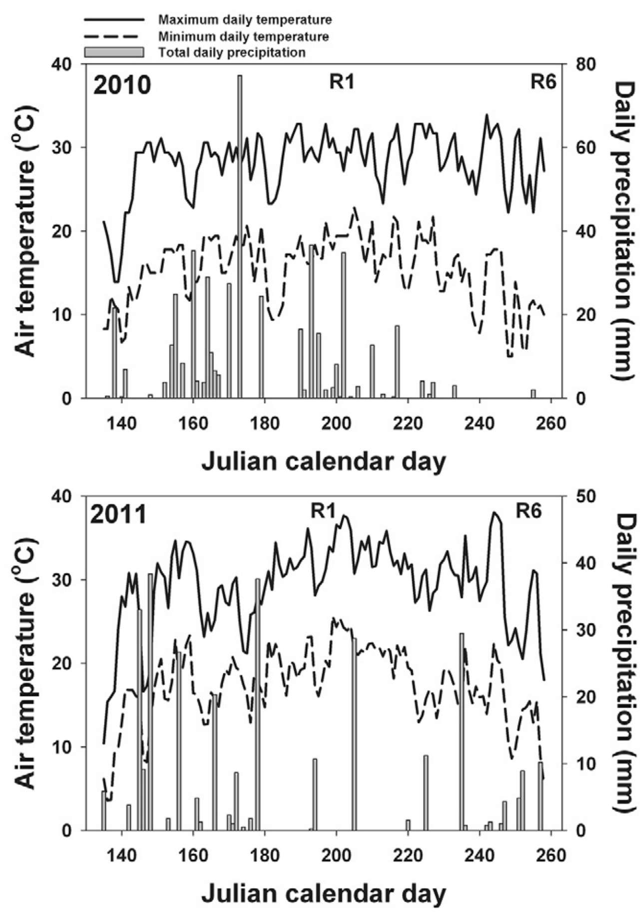

Fig. 1. Daily weather conditions from Julian Day 135 (15 May) to Julian Day 258 (15 September) at Lewisville, IN, in 2010 (top panel) and at Champaign, IL, in 2011 (bottom panel). Solid and dashed lines represent the daily maximum and minimum temperatures, respectively. Solid vertical bars are the recorded daily precipitation. The approximate dates of flowering (R1) and physiological maturity (R6) have been indicated. Weather data for Lewisville, IN, were obtained from NOAA-NCDC (2013), and data for Champaign, IL, were obtained from the Illinois Climate Network (2013).

approximately 296 mm, and nearly 69% of this occurred before flowering. Monthly precipitation totals during July and August of 2011 were 80 and 36 mm below their respective 10-yr averages and much of central Illinois experienced moderate drought conditions. Despite these presumably more limiting environmental conditions, the mean grain yield of the 2011 trial was greater (10.3 Mg ha^{-1}) than that of the 2010 trial even though cultural practices were relatively similar between years.

Row Arrangement and Plant Density Responses

Although a significant row arrangement by plant density interaction was detected in the 2010 data, twin rows did not increase grain yield at any level of plant density (Table 1). Yields were not statistically different between twin rows and single rows at the densities of 86,485; 98,840; or 111,195 plants ha^{-1}, while a significant yield decrease of approximately 0.8 Mg ha^{-1} ($P \leq 0.10$) associated with twin row arrangement occurred at ultra-high densities ≥123,550 plants ha^{-1}.

A significant interaction of row arrangement and plant density also occurred in 2011 (Table 2). Like the previous year, single and twin rows were not significantly different at the target density of 86,485 plants ha^{-1}, while grain yields of single rows were greater than those of twin rows at target densities of 111,195 and 135,905 plants ha^{-1} ($P < 0.05$). The decrease associated with twin row arrangement in 2011 was approximately 0.55 Mg ha^{-1} ($P < 0.05$) at target densities ≥111,195 plants ha^{-1}. Densities <86,485 plants ha^{-1} were not explored in 2010; however, twin row arrangement had a greater mean yield compared to single rows at the target density of 61,775 plants ha^{-1} in 2011 (+0.39 Mg ha^{-1}; $P < 0.1$). Although the three-way interaction of row arrangement, plant density, and hybrid was not significant in the 2011 study, the apparent advantage of twin rows at low density tended to be greater for the flex-ear hybrid (DKC61–21 SmartStax) (Fig. 2A).

The main effect of plant density resulted in the greatest source of variation for yield in 2010. Grain yields measured in single rows were not different in the range of 86,485 to 123,550 plants ha^{-1} (mean = 10.2 Mg ha^{-1}), but decreased significantly by 0.9 Mg ha^{-1} ($P < 0.01$) at the two highest levels of plant density. In contrast to plant density response in single rows, grain yields of the twin row arrangement in 2010 were greatest (10.3 Mg ha^{-1}) at densities of 86,485 and 98,840 plants ha^{-1} (Table 1). Densities >98,840 plants ha^{-1} caused a decrease in yield of approximately 1.4 Mg ha^{-1} ($P < 0.01$).

Plant density response patterns in 2011 did not exhibit the marked decrease in yield associated with densities beyond the treatment level that resulted in maximum yield when averaged across hybrids (Table 2). Grain yield of the single row arrangement was least at 61,775 plants ha^{-1} (9.8 Mg ha^{-1}), and reached a plateau of approximately 10.6 Mg ha^{-1} at densities ≥86,485 plants ha^{-1}. Yield of the twin row arrangement (10.7 Mg ha^{-1}) was greatest at a density of 86,845 plants ha^{-1}, and densities beyond this threshold resulted in a yield decrease of 0.6 Mg ha^{-1} ($P < 0.01$) (Table 2). Thus, plant densities in excess of the density treatment levels that maximized yield tended to result in decreased yield for both types of row arrangement; however, this decrease appeared to be magnified by the twin row arrangement in both years.

Kernel number ranged from 3609 to 4627 kernels per square meter in 2010 depending on row arrangement and plant density, and this yield component exhibited an identical response to the interaction of row arrangement and plant density (Table 1). Kernel

Table 1. Row arrangement, plant density, and P fertilizer rate influences on grain yield, kernel number, and kernel weight of maize grown near Lewisville, IN, during 2010. Grain yield and kernel weight are expressed at 0 g kg^{-1} moisture concentration.

Treatment factor	Grain yield			Kernel number			Kernel weight		
	Single	Twin	Mean	Single	Twin	Mean	Single	Twin	Mean
	Mg ha^{-1}			m^{-2}			mg per kernel		
Plant density, plants ha^{-1}									
86,485	10.1	10.3	10.2	4416	4627	4522			225
98,840	10.5	10.3	10.4	4620	4557	4588			226
111,195	10.2	9.3	9.7	4562	4236	4399			221
123,550	10.1	9.0	9.6	4559	4171	4365			218
135,905	9.1	9.3	9.2	4208	4287	4248			217
160,615	9.5	8.0	8.7	4290	3609	3949			218
P fertilizer rate, kg ha^{-1}									
0			9.1			4159			217
56			9.6			4287			223
112			9.7			4441			219
168			10.1			4494			225
Source of variation:									
Row arrangement (R)			ns†			ns			ns
Plant density (D)			**			**			**
R × D			*			**			ns
P fertilizer rate (F)			**			**			**
R × F			ns			ns			ns
D × F			ns			ns			ns
R × D × F			ns			ns			ns

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† ns, not significant at $P \leq 0.05$.

weight was unaffected by row arrangement; however, plant density was a significant source of variation ($P < 0.01$) (Table 1). Averaged across the "high" target densities of 86,485 to 111,195 plants ha^{-1}, kernel weight was approximately 224 mg per kernel, while kernel weight averaged across the ultra-high target densities of 123,550 to 160,615 plants ha^{-1} was nearly 218 mg per kernel ($\Delta = -6.6$ mg per kernel; $P < 0.01$).

Compared to 2010, kernel number in 2011 averaged across both hybrids was approximately 12% less (Tables 1 and 2). Although there were fewer kernels per unit area in the second year of the study, yields were greater suggesting that kernel weight compensated for the reduction in kernel number. Fittingly, kernel weight of the hybrid common to both years (DKC61-21 SmartStax) was 29 mg per kernel heavier in 2011 (Tables 1 and 2). Like 2010, plant density was a significant source of variation for kernel weight in 2011 (Table 2). Averaged across both hybrids, kernel weight was greatest (280 mg per kernel) at the target density of 61,775 plants ha^{-1} and decreased by 13 mg per kernel at the highest target plant densities of 111,195 and 135,905 plants ha^{-1} ($P < 0.01$).

Response to Phosphorus Fertility

Grain yield responded to supplemental fertility (primarily P, but fertilizer source also contained lesser amounts of N, Zn, and S) in both years of the study. There was no interaction of fertility rate with plant density or row arrangement suggesting that enhanced fertility was of equal benefit across all other treatment combinations. The non-treated control fertility treatment in 2010 achieved a mean yield of 9.1 Mg ha^{-1} when averaged across plant densities and row arrangements (Table 1). Responses to application of either 56 or 112 kg P_2O_5 ha^{-1} (24.4 or 48.8 kg P ha^{-1}) were similar (approximately 0.55 Mg ha^{-1}; $P < 0.05$), while application of 168 kg P_2O_5 ha^{-1} (73.2 kg P ha^{-1}) resulted in a mean response of 1.0 Mg ha^{-1} over the non-treated control ($P < 0.01$) (Table 1). The mean yield of the highest fertility rate was significantly different ($P < 0.05$) than the mean yields of the 56 and 112 kg P_2O_5 ha^{-1} (24.4 and 48.8 kg P ha^{-1}) rates suggesting that this site was highly responsive to supplemental P fertility.

The response to fertility was of lesser magnitude in 2011 (Table 2). The non-treated control treatment achieved a mean yield of 10.1 Mg ha^{-1} when averaged across all combinations of plant

Table 2. Row arrangement, hybrid, plant density, and P fertilizer rate influences on grain yield, kernel number, and kernel weight of maize grown at Champaign, IL, during 2011. Grain yield and kernel weight are expressed at 0 g kg^{-1} moisture concentration.

Treatment factor	Grain yield			Kernel number			Kernel weight		
	Single	Twin	Mean	Single	Twin	Mean	Single	Twin	Mean
	Mg ha^{-1}			m^{-2}			mg per kernel		
Hybrid:									
DKC61-21 SmartStax			10.2			4032			254
Croplan 7505VT3P			10.4			3608			288
Plant density, plants ha^{-1}									
61,775	9.8	10.1	10.0	3491	3649	3570			280
86,485	10.5	10.7	10.6	3884	3969	3926			271
111,195	10.8	10.2	10.5	4037	3820	3928			267
135,905	10.5	10.0	10.3	3934	3777	3855			267
P fertilizer rate, kg ha^{-1}									
0			10.1			3746			270
56			10.4			3823			272
112			10.5			3903			271
168			10.3			3808			271
Source of variation:									
Hybrid (H)			ns†			**			**
Row arrangement (R)			ns			ns			ns
H × R			ns			ns			ns
P fertilizer rate (F)			*			**			ns
H × F			ns			ns			ns
R × F			ns			ns			ns
H × R × F			ns			ns			ns
Plant density (D)			**			**			**
H × D			**			**			ns
R × D			**			**			ns
H × R × D			ns			ns			ns
F × D			ns			ns			ns
H × F × D			ns			ns			ns
R × F × D			ns			ns			ns

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† ns, not significant at $P \leq 0.05$.

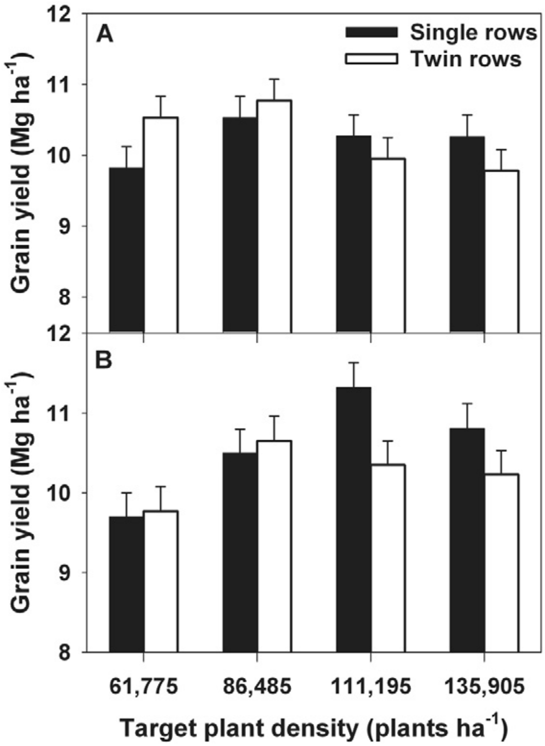

Fig. 2. Responses of grain yield to plant density for two hybrids evaluated under single 0.76-m rows (closed bars) and twin row planting arrangement (open bars) at Champaign, IL, in 2011. Data shown in top panel (A) is for DKC61-21 SmartStax and data shown in bottom panel (B) is for Croplan 7505VT3P. Grain yield means are averaged across levels of P fertility treatment, and are expressed at 0 g kg^{-1} moisture concentration. Vertical bars represent the standard errors of the treatment means.

density, row arrangement, and hybrid. There were no significant differences between the three levels of supplemental fertility application, and the mean response relative to the non-treated control was 0.32 Mg ha^{-1} ($P < 0.01$).

The relatively large fertility response measured in 2010 was associated with increases in both kernel number and kernel weight. In comparison to the non-treated control treatment, the 168 kg P_2O_5 ha^{-1} (73.2 kg P ha^{-1}) application rate resulted in yield component increases of 335 kernels per square meter ($P <$ 0.01) and 8 mg per kernel ($P < 0.01$) (Table 1). Unlike 2010, kernel number was the only yield component affected by P fertility in 2011 (Table 2). Kernel number increased by approximately 100 kernels per square meter ($P < 0.01$) when averaged across the three supplemental fertility treatments.

Hybrid Effects on Yield and Plant Density Response

An additional hybrid (Croplan 7505VT3P) was included in the 2011 study to investigate the effect of hybrid selection (i.e., flex- vs. fixed-ear type) on response to row arrangement and plant density. The main effect of hybrid was not significant for grain yield (10.2 vs. 10.4 Mg ha^{-1}), yet there were significant differences in how these hybrids achieved similar yields (i.e., contrasting yield components) (Tables 2 and 3). The hybrid (DKC61-21 SmartStax) selected for a greater degree of ear flex (i.e., ability to increase ear size in response to reduced plant density) was characterized by greater kernel number (4032 vs. 3608 kernels per square meter; $P < 0.01$) compared to Croplan 7505VT3P which was selected for a more determinate ear type. In contrast to DKC61-21 SmartStax, Croplan 7505VT3P possessed heavier individual kernels (288 vs. 254 mg per kernel; $P < 0.01$) at the mean yield.

A significant hybrid by plant density interaction occurred for grain yield (Table 2). The hybrids possessed similar yields at the target densities of 61,775; 86,485; and 135,905 plants ha^{-1} yet differed ($P < 0.05$) at 111,195 plants ha^{-1} (Fig. 2). Maximum yield of DKC61-21 SmartStax (10.7 Mg ha^{-1}) occurred at 86,485 plants ha^{-1}, while yields of this hybrid at the other three target populations were significantly less than the maximum ($P < 0.01$) and did not differ from one another (mean = 10.1 Mg ha^{-1}) (Fig. 2A). In contrast, maximum yield of Croplan 7505VT3P (10.8 Mg ha^{-1}) occurred at the target density of 111,195 plants ha^{-1} and single row spacing, representing a 1.1 Mg ha^{-1} increase in yield over the least dense treatment (Fig. 2B). While yield of Croplan 7505VT3P measured at 135,905 plants ha^{-1} decreased relative to the maximum yield occurring at 111,195 plants ha^{-1}, yield at this supra-optimal density was similar to or exceeded yields measured at the lowest two levels of plant density explored in 2011 (Fig. 2B).

Like grain yield, kernel number was also subject to a hybrid × plant density interaction in 2011 (Table 3). Kernel number of DKC61-21 SmartStax was significantly different than Croplan 7505VT3P at all levels of plant density (Table 3). The greatest kernel numbers for both varieties occurred at the middle target densities of 86,485 and 111,195 plants ha^{-1}. Kernel weight of Croplan 7505VT3P was greatest (295 mg per kernel) at the lowest target density and decreased to approximately 286 mg per kernel when averaged across the three highest levels of density. The other hybrid, DKC61-21 SmartStax, exhibited a greater decrease in kernel weight (approximately 15 mg per kernel) associated with increased density (Table 3).

DISCUSSION

Our hypothesis was that twin row planting arrangement would be superior to single 0.76-m rows at planting densities in excess of those typically used by maize growers in the central United States. Contrarily, we found no evidence to support this hypothesis, and twin row arrangement was actually a detriment to yield at elevated levels of plant density. Other studies which have examined row arrangement across a range of plant densities have not documented significant yield increases associated with the twin row planting arrangement (Kratochvil and Taylor, 2005; Nelson and Smoot, 2009; Balkcom et al., 2011; Robles et al., 2012; Novacek et al., 2013), yet few have explored ultra-high densities such as those in this study. For example, maximum densities in past studies have ranged from 79,072 plants ha^{-1} (Kratochvil and Taylor, 2005) to 105,000 plants ha^{-1} (Robles et al., 2012; Novacek et al., 2013). Consistent with these other examples of twin row by plant density studies, our results indicate no difference between single 0.76-m rows and twin rows at densities <111,195 plants ha^{-1}; however, a significant row configuration by plant density interaction occurred for yield in both years of the study (Tables 1 and 2). This interaction resulted in relatively greater yield decreases associated with supra-optimal plant density (>111,195 plants ha^{-1}) for the twin row arrangement compared to single 0.76-m rows. While it was not an objective to establish biologically optimum plant densities for single rows vs. twin rows, maximum mean yields of the twin row arrangement occurred at lower target plant densities relative to single rows in both years. This trend along with the finding that twin

Table 3. Yield components (kernel number and individual kernel weight) of two maize hybrids grown under four levels of plant density at Champaign, IL, in 2011. Means are averaged across row arrangements and P fertility treatments. Kernel weight is expressed at 0 g kg^{-1} moisture concentration.

Target plant density	Kernel number†		Kernel weight‡	
	DKC61-21 SmartStax	Croplan 7505VT3P	DKC61-21 SmartStax	Croplan 7505VT3P
plants ha^{-1}	—— kernels m^{-2} ——		—— milligrams per kernel ——	
61,775	3842	3297	264	295
86,485	4180	3673	254	287
111,195	4082	3775	248	287
135,905	4023	3688	249	285

† Hybrid × plant density interaction LSD ($P < 0.05$) = 133 kernels m^{-2}.

‡ Plant density LSD ($P < 0.05$) = 4.5 milligrams per kernel.

rows yield less than single rows at ultra-high densities suggests that maize producers using a twin row planting arrangement should not exceed plant densities currently employed for single 0.76-m rows.

The row arrangement by plant density interaction was also evident for kernel number. This was not completely unexpected as kernel number was calculated from the yield of an individual experimental unit and some degree of autocorrelation occurred. Kernel weight, however, was not affected by row arrangement suggesting that the physiological determinants responsible for the lack of a positive plant density response for twin rows acted on processes responsible for establishing kernel number. Greater average yields for single rows at similar or higher density levels indicated twin-row arrangement did not lessen inter-plant competition for water and nutrients, and that some other uncharacterized factor was responsible for the reduced kernel number and productivity of twin row arrangement at elevated plant density. While twin row planting arrangement does create more equidistant plant spacing, and presumably lessens inter-plant competition (Bullock et al., 1988), other micro-climatic factors such as canopy air temperature associated with different row spacing or arrangement may contribute to unexpected yield responses. Although temperature gradients in narrow row or twin row maize production have not been reported in detail and were not measured in this study, Chelle and Cellier (2009) established that horizontal temperature profiles within a maize canopy are relatively constant for a given row width, and that air temperatures vary vertically within the maize canopy with the greatest temperatures being found in the middle canopy. In a comparison of 0.76 and 1.52 m sorghum [*Sorghum bicolor* (L.) Moench] production, Graser et al. (1987) showed that 0.76-m rows resulted in higher inter-row air temperatures relative to the wide row treatment. Thus, it is plausible that narrow row (<0.76 m) or twin row arrangement in maize production may promote greater temperatures in the middle canopy where the leaf subtending the ear and those immediately above and below the ear contribute a greater proportion of assimilates to developing grain tissues relative to other parts of the canopy (Eastin, 1969). Higher temperatures within this stratum of the canopy might promote accelerated leaf senescence (Badu-Apraku et al., 1983) or increase leaf dark respiration (Kaše and Čatský, 1984; Thompson et al., 2013), thereby reducing photoassimilate availability for kernel development. In our study, differences in leaf senescence below the ear were visible between row arrangements (greater senescence in twin row arrangement) during reproductive stages, particularly during the 2011 growing season at Champaign, IL. Thus, we speculate that twin row arrangement at high plant densities may increase canopy air and leaf temperature, particularly within the 0.19 m spacing between adjacent subrows, resulting in accelerated leaf senescence and decreased yield. A possible detrimental effect of twin row planting arrangement on canopy temperature supports future examination of additional micro-climatic factors in narrow row and altered row arrangement maize production.

Optimum plant density is a key consideration for maximizing maize grain yield, yet inconsistent responses influenced by environmental conditions and hybrid genetics make it difficult to establish this optimum in advance of planting (Cox and Cherney, 2012; Reeves and Cox, 2013). Fittingly, responses of grain yield to plant density varied between years, and differed for the two hybrids evaluated in the 2011 study. In 2010, yields were similar for the four lowest plant densities in single 0.76-m rows and decreased at the two highest densities. A similar pattern occurred for the twin row arrangement in which yields were similar at the two lowest levels of plant density along with decreased yields at greater densities. The lack of a positive plant density response for either row arrangement in 2010 suggested that the range of target plant densities be amended in 2011 to include potentially suboptimal (61,775 plants ha^{-1}), optimal (86,485 and 111,195 plants ha^{-1}) and supra-optimal (135,905 plants ha^{-1}) levels. While plant density responses were more curvilinear in pattern in 2011 for both row arrangements, a significant hybrid by plant density interaction occurred. In agreement with 2010 results, the response of the flex-ear hybrid (DKC61-21 SmartStax) was more modest with maximum yield occurring at lower levels of plant density when averaged across row arrangements. In contrast, yield of the fixed-ear hybrid (Croplan 7505VT3P) increased to a maximum at 111,195 plants ha^{-1}. Although yield per plant was not measured in this study, these results support the notion that maize hybrids may differ in ear plasticity in response to variations in plant density (Bonaparte and Brawn, 1975; Sarlangue et al., 2007), and that these genetic characteristics condition a genotype's suitability for planting at high density.

Yield components (i.e., kernel number and individual kernel weight) contribute to overall grain yield, and may be affected differently by cultural factors such as row spacing, plant density, fertility, and planting date (Hashemi-Dezfouli and Herbert, 1992; Maddonni et al., 2006; Boomsma et al., 2009; Tsimba et al., 2013), or by genetic characteristics (Gambín et al., 2006; D'Andrea et al., 2008). While twin row arrangement decreased kernel number, especially at high plant densities, this cultural factor had no impact on the weight of individual kernels. In contrast, plant density affected both yield components; however, the response patterns differed markedly for kernel number and kernel weight. Unlike kernel number, which was maximized at the same plant densities that resulted in maximum yield, kernel weight decreased consistently with increasing seeding rate. Although kernel number per plant declines with increasing density (Lemcoff and Loomis, 1994; Cox, 1996), the increase in number of plants (i.e., harvestable ears) results in greater kernel number per unit of area, consistent with our findings. Greater shading associated with denser stands, however, promotes reduced carbon exchange rate (Cox, 1996), thereby reducing the subsequent weight of individual kernels (Hashemi-Dezfouli and Herbert, 1992; Lemcoff and Loomis, 1994). The yields of the two hybrids evaluated in 2011 were only significantly different at the target density of 111,195 plants ha^{-1} (Croplan 7505VT3P possessed greater yield). At this density, kernel weight of the less density tolerant hybrid (DKC61-21 SmartStax) decreased 16 mg per kernel (6.1% relative change), while kernel weight of the more density tolerant hybrid (Croplan 7505VT3P) decreased by only 8 mg per kernel (2.7% relative change) compared to their respective kernel weights at the lowest plant density of 61,775 plants ha^{-1} (Table 3). Thus, maize hybrids that have a greater intrinsic kernel weight, such as the Croplan 7505VT3P hybrid evaluated in 2011, or those which possess more stable kernel weight in response to greater competition might be best suited to planting at high density.

A range of supplemental P fertilizer (containing lesser amounts of N, Zn, and S) application rates was designed to match the total uptake and grain removal requirements of a high yielding maize crop (Bender et al., 2013). Our hypothesis was that supplemental P fertility, especially when placed in a band directly beneath the row, would minimize competition for nutrients such as P, which moves to the plant root by diffusion. Significant responses to supplemental fertility occurred in both years, although the yield improvement was more modest in 2011 compared to 2010. The year effect on fertility response was associated with differences in soil P test value; the lower fertility site (2010 at Lewisville, IN; P soil test value of 24 mg kg^{-1}) resulted in a maximum fertility response of 1.0 Mg ha^{-1} compared to only 0.3 Mg ha^{-1} at Champaign in 2011 (P soil test value of 43 mg kg^{-1}). Although grain yields responded positively to the fertility treatments, we found no evidence to suggest that high plant densities were more responsive to supplemental P fertility. This suggests that inter-plant competition for P is of little consequence or that other effects of increased plant density counterbalance demand for nutrients. Fittingly, Ciampitti et al. (2013) reported that plant P uptake at physiological maturity when other nutrients such as N were not limiting decreased modestly by 4% as plant densities increased from 54,000 to 104,000 plants ha^{-1}. The decrease in plant P content documented by Ciampitti et al. (2013) was almost entirely associated with declining grain P content mediated by plant density effects on ear biomass. The dependence of P uptake on grain yield potential was also documented by Bender et al. (2013) who showed that >50% of total maize P uptake occurred post-flowering, and that nearly 80% of plant P content was found in grain tissues. Thus, improved P fertility might only be of benefit to high density planting systems when other management practices or density tolerant hybrids result in greater yields (i.e., more stable grain yield of individual plants).

Although there was not a significant plant density by fertility interaction, and twin row arrangement was not superior to single rows, the importance of individual factors should not be overlooked in managing for greater maize yields. In 2010, yield was greatest at 98,840 plants ha^{-1} although statistically similar yields could be achieved across a broad range of densities (86,485 to 123,550 plants ha^{-1}). When combined with single 0.76-m row spacing and a high input of P fertility (168 kg P_2O_5 ha^{-1}), these three factors (optimal row arrangement, plant density, and fertility) combined to result in a mean yield of 11.7 Mg ha^{-1}, nearly 22% greater than the trial mean of 9.6 Mg ha^{-1}. A departure from this optimal combination of factors, use of twin row arrangement for example, resulted in a yield reduction of 1.4 Mg ha^{-1}. Likewise, no input of supplemental fertility or a change in plant density from 98,840 to 86,485 plants ha^{-1} resulted in yield reductions of 2.0 and 1.0 Mg ha^{-1}, respectively. Similarly, maximum yields in the 2011 study occurred when optimal row arrangement (single 0.76-m rows) was combined with supplemental fertility (application ≥56 kg P_2O_5 ha^{-1}) and the optimum density for each hybrid.

CONCLUSIONS

The premise of this study was that management practices such as altered planting arrangement and supplemental P fertility could be used to minimize inter-plant competition associated with dense stands of maize. Twin row planting arrangement did not provide an advantage over single 0.76-m rows at elevated plant density. Similarly, there was no interaction of plant density and P fertility suggesting that simply increasing resource availability at elevated plant densities does not necessarily result in improved productivity. These results show that optimum row spacing, single 0.76-m rows in this case, combined with optimum levels of soil fertility provide the basis for achieving greater yields of maize. Plant density is an important factor for maize yield, yet yield gains associated with higher densities may be dependent on the genetic predisposition of maize hybrids to tolerate greater competition and respond with additional yield.

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