MANAGEMENT OF HIGHER POPULATIONS IN MAIZE

BY

RYAN J. BECKER

THESIS

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Adviser:

Professor Frederick Below

Abstract

While increasing plant density is a promising strategy for higher grain yield in maize, high plant populations must be managed to lesson plant competition. Previous research has focused on different management strategies for higher plant densities, mainly row configuration, but rarely a combination of strategies. The initial experiment for the 2010 growing season was conducted in Lewisville, IN to examine the main effects and interactions of plant density, row configuration, and additional fertility on grain yield and yield components. One commercial hybrid (DKC 61-21 SSTX) was grown in two row configurations (single or twin) at different plant density levels (86, 99, 111, 124, 136 and 161 plants ha^{-1} x 1,000). MESZ (MicroEssentials SZ) was banded within the row at planting at one of the following rates in terms of P_2O_5 (0, 56, 112, 168 kg ha^{-1}). Plant density was the most influential factor in limiting grain yield, which may have been influenced by hybrid selection. The placed fertilizer was beneficial for grain yield and vegetative growth, but was not able to overcome the yield limiting effects of high plant density. Also, row configuration resulted in higher yields for single rows than twin rows at higher levels of plant density. From the 2010 experimental results, revisions to the experimental design were made for 2011. In 2011, research was conducted in Champaign, IL using two hybrids (61-21 SSTX and CG 7505 VT3/P) with the same row configurations and fertilizer rates. However, plant density treatment factors were reduced to four levels (62, 86, 111, and 136 plants ha^{-1} x 1,000) due to a constant decline in average grain yield associated with increasing plant densities in 2010. For 2011, fertility and plant density exhibited similar results to the 2010 experiment, but the inclusion of a second hybrid was the most important finding. Yield differences between hybrids did not exist when averaged across all other treatments; however, kernel number and weight were significantly different and these differences accentuated grain yield under different management strategies. The selection of hybrids that can maintain a high kernel weight, without significantly reducing kernel number, is essential towards increasing yield through the use of higher plant densities.

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Chapter 1 Use of Row Configuration and Additional Fertility as Management Tools for Plant Density in Maize

Introduction

Maize (*Zea mays* L.) is a staple of modern American agriculture and has been for the past century due to its beneficial properties as a food source for livestock. Furthermore additional uses for maize developed over time that transformed it from a local feed source into a cash crop that is one of America's leading exports. The global demand experienced today is due largely to the overall increase in average grain yield from around 1.0 Mg ha^{-1} to around 8.0 Mg ha^{-1} over the past sixty years (USDA NASS, 2011). Since average yields have trended upward in the past, future predictions continue this upward projection, and it is up to farmers and researchers alike to insure this continued growth in developed countries (Alexandratos, 1999).

Historically, the development and management of maize is largely responsible for the increase in average grain yield. Since weather is the most influential factor in every growing season, other crop growth factors had to be managed in order to limit those adverse effects associated with weather. Rasumussen *et al*. (1998) and Aref and Wander (1998) discussed how the use of hybrid seed and fertilizer application were the predominant management factors that led to the observed increase in crop yields since the 1940s.

Hybrid

The first major step towards increasing grain yield began with the introduction of hybrid seed. The planting of hybrid seed at sites like the Morrow Plots at the University of Illinois established that yield from hybrid plants was greater than those observed from parental lines (Aref and Wander, 1998). Similar studies confirm that hybrids have an overall higher yield potential than original parent lines when comparing the two across a wide range of environments (Cardwell, 1982, Duvick *et al*., 2004b). A large portion of this realized gain in grain yield was associated with greater tolerance to stress exhibited by hybrid plants compared to parent lines. The abiotic stresses that would result in extensive yield reduction for parent lines were lessened through breeding programs that made hybrids more tolerant to adverse conditions; thus allowing hybrids to yield higher (Duvick *et al*., 2004b, Duvick, 2005).

An example of better tolerance exhibited by hybrid maize is demonstrated by the growing of plants closer together than what was previously recommended. Parental lines required proper spacing between plants to produce a viable ear, and when that spacing between plants was reduced (higher plant density), plants either produced a significantly smaller ear or did not produce one at all (barren). Hybrids tolerated that reduction in plant spacing better in that plants were still able to produce viable ears when spaced closer together than what was previously possible (Duvick, 2005). Although the initial increase in grain yield was associated with a higher yield potential for hybrid plants over parental lines, future improvements in hybrids did not result in an additional increase in individual yield potential when stress was limited. Duvick *et al*. (2004b) demonstrated this by comparing hybrids from the 1930s to the 1990s and showing that they did not differ in terms of grain yield when grown at a low plant density.

Modern hybrids exhibited better overall yields at a higher density level due to density tolerance exhibited by newer hybrids (Duvick *et al*., 2004b, Tollenaar and Wu, 1999). Tollenaar

(1989) also found that newer hybrids had a significantly higher grain yield than older hybrids at low plant densities along with at high plant densities. It is important to note though that Tollenaar compared four individual hybrids each from different eras as opposed to Duvick *et al*. (2004b), that used a more era encompassing approach for comparing hybrids. However, both found that newer hybrids yielded the best at higher plant densities, which is the most important finding. Duvick (2005) also surmised that hybrid tolerance to plant density was not solely responsible for the observed increase in grain yield. Rather, it was a combination of density tolerance and the ability of newer hybrids to produce heavier kernels with similar kernel numbers ear^{-1} as older hybrids. The development and use of hybrid maize is one of the most important factors that contributed to higher yields through the decades.

Plant Density and Row Configuration

One of the additional benefits associated with the planting of hybrid maize included the ability of the grower to raise plant density levels. Cardwell (1982) reported a 2% increase year^{-1} in seeding rates for fifty years in Minnesota, which initially began with the introduction of hybrid seed to growers. Since the 1980s, seeding rates have continued this upward trend, but only at ≈ 1.0% year^{-1} (Anonymous, 2011). There is a general positive trend between higher seeding rates and higher yields that has been observed for the past 80 years. Therefore, a projected increase in grain yield over the next few decades would most likely involve the incorporation of higher plant densities. There are inherent problems associated with higher plant density, mainly inter-plant competition that tends to occur at more frequent intervals. Tollenaar and Wu (1999) reported that uniform stands are essential at higher plant density levels in order to avoid yield reductions affiliated with inter-plant competition. One of the most common ways to reduce inter-plant competition is to alter the spacing pattern between plants.

Historically, the spacing between planted rows has trended downward since the 1930s. Row configuration was inversely correlated to grain yield and plant density, whereby as yield and density increased through the decades, row spacing has decreased over the decades. Cardwell (1982) reported a reduction in row spacing from 1.07 m in the 1930s to around 0.90 m in the 1970s for Minnesota growers. This reduction in row spacing resulted in a 4% increase in grain yield for Minnesota farmers according to Cardwell. Eventually row configuration was reduced to the 0.76 m spacing pattern that is predominantly used by growers today due to its yield advantages. Row configurations combined with hybrid use were two influential factors that led to increases in plant density and resulting higher yields. Since density levels likely need to increase to further increase yield, a popular approach to increasing densities involves the narrowing of rows more than the current 0.76 m practice.

The most common narrower rows tested are 0.38 m rows and twin rows, which are spaced 0.19 m apart (0.57 m between rows), but are on 0.76 m centers. The 0.19 m twin row is the more popular of the two narrow row strategies because it allows producers to use the same harvesting equipment that is used for 0.76 m rows. An additional benefit of narrower rows is better light interception by the crop during vegetative growth. One of the drawbacks associated with 0.76 m rows includes the inability of the crop canopy to intercept all of the available light until late into vegetative growth or early reproductive stages, while narrower rows allow the canopy to intercept light more efficiently than 0.76 m rows during vegetative growth (Nafziger, 2006). Reducing row spacing further than 0.76 m would hopefully increase yield through better light interception and limiting inter-plant competition.

Most studies conducted in the past 2 decades have compared 0.76 m rows to narrower row configurations across several plant densities, which mostly ranged between 62,000 and 99,000 plants ha^{-1}. In Indiana, Nielsen (1988) reported that 0.38 m rows yielded 0.2 Mg ha^{-1} higher than 0.76 m rows when averaged over nine site years, two hybrids and four plant density levels. However, there was only a significant difference in grain yield between row configurations at the lowest plant density of 44,000 plants ha^{-1}. Conversely, in Iowa, Farnham (2001) found that 0.76 m rows had a higher average yield (0.2 Mg ha^{-1}) than 0.38 m rows when averaged over six locations and three years. Farnham only reported a significant difference at the 89,000 plants ha^{-1} density level where on average, 0.76 m rows yielded 0.3 Mg ha^{-1} higher than 0.38 m rows. In the Chesapeake region of Maryland and Delaware, Kratochvil and Taylor (2005) reported a yield advantage of 0.3 Mg ha^{-1} for 0.76 m rows over 0.19 m twin rows when averaged over all years, hybrids and populations. Varying plant stands did not result in one row configuration consistently being better than the other. In the gulf region, Balkcom *et al*. (2011) reported higher average yields for 0.19 m twin rows over 0.76 m rows at medium to higher density stands, although the only significant difference was at the high (81,000 plants ha^{-1}) density treatment. When averaged across all hybrids, both row configurations significantly increased yield from the low density stand (42,000 plants ha^{-1}) to the medium (62,000 plants ha^{-1}) density stand, but yield only further increased for 0.19 m twin rows when density increased to 81,000 plants ha^{-1}. In Missouri, Nelson and Smoot (2009) found that yields did not differ significantly between 0.76 m, 0.19 m twin, or 0.38 m rows when averaged across density levels ranging from

62,000 – 99,000 plants ha^{-1}. In Minnesota, Sharratt and McWilliams (2005) reported significant differences in grain yield between row configurations in 1999, but not in 1998. In 1999, 0.38 m rows yielded significantly better than 0.19 m twin and 0.76 m rows for two hybrids at 75,400 plants ha^{-1}. Along with university research, industry has also conducted many studies concerning rows narrower than 0.76 m. In 2010, Pioneer (Pioneer Hi-bred, Johnston, IA) conducted field research in Illinois, Iowa, and Minnesota and found on average that yield differences did not occur between 0.76 m and 0.19 m twin rows for varying plant density stands (Jeschke, 2010). Overall, most research has found that altering row configuration to narrower than 0.76 m resulted in minimal yield differences compared to 0.76 m rows regardless of plant density.

Another factor that is relevant, involves how different hybrids might influence yield for different row configurations. Farnham (2001) tested six different hybrids with varying relative maturities (RM) and detected a small row configuration x hybrid interaction for two of the six hybrids when averaged across all plant densities. One of the shorter RM hybrids (< 100 d) yielded significantly better in 0.76 m rows, while a longer RM hybrid (> 110 d) performed significantly better in 0.38 m rows. Farnham concluded that hybrids may respond differently to altering row configurations, which may be partly influenced by RM. Conversely, many studies have found that yield is not significantly different between row configurations for different hybrids (Jeschke, 2010, Kratochvil and Taylor, 2005, Sharratt and McWilliams, 2005). Pioneer has compared hybrids with RM dates ranging from 94 d to 111 d and found no statistical differences in grain yield between 0.76 m and 0.19 m twin rows (Jeschke, 2010). Overall, there is no definitive evidence to suggest that hybrids do or do not yield differently under alternative row configurations, and further research is needed to determine if hybrid selection is an important factor that affects yield under varying row configurations.

Fertility

Another cultural practice that has facilitated gains in grain yield through the decades is the application of synthetic fertilizers (Aref and Wander, 1998). Manure application was historically the key contributor to soil fertility, but that all changed during the latter half of the 21st century with synthetic fertilizers. Since the 1960s, total fertilizer application of N, P, and K has grown by 150% and contributed largely to increases in yield per unit land area (USDA NASS, 2011). Since projected increases in yield will undoubtedly involve an increase in plant density, strategies to reduce plant-to-plant competition involve improved plant management through better fertility practices.

As plant density increases, there is a greater need for total nutrient availability to promote optimal growth for all plants. It is well known that Nitrogen (N) is the most limiting nutrient in the life span of a maize plant and is managed accordingly. Since N is already so closely monitored due to its importance, it is fair to assume that increasing plant density will not severely alter the management and fertilization of N. However, other nutrients, particularly a soil immobile nutrient like Phosphorus (P), may need more precise management in order to insure sufficient availability for optimum crop growth. According to Abendroth *et al.* (2011), P is most important during late vegetative and reproductive growth, but deficiencies are commonly observed only during the early vegetative growth stages. Deficiencies appear when root growth is inhibited by factors such as cool or wet weather conditions or due to soil issues like compaction. These conditions result in P deficiencies due to a lack of proper root development that results in the shoot growing faster than the current rate of uptake. Generally, phosphorus deficiencies disappear as the maize plant matures due to better root development during later vegetative growth.

Therefore, previous research regarding P-fertilization has focused on the use of fertilizers during early plant development and is commonly referred to as starter fertilizer. Most starter fertilizers consist of varying percentages of N and P with the intention to entice early plant development in order to establish stand. The amount of starter fertilizer applied heavily influences which application method will be used. In-furrow applications are made at planting and require the lowest amount, around 3 kg of N ha^{-1} and 5-7 kg of P ha^{-1}, in order to avoid seedling damage (Mallarino *et al*., 2011). Slightly higher rates between 8-15 kg of N ha^{-1} and 10-25 kg of P ha^{-1} can be applied when using the "5 x 5 approach", or 5 cm to the side of the seed and 5 cm below the seed and are usually applied at planting (Bullock *et al.*, 1993, Roth *et al*., 2006, Wolkowski, 2000). For the highest rates, which are anything greater than 40 kg of P ha^{-1}, broadcast application is required and is usually applied before planting; although it is no longer referred to as starter (Kaiser *et al*., 2005, Mallarino *et al*., 2011, Sneller and Laboski, 2009, Wortmann *et al*., 2009).

Mallarino *et al*. (2011) reported that dry matter (DM) accumulation and P uptake were increased by in-furrow application in three of the six site years for maize at the V5-V8 growth stages. In the same study, a broadcast application increased DM accumulation and P uptake in four of the six site years for maize at the V5-V8 growth stages. For grain yield, Mallarino reported a significant yield increase for broadcast applications in five out of the six years, but only two out of the six years for in-furrow applications. Kaiser *et al*. (2005) reported similar increases in DM accumulation around the V6 growth stage for both broadcast and in-furrow placement. However, significant yield gains were more frequently reported for broadcast applications than in-furrow applications. For the 5 x 5 placement method, early season growth and P-uptake were significantly increased by fertilizer application, but significant increases in yield were rarely reported (Bullock *et al*., 1993, Roth *et al*., 2003, Roth *et al*., 2006, Wolkowski, 2000).

Another contributing factor to consider is soil test levels of P that heavily influenced when yield responses were observed. For situations where soil test levels of Bray-1 P were less than 10 mg kg^{-1} (low), early season uptake and growth along with final grain yield, routinely responded to fertilizer that was either applied in-furrow or broadcast (Kaiser *et al*., 2005, Wortmann *et al*., 2009). For soil test values where Bray-1 P was rated as above optimum or high, early season growth and P uptake were routinely enhanced by starter fertilizers, but grain yield usually was not affected regardless of application method (Roth *et al*., 2006, Sneller and Laboski, 2009, Wortmann *et al*., 2009). However, there were instances where broadcast or in-furrow applications (broadcast more so than in-furrow) significantly increased yield when Bray-1 P tests did not advise fertilizer application (Kaiser *et al*., 2005, Mallarino *et al*., 2011). Although application methods and rates varied, starter fertilizers routinely increased dry matter accumulation during early vegetative growth. Yield response was generally influenced by soil P levels, but there were some exceptions reported.

Plant density was one component not considered in these studies, and as mentioned before, higher plant densities result in more inter-plant competition. It is possible that increasing plant density could make starter and other P-based fertilizers more essential towards managing higher plant densities, due to the importance of a uniform stand. The objective of this study was to increase grain yield through the management of higher plant densities that were to be managed through (i) row configuration and (ii) additional fertility.

Research Approach

The 2010 study was conducted at Fairholme Farms near Lewisville, IN (39°46’30” N 85°14’10” W) using one high yielding commercial hybrid, DKC 61-21 SSTX. This hybrid contained the “SmartStax” package which contains herbicide tolerance traits (glyphosate and glufosinate) as well as corn borer and rootworm resistance (*Cry* Bt protein). The experiment was designed with three factors (Table 1.1) which were arranged in a complete factorial arrangement as a split-plot completely randomized block design with four replications. The three factors and their accompanying levels included: plant density (88, 99, 111, 124, 136, and 161 plants ha^{-1} x 1,000), row configuration (0.76 m Single- and 0.19 m Twin rows), and additional fertility (0, 56, 112, and 168 kg ha^{-1} of P_2O_5). Additional fertility was applied as MESZ (MicroEssentials SZ, The Mosaic Company, Plymouth, MN) that has a fertilizer grade of 12-40-0-10S-1Zn (Granular formation). Each experimental unit consisted of four rows approximately 11.4 m in length and either 0.76 m row spacing for single rows or 0.19 m row spacing for twin rows. The twin rows are still on a 0.76 m center which makes mechanical harvesting with a traditional 0.76 m header possible. Plots were planted May 26th, 2010 on a Westland clay loam soil series that is classified as a Typic Argiaquolls. Soil test values (obtained from soil core samples) at Fairholme Farms were as follows: 4.1 % organic matter, 24.3 mg kg^{-1} of P, 160.5 mg kg^{-1} of K, 6.7 mg kg^{-1} of S, and 2.5 mg kg^{-1} of Zn.

A prototype twin row planter (AGCO Corp., Duluth, GA) was used to first place the desired fertilizer rate in row followed immediately by planting. For the single rows (0.76 m) an ALMACO SeedPro 360 planter (ALMACO, Nevada, IA) with variable seeding rate technology was used to plant over where the fertilizer was already placed in row by the twin row planter. The experimental site had a previous crop of soybean and was cultivated in the spring before planting. The experiment received 314 kg ha^{-1} of nitrogen in the form of urea which was applied April 25th, 2010. Plots received an in-furrow application of the insecticide tefluthrin (Force 3G, Syngenta AG, Basel, Switzerland) at a rate of 0.11 kg a.i. ha^{-1}. Weed control consisted of a pre-emergence mix application of Lumax (S-metolachlor + atrazine + mesotrione, Syngenta AG, Basel, Switzerland) at a rate of 7.0 L ha^{-1} with an additional post-emergence application of Cornerstone Plus (Glyphosate, Winfield Solutions LLC., St. Paul, MN) at a rate of 1.2 L ha^{-1}. At physiological maturity, plant stand was measured prior to harvest and were roughly 2,500 plants ha^{-1} (≈1,000 plants $acre^{-1}$) within their desired plant density level (data not shown). The center two rows of each four row plot were harvested via combine to determine grain yield, and a grain sample was collected from each plot to determine kernel weight (300 kernel counts) and kernel number on an area basis (total plot weight divided by individual kernel weight and plot area). This sample was then analyzed for grain quality (starch, protein, oil) using near-infrared transmittance spectroscopy (FOSS 1241 Grain Analyzer). All grain yields are reported at 0% moisture concentration in Mg ha^{-1}, but will also be shown in units of bushels $acre^{-1}$ at 15.5% moisture for reference. For the kernel data, kernel weight is reported in mg $kernel^{-1}$, kernel number is reported in kernels m^{-2}, and both are reported at 0% moisture.

Statistical analyses for the grain data were performed using PROC MIXED of SAS (SAS 9.2; SAS Institute Inc., Cary, NC) with plant density, row configuration, and fertilizer rate included as fixed effects and replication and replication*row configuration as random effects. Issues of normality of the residuals were addressed using PROC UNIVARIATE to determine potential outliers, which if found were removed (SAS 9.2; SAS Institute Inc., Cary, NC). Fisher's protected

LSD analyses were run for those factors along with any interaction(s) that were considered significant at an alpha level of 0.1. Figures were prepared using Sigma Plot (Sigma Plot 12.0; Systat Software Inc., San Jose, CA).

Results and Discussion

2010 Weather Conditions at Lewisville, IN

Daily weather conditions (temperature and precipitation) for Fairholme Farms, IN were collected from the regional NOAA weather station (National Oceanic and Atmospheric Administration, Silver Spring, MD) and are shown in Figure 1.1. Weather conditions following planting were on average wetter and warmer than previous years. The 2010 growing period (May 26th – August 31st) was warmer than average, with maximum and minimum daily temperatures exceeding the 10 year average (≈2°C). However, the record high temperatures appeared to have relented for around a week during grain fill. As a result the average grain yield was 9.6 Mg ha^{-1} (181 bu acre^{-1}), but we observed multiple plot yields at or above 10.6 Mg ha^{-1} (200 bu acre^{-1}).

Statistical Analysis

Two of the three treatment factors had a high source of variation ($P \leq 0.1$) as a main effect but only one interaction had a similar source of variation (Table 1.2). Both plant density and fertilizer rate were the main treatment effects that exhibited a significant influence on each of the parameters measured so a section will be devoted to describing each of those treatments. Row configuration did not differ as a main effect but the interaction between row configuration and plant density did for both yield and kernel number. Thus, the row configuration section will focus primarily on describing the interaction between the two factors. All other treatment interactions did not exhibit a significant source of variation and therefore, will not be included in the discussion section.

Plant Density

Plant density exhibited the highest source of variation for each of the parameters measured. Grain yields were highest at the lowest two planting densities (86,000 and 99,000 plants ha^{-1}) with yields decreasing with increased plant density level (Table 1.3). Farnham (2001) also reported the highest average yield at 89,000 plants ha^{-1}, although it was the highest plant density tested in that experiment. The yield components, individual kernel weight and kernels m^{-2}, exhibited similar changes as grain yield to plant density. For individual kernel weight, the lower plant densities had the highest weights and the higher plant densities had the lowest weights (Table 1.3). Kernels m^{-2} were most abundant at the two lowest plant densities with reduced kernel number occurring incrementally as plant density increased. The decrease in kernel number with increasing plant density was associated with fewer kernels per plant primarily as a result of greater kernel abortion. Our data is consistent with results reported by Cox (1996), who similarly found that increasing plant density reduced both kernel number and kernel weight. Our data suggests that limiting the decrease in kernel number (m^2) or the decrease in individual kernel weight is needed to increase yield through higher plant populations.

Row Configuration

Although row configuration as a main effect, did not influence yield or either of the yield components, there was a significant row configuration x plant density interaction detected for yield and kernel number. Examining this interaction showed that single rows performed better than twin rows as the density level reached 111,000 plants ha^{-1} and higher, and this difference was due to differences in kernel number (Table 1.4). There was a clear decrease in grain yield with increased plant density in both row configurations, but the twin rows were affected more than single rows. Other studies have failed to detect a row configuration x density interaction for yield, but these studies did not evaluate as high densities as was done in the current experiment (Farnham, 2001, Nelson and Smoot, 2009, Nielsen, 1988). Farnham (2001) and Nelson and Smoot (2009) tested plant density up to a maximum level of around 89,000 plants ha^{-1}, and at similar levels, we found no difference in yield between row configurations. Therefore, we suggest that significant interactions between row configuration and plant density are not detected until density levels increase to above 100,000 plants ha^{-1}. Poor twin row performance at high density levels suggests that some additional stress was limiting grain yield. Higher average grain yields for single rows at similar density levels argue that inter-plant competition for water and nutrients was not the reason for the lower yields of twin rows at high plant density.

Fertility

Application of any level of MESZ (MicroEssentials SZ) increased yield over those plots receiving no additional fertilizer (+0.5.Mg ha^{-1} or +10 bu $acre^{-1}$) (Table 1.5). Although not always statistically significant, each successive level of fertilizer increased yield such that the highest yield reported, corresponds with the highest fertilizer rate. Kernel number and individual kernel weight also attained their highest values at the highest fertilizer rates, although similar to yield, using a lesser rate for each did not necessarily result in a significantly different value.

Any rate of additional fertilizer resulted in larger vegetative plants (Figure 1.2) and these larger plants generally corresponded to high grain yields (Table 1.5). Kaiser *et al*. (2005) and Mallarino *et al*. (2011) reported similar early season growth enhancement and increases in grain yield when a P-based fertilizer was added either in-furrow or broadcast, but only when the soil-P levels of that site were at or below optimum levels. For our experiment, the yield response to the fertilizer was a little surprising because the soil P levels were greater than 20 mg kg^{-1}, which is considered adequate for 9.8 Mg ha^{-1} (185 bu $acre^{-1}$) production. Because of our application and placement approach (at planting, within the row, and use of MESZ), we believe that more of the P was readily-available to the plant during the season. Either the increased plant densities required additional P that the soils had not been able to provide in a timely manner, or the extra N, Zn or S (that accompanies the MESZ) resulted in the observed yield response.

Conclusion

The higher than average temperatures experienced by the crop in 2010 are generally thought to have decreased yield, as the state average was 0.8 Mg ha^{-1} less than the previous year (USDA NASS, 2011). In this experiment, these abnormally warm temperatures were also detrimental for the higher plant densities, especially for the twin rows. In terms of spacing, plants in single rows are closer together since they can only occupy one row that is 11.4 m in length. The twin row can provide better spacing on a per plant basis since it has a plot area with two rows spaced 0.19 m apart and still 11.4 m in length. Twin row plants are spaced further apart at high densities compared to plants in single rows, which implies less inter-plant competition for nutrients and light. Since twin rows exhibited poorer performance than single rows at higher plant densities, the cause does not appear to be due to increased inter-plant competition.

The need for fertilizer was apparent with grain yields increasing for every fertilizer level when compared to the check plot treatment. We speculate that P was largely responsible for the observed yield response because P_2O_5 makes up roughly 40% of MESZ, and a large application of urea (314 kg ha^{-1}) was made in the spring, so that N would be non-limiting and this should negate any early season benefits associated with N from the MESZ. Furthermore, Abendroth *et al*. (2011) showed that N-uptake by the V7 growth stage is only 10% of total seasonal plant uptake, which along with the high rate of N applied as urea, suggests that the extra N from MESZ was not the cause of the yield enhancement. MESZ also contains Sulfur and Zinc, and these elements could also be responsible for the increases in grain yield, but we speculate that P-fertilizer increases grain yield through more robust plants during vegetative growth that increases kernel number during early ear development.

Overall, it appears that there is an advantage to adding extra fertilizer (P) when increasing plant density, but altering row configuration (twin rows) does not offer similar advantages. Since plant density is a large factor in determining yield potential, further studies are needed to identify the maximum density level at which the added fertilizer can adequately maintain average to above-average grain yields on an individual plant basis.

References

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009. Iowa State University Extension, Ames, Iowa.

Alexandratos, N. 1999. World food and agriculture: Outlook for the medium and longer term. *Proc. Natl. Acad. Sci. USA* 96:5908-5914.

Anonymous. 2011. Pioneer Brand Concentration Survey. Available at https://www.pioneer.com/home/site/us/agronomy/library/template.CONTENT/guid.9C26CEFA-2FB0-483D-1308-F02D23AB6293.

Aref, S., and M.M. Wander. 1998. Long-term trends of corn yield and soil organic matter in different crop sequences and soil fertility treatments on the Morrow Plots. *Advances in Agronomy* 62:153-197.

Balkcom, K.S., J.L. Satterwhite, F.J. Arriaga, A.J. Price, and E. van Santen. 2011. Conventional and glyphosate-resistant maize yields across plant densities in single- and twin-row configurations. *Field Crops Research* 120:330-337.

Bullock, D.G., F.W. Simmons, I.M. Chung, and G.I. Johnson. 1993. Growth analysis of corn grown with or without starter fertilizer. *Crop Sci.* 33:112-117.

Cardwell, V.B. 1982. Fifty years of Minnesota corn production: Sources of yield increase. *Agron. J*. 74:984-990.

Cox, W.J. 1996. Whole-plant physiological and yield responses of maize to plant density. *Agron. J.* 88:489-496.

Duvick, D.N. 2005. The contribution of breeding to yield advances in maize (*Zea Mays* L.). *Advances in Agronomy* 86:83-145.

Duvick, D.N., J.S.C. Smith, and M. Cooper. 2004b. Long-term selection in a commercial hybrid maize breeding program. pp. 109-151. *In*. J. Janick (Ed.) Plant Breeding Reviews. Part 2. Long Term Selection: Crops, Animals and Bacteria, Vol. 24. John Wiley & Sons, New York.

Farnham, D.E. 2001. Row spacing, plant density, and hybrid effects on corn grain yield and moisture. *Agron. J.* 93:1049-1053.

Jeschke, M. 2010. Twin-row corn production. *Crop Insights* 20(15):1-6. Available at https://www.pioneer.com/home/site/us/agronomy/library/template.CONTENT/guid.B6436E5B-B696-7338-F3B2-DC958644F8FE

Kaiser, D.E., A.P. Mallarino, and M. Bermudez. 2005. Corn grain yield, early growth, and early nutrient uptake as affected by broadcast and in-furrow starter fertilization. *Agron. J.* 97:620-626.

Kratochvil, R.J., and R.W. Taylor. 2005. Twin-row corn production: An evaluation in the mid-Atlantic Delmarva region. Online. Crop Management doi: 10.1094/CM-2005-0906-01-RS.

Mallarino, A.P., N. Bergmann, and D.E. Kaiser. 2011. Corn responses to in-furrow Phosphorus and Potassium starter fertilizer applications. *Agron. J.* 103:685-694.

Nafziger, E.D. 2006. Inter- and intraplant competition in corn. Online. Crop Management doi: 10.1094/CM-2006-0227-05-RV.

Nelson, K.A., and R.L. Smoot. 2009. Twin- and single-row corn production in northeast Missouri. Online. Crop Management doi: 10.1094/CM-2009-0130-01-RS.

Nielsen, R.L. 1988. Influence of hybrids and plant density on grain yield and stalk breakage in corn grown in 15-inch row spacing. *J. Prod. Agric.* 1:190-195.

Rasmussen, P.E., K.W.T. Goulding, J.R. Brown, P.R. Grace, H.H. Janzen, and M. Körschens. 1998. Long-term agroecosystem experiments: Assessing agricultural sustainability and global change. *Science* 282:893-896.

Roth, G.W., D.B. Beegle, and M.E. Antle. 2003. Evaluation of starter fertilizers for corn on soils testing high for Phosphorus. *Commun. Soil Sci. Plant Anal.* 34:1381-1392.

Roth, G.W., D.B. Beegle, S.M. Heinbaugh, and M.E. Antle. 2006. Starter fertilizers for corn on soils testing high in Phosphorus in the northeastern USA. *Agron. J.* 98:1121-1127.

Sharratt, B.S., and D.A. McWilliams. 2005. Microclimatic and rooting characteristics of narrow-row versus conventional-row corn. *Agron. J.* 97:1129-1135.

Sneller, E.G., and C.A.M. Laboski. 2009. Phosphorus source effects on corn utilization and changes in soil test. *Agron. J.* 101:663-670.

Tollenaar, M. 1989. Genetic improvement in grain yield of commercial maize hybrids grown in Ontario from 1959 to 1988. *Crop Sci.* 29:1365-1371.

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

USDA-NASS. 2011. United States Department of Agriculture – National Agricultural Statistics Service. Available at http://www.nass.usda.gov.

Wolkowski, R.P. 2000. Row-placed fertilizer for maize grown with an in-row crop residue management system in southern Wisconsin. *Soil & Tillage Research* 54:55-62.

Wortmann, C.S., A.R. Dobermann, R.B. Ferguson, G.W. Hergert, C.A. Shapiro, D.D. Tarkalson, and D.T. Walters. 2009. High-yielding corn response to applied Phosphorus, Potassium, and Sulfur in Nebraska. *Agron. J.* 101:546-555.

Tables and Figures

Table 1.1. Treatment factors and their levels included in the 2010 study.

Row configuration	Plant density	Fertilizer rate
	plants ha^{-1}	kg ha^{-1} as P_2O_5
Single (0.76 m)	86,000	0
Twin (0.57 m)	99,000	56
	111,000	112
	124,000	168
	136,000	
	161,000	

Figures

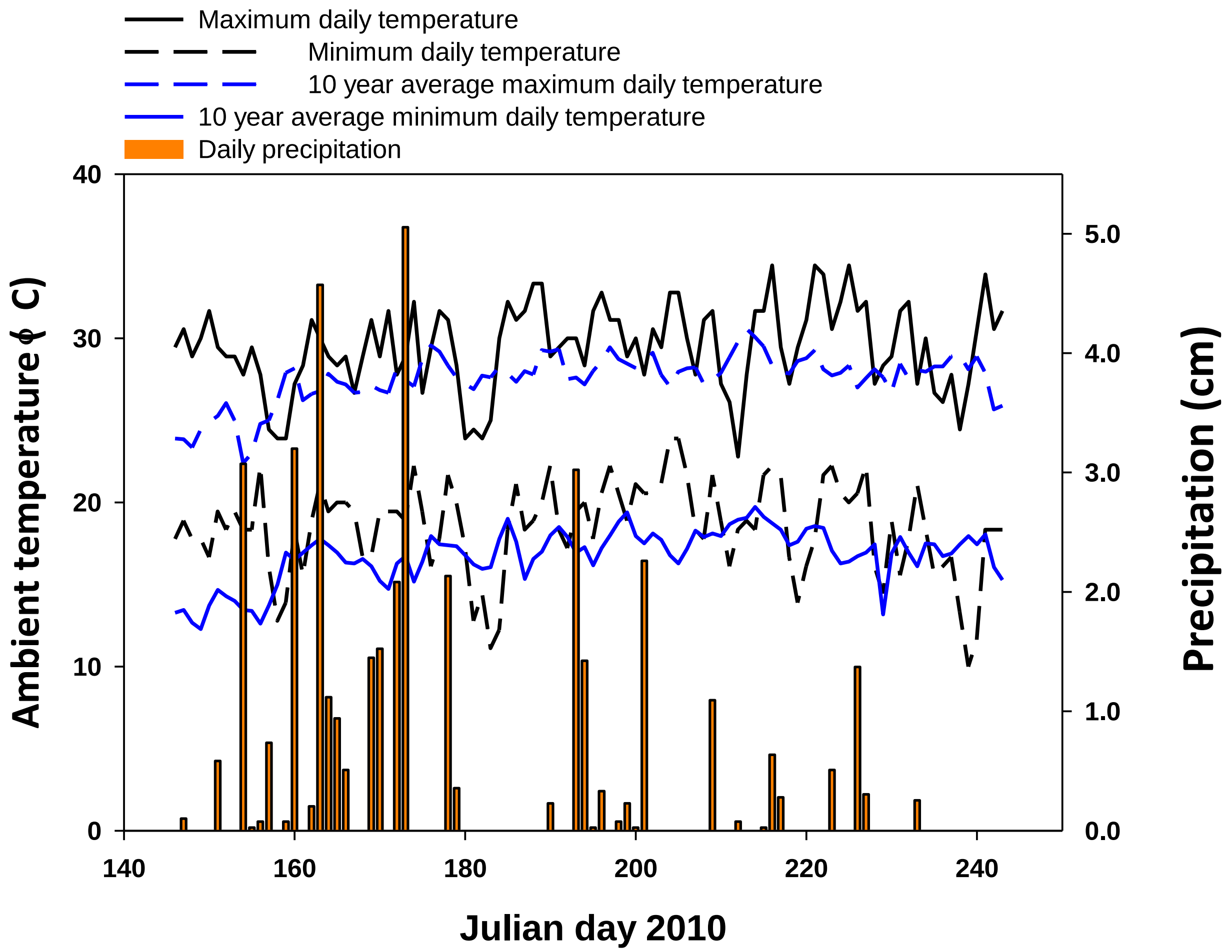

Figure 1.1. Daily weather conditions at Lewisville, IN in 2010.

Table 1.2. Analysis of variance for the effects of plant density, row configuration and fertilizer rate on grain yield and yield components measured at Fairholme Farms, IN in 2010.

Source of variation	df	Grain yield	Kernel number	Individual kernel weight
		$Mg\ ha^{-1}$	m^{-2}	$mg\ kernel^{-1}$
Density	5	<0.0001	<0.0001	0.0031
RC	1	0.2775	0.2678	0.4837
RC x Density	5	0.0322	0.0107	0.6415
Fertrate	3	0.0018	0.0102	0.0046
RC x Fertrate	3	0.7863	0.5984	0.7009
Density x Fertrate	15	0.8384	0.6236	0.8954
RC x Density x Fertrate	15	0.7270	0.6546	0.7646

†Probability values less than 0.1 (P ≤ 0.1) are considered a significant source of variation.

‡RC = Row configuration, Fertrate = Additional fertility, Density = Plant density

Table 1.3. Main effect of plant density on grain yield and yield components measured at Fairholme Farms, IN in 2010. Values reported are averaged across all fertilizer and row configuration combinations.

Plant density	Grain yield	Kernel number	Individual kernel weight
plants ha^{-1}	Mg ha^{-1} (bu $acre^{-1}$)	m^{-2}	mg $kernel^{-1}$
86,000	10.2 (192) ab	4522 ab	225 a
99,000	10.4 (196) a	4586 a	226 a
111,000	9.8 (184) bc	4397 abc	221 ab
124,000	9.6 (180) c	4365 bc	218 b
136,000	9.2 (174) cd	4248 c	217 b
161,000	8.7 (164) c	3948 d	218 b

† Means within a column followed by the same letter are not significantly different at $P \leq 0.1$.

Table 1.4. Effects of the interaction between row configuration and plant density on grain yield and other yield components for Fairholme Farms, IN in 2010. Values reported are averaged across all fertilizer treatments.

	Plant density x row configuration interaction								
	------------Grain yield------------			---Kernel number---			Individual kernel weight		
Plant density	Single	Twin	P > F	Single	Twin	P > F	Single	Twin	P > F
	Mg ha^{-1} (bu $acre^{-1}$)			m^{-2}			mg $kernel^{-1}$		
86,000	10.1 (189)	10.3 (194)	NS[‡]	4417	4627	NS	228	223	NS
99,000	10.5 (198)	10.3 (193)	NS	4618	4555	NS	227	225	NS
111,000	10.2 (191)	9.4 (175)	NS	4562	4233	NS	223	220	NS
124,000	10.1 (191)	9.0 (169)	< 0.1	4559	4171	< 0.1	222	214	NS
136,000	9.1 (172)	9.3 (176)	NS	4208	4287	NS	216	218	NS
161,000	9.5 (179)	7.9 (150)	< 0.05	4289	3609	< 0.01	217	218	NS

† Comparisons are only made between row configurations at the same plant density level.

‡ NS denotes non-significance

Table 1.5. Main effect of additional fertilizer on grain yield and yield components measured at Fairholme Farms, IN in 2010. Values reported are averaged across all plant density and row configuration combinations.

Fertilizer rate	Grain yield	Kernel number	Individual kernel weight
kg ha^{-1} as P_2O_5	Mg ha^{-1} (bu $acre^{-1}$)	m^{-2}	mg $kernel^{-1}$
0	9.1 (171) c	4159 c	217 b
56	9.6 (180) b	4287 bc	223 a
112	9.7 (183) ab	4441 ab	219 b
168	10.2 (191) a	4492 a	225 a

† Means within a column followed by the same letter are not significantly different at P ≤ 0.1

Figure 1.2. Picture taken at the V6 growth stage of two single row plots that received different treatments at Fairholme Farms, IN. The plot on the left received the 0 kg ha^{-1} treatment at 124,000 plants ha^{-1} (yield = 11.3 Mg ha^{-1} or 212 bu acre^{-1}), and the plot on the right received the 168 kg ha^{-1} treatment at 161,000 plants ha^{-1} (yield = 11.9 Mg ha^{-1} or 223 bu acre^{-1}). There is a clear response to the additional fertilizer since plots that received the treatment contain plants that are considerably bigger and yielded higher.

Chapter 2 The Importance of Hybrid Selection in Managing Higher Plant Densities in Maize

Introduction

The previous chapter included a literature review of factors associated with managing higher plant densities, which influenced the study initiated in 2010. Briefly, the major findings of the 2010 experiment were the following: (i) plant density was the most limiting factor in terms of grain yield, (ii) row configuration did not influence grain yield alone but an interaction between row configuration x plant density demonstrated that single rows perform better at high densities than twin rows and (iii) additional fertility increased yield but did not overcome yield stresses caused by high plant density. For 2011, the first change involved the inclusion of a second hybrid to the experimental design. For 2010, the average grain yield was 9.6 Mg ha^{-1} (181 bu $acre^{-1}$), which we considered low given the additional fertility and hybrid selection. A second hybrid, Croplan Genetics (CG) 7505 VT3/P was selected based on results from a separate plant density experiment in 2010 that demonstrated this specific hybrid's high yielding ability, while under stressful conditions (high plant density in unusually warm growing season). Having a second hybrid in the experimental design allowed us to test for significant interactions between hybrid x row configuration and hybrid x plant density, which have been previously reported by Farnham (2001) and Cox (1996). The other change in the treatments involved the reduction of plant density from 6 levels to 4 levels with density levels being spaced further apart from one another. The goal in selecting populations to examine was to observe a quadratic response to plant density in terms of grain yield as opposed to the linear response observed in 2010. Therefore, the lowest plant density was well below the optimal plant density level and additional levels increased to well above the optimal density level recommended for today's growers. Additional fertility treatments and row configurations were similar to those evaluated in 2010.

Additionally, I speculated that canopy temperature was a potential factor limiting grain yield for twin rows at higher plant densities. Our original hypothesis for this experiment was based around the notion that limiting competition at higher levels of plant density was crucial towards increasing yield through higher densities. Row configuration was one of the treatments used to limit competition effects by spacing plants more efficiently using the twin row configuration. However, using the yield data from the 2010 experiment, twin rows tended to yield significantly worse than single rows when density levels were raised above the 99,000 – 111,000 plants ha^{-1} level. Somewhere between these stated levels, single rows tend to yield better than twin rows, due to the sharper decline in yield with increasing densities for twin rows.

In other 2010 twin row studies using a high-tech omission plot design, there was premature senescence of leaves below the ear after pollination, when compared to single rows planted at the same plant density (104,000 plants ha^{-1}). With the stagger configuration of twin rows, plants within a row are further apart from one another than in 0.76 m rows at each plant density level; however, the narrow 0.19 m spacing within the row, or 0.57 m spacing between rows may limit air flow. In this scenario, increased temperatures would occur within the crop canopy of twin rows, and stress the plant into premature leaf senescence below the ear. Our speculation is further developed from my 2010 data where there is a significant interaction occurring between plant density and row configuration at higher levels of plant density. Our temperature hypothesis would then help explain the greater reduction in grain yield and kernel number for twin rows as compared to single rows.

Most of the previous research regarding temperature effects on maize has focused on the detrimental effects of high temperature during the grain fill period. Both Badu-Apraku *et al*. (1983) and Wilhelm *et al*. (1999) demonstrated that maize plants had a significantly reduced kernel weight when subjected to increased temperatures from grain fill (15-18 days post silking) all the way to physiological maturity. Both authors stated that kernel weight was decreased due to a reduction in the duration of the grain fill period as well as the rate of grain fill. There has been other research conducted regarding temperature effects on a period bracketing flowering that concerns pollen shed and viability, which would thus influence kernel number. Cicchino *et al*. (2010) insured that pollen was non-limiting when a heat stress was applied pre-silking for a period bracketing anthesis, and reported a decrease in kernel number. However, Cicchino *et al*. stated that the heat stress may have indirectly reduced kernel number that was more of an effect of water stress experienced by the plant. Water stress is especially detrimental during silking because it reduces the amount of ovules that can be fertilized or that abort, which leads to a decrease in kernel number and yield (Otegui *et al*., 1995). Andrade *et al*. (1999) also reported a significant reduction in kernel number when night temperatures were high due to a reduction in the critical time period that determines kernel number. It is clear that high daytime/nighttime temperatures can be deleterious to final grain yield either through a reduction in kernel number or kernel weight that is dependent on the time period during which the stress occurs.

The objective of the study was to increase grain yield through the management of higher plant densities that were to be managed through (i) row configuration (ii) additional fertility and (iii) hybrid selection. An additional objective of the 2011 experiment was to further validate the detrimental effect of twin rows at higher plant densities as compared to single rows, which would be accomplished by using an infrared camera to document differences in canopy temperatures between the two row configurations.

Research Approach

The 2010 and 2011 experimental designs consisted of the same row configurations and fertility rates, however, plant density levels were reduced from 6 levels in 2010 (86,000, 99,000, 111,000, 124,000, 136,000, and 161,000 plants ha^{-1}) to four levels in 2011 (62,000, 86,000, 111,000 and 136,000 plants ha^{-1}). The other change included the planting of two hybrids instead of one. DKC 61-21 with the "SmartStax" package was planted again for consistency between the two years, and another hybrid, CG 7505 VT3/P, was included. The hybrid 61-21 has a relative maturity (RM) of 111 days while CG 7505 has a RM of 115 days. Treatments were arranged in a complete factorial in a split-split experimental design plot with four replications (Table 2.1). The main plot was hybrid and sub plot was row configuration along with different combinations of plant density and additional fertility. Each experimental unit consisted of four rows approximately 11.4 m in length and either 0.76 m row spacing for single rows or 0.19 m row spacing for twin rows. Plots were planted May 20th, 2011 near Champaign, IL on the University of Illinois Department of Crop Sciences' Maxwell Farm (40°03'22" N 88°14'02" W) that was planted to soybean the previous season and was cultivated in the following spring before planting. Soil test values (obtained from soil core samples) for the Drummer series that is a Typic Endoaquoll were as follows: 0 – 0.15 m soil depth, 4.8% organic matter, 43 mg kg^{-1} of P, 131 mg kg^{-1} of K, 10 mg kg^{-1} of S and 2.0 mg kg^{-1} of Zn, for 0.15 – 0.30 m soil depth, 4.8% organic matter, 34 mg kg^{-1} of P, 97 mg kg^{-1} of K, 7 mg kg^{-1} of S, and 1.4 mg kg^{-1} of Zn.

For all plots, the MESZ treatment was banded (10-15 cm) directly below the future row by a fertilizer toolbar (Dawn Equipment, Sycamore, IL). Single row plots were then planted using an ALMACO SeedPro 360 planter (ALMACO, Nevada, IA) with variable seeding rate technology over the rows where MESZ had been placed, and a twin row planter (AGCO Corp., Duluth, GA) was used to plant the twin rows over the fertilized rows. The experimental area received 202 kg ha^{-1} of nitrogen applied as 28% UAN in the spring with a further 67 kg ha^{-1} of nitrogen applied as SuperU (Koch Fertilizer LLC., Wichita, KS) at the V6 growth stage. Also at planting, each experiment received an in-furrow application of the insecticide tefluthrin (Force 3G, Syngenta AG, Basel, Switzerland) at a rate of 0.11 kg a.i. ha^{-1} to suppress pests. Weed control consisted of a pre-emergence application of Lumax (s-metolachlor + atrazine + mesotrione, Syngenta AG, Basel, Switzerland) at a rate of 7.0 L ha^{-1} with an additional post-emergence application of glyphosate at a rate of 1.6 L ha^{-1} where needed.

At the VT/R1 growth stage, the entire experimental area received an aerial blanket application of Quilt Xcel Fungicide (Syngenta AG, Basel, Switzerland) at a rate of 0.88 L ha^{-1} for preventive purposes. During the period following flowering, plots were scouted and photos were taken to document premature senescence below the ear. Also, an infrared camera (FLIR Systems, Wilsonville, OR) was used to document canopy temperatures by estimating the hottest area within the image scanned for each row configuration at different plant density levels. The infrared camera was used to estimate each density x row configuration combination's temperature for a week's duration at a selected period in the morning, afternoon and evening hours. After physiological maturity and sufficient dry down, stand counts were taken to determine plant density (approximately 3500 plants ha^{-1} within the desired level, data not shown) and the center two rows of each four row plot were harvested using a plot combine in order to determine grain yield. A grain sample was also collected from each plot to determine kernel weight (300 kernel counts) and kernel number per m^2 (total plot weight divided by individual kernel weight and plot area) and this sample was analyzed for grain quality (starch, protein, oil) using near-infrared transmittance spectroscopy (FOSS 1241 Grain Analyzer). All grain yields are reported at 0% moisture concentration in Mg ha^{-1}, but will also be shown in units of bushels $acre^{-1}$ at 15.5% moisture for reference. Kernel number and kernel weight will both be reported at 0% moisture.

Statistical analyses for the grain data were performed using the PROC MIXED function in SAS (SAS 9.2; SAS Institute Inc., Cary, NC) with plant density, hybrid, fertilizer rate and row configuration included as fixed effects, and replication, replication*hybrid, and replication*hybrid*row configuration as random effects. Residuals were tested for normality using the PROC UNIVARIATE function and notable outliers were removed (SAS 9.2; SAS Institute Inc., Cary, NC). Fisher's protected LSD analyses were run for those main effect factors that demonstrated significant differences along with significant interactions at an alpha level of 0.1. All figures were prepared using Sigma Plot (Sigma Plot 12.0, Systat Software Inc., San Jose, CA).

Results and Discussion

2011 Weather Conditions at Champaign, IL

Daily weather conditions (temperature and precipitation) for Champaign, IL were collected from the regional NOAA weather station (National Oceanic and Atmospheric Administration, Silver Spring, MD) and are shown in Figure 2.1. Weather conditions were similar to the seasonal average in terms of temperature and rainfall for much of the beginning part of the growing season. However, towards the latter part of vegetative growth and for much of the reproductive phase (July 1^{st} – August 15^{th}), daily high and low temperatures exceeded the ten year average. Along with this unusual warm weather, monthly precipitation totals were well below their averages and much of the middle portion of IL experienced drought like conditions (Illinois State Water Survey, 2012). Grain yields were respectable considering the adverse weather conditions, which could be due to the wet spring that helped keep the soil saturated for much of the growing season.

Statistical Analysis

Of the four main effects, plant density exerted the largest source of variation for each of the three parameters measured (Table 2.2), which is similar to what we observed in 2010 (see Chapter 1). Also similar to 2010, row configuration did not affect grain yield or yield components as a main effect, but there was an interaction between row configuration and plant density. Fertilizer rate exhibited similar sources of variation to 2010 for both yield and kernel number, but kernel weight was unaffected. Interestingly, the addition of hybrid as a main effect was only a significant source of variation for kernel number and individual kernel weight, but these differences resulted in different yield levels for the interaction between hybrid and plant density. There were other significant interactions ($P \leq 0.1$) reported for each measured parameter, but further analysis was not pursued due to a lack of relevance in managing higher populations for additional yield.

Plant Density

Grain yields reported for plant density are averaged across all other treatment options in order to demonstrate the main effect of plant density. Average grain yields and kernel number were highest at the middle two density levels with the lowest values being reported for the lowest density level, although significant differences between each density level varied (Table 2.3). Conversely, individual kernel weight was highest at the lowest density level and decreased incrementally as plant density increased. The results show that kernel weight decreases as plant density levels are increased, but this can be offset by getting more kernels in the field. The optimal level appears to be somewhere between 86,000 and 111,000 plants ha^{-1} due to the balance of there being more plants to intercept light and an ability to maintain a respectable kernel weight; thus maximizing yield.

Row Configuration

The main effect of row configuration was not significant for grain yield or either of the yield components. Instead, row configuration was most important when viewed in an interaction with plant density that showed how the two row configurations respond differently to changes in plant density (Table 2.4). For the lowest density level tested, twin rows yielded better than single rows but this difference between row configurations disappeared at the 86,000 plants ha^{-1} level, although the twin row obtained its highest yield at this density. Kratochvil and Taylor (2005) reported similar results where a 111 day RM hybrid achieved its highest average yield for twin rows at 86,000 plants ha^{-1}. Conversely, for the two highest plant densities tested, there was a clear increase in yield for single rows over twin rows. Interestingly, an increase in kernel number was responsible for the difference in yield between row configurations at varying density levels, while individual kernel weight was unaffected. These results were similar to those from the 2010 experiment where significant differences in yield between single rows and twin rows were observed after density levels increased to well above the optimal planting range. However, this year's study also demonstrated that when density levels are reduced to well below the optimal plant density, grain yield can also differ between row configurations.

Fertility

Application of MicroEssentials SZ (MESZ) resulted in a significant grain yield response and resulted in gains of 0.2-0.4 Mg ha^{-1} (4-8 bu acre^{-1}) over plots receiving no additional fertility (Table 2.5), although the response was not as large as it was for 2010. Kernel number responded similarly to grain yield, where both reported the highest and lowest values at the same fertility level, which clearly demonstrates a link between yield and kernel number in response to fertilizer. In contrast, individual kernel weight was unaffected by additional fertilizer, and points toward the benefit of the fertility being realized during initial ear development due to the increase in kernel number. Additional fertilizer resulted in plots having larger, greener plants than those receiving no additional fertility (Figures 2.2, 2.3); similar to what was observed in 2010. Soil test levels for P and S were rated high and medium, respectively, so the yield response to the placed fertilizer was not necessarily expected. However, our 2010 experiment in Lewisville, IN exhibited similar findings, where grain yield was highly responsive to additional fertility when compared to check plots with high soil test levels.

Hybrid

As a main effect, the hybrids did not differ in grain yield, although they did differ in kernel number and kernel weight (Table 2.6). In regards to kernel number, the hybrid 61-21 had a much higher kernel count than did 7505, while the converse was true for individual kernel weight. Gambín *et al*. (2006) reported that hybrids differ in their ear formation strategy through compensatory adjustments between kernel number and kernel weight, that when tested over twelve commercial hybrids, demonstrated that hybrids that produced heavier kernels, set a lower number of kernels per plant and vice versa. The work of Gambín *et al* and our study shows that different hybrids can vary in their ear formation, but can still produce similar yields. The interaction between plant density and hybrid further showed how different hybrids perform in different systems (Table 2.7). On average, the hybrid 61-21 had a higher grain yield at low plant density levels, while the hybrid 7505 consistently yielded greater at the higher plant density levels. Interestingly, both hybrids yielded roughly the same when grown at the current density level used by most producers (86,000 plants ha^{-1}). Regardless of plant density, the hybrid 7505 consistently had a much higher kernel weight than did hybrid 61-21, and 61-21 had a much higher kernel number than 7505. Furthermore, each hybrid reported the highest average yield at the plant density level where its kernel number was at its greatest.

In order to identify the ideal situation for each hybrid, the interactions for both row configuration x plant density and hybrid x plant density provide clues toward the best combinations of each factor. Since the hybrid 61-21 yielded higher than 7505 at the lowest density level, and twin rows were better than single rows at low density, the best combination at low density was twin row configuration with the hybrid 61-21 (Figure 2.4). As mentioned earlier, the current recommended density level does not favor either hybrid or row configuration at the 86,000 plants ha^{-1} density level, so any combination of the three factors roughly yielded the same. At higher density levels, the hybrid 7505 yielded better than 61-21, and single rows were better than twin rows, so the best combination at high plant densities would be the hybrid 7505 in the single row configuration (Figure 2.5).

Temperature Effects

Similar to 2010, at high plant densities single rows consistently outperformed the twin rows. Both grain yield and kernel number were reduced for twin rows compared to single rows at high densities, although kernel weight was unaffected (Table 2.4). Photos taken at the R3 growth stage depict the early senescence exhibited by twin rows over single rows at a plant density of 111,000 plants ha^{-1} (Figure 2.6) and above, which we believe is the reason for the lower yield of twin rows at higher densities. The twin row plot appears to have “burnt” leaves in the lower canopy when compared to the healthier canopy of the single row plot. Around a week later, an infrared camera was used to document temperature differences at ear height between the two row arrangements. Along with the camera reporting the highest temperature detected numerically, the thermal image demonstrated that twin rows are almost 1°C warmer than single rows at a density level of 111,000 plants ha^{-1} and above (Figure 2.7).

Conclusion

Although adverse weather persisted for much of the latter part of the 2011 growing season, the average grain yield for the experiment was a respectable 10.3 Mg ha^{-1} (194 bu $acre^{-1}$), which was higher than both the average from the 2010 experiment (9.6 Mg ha^{-1}) and the yield average for central IL, which was 8.7 Mg ha^{-1} (164 bu $acre^{-1}$) (USDA NASS, 2011). The main problem was higher than average maximum and minimum temperatures along with lack of rain. In the 2010 experiment, twin rows were worse than single rows at all levels of plant density greater than 99,000 plants ha^{-1}. The same result was observed in 2011 when comparing the three levels of plant density that were used in both years, which were 86,000, 111,000 and 136,000 plants ha^{-1}. At the 86,000 plants ha^{-1} level, average grain yields were similar between single rows and twin rows, which were similar to the 2010 results. However, as plant density increased to 111,000 and beyond, the twin rows yielded less than single rows in both 2010 and 2011. The lower density level of 62,000 plants ha^{-1} was used in 2011 and it showed higher yields for twin rows over single rows. Similar to our results, other studies have demonstrated that narrower rows can yield higher than 0.76 m rows at plant densities ranging from 62,000 plants ha^{-1} to 81,000 plants ha^{-1} (Balkcom *et al*. 2011, Sharratt and McWilliams, 2005). However, above these density levels, it does not appear that twin row performance is better than single row as demonstrated by our experiments.

The value of added fertilizer was visually apparent in more rapid plant growth, and plots that received any additional fertility, had higher grain yields than those plots receiving no additional fertility. Higher yields due to fertilizer were mainly through increasing kernel number and not kernel weight. We speculate that the more rapid plant growth during vegetative development

(Figures 2.2, 2.3) is responsible for increased kernel number because kernel rows and kernels per row are determined by the plant during vegetative growth. Every plant density, except the 62,000 plants ha^{-1} level, exhibited a yield response to additional fertilizer that points toward the ability of the soil (rated high to moderate for P, K, and S) to provide adequate nutrition for plants grown at this low density level (data not shown). However, increasing plant densities to or above the recommended level could be detrimental, possibly due to the total amount of nutrients needed and the soil not being able to release those nutrients fast enough without supplemental fertilization. In both 2010 and 2011, there was a distinguishable increase in yield through the use of additional fertilizer on fields with soil tests that were rated from moderate to high, which suggests that soil test values need to be updated to reflect the increases in average plant density that have occurred over the last three decades (USDA NASS, 2011). We also speculate that modern hybrids are different in their patterns of nutrient uptake and partitioning than those hybrids that were used by research groups to calibrate soil test values during the 1960s and 1970s.

Overall, plant density was the most significant factor in determining grain yield. On average, yields increased as you increased plant density from the 62,000 plants ha^{-1} mark, but eventually declined when increased above 111,000 plants ha^{-1}. The inclusion of the second hybrid was of particular interest because it demonstrated how important it is to choose the correct hybrid when trying to increase yield through increasing plant density. We did observe a significant effect for the hybrid x density interaction like Cox (1996) reported, and we agree with Cox that ear type is an important reason for this interaction. For our experiment, the hybrid 61-21 performed best at lower densities, while hybrid 7505 was best at higher densities. When comparing the hybrids 61-21 and 7505, 7505 consistently had a higher kernel weight than 61-21, but 61-21 had a higher kernel number than 7505. The difference between the two yield components thus influenced how the hybrid responded to changes in plant density.

The first important finding was that yield levels for each hybrid were maximized at a plant density level where kernel number was at its highest, but yield components work in concert with one another, so that individual kernel weight along with kernel number influenced final grain yield. Although the highest individual kernel weights were attained at the lowest density level, the rate of decline in kernel weight for each hybrid was different as density levels were increased. Hybrid 7505 attained its highest yield and kernel number at 111,000 plants ha^{-1} due to the small decline in kernel weight observed when density increased from the 86,000 plants ha^{-1} level. Conversely, kernel weight for hybrid 61-21 declined more rapidly from the 86,000 plants ha^{-1} to the 111,000 plants ha^{-1}, and resulted in a higher kernel number and yield for the 86,000 plants ha^{-1} density level. Andrade *et al*. (1999) reported that higher plant densities had a reduced kernel number due to kernel abortion that can be attributed to a weaker sink. Therefore, the different plant density level at which each hybrid achieved its highest kernel number may have been influenced by differing sink strengths at varying levels of plant density. Furthermore, Gambín *et al*. (2008) demonstrated that a hybrid that does not set as many kernels, when compared to others, has the ability to increase kernel weight if source material is non-limiting. Our results would lead us to believe that since the hybrid 7505 set a lower kernel number, it could maintain higher sink strength at higher densities that led to higher yield than 61-21 at similar density levels.

The differences in kernel weight and kernel number were indicative of the differences in ear formation between these two hybrids. Although there is a lack of research on differing ear types, private companies have promoted their commercial hybrids according to ear types, which can be classified as indeterminate (flexed), determinate (fixed) or a variation of the two (Bechman, 2006, Mascagni and Bell, 2004). Our classification of ear types is based on what we observed regarding yield components and how they interacted with density to determine yield, since the goal of the experiment was to manage high plant densities. Therefore, we classify hybrid 61-21 as density intolerant due to its lower yields at higher densities that was a result of a rapidly decreasing kernel weight. Conversely, hybrid 7505 is considered density tolerant due to its higher yields at higher densities that were a result of maintaining kernel weight when density is increased.

Finally, plant density was also affected by row configuration in terms of yield, and further influenced by hybrid choice. Although we did not observe a hybrid x row configuration interaction like Farnham (2001) reported, there was definitely an influence of hybrid that is apparent when considering hybrid, row configuration and density together. The density intolerant hybrid, 61-21, performed better in the twin row configuration at low levels of plant density that can probably be attributed to better plant spacing. Conversely, the density tolerant hybrid, 7505, performed better at higher densities in the single row configuration.

The advantage for hybrid 7505 in the single row configuration over the twin row configuration, hinted at a factor other than tolerance to high plant density that was limiting yield in the twin row configuration. In both 2010 and 2011, yield and kernel number were reduced at higher densities for the twin row configuration regardless of hybrid, while individual kernel weight was unaffected. The photos and infrared images taken during the grain fill period for the 2011 experiment suggest that higher canopy temperatures might be a limiting factor for high densities in the twin row configuration. However, kernel number was reduced in both seasons and kernel weight was not, which points toward a heat stress bracketing flowering as reported by Cicchino *et al*. (2010). For our hypothesis, further research that is more precise at recording temperatures within the crop canopy is needed to validate that temperature influences plants differently in the twin row configuration more than single rows at high plant densities. However, it must be noted that both experiments were conducted during unusually warm growing seasons, so our conclusions cannot definitively say whether the two selected hybrids would perform similarly under different weather conditions (i.e. cool summer conditions).

Although a high kernel weight appears to be the most important attribute of a hybrid when attempting to increase yield through the management of higher plant densities, understanding how factors interact in a system is essential towards achieving higher grain yields through the use of hybrid, row configuration, and additional fertility as management tools for plant density.

References

Andrade, F.H., M. Cantarero, A. Cirilo, S. Uhart, O. Valentinuz, and C. Vega. 1999. Kernel number determination in maize. *Crop Sci.* 39:453-459.

Badu-Apraku, B., R.B. Hunter, and M. Tollenaar. 1983. Effect of temperature during grain filling on whole plant and grain yield in maize (*Z. mays* L.). *Can. J. Plant Sci.* 63:357-363.

Balkcom, K.S., J.L. Satterwhite, F.J. Arriaga, A.J. Price, and E. van Santen. 2011. Conventional and glyphosate-resistant maize yields across plant densities in single- and twin-row configurations. *Field Crops Research* 120:330-337.

Bechman, T. 2006. How will ear type impact corn yield?. *Dakota Farmer*. Available at http://magissues.farmprogress.com/DFM/DK08Aug06/dfm32.pdf.

Cicchino, M., J.I. Rattalino Edreira, M. Uribelarrea, and M.E. Otegui. 2010. Heat stress in field-grown maize: Response of physiological determinants of grain yield. *Crop Sci.* 50:1438-1448.

Cox, W.J. 1996. Whole-plant physiological and yield responses of maize to plant density. *Agron. J.* 88:489-496.

Farnham, D.E. 2001. Row spacing, plant density, and hybrid effects on corn grain yield and moisture. *Agron. J.* 93:1049-1053.

Gambín, B.L., L. Borrás, and M.E. Otegui. 2006. Source-sink relations and kernel weight differences in maize temperate hybrids. *Field Crops Research* 95:316-326.

Gambín, B.L., L. Borrás, and M.E. Otegui. 2008. Kernel weight dependence upon plant growth at different grain-filling stages in maize and sorghum. *Australian J. of Ag. Research* 59:280-290.

Illinois State Water Survey. 2012. *Prairie Research Institute*. Available at http://www.isws.illinois.edu/atmos/statecli/

Kratochvil, R.J., and R.W. Taylor. 2005. Twin-row corn production: An evaluation in the mid-Atlantic Delmarva region. Online. Crop Management doi: 10.1094/CM-2005-0906-01-RS.

Mascagni, R, and R. Bell. 2004. Flex-ear, fixed-ear corn and optimum plant population. *LSU AgCenter*. Available at http://www.lsuagcenter.com/en/communications/publications/agmag/Archive/2004/Summer/Flexear+Fixedear+Corn+and+Optimum+Plant+Population.htm.

Otegui, M.E., F.H. Andrade, and E.E. Suero. 1995. Growth, water use, and kernel abortion of maize subjected to drought at silking. *Field Crops Research* 40:87-94.

Sharratt, B.S., and D.A. McWilliams. 2005. Microclimatic and rooting characteristics of narrow-row versus conventional-row corn. *Agron. J.* 97:1129-1135.

USDA-NASS. 2011. United States Department of Agriculture – National Agricultural Statistics Service. Available at http://www.nass.usda.gov.

Wilhelm, E.P., R.E. Mullen, P.L. Keeling, and G.W. Singletary. 1999. Heat stress during grain filling in maize: Effects on kernel growth and metabolism. *Crop Sci.* 39:1733-1741.

Tables and Figures

Table 2.1. Treatment levels and their factors included in the 2011 experiment.

Hybrid	Row configuration	Plant density	Fertilizer rate
		plants ha^{-1}	kg ha^{-1} as P_2O_5
DKC 61-21 SSTX	Single (0.76 m)	62,000	0
CG 7505 VT3/P	Twin (0.57 m)	86,000	56
		111,000	112
		136,000	168

Figures

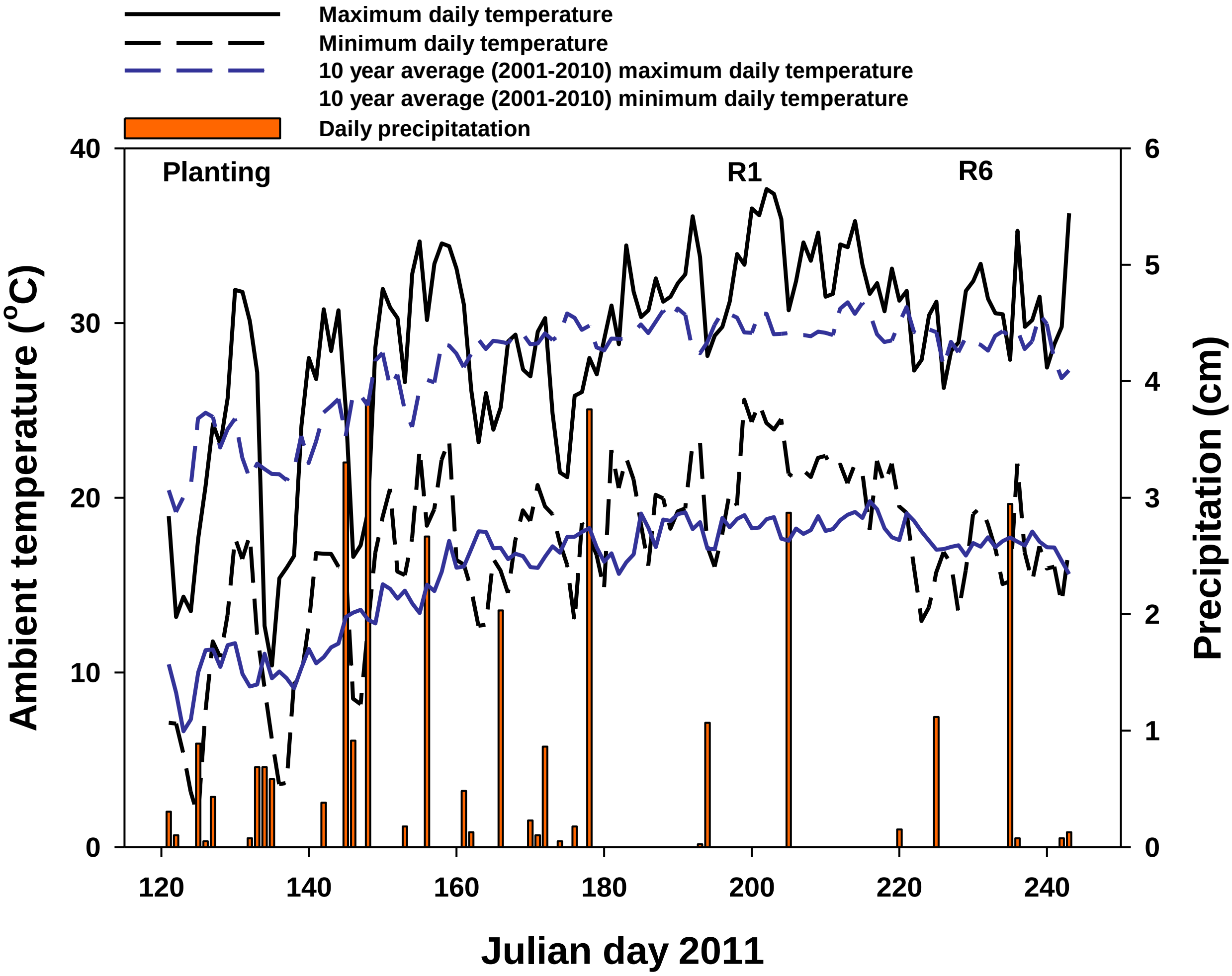

Figure 2.1. Daily weather conditions at Champaign, IL in 2011.

Table 2.2. Analysis of variance for the effects of hybrid, row configuration, fertilizer rate and plant density on grain yield and yield components measured at Champaign, IL in 2011.

Sources of variation	df	Grain yield	Kernel number	Individual kernel weight
		Mg ha^{-1}	m^{-2}	mg $kernel^{-1}$
Density	3	<.0001	<.0001	<.0001
RC	1	0.3608	0.7690	0.6466
RC x Density	3	0.0007	0.0004	0.9850
Fertrate	3	0.0229	0.0101	0.9229
RC x Fertrate	3	0.6362	0.8765	0.5017
Density x Fertrate	9	0.2136	0.4024	0.3404
RC x Density x Fertrate	9	0.1881	0.1818	0.0517
Hybrid	1	0.6379	0.0034	0.0073
Hybrid x Density	3	0.0004	0.0225	0.3860
Hybrid x RC	1	0.1970	0.3734	0.5462
Hybrid x Fertrate	3	0.0869	0.0760	0.2109
Hybrid x RC x Fertrate	3	0.0098	0.2963	0.1221
Hybrid x RC x Density	3	0.6559	0.3907	0.4252
Hybrid x Fertrate x Density	9	0.1123	0.1475	0.2780

†Probability values less than 0.1 ($P \leq 0.1$) are considered a significant source of variation.

‡RC = Row configuration, Fertrate = Additional fertility, Density = Plant density

Table 2.3. Main effect of plant density on grain yield and yield components measured at Champaign, IL in 2011. Values reported are the averages of all treatment combinations at a given plant density.

Plant Density	Grain yield	Kernel number	Individual kernel weight
plants ha^{-1}	Mg ha^{-1} (bu $acre^{-1}$)	m^{-2}	mg $kernel^{-1}$
62,000	10.0 (187) c	3569 c	280 a
86,000	10.6 (200) a	3926 a	271 b
111,000	10.5 (197) ab	3916 a	267 c
136,000	10.3 (194) b	3828 b	266 c

†Means within a column followed by the same letter are not significantly different at P ≤ 0.1.

Table 2.4. Effects of the interaction between plant density and row configuration on grain yield and yield components for Champaign, IL in 2011. Values reported are the average of all other treatment combinations in respect to each level of plant density for each row configuration.

	Plant density x row configuration interaction								
	------------Grain yield------------			-----------Kernel number------------			-----Individual kernel weight-----		
Plant density	**Single**	**Twin**	**P > F**	**Single**	**Twin**	**P > F**	**Single**	**Twin**	**P > F**
	Mg ha^{-1} (bu acre^{-1})			m^{-2}			mg kernel^{-1}		
62,000	9.8 (184)	10.2 (191)	<0.1	3491	3648	<0.05	280	279	
86,000	10.5 (198)	10.7 (202)	NS[‡]	3884	3968	NS	271	271	
111,000	10.8 (203)	10.2 (191)	<0.01	4011	3820	<0.01	267	267	
136,000	10.5 (198)	10.0 (189)	<0.05	3879	3777	NS	267	265	

†Comparisons are only made between row configurations at each plant density level.
‡NS denotes non-significance

Table 2.5. Main effect of fertilizer rate on grain yield and yield components measured at Champaign, IL in 2011. Values reported are the averages of all treatment combinations at a given fertilizer rate.

Fertilizer Rate	Grain yield	Kernel number	Individual kernel weight
$kg\ ha^{-1}$	$Mg\ ha^{-1}$ ($bu\ acre^{-1}$)	m^{-2}	$mg\ kernel^{-1}$
0	10.1 (190) b	3733 c	270
56	10.4 (195) a	3811 b	271
112	10.5 (198) a	3887 a	271
168	10.3 (194) ab	3808 b	271

†Means within a column followed by the same letter are not significantly different at $P \leq 0.1$.

Figure 2.2. Plant samples taken from the single row configuration (86,000 plants ha^{-1}) at the V5 growth stage for Champaign, IL in 2011. The plants from left to right represent the following additional fertilizer rates: 0, 56, 112, 168 kg ha^{-1} as P_2O_5.

Figure 2.3. Picture taken at the V5 growth stage of two single row plots that received different treatments at Champaign, IL in 2011. The plot on the left (two rows) received the 168 kg ha^{-1} treatment at 111,000 plants ha^{-1} (yield = 11.8 Mg ha^{-1} or 222 bu $acre^{-1}$), two center rows (stake on the right of these two rows) that were buffer rows, and the plot on the right (furthest two rows) received the 0 kg ha^{-1} treatment at 62,000 plants ha^{-1} (yield = 10.0 Mg ha^{-1} or 188 bu $acre^{-1}$). Plants showed a clear response to fertilizer in terms of plant vigor, and on main plot average, yielded more than plots receiving no additional fertility.

Table 2.6. Main effect of hybrid on grain yield and yield components measured at Champaign, IL in 2011. Values reported are the averages of all treatment combinations for each hybrid.

Hybrid	Grain yield	Kernel number	Individual kernel weight
	Mg ha^{-1} (bu acre^{-1})	m^{-2}	mg kernel^{-1}
CG 7505 VT3/P	10.4 (196)	3596 b	288 a
DKC 61-21 SSTX	10.3 (193)	4024 a	254 b

†Means within a column followed by the same letter are not significantly different at P ≤ 0.1.

Table 2.7. Effects of the interaction between plant density and hybrid on grain yield and yield components for Champaign, IL in 2011. Values reported are the average of all other treatment combinations in respect to each level of plant density for each hybrid.

	Plant density x hybrid interaction								
	---------Grain yield---------			---------Kernel number---------			-----Individual kernel weight-----		
Plant density	**7505**	**61-21**	**P > F**	**7505**	**61-21**	**P > F**	**7505**	**61-21**	**P > F**
	Mg ha^{-1} (bu acre^{-1})			m^{-2}			mg kernel^{-1}		
62,000	9.7 (183)	10.2 (192)	NS‡	3296	3842	<0.01	295	264	<0.01
86,000	10.6 (199)	10.7 (200)	NS	3673	4180	<0.01	288	254	<0.01
111,000	10.8 (204)	10.1 (191)	<0.1	3749	4082	<0.01	286	248	<0.01
136,000	10.5 (198)	10.1 (189)	NS	3665	3992	<0.01	284	248	<0.01

†Comparisons are only made between hybrids at each plant density level.
‡NS denotes non-significance.

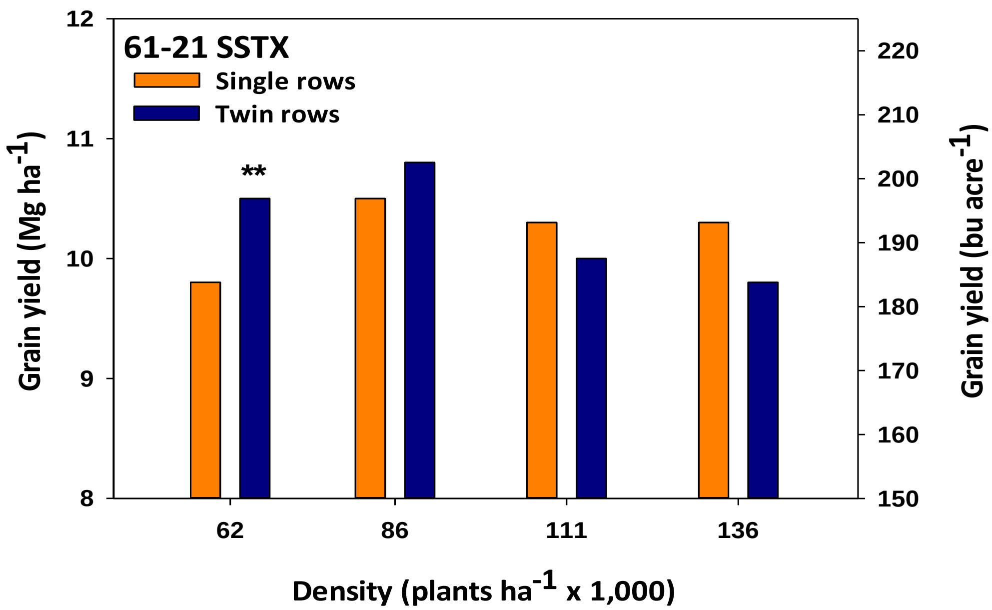

Figure 2.4. Effect of the interaction between row configuration x hybrid x density on grain yield for the hybrid 61-21 in Champaign, IL in 2011. ** denotes significant differences between row configurations at P ≤ 0.1 for both yield and kernel number (KN data not shown).

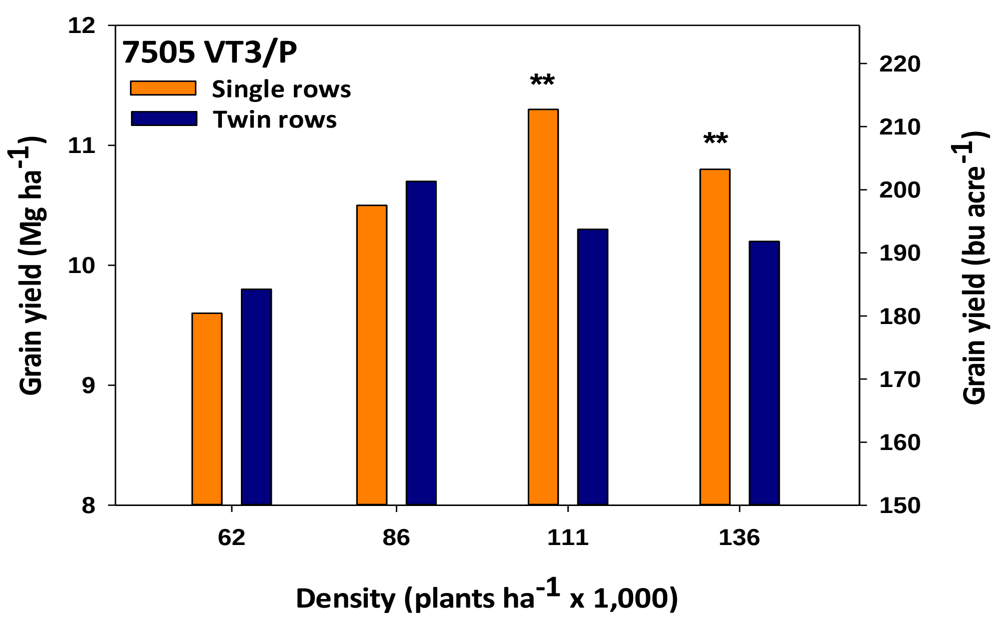

Figure 2.5. Effect of the interaction between row configuration x hybrid x density on grain yield for the hybrid 7505 in Champaign, IL in 2011. ** denotes significant differences between row configurations at P ≤ 0.1 for both yield and kernel number (KN data not shown).

Figure 2.6. Lower canopy images of the hybrid 7505 in a single row plot (left) and twin row plot (right) at a density level of 111,000 plants ha^{-1} in 2011. The twin row plot has brown, "burnt" leaves as opposed to the greener leaves in the single row plot.

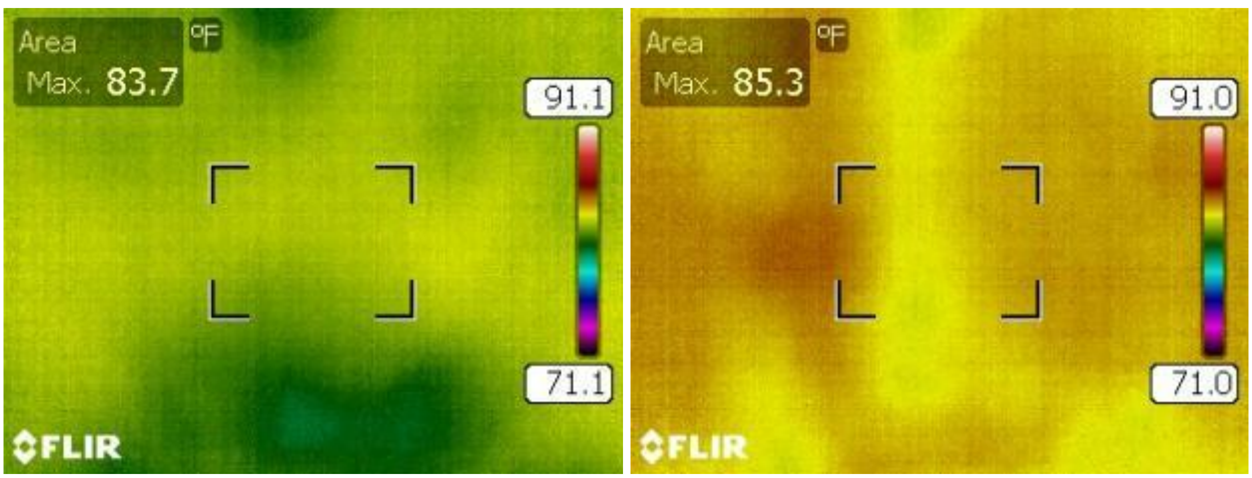

Figure 2.7. Lower canopy infrared images of the hybrid 7505 in a single row plot (left) and twin row plot (right) at a density level of 111,000 plants ha^{-1} in 2011. Infrared images were taken from the same plots that were shown in Figure 2.6. Max temperatures were estimated within the canopy by the camera (+1°C warmer in twin row), but more importantly, the visual comparison between the plots with similar temperature ranges, suggests that twin rows are warmer than single rows at a density level of 111,000 plants ha^{-1}.