

NITROGEN FERTILITY, PLANT POPULATION, ROW SPACING, AND HYBRID
EFFECTS ON CORN GRAIN YIELD

BY

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THESIS

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ABSTRACT

Strategic selection and utilization of corn (*Zea mays* L.) hybrids for a given yield environment and agronomic management system will require better understanding and documentation of the interactions between current commercial hybrids and the agronomic factors that have the greatest effects on yield (i.e., nitrogen (N) fertilization, plant population, and row spacing). This study serves to evaluate the effects that N fertility, plant population, and row spacing have on grain yield of corn and assess the potential range in yield responses among commercial hybrids to these agronomic management factors. From 2015 to 2018, 147 commercial hybrids were grown at three locations across the state of Illinois under three N rates (0, 60, and 280 lb N acre⁻¹), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹), and two row spacing configurations (20 and 30 inches). The average check plot yield (yield at 0 lb N acre⁻¹) was 158 bu acre⁻¹, while the response to high N (yield change between 0 and 280 lb N acre⁻¹ at 32,000 plants acre⁻¹) was +86 bu acre⁻¹. However, 72% of the yield increase from the N fertilizer was achieved by using the low N rate (60 lb N acre⁻¹). Location affected the yield response to N fertilizer, as locations with higher soil fertility levels had higher check plot yields, thereby decreasing the yield response to N fertilization. Increasing plant population to 38,000 or 44,000 plants acre⁻¹ in a 30-inch row did not increase yields, although the highest yields tended to occur under the higher planting populations. Narrower row spacing was a better arrangement of the highest plant population, resulting in an average increase of 9 bu acre⁻¹ (response to row spacing; yield change between 30 and 20 inch row spacing at 44,000 plants acre⁻¹ and 280 lb N acre⁻¹). Similar yield gains in response to narrower row spacing were observed across the entire state. Selecting the appropriate hybrid for a given N fertility level is crucial, as substantial ranges in check plot yields (47 bu acre⁻¹), yield responses to low N (33 bu acre⁻¹), and yield responses to high N (36 bu acre⁻¹)

were observed. Furthermore, yield changes in response to the high plant population and narrow row spacing ranged from -5 to +6 and -8 to +22 bu acre⁻¹, respectively, among the hybrids. Evaluating twelve environments with an inclusive representation of current commercial corn hybrids advances our understanding of N rate, plant population, and row spacing effects on production in Illinois. Hybrids exhibited wide variation of yield in response to, and in interactions with, different agronomic conditions making selection of the appropriate hybrid an important decision for increasing corn grain yields with intensive agronomic management.

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TABLE OF CONTENTS

LITERATURE REVIEW	1
INTRODUCTION	12
MATERIALS AND METHODS.....	15
RESULTS AND DISCUSSION	20
CONCLUSIONS.....	27
TABLES AND FIGURES	29
REFERENCES	41
APPENDIX: SUPPLEMENTARY TABLES	48

LITERATURE REVIEW

The arrival of corn (*Zea mays* L.) to the United States first began with the introduction of flint corn from Mexico around 1000 BC, followed by dent corn around 1500 A.D. (Troyer, 1999). Cultivars originating from both natural and artificial selection in flint and dent crosses developed parents of inbred lines used in production of hybrid corn (Troyer, 1999). Hybrid selection has been driven by progressive cultural practices such as earlier planting, higher planting populations, increased nitrogen (N) fertilizer usage, and environmental adaptation (Troyer, 1999). The average yield of corn in the US has drastically improved since the 1930s, which was largely related to increased stress tolerance through improved capitalization of genotype-by-management interaction (Tolenaar and Lee, 2002). Corn grain yield demonstrates sizeable responses to different agronomic management practices (Ruffo et al., 2015). The high potential and elasticity of corn grain yield highlights the importance of researching corn production in response to agronomic management.

With the intense focus on increasing yields throughout the history of corn research, a large emphasis has been placed on advancement in crop genetics and breeding methods. However, crop management has played an equal or arguably more important role in increasing corn yields (Egli, 2008). The practice of high-input corn production, characterized by the use of commercial hybrids, manufactured N fertilizer, pesticides, and increased plant populations, led to an era of rapid grain yield increases starting in the mid-1900s, whereas prior, low-input corn production saw little improvement in yield (Egli, 2008). For continued increases in corn yield, incessant examination of the interaction between contemporary corn hybrids and shifting agronomic management practices, such as N fertilization, plant population, and row spacing, will be necessary.

Nitrogen management

Nitrogen is the mineral nutrient that is most often limiting yield of crops (Below, 2002) and is required in the greatest quantity ($>255 \text{ lb N acre}^{-1}$ to produce 180 bu acre^{-1} of grain) for corn production (Bender et al., 2013). Nitrogen is important for the growth of corn largely because of the roles it has in establishing and maintaining photosynthetic capacity and reproductive sink capacity and function (Below, 2002). Because the majority of N needed by corn is acquired from the soil, and most soils do not have sufficient N available, N fertilization is often required to maximize corn yields. Determining the proper N rate is a critical decision made by farmers each year because insufficient N can lead to low yield, poor grain quality, and reduced profitability. Over applying N is not likely to harm yield or quality, but this can be uneconomical and harmful to the environment. Making N management decisions even more challenging, differences in N source, application method, timing, previous crop, and the environment can each have an effect on the availability of applied N (Kyveryga et al., 2007).

A common N management strategy of growers is to over apply N fertilizer to hedge against N loss and protect yield (Solari et al., 2008). It is often more economical for a grower to over-apply N than to experience yield losses due to inadequate N availability (Stranger and Lauer, 2008). However, the use of higher N rates and over-application of N are not recommended due to their consequential contributions to water source pollution (Sawyer et al., 2006). Nitrate contamination of a water source is often caused by over applying N or poorly timed applications of either synthetic N fertilizers or animal manure (Dinnes et al., 2002). When applying an optimal rate of N, high yield potential can still be achieved while lessening environmental impacts. Despite many N recommendations calling for increased N rates to increase yield, there is a point at which corn yields do not continue to increase as N rate increases. A study that compared corn yields

across five N rates (0, 60, 120, 180, and 240 lb N acre⁻¹) in Ohio and Illinois over two years concluded that there was a curvilinear response in yield as N rate increased, with the highest yield achieved with 180 lb N acre⁻¹ (Shepard et al., 2011). A similar study used six N rates (0, 40, 80, 120, 160, and 200 lb N acre⁻¹), and found little yield response between applications of 120 and 160 lb N acre⁻¹ and no yield response to further increasing the N rate to 200 lb acre⁻¹ (Derby et al., 2005).

Corn plant responses to fertilizer N can vary considerably depending on the effects of environmental, cultural (e.g. crop rotation), and soil factors (Below, 2002). For example, soil texture has a significant effect on the plant's response to N fertility (Troyer et al., 2012). Fine textured soils resulted in a much greater yield response to applied N than when plants were grown on medium or coarse textured soils. Additionally, the N rate required to achieve maximum yield or optimal return on investment is lower in soils with higher organic matter concentration (Oberle and Keeney, 1990). Thus, a greater yield response to N would be expected in areas of low relative soil fertility. Understanding the effects of soil amendments and fertility levels on yield responsiveness to N is necessary to optimize N fertilization.

Nitrogen use efficiency (NUE) is the yield gain per unit of supplied N and is the product of two processes: N uptake efficiency (additional N uptake per unit of fertilized N) and N utilization efficiency (additional yield increase per unit of increased plant N content due to N fertilization) (Hirel et al., 2007). Nitrogen use efficiency is largely influenced by different plant physiological mechanisms, and has genetically improved over time through indirect selection for higher-yielding hybrids (Moose and Below, 2009). As NUE continues to improve, hybrids will likely be managed for N differently by either maintaining current levels of N fertilizer use in conjunction with achieving higher yields or reducing N use yet maintaining yield levels (Moose

and Below, 2009). Genotypic differences in corn NUE have been reported (Uribelarrea et al., 2007; Haegerle et al., 2013). In a comparison of corn hybrids from the 1970s to those released after 2000, newer hybrids accumulated an additional 15 lb N acre⁻¹ over the season and demonstrated a 40% increase in post-flowering N uptake then that of older hybrids (Haegerle et al., 2013). Similar evidence of improved N uptake of today's hybrids was found when compiling the results of numerous research trials covering old and new hybrids (Ciampitti and Vyn, 2012). Different management practices have also been found to influence NUE, including row spacing (Barbieri et al., 2008), timing of N application (Vetsch and Randall, 2004), and tillage (Vetsch and Randall, 2004).

Corn growers and researchers are interested in exploring the potential differences among hybrids in their responses to N, as it creates a way to more efficiently manage N for corn production. Theoretically, there are two ways plants can differ in their use of N: in the total amount of N needed to produce maximum yield or at what stage during the growing season the N is acquired (Below, 2002). Within a single environment, corn hybrids can vary in their check plot yield (i.e. yield without N fertilization) and in their N requirements to achieve maximum yield (Tsai et al., 1984). However, Gardner et al. (1990) found differences among hybrids in their yield responses to N rates in some environments, but suggested that hybrids responded similarly when data was averaged across all environments, making it challenging to predict yield responses to N availability. Additionally, hybrids can differ in their grain yield, NUE, and grain quality when under water and nutrient stresses (Sabata and Mason, 1992). Hybrids that exhibit high grain yield potential and NUE when grown under N-limiting conditions are recommended for growers planning to use low N rates or for areas of low soil fertility. Different corn hybrids can exhibit

varying yield-response patterns to N fertilization at a given location, but this interaction is highly controlled by the environment.

Planting population

Continued increases in corn yield in the U.S. have been closely associated with increasing plant population, as higher populations have led to a more rapid increase in yield since 1930 (Hammer et al., 2009). As corn production has shifted from relatively low to more intensive fertilizer usage and plant populations (York et al. 2015), genetic improvements have acted in conjunction with changes in agronomic management to increase yields (Duvick, 2005). Today's corn hybrids have demonstrated an increased ability to tolerate stresses such as crowding, which creates the opportunity for increased yields with higher populations. Planting too low of a plant population can limit yield per area due to not using the full population tolerance of the corn hybrid; however, planting too high of a plant population can limit yield by increasing kernel abortion and barren stalks (Hashemi et al, 2005). Achieving optimal plant populations increases production efficiency, as seeding rate is a regulator of plant-to-plant competition (Jiang et al, 2013).

When plants become more crowded due to higher plant populations, intraspecific competition for limiting resources increases (Boomsma et al., 2009). Additionally, higher plant populations have led to a higher degree of variability in inter-row spacing and plant height, which can be a detriment to yield (Boomsma et al., 2009). More so than aboveground competition for light, belowground competition for available soil resources, such as nutrients and water, reduces neighboring plant growth and survival (Casper and Jackson, 1997). For example, root biomass decreases when plants are spaced closer together, potentially reducing grain yield (Jiang et al., 2013). Larger root systems, common with lower plant populations, increase the opportunity for

nutrient acquisition from the soil, while higher plant populations can decrease the root volume of individual plants and the ability to accumulate nutrients from the soil (Caassen and Barber, 1976). Because of this inverse correlation, planting corn at increased planting populations may require a more intensive nutritional management approach.

As corn hybrids have become more tolerant to crowding stress through genetic improvement (Gonzalez et al., 2018), there has been increased interest in planting at greater populations to achieve optimum corn grain production. Haegele et al. (2014) assessed the yield potential of corn at various plant populations, ranging from 25,000 to 65,000 plants acre⁻¹ with a row width of 30 inches, from 2010 to 2011 in Indiana and Illinois. Measured grain yields were maximized at 156 bu acre⁻¹ with 40,000 plants acre⁻¹ in 2010 and 161 bu acre⁻¹ with 45,000 plants acre⁻¹ in 2011. Therefore, corn grain yields increased to a maximum at populations ranging from 40,000 to 45,000 plants acre⁻¹; however, there was a yield disadvantage to planting too high of a population. In 2011, significant interactions between hybrid and both yield and kernel number were observed, suggesting varied responses to plant population depending on the hybrid being grown. A different study showed similar results when assessing three corn hybrids with a range of relative maturities (95 to 105 days) at two row widths (22 and 30 inches) and plant populations ranging from 16,500 to 44,000 plants acre⁻¹ (Van Roekel and Coulter, 2012). Maximum grain yields of 164 bu acre⁻¹ were achieved at 33,000 and 38,000 plants acre⁻¹ with greater and lesser plant populations producing slightly lower yields. Additionally, the hybrid possessing the longest maturity produced 13% more yield compared to the hybrid having the shortest maturity.

Planting corn at the appropriate population is key when taking into consideration the many existing influential factors. When populations are increased to a level that induces stressed environments, yields can be reduced (Stranger and Lauer, 2006). Hybrid, soil type, fertility

management, planting date, and row spacing are only some of the variables that should be considered when selecting plant populations.

Row spacing

Optimum row spacing for corn has been widely discussed as planting rates increase and the genetics of today's hybrids improve. Advancements in agricultural machinery have created the ability to plant corn with narrower row spacings, raising the interest of growers and researchers in the possibility of using narrower rows to accommodate increased plant populations and potentially produce higher yields. When keeping plant population constant, narrower row arrangements increase plant-to-plant spacing within the row and potentially increase yields through better light interception and more efficient usage of available space and resources. Past research, however, on narrow-row corn (row spacing less than the current U.S. average of 30 inches) has shown mixed results (Porter et al., 1997; Cox et al., 1998; Nielsen, 1988), suggesting geography, hybrid, and other factors may affect the responsiveness of corn to narrow row spacing. In cases where significant, yet minimal, yield increases are observed in response to narrow rows, changing the row width of a grower's production system may not be economically viable when considering the substantial costs of purchasing or altering equipment (Hallman and Lowenberg-DeBoer, 1999). However, continued increases in corn yield and ever-changing agronomic practices warrant further research of narrow-row corn and its interactions with genetics, agronomic management, and the environment.

The basis for the adoption of narrow-row corn is the reduction of crowding stress within the row and more efficient usage of resources such as light, nutrients, and water by lessening competition between neighboring plants (Haegele et al., 2014). Research has shown that, at a

constant population, corn in narrow rows can intercept a greater percentage of solar radiation than in 30-inch rows, which has led to increased yields (Andrade et al., 2002). However, other studies have found that the light interception advantage of narrow rows diminishes by the time of flowering (Nafziger, 2006; Robles et al. 2012). Positive yield responses to narrow rows have occurred more frequently in the region north of 43°N latitude (Lee, 2006), which is believed to be caused by greater light interception in shorter growing seasons. Growth stages where narrow rows are intercepting a higher percentage of light than 30-inch rows (prior to flowering) coincides with the period of maximum day length in northern latitudes (Thelen, 2006). Corn grown in southern regions are less benefited by row spacing, as corn in both 30-inch and narrow rows are developmentally closer to the silking stage and intercepting similar percentages of light at the solstice.

Coinciding with increased light interception, corn grown in narrow rows has the potential advantage of improved uptake of soil resources, such as nutrients and water, compared to corn grown in 30-inch rows. Increased inter-row plant spacing derived from a narrow row arrangement more evenly distributes roots in the soil profile, reducing competition among neighboring plants for soil resources (Sharratt and McWilliams, 2005). The more equidistant spacing of plants in narrow rows increases N recovery from the soil and overall NUE, creating a yield advantage to narrow rows in conditions of low N availability (Barbieri et al., 2008). The crop may also have greater water uptake in its early growth stages when grown in narrow rows, but season-long water uptake has been found to be similar regardless of planting row width (Barbieri et al., 2008). Deeper and more uniformly distributed roots associated with corn grown in narrow rows could be an advantage when drought stress occurs early in the growing season or in areas with low soil fertility levels.

Plant population and corn hybrid are two major management factors that could potentially interact with row spacing. As planting populations increase and plants become more crowded, it is speculated that there is a maximum population for a 30-inch row arrangement, but that a higher optimum population is possible when using narrower rows. One study found a yield increase when growing corn in 22-inch rows compared to 30-inch rows at populations of 38,500 or 44,000 plants acre⁻¹, which were the highest populations in the trial (Coulter and Shanahan, 2012). Despite some evidence of this interaction, other studies that showed a yield increase from narrow rows as compared to 30-inch rows did not find different optimal planting populations among the row arrangements tested (Porter et al., 1997; Widdecombe and Thelen, 2002). Like planting population, there are few reports of modern corn hybrids exhibiting different yield responses to row spacing. However, a comparison of six hybrids in both 30 and 15-inch row widths at plant populations ranging from 24,000 to 36,000 plants acre⁻¹ in Iowa showed a significant interaction between hybrid and row spacing as hybrid yield changes ranged from -7 bu acre⁻¹ to +3 bu acre⁻¹ in response to narrow rows (Farnham, 2001). Potentially, the interactions of plant population and hybrid with row spacing may be amplified if evaluated at higher populations or with a more inclusive set of current commercial corn hybrids.

Hybrid disparities

With the introduction of double and single cross hybrids in the 1930's and 1960's respectively, average grain yield of corn has drastically increased (Crow, 1998). Tolerance to stresses and resistance to pests and herbicides are the primary reasons for the higher yield potential of modern hybrids. Corn hybrids are widely diverse in their yield potential, maturity, emergence under stress, drought tolerance, resistance to pests, biotech traits, and standability, making hybrid

selection one of the most important decisions a grower performs each year. Within a single field site, it is common for commercial hybrids to vary in yield by more than 30 bu acre⁻¹ when tested against each other (e.g. university and industry variety testing trials). Hybrids have been found to differ in their responses to N fertility level (Tsai et al., 1984; Gardner et al., 1990; Sabata and Mason, 1992), increased plant population (Haegele et al., 2014; Stranger and Lauer, 2008), and narrower row spacing (Farnham, 2001). Moreover, corn hybrids differ in their N uptake and efficiency (Bender et al., 2013; Haegele et al., 2013; Sabata and Mason, 1992).

When considering the genetic variation among commercial corn hybrids, seed agronomists tend to categorize hybrids for how they may perform across different environments and agronomic managements. Corn hybrids are often characterized as “fix/flex”, “offensive/defensive”, or “racehorse/workhorse”. “Racehorse” hybrids are described as being high-yielding and requiring adequate growing conditions to reach their top yield potential (i.e. responsive to intensive agronomic management), and are recommended to be placed in productive soils (Lauer and Hicks, 2005). On the other hand, “workhorse” hybrids demonstrate more yield stability in response to environmental challenges (Ebhart and Russell, 1966). Thus, it would be expected that “workhorse” hybrids potentially yield better than “racehorse” hybrids in areas of low productivity but demonstrate minimal yield increases in response to environments conducive to increased productivity. Mastrodomenico et al. (2018) grew 101 commercial corn hybrids across eight environments in Illinois at varying N fertilizer levels (0, 60, and 225 lb N acre⁻¹) and plant populations (32,000 and 44,000 plants acre⁻¹) to assess the hybrids for their yield stability and adaptability to crop management. Hybrids that demonstrated above-average yield under unfertilized and low-N conditions showed more yield stability across environments when grown under high-N conditions, whereas hybrids that were adaptable to high plant populations and N

conditions demonstrated greater than average yield potential and yield variation across environments. Contemporary corn hybrids express vast genetic variation for yield in tolerance to low N, response to N fertilizer, and tolerance to crowding stress/row spacing, requiring continued evaluation to determine optimal levels of these management factors to aid farmers and agronomists in producing corn the most efficiently.

INTRODUCTION

Despite significant increases in the average U.S. corn grain yield over the last several decades (USDA-NASS, 2018), a substantial yield gap (the difference between the average yield and potential yield) still exists (NCGA, 2019). Lessening the corn yield gap will require increased plant populations in conjunction with better soil fertility and other intensified agronomic factors (Ruffo et al., 2015). This intensified management includes coordinating select genetics with complementary higher N fertility, increased plant population, and narrower row spacing.

For corn production, N is the nutrient that is often most limiting and is required in the greatest amounts (Bender et al., 2013). As such, increasing N fertilizer rate has significantly contributed to increased corn yields (Egli, 2008). Additionally, today's hybrids have improved N utilization to produce yields under low N conditions (Haegele et al., 2013). Corn hybrids have also shown differences in their yield responses to N availability (Tsai et al., 1984; Gardner et al., 1990; Sabata and Mason, 1992). Despite genetic differences in N-response characteristics, current university and industry variety testing trials typically only evaluate hybrids under adequate N conditions, failing to demonstrate a hybrid's responsiveness to N fertilization or tolerance to low N conditions.

As U.S. corn yields have increased, average planting population has also increased (Assefa et al., 2018; Duvick, 2005). Higher planting populations, rather than increased yield potential of individual plants, is the primary basis of the higher yields obtained with today's corn hybrids (Tollenaar and Lee, 2002). It was recently suggested that genetic improvement of corn during the hybrid era has not increased yield potential; rather, there has been improvement in the tolerance of higher plant populations (Gonzalez et al., 2018). Because the yield potential of individual corn

plants has not increased, the use of higher plant populations will be important for continued yield increases (Egli, 2015).

The response of corn to greater plant populations is dependent on the plant's yield potential and tolerance to crowding stress (Hernandez et al., 2014). Additionally, as plant populations increase, intraspecific competition for limiting resources increases, leading to greater plant-to-plant variability (Boomsma et al., 2009) and reduced plant growth and survival (Casper and Jackson, 1997). Several physiological changes, such as decreased root biomass, can occur due to increased plant populations, which can lessen the crop's ability to obtain resources, and in turn, potentially reduce grain yield (Jiang et al., 2013). Reducing row spacing (< 30 in.) can reduce plant-to-plant competition (Haegele et al., 2014), increase interception of solar radiation (Andrade et al., 2002), and alter light quality (red:far-red ratio) within the canopy (Borras et al., 2003). Therefore, narrower row spacing is a potential strategy for managing higher corn populations while maintaining individual plant yield potential; however, yield increases due to narrow row widths can be difficult to achieve in southern regions of the U.S. Corn Belt (Lee, 2006). Hybrids also have been found to differ in their tolerance to increased plant population-induced crowding stress (Haegele et al., 2014; Stranger and Lauer, 2008); yet yield data regarding the interactions of current, elite commercial hybrids with plant population and row spacing variations is widely unavailable.

Strategic selection and utilization of corn hybrids for a given yield environment and agronomic management program will require better understanding and knowledge of the interactions between current commercial hybrids and the agronomic factors that have the greatest effect on yield (i.e., N fertilization, plant population, and row spacing). Corn hybrids that demonstrate above-average yield increases in response to N fertilization, increased plant

populations, and narrower row spacing may express higher yields and efficiency when placed under intensive agronomic management. On the contrary, hybrids that demonstrate tolerance to low N conditions may exhibit a higher degree of yield stability across agronomic environments, including situations typical of low productivity. Therefore, the objective of this study was to examine the effects of different N fertility levels, higher plant populations, and narrower row spacings on the grain yield of a wide selection of commercial corn hybrids, including the variation and correlation among the observed yield responses to these agronomic factors.

MATERIALS AND METHODS

Field characteristics

The experiment was conducted during the years 2015 through 2018 at four locations in Illinois (DeKalb, Yorkville, Champaign, and Harrisburg). Research sites were planted for one year at DeKalb, IL (41°47' N, 88°50' W; 22 May 2015), three years at Yorkville, IL (41°36' N, 88°22' W; 20 May 2016, 16 May 2017, and 17 May 2018), and four years each at Champaign, IL (40°03' N, 88°14' W; 06 May 2015, 24 April 2016, 19 April 2017, and 27 April 2018) and Harrisburg, IL (37°43' N, 88°26' W; 02 May 2015, 26 April 2016, 9 May 2017, and 1 May 2018). The DeKalb and Yorkville trial locations were 27 miles apart, but with similar environmental conditions, so were combined for analysis. The primary soil types at the four research sites include a Flanagan silt loam at DeKalb and Yorkville, a Drummer silty clay loam at Champaign, and a Patton silty clay loam at Harrisburg. Average soil test values for the Northern (DeKalb/Yorkville), Central (Champaign), and Southern (Harrisburg) Illinois locations are presented in Table 1, and the soil test values for the individual environments are presented in the appendix (Table 9). All field experiments were conducted following a soybean crop [*Glycine max* (L.) Merr.] the previous year and under conventional tillage (primary tillage in fall with chisel plow and secondary tillage in spring with a field cultivator).

Agronomic management

The trial was planted using a precision plot planter with variable seeding rate and row spacing capabilities (SeedPro 360, ALMACO, Nevada, IA). Plots were 17.5 feet in length and two rows in width. At planting, Force 3G (AMVAC, Los Angeles, CA) [Tefluthrin: (2,3,5,6-tetrafluoro-4-methylphenyl)methyl-(1 α ,3 α)-(Z)-(±)-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-

dimethylcyclopropanecarboxylate; Syngenta Crop Protection, Greensboro, NC] soil insecticide was applied in-furrow at a rate of 5 oz 1,000 ft⁻¹ of row. Pre-emergence herbicide Lumax EZ (mixture of S-metolachlor, atrazine, and mesotrione; Syngenta Crop Protection, Greensboro, NC) was applied at a rate of 3 qt acre⁻¹ to control early season weeds. Post-emergence herbicide RoundUp Powermax (N-(phosphonomethyl)glycine; Monsanto Company, St. Louis, MO) was applied at a rate of 32 fl oz acre⁻¹ when necessary.

Treatments

One hundred forty-seven commercial corn hybrids, representative of nine seed brands from six companies, were evaluated, and are listed in the appendix (Table 10). These hybrids had a variety of biotechnology traits and seed treatments, and ranged in relative maturity from 102 to 120 days. On average, 44 hybrids were planted in each of the 12 environments. Because not all hybrids were planted in every year, hybrid entries were considered nested within year, totaling 194 entries. Hybrids were evaluated for their tolerance to nitrogen stress and responsiveness to N fertilizer by measuring check plot yield (0 lb N acre⁻¹), yield under low N conditions (60 lb N acre⁻¹), and yield under high N conditions (280 lb N acre⁻¹). Yield response and tolerance to increased plant population was determined by planting each hybrid at three populations (32,000, 38,000, and 44,000 plants acre⁻¹, denoted as low, intermediate, and high plant population, respectively). Two row spacing arrangements (30 and 20-inch) were used to evaluate the hybrids for their responsiveness to narrower row spacing.

Treatments included: (i) 32,000 plants acre⁻¹ at 30-inch row space and 0 lb N acre⁻¹, (ii) 32,000 plants acre⁻¹ at 30-inch row space and 60 lb N acre⁻¹, (iii) 32,000 plants acre⁻¹ at 30-inch row space and 280 lb N acre⁻¹, (iv) 38,000 plants acre⁻¹ at 30-inch row space and 280 lb N acre⁻¹,

(v) 44,000 plant acre⁻¹ at 30-inch row space and 280 lb N acre⁻¹, and (vi) 44,000 plants acre⁻¹ at 20-inch row space and 280 lb N acre⁻¹. At Champaign in 2016, treatment (vi) was inadvertently planted at 64,000 plants acre⁻¹ rather than 44,000 plants acre⁻¹ due to a problem in the configuration of the planter's software, so it was removed from the data analysis. Nitrogen treatments were broadcast applied as urea [CO(NH₂)₂; 46-0-0] with Limus Nitrogen Management [N-(n-butyl) thiophosphoric triamide] (BASF Corporation, Research Triangle Park, NC) at the V3 developmental stage in each environment. Nitrogen application dates were 11 June 2015 at DeKalb, IL; 16 June 2016, 6 June 2017, and 5 June 2018 at Yorkville, IL; 28 May 2015, 24 May 2016, 22 May 2017, and 16 May 2018 at Champaign, IL; and 02 June 2015, 01 June 2016, 1 June 2017, and 23 May 2018 at Harrisburg, IL.

Grain yield, yield components, and grain quality

At maturity, both rows of each plot were mechanically harvested with an ALMACO SPC40 combine with a 20- or 30-inch row head (ALMACO, Nevada, IA) to determine grain weight and moisture. Harvest dates were 7 November 2015 at DeKalb, IL; 18 October 2016, 1 November 2017, and 2 October 2018 in Yorkville, IL; 9 October 2015, 2 October 2016, 16 September 2017, and 18 September 2018 in Champaign, IL; and 17 September 2015, 21 September 2016, 8 September 2017, and 12 September 2018 in Harrisburg, IL. Grain yield is expressed as bu acre⁻¹ at 15.5% moisture concentration. A representative subsample of grain was collected at harvest from each plot and analyzed for grain quality and determination of yield components. Of the subsample, 300 random kernels were selected, weighed, and converted to 0% moisture to estimate kernel weight (KW). Kernel number (KN) per unit area was estimated from the total plot grain weight, individual kernel weight, and final plant population. Grain quality was analyzed using

near-infrared transmittance spectroscopy (Infratec 1241 Grain Analyzer; FOSS North America, Eden Prairie, MN), and values are expressed at 0% moisture.

Experimental design, statistical analysis, and derived measurements

The experimental design was a strip-plot with a split-plot arrangement in four randomized complete blocks within each environment. The whole plot factors were row spacing and treatment combinations of plant population and N level, and the subplot factor was hybrid. Statistical analysis was performed using a linear mixed model approach in PROC MIXED in SAS (version 9.4; SAS Institute, Cary, NC). Plant population, row spacing, and N fertilizer levels were included in the model as fixed effects, while year, location, replication, and hybrid nested within year were considered random effects. The normality of residuals were assessed using PROC UNIVARIATE and the assumption of homoscedasticity was tested using the Brown-Forsythe modification of the Levene Test in PROC GLM.

Since it was not possible to plant all available commercial hybrids in this study, and the objective was to make inferences about commercial corn hybrids beyond those evaluated in this study, best linear unbiased predictors (BLUP's) were calculated for the hybrid entries within each N fertilizer, plant population, and row spacing treatment. Best linear unbiased predictors were used to calculate check plot yield, (Check, yield at 0 lb N acre⁻¹ at 32,000 plants acre⁻¹ in a 30 inch row spacing), yield response to low N (RTL_{LowN}, yield change between 0 and 60 lb N acre⁻¹ at 32,000 plants acre⁻¹ in a 30 inch row spacing), yield response to high N (RTH_{HighN}, yield change between 0 and 280 lb N acre⁻¹ at 32,000 plants acre⁻¹ in a 30 inch row spacing), yield response to intermediate plant population (RTI_{IntP}, yield change between 32,000 and 38,000 plants acre⁻¹ in a 30 inch row spacing at 280 lb N acre⁻¹), yield response to high plant population (RTH_{HighP}, yield

change between 38,000 and 44,000 plants acre⁻¹ in a 30 inch row spacing at 280 lb N acre⁻¹), and yield response to narrower row spacing (RTS, yield change between 30 and 20 inch row spacing at 44,000 plants acre⁻¹ and 280 lb N acre⁻¹) for each hybrid to determine the variation among commercial hybrids for each trait.

RESULTS AND DISCUSSION

Grain yield

Nitrogen rate, row spacing, hybrid, and the interactions between hybrid and N rate, plant population, and row spacing affected corn grain yield (Table 2). The profile plot of the BLUPs demonstrates the significant hybrid effect on yield, with similar trends across the years (Figure 1). Despite significant interactions between hybrid and N rate, plant population, or row spacing ($P \leq 0.001$), profile plots of the BLUPs primarily show differing magnitudes in yield change between treatment levels for the hybrids. Additionally, relative hybrid yield performance was comparable across the varying N rates, plant populations, and row configurations (i.e. the highest yielding hybrid within one treatment level tended to have the highest yields in other treatment levels). Hybrids with higher comparative relative maturities (CRM) tended to have higher yields, which was observed in all years. However, there appears to be no correlation between CRM and change in yield between treatment levels.

Averaged across years, locations, and hybrids, N fertilizer increased grain yield by 62 and 86 bu acre⁻¹ with 60 and 280 lb N acre⁻¹ respectively (Table 3). Notably, 72% of the yield gained with 280 lbs N acre⁻¹ was achieved with 60 lbs N acre⁻¹, validating the law of diminishing return often observed with increased N fertilizer rates (Shepard et al., 2011; Derby et al., 2005). Check plot yield (i.e. yield without N fertilization) and yield responses to N fertilization tended to differ across locations (Figure 2), which was linked to the soil productivity of the site (Table 1). Check plot yield was highest in DeKalb/Yorkville (178 bu acre⁻¹), where relative organic matter and fertility levels were also the highest (Table 1), while check plot yields were lower in Champaign (152 bu acre⁻¹) and Harrisburg (135 bu acre⁻¹), where relative soil productivity ranked second and third among the three locations (Figure 2). Yield response to the highest N fertilization rate (280

lb N acre⁻¹) was the least in DeKalb/Yorkville (+67 bu acre⁻¹) but greater in Champaign (+103 bu acre⁻¹) and Harrisburg (+97 bu acre⁻¹). The additional yield gained with 280 lb N acre⁻¹ over the yield achieved at 60 lb N acre⁻¹ was 17 bu acre⁻¹ in Yorkville, 30 bu acre⁻¹ in Champaign, and 27 bu acre⁻¹ in Harrisburg. Higher check plot yields, as a function of inherent levels of soil fertility, led to lower overall yield response to N fertilization and a greater proportion of yield gained with N fertility achieved at the low N rate (60 lb N acre⁻¹).

When hybrids were grown at the high N level in a conventional row spacing (30-inch), average yield remained unchanged, regardless of increasing plant population (Table 3). However, the 15 highest yields of hybrids at 280 lb N acre⁻¹ in a conventional row spacing (averaging 271 bu acre⁻¹) were achieved at an average planting population of 39,600 plants acre⁻¹, while the 15 lowest yields (averaging 217 bu acre⁻¹) were achieved at an average planting population of 35,600 bu acre⁻¹ (Table 4). Therefore, hybrids that tolerated crowding stress produced higher yields compared to hybrids that were susceptible to crowding stress. Narrow row spacing (20-inch) tended to be a better arrangement of the hybrids at the high plant population (44,000 plants acre⁻¹) (Table 3) and was conducive to the highest yields (Table 5). Similar yield responses to narrowing the row spacing was observed at all three locations (Figure 3), despite the large differences in their latitude. These results suggest that there may be a higher optimal plant population in narrow row arrangements and that the yield response to narrow row spacing is similar throughout the state of Illinois.

Yield components and grain quality

Planting population had a significant influence on yield components (Table 2). Increasing plant population has been found to increase kernel number (KN) on an area basis and reduce kernel

weight (KW) (Borras et al. 2003). At the high N rate, switching from the low (32,000 plants acre⁻¹) to the intermediate (38,000 plants acre⁻¹) and high plant populations increased average KN by 7 and 10%, respectively (Table 3). Kernel number was increased by an additional 3% when switching from conventional to narrow row spacing at the high planting population. Kernel weight, however, decreased by 4 and 7 % when increasing the plant population from the low level to the intermediate and high levels, but was unchanged in response to row spacing.

Compared to KW, KN often exhibits more flexibility in response to varying agronomic conditions (Boomsma et al., 2009; Sadras and Slafer, 2012). By the same token, KN was more correlated to yield than KW across all N rates, plant populations, and row spacing configurations, even though all correlations were highly significant (Table 6). When N is limited, dry matter redistribution to the reproductive organs is reduced, potentially resulting in decreased KN and KW (Below et al., 2002). Correlations between yield and KN or KW were higher when plants were grown at the 0 or 60 lb N acre⁻¹ levels than when grown with 280 lb N acre⁻¹. Under N-stress conditions, hybrids that were more tolerant of N deficiency had greater seed-set compared to those that were more susceptible to N deficiency. Nitrogen fertilizer level has been found to have greater influences on yield components than plant population (Ciampitti and Vyn, 2011). Under conventional 30-inch row spacing and high N conditions, correlations between yield and KN and KW remained similar with increasing plant populations. However, when switching to the narrow row spacing at the high plant population, there was a slightly higher correlation between KN and yield than in the conventional row spacing. The lesser correlation observed between KN and yield at the high population in the conventional row spacing may be associated with greater plant-to-plant variability compared to when plants were grown in a narrow row spacing.

In addition to yield components, N rate and plant population both had an effect on grain quality (Table 2). Averaged across hybrids at the low plant population, grain concentrations of oil remained unchanged with increasing N rate, while significant increases in protein and decreases in starch levels were observed (Table 3). Grain protein concentration was the most affected by N fertility, likely because of the inherent composition of N in amino acids that comprise proteins. At the high N fertility rate, oil and protein concentrations in the grain slightly decreased when increasing population from 32,000 to 38,000 plants acre⁻¹ while starch levels were not affected. Row spacing had no effect on grain quality, however, the increased yields observed with narrower row spacing in conjunction with constant grain quality concentrations increased the total content (i.e. amount per land are) of protein, oil, and starch in the grain (data not shown).

Hybrid responses to agronomic management

Evaluating commercial corn hybrids for their yield responses to different agronomic management factors allows growers and agronomists to better select hybrids and achieve maximum yield potential through optimal management. Typical variety testing trials compare hybrids under the low-stress conditions of relatively low plant populations and adequate N levels, failing to determine a hybrid's tolerance to N loss and crowding stress or a hybrid's top yield potential when managed intensively. Increasing corn yields and closing the yield gap will require intensive agronomic management systems and effective hybrid selection (Ruffo et al., 2015).

Hybrids that display above-average yield under unfertilized and low-N levels tend to exhibit greater yield stability across environments, while hybrids that display greater adaptability to high plant populations and N conditions tend to exhibit greater yield potential (Mastrodomenico et al., 2018). Therefore, evaluating commercial hybrids for how they are influenced by different

agronomic conditions is necessary for better hybrid placement and accompanying agronomic recommendations. Commercial hybrids exhibited considerable variation in their tolerance to N deficiency, as average check plot yields ranged from 131 to 178 bu acre⁻¹ (Table 7). The greatest yield responses to agronomic management were observed with the response to low (RTLowN) and high (RTHighN) N fertilizer rates. The RTLowN and RTHighN averaged +62 and +85 bu acre⁻¹, respectively. There were also wide ranges among the commercial hybrids for their RTLowN (33 bu acre⁻¹) and RTHighN (36 bu acre⁻¹). Large ranges among the commercial hybrids for their check plot yield and yield responses to different N fertility levels highlights the importance of appropriate hybrid selection for a given fertility level. Average yield responses to intermediate (RTIntP) and high (RTHighP) plant populations compared to the standard population were +6 and 0 bu acre⁻¹, respectively. Despite minimal to no average yield increase in response to greater plant populations, hybrids differed in their responses to increases in plant population. Hybrids exhibited average yield responses ranging from +2 to +12 bu acre⁻¹ when increasing from the low to the intermediate plant population and -5 to +6 bu acre⁻¹ when increasing from the intermediate to the high plant population. Compared to previous studies using similar agronomic conditions (Haegele et al., 2013; Ruffo et al., 2015; Mastrodomenico et al., 2018), the results of this study showed larger ranges in yield responses to N fertilization and higher plant populations, likely because a greater representation of current commercial corn hybrids were evaluated. In addition, the average yield response to narrow row spacing (RTS) was +9 bu acre⁻¹, with individual hybrids exhibiting average responses ranging from -8 to +22 bu acre⁻¹. Optimal planting population and row spacing differed depending upon the hybrid being grown; and some hybrids yielded less with increases in planting population or when row spacing was narrowed. A shrinkage effect on the BLUPs occurred, reducing the predicted range in yield responses among the hybrids compared to the estimates

within a given year and location, which are accessible in the appendix (Tables 11-22). This shrinkage effect is due largely to the error variability typical of field experiments and is expected to be overcome as future field seasons of data are collected. The wide range in yields among hybrids within the different growing conditions highlights the necessity for hybrid-specific management.

The average hybrid correlation coefficients for yield between Check, RTLowN, RTHighN, RTIntP, RTHighP, and RTS are presented in Table 8. Negative correlations were observed between check plot yield and yield responses to N fertilization. Although high yield potential when under unfertilized (Check) and low N (RTLowN) conditions are sought-after traits for a stable hybrid, the negative correlation between the two suggests that these types of hybrids are not common. However, when comparing yields of hybrids grown without fertilization and in response to low N, 21% of hybrids were found to rate above average for both of these conditions (Figure 4, Group 2A). A previous evaluation commercial hybrids under similar conditions from 2011 to 2014 found that only 9% of hybrids demonstrated above-average yields without fertilization and in response to low N levels (Mastrodomenico et al., 2018). This difference suggests that current commercial hybrids may be better in their ability to combine a high tolerance to N deficiencies and in their yield response to N fertilization.

A strong positive correlation between RTLowN and RTHighN suggests that hybrids are responding similarly to N fertility, regardless of rate (i.e. a hybrid that exhibits an above average yield response to the low N rate will likely be above average in its yield response to the high N rate) (Table 8). Although relatively weak, the positive correlations between responses to N fertilization and RTHighP show that hybrids that produce above-average yield responses to N fertilization may also be able to tolerate high plant populations when N is non-limiting.

Corn hybrids that exhibit above average yield responses to N fertilization, increased plant populations, and narrow row spacing are more suitable for intensive agronomic management practices. However, the negative correlation between RTHighP and RTS suggests that hybrids that tolerate and increase yield with high populations do not always respond positively to narrowing row width. Only 20% of the hybrids demonstrated above average yield responses to both the high plant population and the narrow row spacing (Figure 4, Group 2B). Hybrids that performed well in narrow row spacing tended to be those hybrids that didn't increase yield with high populations in a conventional row arrangement (Figure 4, Group 4B).

CONCLUSIONS

Current commercial corn hybrids differed greatly in their yield responses to different agronomic conditions. Hybrids expressed wide ranges in yield under low N conditions and in response to N fertilization, suggesting that commercial hybrids differ in their tolerance to N deficiency and in their N requirement needed to maximize yield. Additionally, a negative correlation between yield under unfertilized conditions and the yield response to low levels of N fertilization were observed, with only 20% of hybrids ranking above average for both conditions. On average, greater plant populations did not change yield; however, the highest yields in the trial tended to occur at higher plant populations than the lowest yields because of the interaction between hybrid and plant population. The interaction between hybrid and plant population was significant with some hybrids exhibiting greater yield and others produced less yield in response to high populations. Hybrids differed in their responses to higher plant populations, and the negative correlation between yield response to the intermediate plant population and to the high plant population suggests that hybrids differ in their tolerance to crowding stress. Narrowing row spacing increases inter-row plant spacing thereby decreasing plant-to-plant competition, allowing for the use of greater plant populations. However, not all hybrids had greater yields in response to narrowing the row width. The negative correlation between yield responses to increased plant population and narrower row spacing demonstrates that hybrids that increase yields with high plant populations may not produce greater than average yields in response to narrower row spacing. However, the positive correlation between yield response to increased plant populations and to high N fertilization indicates that those hybrids that respond positively to high populations may also be dependent on adequate N availability. This study demonstrates the need for improved variety testing methods and the subsequent value for understanding how hybrids perform under

different N levels, plant populations, and row arrangements. Determining which hybrids perform well without fertilization and in response to low levels of N will give agronomists and farmers better insight when selecting hybrids for low fertility environments. Conversely, understanding the N requirement and tolerance to high plant populations and narrow row arrangements of hybrids will allow for better, hybrid-specific management for maximum yields.

TABLES AND FIGURES

Table 1. Average soil test values for the northern (DeKalb/Yorkville), central (Champaign), and southern (Harrisburg) research locations in Illinois from 2015-2018. Samples were taken prior to planting at a depth of 1 to 6 inches and extracted using Mehlich III.

Location	OM[†]	pH	CEC	P	K	Ca	Mg
	%	units	meq 100g ⁻¹	ppm			
DeKalb/Yorkville	5.1	6.4	22.9	90	182	2837	691
Champaign	3.6	5.9	20.9	46	156	2579	452
Harrisburg	2.6	6.3	17.5	33	152	2358	341

[†]OM, organic matter; CEC, cation exchange capacity.

Table 2. Analysis of variance for grain yield, yield components (kernel number, and kernel weight) and grain composition (oil, protein, and starch concentrations) averaged over all corn hybrids grown at four locations (DeKalb, Yorkville, Champaign, and Harrisburg, IL) and four years (2015, 2016, 2017, and 2018).

Source of variation	Grain Yield	Kernel number	Kernel weight	Oil	Protein	Starch
N rate	**	**	**	**	***	***
Plant population	NS†	***	***	***	***	***
Row spacing	***	*	NS	NS	NS	NS
Hybrid	***	***	***	***	***	***
N rate x Hybrid	***	***	***	***	***	***
Plant population x Hybrid	***	***	***	NS	***	*
Row spacing x Hybrid	***	***	NS	NS	**	NS

*Significant at $P \leq 0.10$.

**Significant at $P \leq 0.01$.

***Significant at $P \leq 0.001$.

†NS = Not significant at $P = 0.10$.

Table 3. Nitrogen rate, plant population, and row spacing effects on yield, yield components (kernel number and weight), and grain quality (oil, protein, and starch concentrations). Values are averaged across all corn hybrids grown at four locations in IL from 2015-2018.

Management treatments			Grain yield	Yield components		Grain quality		
Nitrogen rate	Plant population	Row spacing		Kernel number	Kernel weight	Oil	Protein	Starch
lb N ac ⁻¹	plant ac ⁻¹	in	bu ac ⁻¹	seed m ⁻²	mg seed ⁻¹	———— % ————	———— % ————	———— % ————
0	32,000	30	158	3671	223	4.09	6.39	72.65
60	32,000	30	220	4658	250	4.03	7.14	72.24
280	32,000	30	244	4876	265	4.02	8.18	71.64
280	38,000	30	250	5226	254	3.93	7.96	71.93
280	44,000	30	250	5384	247	3.88	7.89	72.07
280	44,000	20	259	5538	248	3.90	7.90	72.03
SEM†			17	234	7	0.09	0.22	0.53

† SEM, standard error of the difference of the means.

Table 4. Effects of plant population on grain yield from the fifteen highest- and fifteen lowest-yielding corn hybrids within 4 years (2015, 2016, 2017, and 2018) grown under high N conditions (280 lb N ac⁻¹) and wide row spacing (30 in.). Grain yields are averaged over four locations in IL.

Rank	Year	Plant population	Grain yield
		plants ac ⁻¹	bu ac ⁻¹
1	2017	44,000	276
2	2018	38,000	275
3	2017	38,000	275
4	2018	44,000	272
5	2017	38,000	271
6	2017	38,000	270
7	2016	38,000	270
8	2017	38,000	270
9	2016	38,000	270
10	2016	44,000	270
11	2017	38,000	269
12	2016	38,000	269
13	2016	44,000	269
14	2016	44,000	269
15	2018	32,000	269
568	2018	32,000	223
569	2017	32,000	222
570	2015	32,000	221
571	2015	32,000	220
572	2018	38,000	220
573	2018	32,000	220
574	2015	38,000	220
575	2015	44,000	219
576	2015	32,000	218
577	2018	44,000	217
578	2015	32,000	214
579	2018	32,000	214
580	2017	44,000	210
581	2017	38,000	209
582	2017	32,000	203
Average of 15 highest-yielding		39,600	271
Average of 15 lowest-yielding		35,600	217
Standard Error of the Mean			17

Table 5. Effects of row spacing on grain yield from the fifteen highest- and fifteen lowest-yielding corn hybrids within 4 years (2015, 2016, 2017, and 2018) grown under high N conditions (280 lb N ac⁻¹) and high plant population (44,000 plants acre⁻¹). Grain yields are averaged over four locations in IL.

Rank	Year	Row Spacing	Grain yield
		inches	bu ac ⁻¹
1	2016	20	298
2	2017	20	293
3	2015	20	288
4	2016	20	285
5	2017	20	284
6	2015	20	283
7	2017	20	283
8	2018	20	282
9	2016	20	282
10	2016	20	282
11	2018	20	281
12	2018	20	280
13	2016	20	279
14	2016	20	278
15	2016	20	278
374	2018	20	228
375	2017	30	226
376	2015	30	226
377	2015	20	226
378	2015	30	226
379	2018	30	226
380	2016	20	224
381	2015	30	223
382	2015	20	221
383	2015	20	220
384	2015	30	219
385	2018	30	217
386	2015	20	212
387	2017	30	210
388	2017	20	204
Average of 15 highest-yielding		20	284
Average of 15 lowest-yielding		25	221
Standard Error of the Mean			17

Table 6. Pearson's pairwise correlation coefficients between yield and kernel number or kernel weight for the corn hybrids grown at different N rates, plant populations, and row spacings averaged over four locations in IL and four years (2015, 2016, 2017, and 2018).

Management treatments			Yield components	
Nitrogen rate	Plant Population	Row spacing	Kernel number	Kernel weight
lb ac ⁻¹	plants ac ⁻¹	in		
0	32,000	30	0.92*	0.76*
60	32,000	30	0.83*	0.65*
280	32,000	30	0.70*	0.58*
280	38,000	30	0.72*	0.59*
280	44,000	30	0.74*	0.55*
280	44,000	20	0.81*	0.59*

*Significant at $P \leq 0.01$.

Table 7. Summary statistics for unfertilized check plot yield (Check) and changes in yield in response to low N fertilizer (RTLowN), high N fertilizer (RTHighN), intermediate plant population (RTIntP), high plant population (RTHighP), and narrower row spacing (RTS). Summary statistics were calculated of the BLUPs of each parameter for 194 corn hybrid entries from four years averaged over four locations in IL.

Statistic	Check	RTLowN	RTHighN	RTIntP	RTHighP	RTS
	bu ac ⁻¹					
Maximum	178	84	102	12	6	22
3 rd Quartile	163	65	89	7	1	12
Median	158	62	84	6	0	9
1 st Quartile	153	60	81	5	-2	6
Minimum	131	51	66	2	-5	-8
Range	47	33	36	10	11	30
Mean	158	62	85	6	0	9
Standard Deviation	7	5	7	2	2	5

Table 8. Pearson's pairwise correlation coefficients between check plot yield (Check), yield response to low N (RTLowN), response to high N (RTHighN), response to intermediate plant population (RTIntP), response to high plant population (RTHighP), and response to row spacing (RTS). Coefficients were calculated using 194 hybrid entries from four years averaged over four locations in IL.

Parameters	Check	RTLowN	RTHighN	RTIntP	RTHighP
RTLowN	-0.64*				
RTHighN	-0.74*	0.77*			
RTIntP	0.06	-0.07	-0.23*		
RTHighP	-0.06	0.13*	0.12*	-0.43*	
RTS	NS†	-0.06	-0.05	-0.06	-0.31*

*Significant at $P = < 0.0001$.

†NS, not significant at $P = 0.10$.

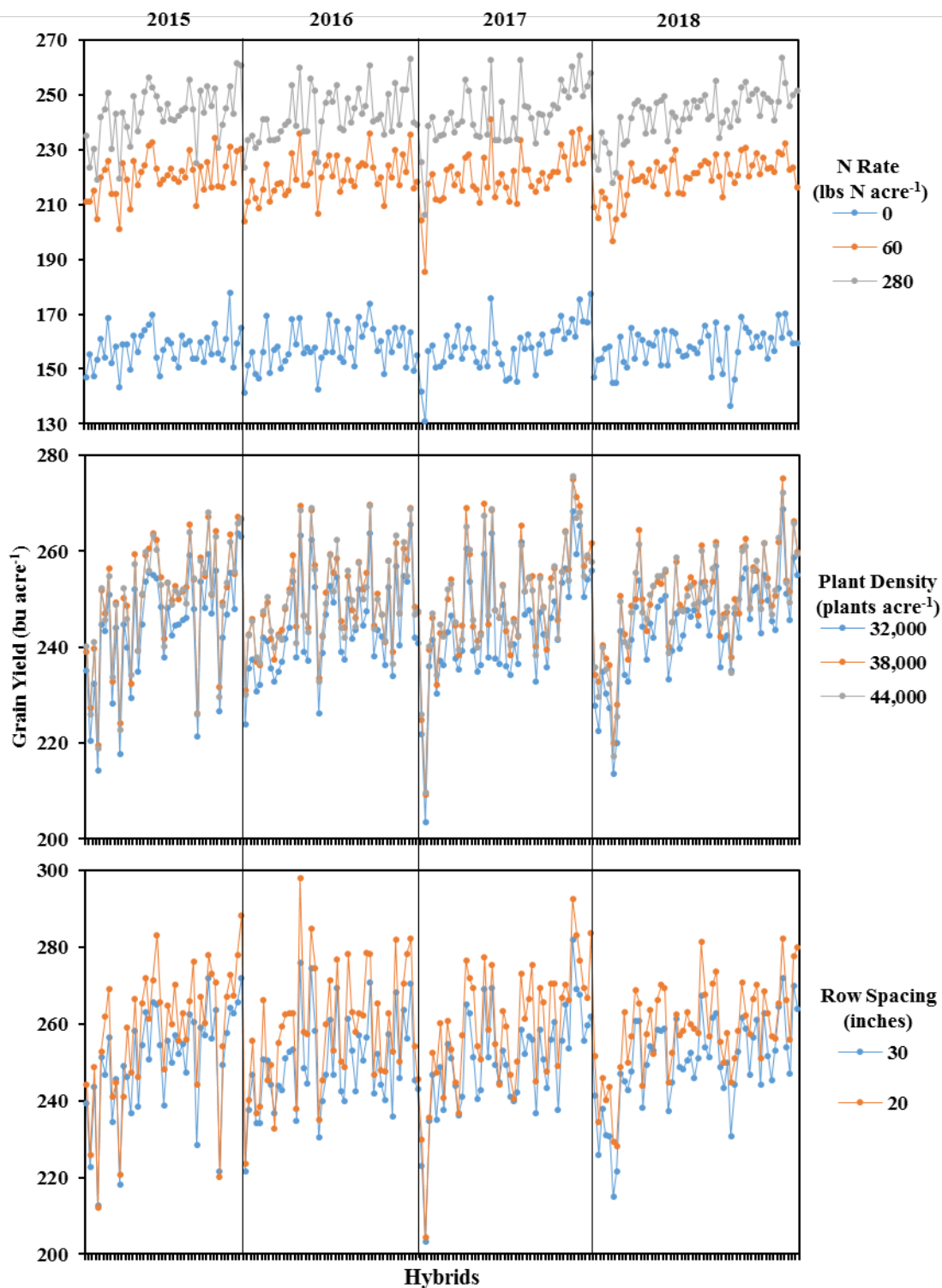


Figure 1. Profile plot of the hybrid entry BLUPs at different nitrogen fertility levels (A), plant populations (B), and row spacing arrangements (C) over four year. Within each year, hybrids are sorted by increasing comparative relative maturity.

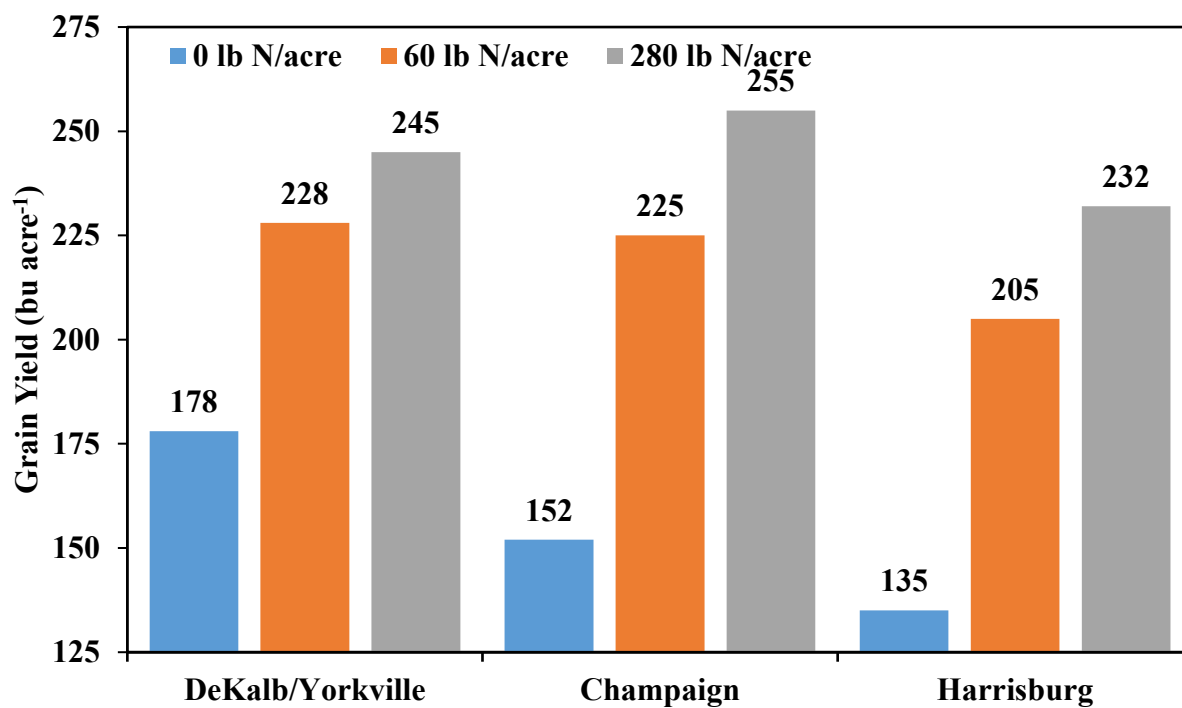


Figure 2. The effect of N fertility level on average grain yield of corn grown at 32,000 plants acre⁻¹ in DeKalb/Yorkville (Northern IL), Champaign (Central IL), and Harrisburg (Southern IL), averaged over all corn hybrids and four years (2015, 2016, 2017, and 2018). N Rate x Location: $P = 0.0797$.

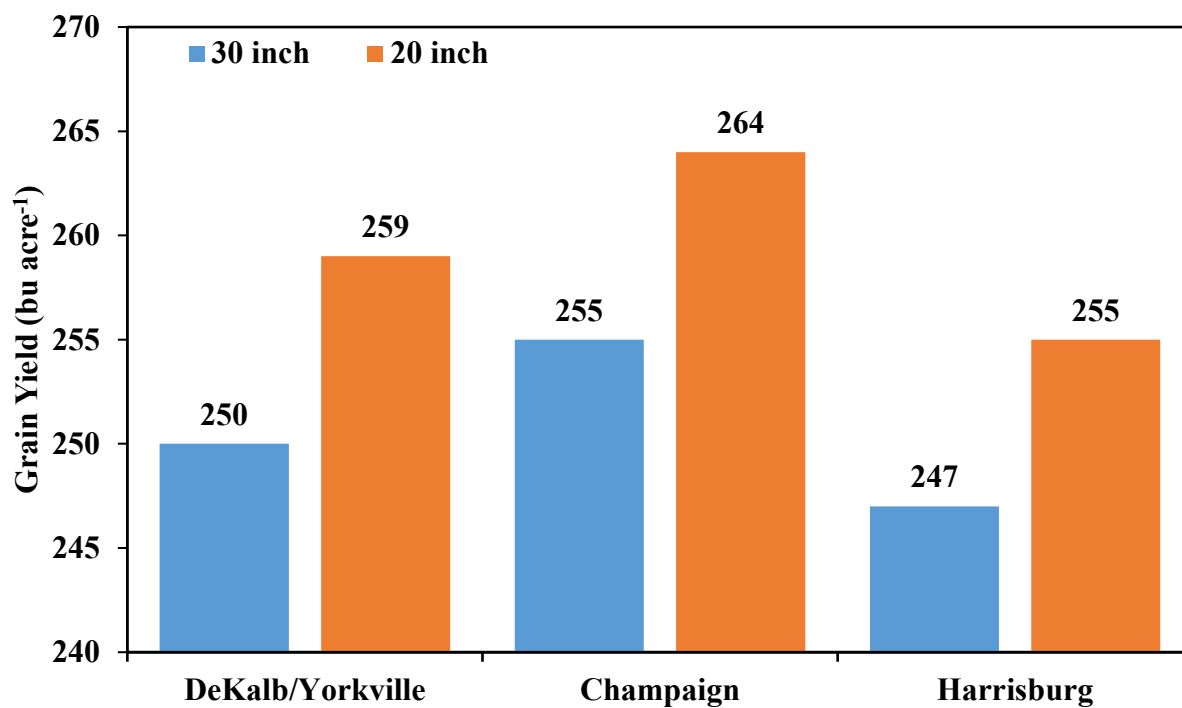


Figure 3. The effect of row width on average grain yield of corn grown at 44,000 plants acre⁻¹ with 280 lb N acre⁻¹ at DeKalb/ Yorkville (Northern IL), Champaign (Central IL), and Harrisburg (Southern IL) averaged over all corn hybrids and four years (2015, 2016, 2017, and 2018). Row spacing x Location: $P = 0.0024$.

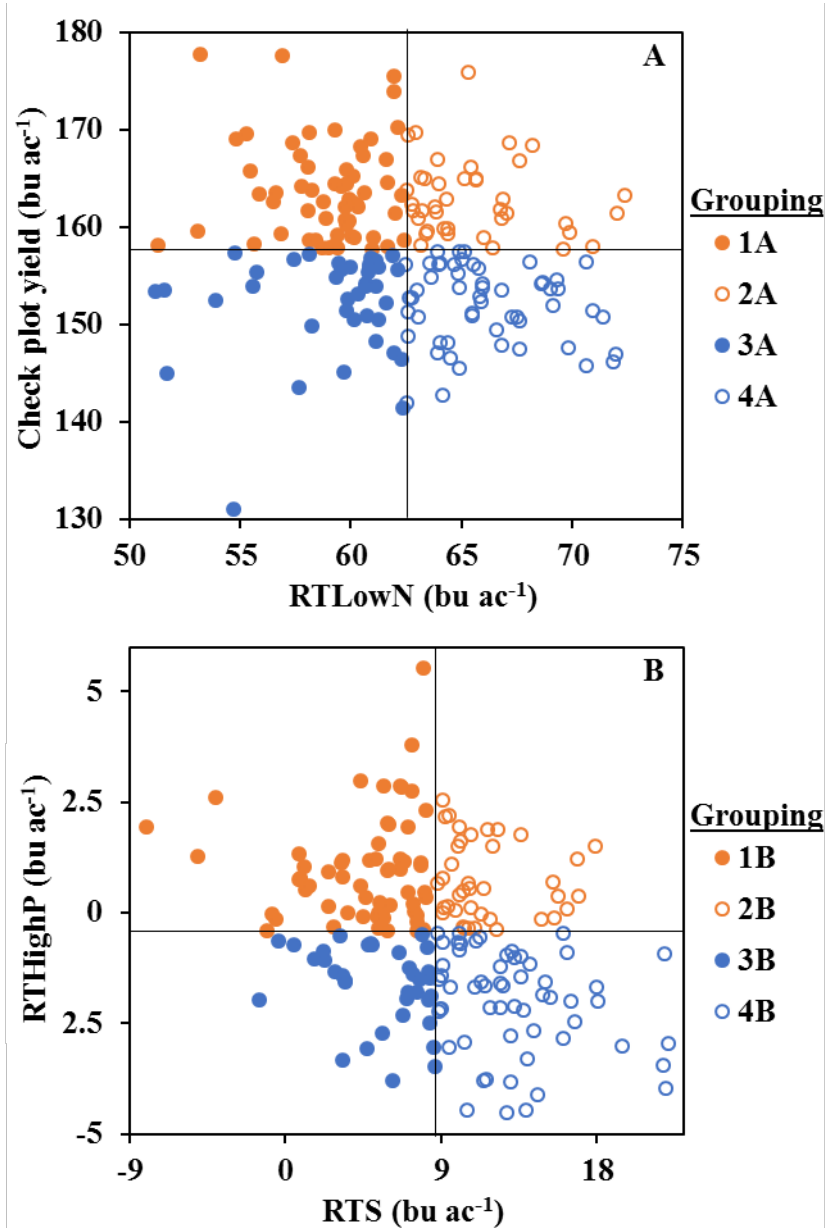


Figure 4. Grouping of 194 corn hybrid entries for their relationship between Check plot yield and yield response to low N (RTLowN) (A), and their relationship between yield response to high population (RTHighP) and yield response to narrow row spacing (RTS) (B). Hybrids were grouped based on below- or above-average yield response for each agronomic condition. Values are averaged over four locations (DeKalb, Yorkville, Champaign, and Harrisburg, IL). Lines represent the average yield response from all hybrids within each agronomic condition.

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APPENDIX: SUPPLEMENTARY TABLES

Table 9. Soil test values for the 12 individual environments in Illinois used in the study. Samples were taken prior to planting at a depth of 1 to 6 inches and extracted using Mehlich III.

Location, Year	OM [†]	pH	CEC	P	K	Ca	Mg
	%	units	meq 100g ⁻¹	ppm			
DeKalb, 2015	6.1	6.7	25.5	42	156	3274	873
Yorkville, 2016	4.4	5.5	22.2	99	186	2195	574
Yorkville, 2017	4.1	7.0	21.1	34	171	2939	711
Yorkville, 2018	5.6	6.4	22.7	185	213	2938	606
Champaign, 2015	4.0	5.8	22.3	26	119	2647	481
Champaign, 2016	3.2	5.6	21.2	40	136	2550	402
Champaign, 2017	3.8	6.0	22.3	78	222	2846	470
Champaign, 2018	3.3	6.3	17.9	39	145	2272	453
Harrisburg, 2015	2.9	6.9	15.9	56	175	2550	303
Harrisburg, 2016	2.8	5.9	23.0	14	165	2454	665
Harrisburg, 2017	2.3	6.2	13.8	31	114	1945	165
Harrisburg, 2018	2.5	6.3	17.1	32	154	2482	231

[†]OM, organic matter; CEC, cation exchange capacity.

Table 10. The distribution of 147 hybrids evaluated from 2015 through 2018 at DeKalb (DK), Yorkville (YV), Champaign (CH), and Harrisburg (HB), Illinois. Hybrids are sorted by their brand name and comparative relative maturity (CRM).

Brand†	CRM	Hybrid	2015			2016			2017			2018		
			DK	CH	HB	YV	CH	HB	YV	CH	HB	YV	CH	HB
AgriGold	111	A641-78STXRIB										X	X	X
AgriGold	112	A642-59STXRIB										X	X	X
AgriGold	114	A6544STXRIB										X	X	X
Channel	107	207-27STXRIB	X	X	X									
Channel	108	208-23STXRIB				X	X	X						
Channel	109	209-15STXRIB										X	X	X
Channel	110	210-26STXRIB							X	X	X			
Channel	110	210-79STXRIB										X	X	X
Channel	112	212-20STXRIB							X	X	X			
Channel	112	212-90STXRIB										X	X	X
Channel	113	213-19STXRIB				X	X	X						
Channel	114	214-45STXRIB	X	X	X									
Channel	115	215-05STXRIB	X	X	X									
Channel	115	215-75STXRIB							X	X	X			
Channel	116	216-36STXRIB				X	X	X						
Croplan	104	4488SS/RIB							X			X		
Croplan	105	5369SS	X	X	X									
Croplan	106	4644DGV2P				X	X	X						
Croplan	106	5516SS	X	X	X									
Croplan	108	4895SS/RIB				X	X	X	X	X	X	X	X	X
Croplan	108	5887VT2P				X	X	X	X		X			
Croplan	108	5887VT3P/RIB	X	X	X									
Croplan	109	4997VT2P/RIB										X	X	X
Croplan	109	5978VT3P	X	X	X									
Croplan	110	6110SS/RIB	X	X	X	X	X	X	X	X	X			
Croplan	111	6065SS/RIB	X	X	X	X	X	X						
Croplan	112	5277AS3220-EZ										X	X	X
Croplan	112	5290DGV2P/RIB				X	X	X	X	X	X	X	X	X
Croplan	112	6265SS/RIB	X	X	X	X	X	X						
Croplan	113	5370VT2P/RIB										X	X	X
Croplan	113	6594SS/RIB	X	X	X	X	X	X	X	X	X			
Croplan	113	6640VT3P	X	X	X	X	X	X	X	X	X			
Croplan	114	7087VT2P/RIB				X	X	X						
Croplan	114	7087VT3P/RIB	X	X	X									
Croplan	116	5678SS/RIB										X	X	X
Croplan	116	5678VT2P							X	X	X			
Croplan	117	5789VT2P/RIB										X	X	X
Croplan	117	7927VT3P/RIB	X	X	X	X	X	X	X	X	X	X	X	X
Croplan	117	8621VT2P/RIB	X	X	X	X	X	X	X	X	X			

Table 10. (Continued)

Brand	CRM	Hybrid	2015			2016			2017			2018		
			DK	CH	HB	YV	CH	HB	YV	CH	HB	YV	CH	HB
DEKALB	108	DKC58-06RIB	X	X	X									
DEKALB	108	DKC58-34RIB										X	X	X
DEKALB	109	DKC59-50RIB				X	X	X						
DEKALB	110	DKC60-87RIB				X	X	X	X	X	X	X		
DEKALB	111	DKC61-54RIB	X	X	X									
DEKALB	112	DKC62-52RIB							X	X	X	X	X	
DEKALB	112	DKC62-53RIB												X
DEKALB	112	DKC62-77RIB	X	X	X									
DEKALB	112	DKC62-97RIB	X	X	X									
DEKALB	113	DKC63-21RIB							X	X	X	X	X	X
DEKALB	113	DKC63-33RIB	X	X	X									
DEKALB	113	DKC63-60RIB				X	X	X						
DEKALB	113	DKC63-71RIB	X	X	X	X	X	X						
DEKALB	114	DKC64-34RIB				X	X	X	X	X	X	X	X	X
DEKALB	114	DKC64-87RIB	X	X	X									
DEKALB	115	DKC65-94RIB							X		X			
DEKALB	115	DKC65-95RIB												X
DEKALB	116	DKC66-74RIB				X	X	X	X	X	X			
DEKALB	117	DKC67-44RIB											X	X
DEKALB	120	DKC70-27RIB											X	X
Dyna-Gro	111	D51SS54							X	X	X			
Dyna-Gro	112	D52SS63							X	X	X			
Dyna-Gro	112	D52SS91							X	X	X			
Dyna-Gro	112	D52VC15										X		
Dyna-Gro	112	D52VC63										X	X	X
Dyna-Gro	112	D52VC91				X	X	X						
Dyna-Gro	114	D54DC94				X	X	X						
Dyna-Gro	114	D54DC94							X	X	X			
Dyna-Gro	114	D54VC14										X	X	X
Dyna-Gro	114	D54VC52							X	X	X	X	X	X
Dyna-Gro	114	D54VC94										X	X	X
Dyna-Gro	115	D55VC45							X		X			
Dyna-Gro	115	D55VC77				X	X	X						
Dyna-Gro	116	D56VC46				X	X	X	X	X	X	X	X	X
Dyna-Gro	117	D57VC51							X	X	X			
Dyna-Gro	118	D58VC65							X	X	X		X	X
GH	102	G02W74-3000GT				X								
GH	103	G03H42-3000GT				X								
GH	105	G05B91-3010							X	X				
GH	105	G05K08-3010A										X		
GH	105	SL5536ZL							X	X				
GH	106	G06N80-3111	X	X	X	X								
GH	106	G06Z97-3120							X	X				
GH	107	G07B39-3111A	X	X	X									
GH	107	G07B39-3122A				X	X	X						

Table 10. (Continued)

Brand	CRM	Hybrid	2015			2016			2017			2018		
			DK	CH	HB	YV	CH	HB	YV	CH	HB	YV	CH	HB
GH	107	G07F23-3111	X	X	X	X	X	X	X	X	X			
GH	108	G08D29-3120A										X	X	X
GH	109	G09A86-3000GT										X		
GH	109	G09A86-3111							X	X	X			
GH	109	G09E98-3000GT	X	X	X									
GH	109	G09E98-3122				X	X	X						
GH	109	G09Y24-3220A							X	X	X	X	X	X
GH	110	G10S30-3110	X	X	X									
GH	110	G10S30-3220-EZ0				X	X	X						
GH	110	G10T63-3000GT	X	X	X	X	X	X						
GH	110	G10T63-3122							X	X	X	X	X	X
GH	110	SK6405-3220							X	X	X			
GH	111	G11A33-3111										X	X	X
GH	111	G11F16-3111A				X	X	X						X
GH	111	G11K47-GT	X	X	X									
GH	111	G11X64-3010								X	X			
GH	112	G12J11-3111A	X	X	X	X	X	X						
GH	112	G12W66-3000GT				X	X	X	X	X	X	X	X	X
GH	113	G13G41-3000GT	X	X	X									
GH	113	G13T41-3010											X	X
GH	113	G13Z50-3110											X	X
GH	114	G14H66-3010A	X	X	X									
GH	114	G14R38-3000GT	X	X	X	X	X	X						
GH	114	G14R38-3122							X	X	X			
GH	114	G14V04-3000GT								X	X			
GH	114	G14V04-3120												X
GH	114	G14Y81-3010	X	X	X									
GH	115	G15L32-3000GT											X	X
GH	115	G15L32-3111							X	X	X			
GH	115	G15Z99-3111					X	X						
GH	116	G16C59-3000GT	X	X	X									
GH	116	G16K01-3122					X	X						
GH	116	SL8675-3110								X	X			
GH	118	G18D87-3000GT					X	X						
GH	118	G18D87-3111								X	X			X
NK	106	NK0602-3010										X		
NK	106	NK0624-3220										X	X	
NK	107	NK0763-3010										X	X	
NK	112	NK1284-3220											X	
Pioneer	104	P0419AMI	X	X	X									
Pioneer	105	P0574AMXT										X		
Pioneer	107	P0707AMXT										X	X	
Pioneer	109	P0987AMX	X	X	X									
Pioneer	111	P1197AMXT				X	X	X	X	X	X			
Pioneer	112	P1221AMXT	X	X	X									

Table 10. (Continued)

Brand	CRM	Hybrid	2015			2016			2017			2018		
			DK	CH	HB	YV	CH	HB	YV	CH	HB	YV	CH	HB
Pioneer	112	P1257AMXT				X	X	X				X	X	X
Pioneer	113	P1311AMXT				X	X	X	X	X	X	X	X	X
Pioneer	113	P1339AMI	X	X	X									
Pioneer	113	P1366AMXT										X	X	X
Pioneer	114	P1479AM				X	X	X						
Stone	108	5848SSRIB							X	X	X			
Stone	108	5858SSRIB										X	X	X
Stone	109	5938RIB	X	X	X									
Stone	110	6068RIB				X	X	X						
Stone	110	6072VT2PRIB										X	X	X
Stone	111	6148RIB	X	X	X									
Stone	111	6188SSRIB							X	X	X			
Stone	112	6288RIB	X	X	X									
Stone	114	6448RIB	X	X	X									
Stone	114	6458RIB				X	X	X						
Stone	114	6468SSRIB										X	X	X
Stone	115	6538SSRIB							X	X	X			
Stone	117	6718RIB				X	X	X						

†GH, Golden Harvest.

Table 11. Yields of individual hybrids ($n = 43$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **DeKalb, IL in 2015**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Maturity: Values are the LS Means of four Replications.						
Hybrid	Row spacing					20 inches
	30 inches					
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000	44,000	
	Nitrogen level (lb N acre ⁻¹)					
0	60	280	280	280		
bu acre ⁻¹						
P0419AMI	117	208	213..7	217	208	197
5369SS	134	196	199	205	197	155
5516SS	120	214	205	215	218	208
G06N80-3111	136	178	184	183	174	155
207-27STXRIB	150	234	249	266	251	220
G07B39-3111A	143	205	219	210	195	209
G07F23-3111	164	225	236	235	231	229
5887VT3P/RIB	118	212	210	204	189	183
DKC58-06RIB	152	235	250	247	239	205
5938RIB	134	199	195	209	178	166
5978VT3P	138	232	231	238	244	193
G09E98-3000GT	139	222	228	222	200	200
P0987AMX	124	201	203	189	196	206
6110SS/RIB	161	239	253	244	26	227
G10S30-3110	157	225	226	218	175	189
G10T63-3000GT	131	214	219	224	213	206
6065SS/RIB	149	231	234	229	231	217
6148RIB	151	237	266	263	250	241
DKC61-54RIB	158	243	257	282	271	215
G11K47-GT	132	210	231	245	218	255
6265SS/RIB	132	222	232	235	226	220
6288RIB	156	216	214	213	195	188
DKC62-77RIB	145	227	227	227	232	221
DKC62-97RIB	150	233	226	239	220	216
G12J11-3111A	154	216	225	230	231	228
P1221AMXT	143	222	236	227	222	203
6594SS/RIB	166	249	255	255	250	249
6640VT3P	142	223	230	231	223	197
DKC63-33RIB	144	235	246	246	237	221
DKC63-71RIB	152	238	240	237	232	258
G13G41-3000GT	128	186	174	177	178	185
P1339AMI	126	223	229	226	207	207
214-45STXRIB	139	222	238	257	249	219
6448RIB	132	219	242	251	237	219
7087VT3P/RIB	130	215	239	227	222	239
DKC64-87RIB	157	241	251	257	250	225
G14H66-3010A	124	197	180	166	158	135
G14R38-3000GT	146	213	208	209	198	178
G14Y81-3010	155	219	221	204	217	212
215-05STXRIB	136	231	241	241	226	276
G16C59-3000GT	118	194	221	204	216	186
7927VT3P/RIB	113	218	258	233	233	214
8621VT2P/RIB	166	212	207	209	192	189
LSD (P ≤ 0.10)	22	22	22	25	25	38
Mean	141	219	227	227	218	208
Range	112-116	177-248	173-265	166-281	157-271	135-275

Table 12. Yields of individual hybrids ($n = 43$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Champaign, IL in 2015**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Maturity: Values are the LS Means of Four Replications.						
Hybrid	Row spacing					20 inches
	30 inches					
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000	44,000	
	Nitrogen level (lb N acre ⁻¹)					
0	60	280	280	280		
bu acre ⁻¹						
P0419AMI	131	228	258	252	262	241
5369SS	146	248	236	245	240	244
5516SS	124	226	248	263	265	259
G06N80-3111	138	231	232	232	224	206
207-27STXRIB	146	228	252	265	274	261
G07B39-3111A	126	239	275	270	270	304
G07F23-3111	160	242	284	288	284	299
5887VT3P/RIB	146	231	255	263	271	265
DKC58-06RIB	140	221	262	272	274	269
5938RIB	116	211	234	234	240	232
5978VT3P	139	241	262	267	270	234
G09E98-3000GT	139	238	256	284	269	291
P0987AMX	144	219	258	262	259	256
6110SS/RIB	140	234	270	287	279	292
G10S30-3110	123	220	251	254	257	269
G10T63-3000GT	167	245	277	286	291	320
6065SS/RIB	159	245	286	289	293	313
6148RIB	152	265	284	286	277	301
DKC61-54RIB	166	266	271	291	278	304
G11K47-GT	141	241	282	294	288	310
6265SS/RIB	112	226	280	287	278	299
6288RIB	133	228	269	259	250	266
DKC62-77RIB	145	225	287	284	284	296
DKC62-97RIB	142	244	274	273	269	281
G12J11-3111A	119	234	275	287	281	300
P1221AMXT	135	224	265	274	282	273
6594SS/RIB	140	227	268	269	275	281
6640VT3P	135	247	271	274	248	280
DKC63-33RIB	135	247	295	297	293	285
DKC63-71RIB	118	220	255	266	261	297
G13G41-3000GT	152	230	251	248	249	280
P1339AMI	157	243	296	287	290	309
214-45STXRIB	119	213	265	274	262	266
6448RIB	146	245	283	292	309	316
7087VT3P/RIB	145	225	273	277	285	313
DKC64-87RIB	153	271	275	296	279	306
G14H66-3010A	146	242	258	268	253	220
G14R38-3000GT	131	233	280	295	299	293
G14Y81-3010	139	239	274	285	279	285
215-05STXRIB	162	255	273	286	271	279
G16C59-3000GT	125	241	277	309	284	283
7927VT3P/RIB	156	281	303	311	303	334
8621VT2P/RIB	137	246	323	317	324	360
LSD (P ≤ 0.10)	26	26	26	21	21	27
Mean	140	237	270	277	274	283
Range	112-166	210-280	232-323	231-316	224-324	205-359

Table 13. Yields of individual hybrids ($n = 43$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Harrisburg, IL in 2015**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Maturity: Values are the LS Means of four Replications.						
Hybrid	Row spacing					20 inches
	30 inches					
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000	44,000	
	Nitrogen level (lb N acre ⁻¹)					
0	60	280	280	280		
bu acre ⁻¹						
P0419AMI	77	182	216	209	217	238
5369SS	94	175	185	196	192	205
5516SS	82	202	207	212	219	226
G06N80-3111	95	180	187	192	196	188
207-27STXRIB	92	190	210	213	217	221
G07B39-3111A	84	227	233	236	232	244
G07F23-3111	97	211	230	235	222	253
5887VT3P/RIB	89	189	191	189	205	219
DKC58-06RIB	88	170	190	207	206	194
5938RIB	75	167	183	188	191	186
5978VT3P	94	208	223	222	234	216
G09E98-3000GT	105	194	210	227	227	254
P0987AMX	75	184	204	199	211	235
6110SS/RIB	86	208	223	243	244	246
G10S30-3110	89	198	209	211	212	229
G10T63-3000GT	94	203	220	224	229	237
6065SS/RIB	92	197	235	245	244	255
6148RIB	98	202	227	233	191	231
DKC61-54RIB	97	200	222	231	240	255
G11K47-GT	80	218	239	249	249	276
6265SS/RIB	75	197	223	230	228	247
6288RIB	86	207	220	225	231	244
DKC62-77RIB	94	202	222	230	224	243
DKC62-97RIB	91	193	218	222	228	243
G12J11-3111A	82	207	210	231	227	258
P1221AMXT	59	205	217	224	232	239
6594SS/RIB	87	188	197	211	213	220
6640VT3P	99	211	229	240	237	248
DKC63-33RIB	96	217	237	253	245	249
DKC63-71RIB	81	212	233	242	254	263
G13G41-3000GT	87	196	207	207	202	226
P1339AMI	91	204	236	251	256	254
214-45STXRIB	94	200	223	237	246	246
6448RIB	104	211	240	256	260	267
7087VT3P/RIB	83	195	224	223	222	250
DKC64-87RIB	96	208	228	241	246	248
G14H66-3010A	100	207	218	217	216	221
G14R38-3000GT	82	194	214	228	226	243
G14Y81-3010	97	216	230	240	250	242
215-05STXRIB	92	202	236	248	254	260
G16C59-3000GT	84	222	250	267	272	283
7927VT3P/RIB	96	217	250	243	237	266
8621VT2P/RIB	99	238	272	263	273	309
LSD (P ≤ 0.10)	14	14	14	17	17	23
Mean	89	201	220	228	229	241
Range	59-104	166-238	182-271	188-266	190-273	186-309

Table 14. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Yorkville, IL in 2016**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Hybrid	Row spacing					
	30 inches					20 inches
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000		44,000
	Nitrogen level (lb N acre ⁻¹)					
	0	60	280	280		280
	bu acre ⁻¹					
G02W74-3000GT	181	201	199	210	200	184
G03H42-3000GT	205	215	221	232	227	213
4644DGV2P	196	238	232	239	238	251
G06N80-3111	195	221	214	215	221	207
G07B39-3122A-EZ0	197	218	222	215	215	224
G07F23-3111	209	234	241	226	240	259
208-23STXRIB	215	227	224	232	230	208
4895SS/RIB	181	216	220	220	225	223
5887VT2P	217	222	222	215	225	200
DKC59-50RIB	211	217	232	235	234	261
G09E98-3122-EZ0	212	245	241	246	230	282
6068RIB	211	225	235	239	242	252
6110SS/RIB	212	240	244	256	253	261
DKC60-87RIB	213	221	246	247	239	251
G10S30-3220-EZ0	213	233	228	222	203	207
G10T63-3000GT	243	270	276	279	263	327
6065SS/RIB	215	224	237	242	233	255
G11F16-3111A	203	237	235	235	235	255
P1197AMXT	224	260	275	281	302	307
5290DGV2P/RIB	206	235	254	244	230	285
6265SS/RIB	179	208	207	219	222	222
D52VC91	220	235	247	241	239	249
G12J11-3111A	210	240	259	258	246	274
G12W66-3000GT	249	256	265	277	262	284
P1257AMXT	210	217	248	259	246	256
213-19STXRIB	240	249	261	271	271	285
6594SS/RIB	220	235	249	256	237	246
6640VT3P	199	242	222	223	199	214
DKC63-60RIB	234	246	256	248	247	293
DKC63-71RIB	220	234	238	233	216	264
P1311AMXT	209	237	232	216	204	265
6458RIB	256	264	262	250	254	255
7087VT2P/RIB	219	231	241	231	223	271
D54DC94	227	251	240	254	226	304
DKC64-34RIB	243	262	273	276	264	288
G14R38-3122	231	232	237	235	229	227
P1479AM	227	238	243	250	237	260
D55VC77	216	226	251	245	242	214
216-36STXRIB	230	252	256	261	267	246
D56VC46	206	236	236	226	196	241
DKC66-74RIB	228	247	264	260	276	303
6718RIB	252	264	268	264	277	280
7927VT3P/RIB	206	254	272	279	250	313
8621VT2P/RIB	221	269	294	289	283	301
LSD ($P \leq 0.10$)	26	20	21	25	37	33
Mean	216	237	244	245	239	256
Range	179-256	201-270	199-294	210-289	196-302	184-327

Table 15. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), four plant populations (32,000, 38,000, 44,000 and 64,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Champaign, IL in 2016**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Hybrid	Row spacing					
	30 inches					20 inches
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000		64,000
	Nitrogen level (lb N acre ⁻¹)					
	0	60	280	280	280	280
	bu acre ⁻¹					
4644DGVT2P	144	214	244	266	263	264
G07B39-3122A-EZ0	121	211	248	246	253	244
G07F23-3111	125	188	239	257	250	253
208-23STXRIB	174	232	208	256	264	222
4895SS/RIB	142	222	241	252	258	243
5887VT2P	138	210	235	242	250	199
DKC59-50RIB	148	226	233	258	250	245
G09E98-3122-EZ0	107	203	232	246	241	191
6068RIB	117	202	245	249	257	244
6110SS/RIB	144	209	254	268	263	246
DKC60-87RIB	144	246	272	278	279	282
G10S30-3220-EZ0	143	212	250	273	251	245
G10T63-3000GT	136	234	272	283	292	302
6065SS/RIB	135	218	235	255	251	254
G11F16-3111A	157	201	239	250	242	254
P1197AMXT	122	208	276	280	288	276
5290DGVT2P/RIB	132	238	264	270	269	295
6265SS/RIB	111	202	227	247	232	247
D52VC91	114	199	235	229	231	212
G12J11-3111A	134	222	251	264	257	248
G12W66-3000GT	147	218	263	275	282	288
P1257AMXT	118	225	266	276	273	234
213-19STXRIB	137	214	267	217	278	270
6594SS/RIB	117	206	232	240	239	237
6640VT3P	136	235	249	265	259	224
DKC63-60RIB	140	220	256	261	265	269
DKC63-71RIB	133	214	240	246	244	245
P1311AMXT	120	226	277	269	275	201
6458RIB	155	228	255	269	260	277
7087VT2P/RIB	143	227	266	272	269	250
D54DC94	156	213	258	275	269	231
DKC64-34RIB	169	236	275	283	287	289
G14R38-3122	154	234	242	256	254	234
P1479AM	124	219	250	259	266	277
D55VC77	126	219	243	243	243	217
G15Z99-3111	109	197	245	250	255	225
216-36STXRIB	145	213	253	267	260	257
D56VC46	138	214	227	232	234	232
DKC66-74RIB	145	236	265	276	269	276
G16K01-3122	154	221	249	268	272	240
6718RIB	131	213	257	268	266	259
7927VT3P/RIB	109	203	262	259	245	253
8621VT2P/RIB	135	237	279	266	283	261
G18D87-3000GT	111	203	252	273	270	264
LSD ($P \leq 0.10$)	26	25	16	18	19	29
Mean	135	218	251	260	261	250
Range	107-174	188-246	208-279	217-283	231-292	191-302

Table 16. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Harrisburg, IL in 2016**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Maturity: Values are the LS Means of four Replications.						
Hybrid	Row spacing					20 inches
	30 inches					
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000	44,000	
	Nitrogen level (lb N acre ⁻¹)					
0	60	280	280	280		
bu acre ⁻¹						
4644DGVT2P	98	139	153	166	167	184
G07B39-3122A-EZ0	74	109	163	159	161	157
G07F23-3111	103	150	188	179	183	224
208-23STXRIB	113	161	194	199	210	178
4895SS/RIB	80	121	173	173	181	192
5887VT2P	90	142	171	172	179	155
DKC59-50RIB	89	141	164	164	170	181
G09E98-3122-EZ0	88	142	173	168	171	184
6068RIB	93	139	181	183	181	211
6110SS/RIB	78	122	168	170	174	199
DKC60-87RIB	107	158	200	197	204	202
G10S30-3220-EZ0	94	144	174	177	178	172
G10T63-3000GT	101	157	202	198	203	245
6065SS/RIB	86	141	172	173	185	192
G11F16-3111A	93	145	169	176	176	200
P1197AMXT	81	131	193	191	186	213
5290DGVT2P/RIB	94	160	197	193	201	217
6265SS/RIB	87	131	164	158	160	159
D52VC91	90	152	179	173	178	165
G12J11-3111A	84	150	185	165	155	184
G12W66-3000GT	99	150	175	169	176	196
P1257AMXT	79	130	186	177	173	173
213-19STXRIB	103	160	198	199	205	208
6594SS/RIB	90	129	171	171	178	182
6640VT3P	84	128	175	178	185	202
DKC63-60RIB	96	149	187	185	198	223
DKC63-71RIB	90	141	181	187	187	187
P1311AMXT	78	120	182	177	168	182
6458RIB	96	152	195	192	198	202
7087VT2P/RIB	97	159	182	190	186	187
D54DC94	98	144	186	184	189	217
DKC64-34RIB	96	161	203	201	210	208
G14R38-3122	90	140	170	171	174	181
P1479AM	87	130	174	181	179	211
D55VC77	96	143	178	177	182	201
G15Z99-3111	85	125	165	158	163	169
216-36STXRIB	84	143	184	185	187	210
D56VC46	93	147	178	182	186	208
DKC66-74RIB	94	152	196	184	196	220
G16K01-3122	79	120	166	162	166	164
6718RIB	86	150	189	188	193	200
7927VT3P/RIB	86	151	190	182	188	217
8621VT2P/RIB	94	156	196	196	186	214
G18D87-3000GT	83	144	173	162	170	184
LSD (P ≤ 0.10)	9	17	10	12	13	30
Mean	91	142	180	179	182	195
Range	74-113	109-161	153-203	158-201	155-210	155-245

Table 17. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Yorkville, IL in 2017**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Hybrid	Row spacing					
	30 inches					20 inches
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000		44,000
	Nitrogen level (lb N acre ⁻¹)					
	0	60	280	280		280
	bu acre ⁻¹					
4488SS/RIB	219	261	277	290	295	279
G05B91-3010	205	251	260	253	273	280
SL5536ZL	191	198	212	222	225	229
G06Z97-3120	218	260	277	273	286	262
G07F23-3111	223	260	284	296	287	318
4895SS/RIB	206	268	272	250	272	296
5848SSRIB	210	254	272	265	287	310
5887VT2P	220	252	274	285	296	289
G09A86-3111	240	266	288	280	302	317
G09Y24-3220A	218	251	275	300	275	291
210-26STXRIB	238	266	268	280	291	283
6110SS/RIB	263	273	287	294	287	286
DKC60-87RIB	212	247	263	274	261	294
G10T63-3122	248	282	323	348	327	334
SK6405-3220	234	283	302	297	305	336
6188SSRIB	222	241	280	274	288	331
D51SS54	201	246	271	272	272	307
212-20STXRIB	208	235	274	267	292	313
5290DGVT2P/RIB	246	327	319	337	336	333
D52SS63	243	245	277	295	299	265
D52SS91	234	241	272	308	312	309
DKC62-52RIB	218	263	292	314	310	321
G12W66-3000GT	206	274	294	293	292	310
6594SS/RIB	210	264	298	287	299	298
6640VT3P	221	259	278	281	272	285
DKC63-21RIB	202	254	280	291	280	296
D54DC94	200	244	282	279	285	310
D54VC52	249	263	299	306	305	316
DKC64-34RIB	224	253	273	320	289	323
G14R38-3122	208	278	264	274	277	301
215-75STXRIB	228	253	273	283	279	356
6538SSRIB	225	250	282	293	293	325
D55VC45	233	270	293	322	312	352
DKC65-94RIB	239	265	295	320	327	360
G15L32-3111	233	279	288	302	298	280
D56VC46	243	275	303	328	320	319
DKC66-74RIB	235	274	307	319	314	338
D57VC51	227	248	281	273	279	329
D58VC65	240	267	285	295	300	311
4488SS/RIB	219	261	277	290	295	279
G05B91-3010	205	251	260	253	273	280
SL5536ZL	191	198	212	222	225	229
G06Z97-3120	218	260	277	273	286	262
G07F23-3111	223	260	284	296	287	318
LSD ($P \leq 0.10$)	30	30	30	30	30	36
Mean	225	263	286	295	295	311
Range	191-263	198-327	212-333	222-356	225-336	229-379

Table 18. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Champaign, IL in 2017**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Maturity: Values are the LS Means of Four Replications.						
Hybrid	Row spacing					20 inches
	30 inches					
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000	44,000	
	Nitrogen level (lb N acre ⁻¹)					
0	60	280	280	280		
bu acre ⁻¹						
G05B91-3010	182	217	236	230	229	233
SL5536ZL	170	207	219	222	232	198
G06Z97-3120	216	249	260	255	258	256
G07F23-3111	223	280	282	273	297	265
4895SS/RIB	209	239	238	258	249	289
5848SSRIB	198	239	270	281	281	310
G09A86-3111	228	263	264	296	297	282
G09Y24-3220A	205	280	284	290	311	279
210-26STXRIB	219	255	265	283	286	276
6110SS/RIB	216	262	258	245	267	250
DKC60-87RIB	208	249	273	271	271	300
G10T63-3122	190	260	283	297	291	304
SK6405-3220	227	261	271	284	281	301
6188SSRIB	213	261	265	253	275	306
D51SS54	219	251	244	272	277	286
G11X64-3010	208	245	253	280	273	282
P1197AMXT	203	251	259	309	296	303
212-20STXRIB	207	272	259	273	295	291
5290DGV2P/RIB	236	280	292	276	292	300
D52SS63	218	251	260	265	266	272
D52SS91	205	260	241	274	282	260
DKC62-52RIB	187	254	279	262	270	303
G12W66-3000GT	185	240	227	257	279	273
6594SS/RIB	185	230	228	240	251	261
6640VT3P	215	263	271	279	285	231
DKC63-21RIB	184	242	243	240	261	281
P1311AMXT	205	245	291	274	253	286
D54DC94	218	261	285	282	285	272
D54VC52	201	264	273	277	288	296
DKC64-34RIB	208	245	262	277	271	328
G14R38-3122	203	240	262	279	270	275
G14V04-3000GT	197	236	266	268	265	301
215-75STXRIB	222	257	271	267	281	275
6538SSRIB	208	249	259	231	274	249
G15L32-3111	227	249	268	268	248	291
5678VT2P	233	279	303	262	274	282
D56VC46	201	269	261	279	297	280
DKC66-74RIB	221	236	264	274	272	285
SL8675-3110	220	286	296	312	321	318
7927VT3P/RIB	210	242	251	300	284	290
8621VT2P/RIB	233	275	314	302	289	298
D57VC51	230	271	270	302	282	282
D58VC65	226	276	284	277	298	299
G18D87-3111	250	269	286	293	262	321
LSD (P ≤ 0.10)	32	31	32	36	33	39
Mean	211	255	266	272	276	282
Range	170-250	207-286	219-314	222-313	230-321	198-328

Table 19. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Harrisburg, IL in 2017**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Maturity: Values are the LS Means of four Replications.						
Hybrid	Row spacing					20 inches
	30 inches					
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000	44,000	
	Nitrogen level (lb N acre ⁻¹)					
0	60	280	280	280		
bu acre ⁻¹						
G07F23-3111	224	258	263	276	284	293
4895SS/RIB	223	251	286	273	294	283
5848SSRIB	231	263	263	286	298	291
5887VT2P	221	260	272	289	278	276
G09A86-3111	222	275	272	287	299	308
G09Y24-3220A	224	284	281	298	304	301
210-26STXRIB	216	260	271	280	289	281
6110SS/RIB	231	262	266	274	283	275
DKC60-87RIB	231	274	292	303	298	316
G10T63-3122	218	282	293	309	309	338
SK6405-3220	231	285	300	320	337	317
6188SSRIB	236	275	273	309	303	321
D51SS54	224	279	285	292	284	302
G11X64-3010	211	254	272	271	287	288
P1197AMXT	225	298	303	320	338	353
212-20STXRIB	221	274	270	301	295	296
5290DGV2P/RIB	258	292	308	319	324	329
D52SS63	233	266	259	293	302	304
D52SS91	214	283	271	290	290	311
DKC62-52RIB	227	282	291	298	303	302
G12W66-3000GT	219	271	273	288	299	326
6594SS/RIB	223	263	272	284	297	297
6640VT3P	228	285	279	288	300	299
DKC63-21RIB	247	258	286	303	311	296
P1311AMXT	217	298	307	315	318	329
D54DC94	243	300	284	308	313	333
D54VC52	239	276	275	301	306	323
DKC64-34RIB	242	278	296	303	321	340
G14R38-3122	213	258	264	280	280	278
G14V04-3000GT	250	287	287	321	334	324
215-75STXRIB	241	287	287	309	312	308
6538SSRIB	229	276	265	292	290	282
D55VC45	217	270	277	293	295	312
DKC65-94RIB	240	277	286	293	299	297
G15L32-3111	238	271	288	281	279	305
5678VT2P	266	310	311	325	323	332
D56VC46	229	288	308	320	320	344
DKC66-74RIB	240	273	300	301	298	315
SL8675-3110	247	300	319	332	343	370
7927VT3P/RIB	235	283	291	317	328	342
8621VT2P/RIB	256	288	299	318	324	340
D57VC51	253	291	314	324	328	341
D58VC65	237	296	311	324	317	322
G18D87-3111	259	304	311	324	328	362
LSD (P ≤ 0.10)	20	20	20	18	17	19
Mean	232	278	286	301	306	314
Range	211-266	251-310	259-319	271-332	279-343	275-370

Table 20. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Yorkville, IL in 2018**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Hybrid	Row spacing					
	30 inches					20 inches
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000		44,000
	Nitrogen level (lb N acre ⁻¹)					
	0	60	280	280		280
	bu acre ⁻¹					
4488SS/RIB	154	195	190	197	212	227
G05K08-3010A	180	181	173	214	188	195
P0574AMXT	169	205	212	213	209	214
NK0602-3010	183	197	200	215	196	206
NK0624-3220	184	201	216	225	199	229
NK0763-3010	160	183	196	193	183	209
P0707AMXT	177	200	209	224	212	193
4895SS/RIB	189	224	227	229	228	216
5858SSRIB	163	187	204	216	215	243
DKC58-34RIB	162	218	222	219	241	242
G08D29-3120A	194	213	216	225	214	247
209-15STXRIB	176	238	247	236	253	248
4997VT2P/RIB	181	211	237	270	246	236
G09A86-3000GT	183	215	235	238	214	207
G09Y24-3220A	146	206	217	221	227	230
210-79STXRIB	195	221	241	223	244	248
6072VT2PRIB	174	201	204	233	223	235
DKC60-87RIB	187	230	236	235	245	249
G10T63-3122	161	226	235	244	248	261
A641-78STXRIB	189	227	243	237	236	237
G11A33-3111	159	211	214	231	210	220
212-90STXRIB	176	219	219	230	243	252
5277AS3220-EZ	180	205	220	235	230	222
5290DGV2P/RIB	170	197	202	216	204	230
A642-59STXRIB	171	228	258	249	229	252
D52VC15	176	216	225	251	235	237
D52VC63	158	208	231	246	216	253
DKC62-52RIB	175	221	242	232	243	244
G12W66-3000GT	199	230	255	251	244	259
P1257AMXT	153	217	238	236	253	251
5370VT2P/RIB	200	247	258	249	239	228
DKC63-21RIB	162	228	224	222	243	245
P1311AMXT	153	236	235	217	214	216
P1366AMXT	153	225	252	238	232	236
6468SSRIB	165	220	222	221	234	248
A6544STXRIB	175	222	241	243	235	240
D54VC14	204	233	241	254	246	242
D54VC52	200	231	251	237	236	225
D54VC94	163	217	234	230	222	246
DKC64-34RIB	174	240	243	222	255	266
5678SS/RIB	163	218	226	235	206	245
D56VC46	170	220	229	231	234	219
5789VT2P/RIB	186	220	207	246	241	238
7927VT3P/RIB	168	240	268	260	241	273
LSD ($P \leq 0.10$)	32	32	28	28	28	28
Mean	174	217	227	232	228	235
Range	146-204	181-247	173-268	193-270	183-255	193-273

Table 21. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Champaign, IL in 2018**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Maturity: Values are the LS Means of Four Replications.						
Hybrid	Row spacing					20 inches
	30 inches					
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000	44,000	
	Nitrogen level (lb N acre ⁻¹)					
0	60	280	280	280		
bu acre ⁻¹						
NK0624-3220	125	181	208	241	237	245
NK0763-3010	105	158	195	224	207	228
P0707AMXT	79	174	193	211	209	229
4895SS/RIB	125	195	235	266	253	233
5858SSRIB	119	187	254	275	261	282
DKC58-34RIB	118	194	232	232	249	265
G08D29-3120A	106	196	233	263	256	255
209-15STXRIB	108	191	257	239	275	277
4997VT2P/RIB	126	199	257	278	284	271
G09Y24-3220A	115	199	243	244	261	271
210-79STXRIB	123	197	247	244	267	270
6072VT2PRIB	127	215	248	278	287	248
G10T63-3122	104	201	257	252	273	278
A641-78STXRIB	131	208	261	264	281	282
G11A33-3111	109	178	223	228	233	251
212-90STXRIB	138	231	233	277	281	253
5277AS3220-EZ	117	186	240	264	265	269
5290DGV2P/RIB	128	203	274	284	292	272
A642-59STXRIB	116	196	245	264	270	291
D52VC63	120	222	272	284	281	263
DKC62-52RIB	108	205	249	233	258	258
G12W66-3000GT	121	212	247	256	268	274
NK1284-3220	132	218	239	262	273	263
P1257AMXT	116	215	238	254	280	295
5370VT2P/RIB	130	210	272	280	289	322
DKC63-21RIB	112	198	223	234	256	241
G13T41-3010	88	187	243	237	242	252
G13Z50-3110	134	227	249	248	254	258
P1311AMXT	57	186	237	238	233	269
P1366AMXT	98	193	252	259	253	256
6468SSRIB	114	203	250	250	269	261
A6544STXRIB	131	213	255	269	276	308
D54VC14	119	214	260	267	267	262
D54VC52	124	203	259	264	271	289
D54VC94	117	209	260	263	278	290
DKC64-34RIB	125	211	262	268	282	287
G15L32-3000GT	95	205	269	266	266	260
5678SS/RIB	134	217	285	260	278	290
D56VC46	125	225	250	272	284	274
5789VT2P/RIB	150	226	277	291	299	299
7927VT3P/RIB	130	222	290	310	317	286
DKC67-44RIB	145	230	289	270	274	294
D58VC65	133	225	287	294	292	299
DKC70-27RIB	128	203	277	270	270	307
LSD (P ≤ 0.10)	25	25	25	29	27	27
Mean	118	204	251	260	267	271
Range	57-150	158-231	193-290	211-310	207-317	228-322

Table 22. Yields of individual hybrids ($n = 44$) grown under two row spacing widths (30 and 20 inches), three plant populations (32,000, 38,000, and 44,000 plants acre⁻¹) and three N levels (0, 60, and 280 lb N acre⁻¹) at **Harrisburg, IL in 2018**. Hybrids are sorted by comparative relative maturity. Values are the LS Means of four replications.

Maturity: Values are the LS Means of four Replications.						
Hybrid	Row spacing					20 inches
	30 inches					
	Plant population (plants acre ⁻¹)					
	32,000		38,000	44,000	44,000	
	Nitrogen level (lb N acre ⁻¹)					
0	60	280	280	280		
bu acre ⁻¹						
4895SS/RIB	93	165	227	244	245	281
5858SSRIB	82	163	223	229	230	237
DKC58-34RIB	127	193	245	262	265	256
G08D29-3120A	78	152	221	230	246	270
209-15STXRIB	75	181	222	245	238	260
4997VT2P/RIB	87	187	235	260	264	257
G09Y24-3220A	92	165	232	241	252	261
210-79STXRIB	101	167	231	254	248	269
6072VT2PRIB	89	170	212	235	233	261
G10T63-3122	67	158	222	219	227	257
A641-78STXRIB	91	164	227	245	249	267
G11A33-3111	102	166	212	224	226	221
G11F16-3111A	106	181	231	245	260	235
212-90STXRIB	91	157	246	264	254	289
5277AS3220-EZ	77	151	203	217	217	215
5290DGV2P/RIB	93	177	235	264	259	298
A642-59STXRIB	92	169	212	234	233	256
D52VC63	98	174	237	250	236	250
DKC62-53RIB	100	184	240	260	265	262
G12W66-3000GT	105	180	219	230	235	253
P1257AMXT	86	145	235	251	260	284
5370VT2P/RIB	102	162	224	221	214	249
DKC63-21RIB	88	186	253	260	261	259
G13T41-3010	87	147	215	212	211	242
G13Z50-3110	99	180	244	259	254	254
P1311AMXT	84	153	212	228	235	247
P1366AMXT	96	153	195	211	204	218
6468SSRIB	127	203	238	239	253	249
A6544STXRIB	100	180	209	231	243	251
D54VC14	83	174	239	235	237	267
D54VC52	92	175	220	234	245	233
D54VC94	108	184	216	225	231	237
DKC64-34RIB	101	167	229	235	228	265
G14V04-3120	87	158	227	245	244	242
DKC65-95RIB	102	174	221	233	251	259
G15L32-3000GT	92	171	220	240	230	235
5678SS/RIB	93	178	231	243	239	276
D56VC46	91	174	244	272	274	281
5789VT2P/RIB	60	156	229	247	242	256
7927VT3P/RIB	66	184	215	224	207	229
DKC67-44RIB	72	164	227	229	229	235
D58VC65	88	151	195	217	223	264
G18D87-3111	93	158	218	238	249	237
DKC70-27RIB	98	171	218	236	244	243
LSD (P ≤ 0.10)	22	22	20	20	20	23
Mean	92	169	225	239	241	254
Range	60-127	145-203	195-253	211-272	204-274	215-298