AGRONOMIC MANAGEMENT TO IMPROVE CORN PRODUCTIVITY UNDER HIGH-YIELDING ENVIRONMENTS

BY

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DISSERTATION

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ABSTRACT

Corn (*Zea mays L.*) grain yields have increased significantly in the U.S. since the 1930s largely due to genetic improvement and better crop management. Three important management decisions a corn grower makes today are: 1) which hybrid to plant, 2) what population to plant, and 3) what nitrogen (N) program to use. Hybrid selection is a critical management decision made by farmers because for any given year the spread in grain yield among current commercial hybrids that year can be greater than 100 bu acre^{-1}. In addition, hybrids vary substantially in their response to management factors such as population and row spacing. Characterizing hybrids phenotypically for their yield-response to different plant spatial arrangement allows breeders, seed advisors, and farmers to predict which hybrids would have a positive yield-response to increased plant populations and narrower row spacings. Adequate fertility and plant nutrition, especially N, become even more important under these more intensive management systems. Better N placement and timing using the correct source can improve nutrient use efficiency and corn grain yield. For these reasons, the objective of this research was to quantify and predict how agronomic and nutritional management practices can be employed to improve corn productivity under high-yielding environments which encompasses three research areas:

How Does Plant Spatial Arrangement Affect Plant Architecture, Growth and Development, and Grain Yield?

Narrower row spacings were documented as a viable method to manage greater plant populations by increasing the plant-to-plant spacing within the crop row. As plant population increased, the yield difference due to row spacing increased. Changes in the architecture of the plant in response to narrower row spacings allowed for greater light penetration into the lower

canopy when crowded at the higher population. Under competitive environments, (i.e. high plant populations) when resources became limited, plants produced more above-ground biomass at the expense of below-ground biomass. However, plants grown in a narrower spacing allocated more energy to producing below-ground biomass instead of above-ground biomass, subsequently reducing the shoot to root ratio.

Which Phenotypic Traits Do Hybrids Possess That Helps Them Yield More When Grown at Increased Populations and Narrower Row Spacings?

Of the six hybrids grown, three hybrids tended to be more positive yield-responsive to higher plant populations and narrower row spacings than the other three hybrids. In general, all six hybrids tended to have similar phenotypic responses to plant spatial arrangement. Thus, it was their inherently distinct phenotypic traits that differentiated them in their yield-response to plant population and/or row spacing alterations rather than the plasticity of their traits. The key traits for increased yields under increased plant populations and narrower row spacings were related to capturing more sunlight (leaf angle, leaf width, leaf length, and leaf area per plant), plant size (stover biomass per acre, total above-ground biomass per acre, and plant width), and root weight per plant.

What is the Best Nitrogen Source, Placement, and Timing to Improve the Efficiency of Nitrogen Utilization and Grain Yield in Corn?

Unfertilized check plots were used to determine the amount of N supplied from the soil during the entire growing season by measuring total N accumulation and grain yield at the R6 growth stage. Site-years that produced corn with low check plot yields tended to yield greater when more

of the N was applied upfront at preplant compared to split applications of N. Under-fertilizing corn at an early growth stage resulted in irreversible yield loss that could not be recovered with a sidedress application. However, site-years with high check plot yields achieved greater yields with split applications of N. When making a split application, sidedressing urea ammonium nitrate (UAN) as Y-drop near the crop row was the best method and source of application. In general, the highest yielding N treatments received banded N at preplant as either urea or polyer-coated urea (PCU).

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ABSTRACT

The average U.S. plant population continues to increase as U.S. growers continue to push corn (*Zea mays* L.) grain yields higher. However, this increased plant population typically causes more stress to the plants, potentially reducing yields. Narrower row spacings can be used to reduce the stress by increasing the plant-to-plant spacing within a row. The objective of this study was to evaluate the influence of plant spatial arrangement (population and/or row spacing) on corn plant growth, morphology, and grain yield. In 2017 and 2018, six contemporary commercial hybrids were planted at 38,000, 44,000, 50,000, and 56,000 plants acre^{-1} in 30” and 20” row spacings at two locations in Illinois. Management system (population and row spacing) significantly affected corn growth, development, and grain yield. The greatest grain yield of 294 bu acre^{-1} resulted from planting 44,000 plants per acre in a 20” row spacing. In a 30” row spacing, the minimum plant population that achieved the greatest yield of 279 bu acre^{-1} was 38,000 plants acre^{-1}. On average across plant populations, plants in a 20” row spacing yielded 12 bu acre^{-1} more than when planted in a 30” row spacing. However, as plant population increased, the yield difference due to row spacing also increased. Under competitive environments (i.e. high plant populations) when resources became limited, plants produced more above-ground biomass at the expense of below-ground biomass. These results document that narrower row spacings can be used to manage crowding at greater plant populations that promoted changes in the architecture of the plants to allow for greater light penetration into the lower canopy, and consequently, greater yield.

INTRODUCTION

Greater global human population and less arable land will require more grain to be produced on fewer acres in order to feed the human population. Grain yield is the product of the number of plants per acre, kernels per plant, and weight per kernel. Since in modern commercial field corn, kernels per plant and weight per kernel are primarily affected by environmental conditions after initial agronomic management factors are implemented, the yield component factor in the grower's greatest control is seeding plants per acre. At low plant populations, grain yield is often limited by an inadequate number of plants whereas at higher populations, it declines due to an increase in the number of aborted kernels and/or barren stalks (Hashemi et al., 2005). Currently the average U.S. corn plant population is just under 32,000 plants acre^{-1} and has increased by an average of 400 plants acre^{-1} year^{-1} since the 1960s (USDA-NASS, 2017b). There is a general positive trend between higher plant populations and higher yields that has been observed over the past 60 years (Duvick, 2005a; Duvick 2005b; USDA-NASS, 2017a, USDA-NASS, 2017b). As this trend continues, the average U.S. corn planting population will reach 44,000 and 50,000 plants acre^{-1} in 30 and 45 years, respectively. These higher plant populations reduce the plant-to-plant spacing within the row and it is reasonable to think that, at some point, the crowding stress could be yield-limiting. Increased attention to management will be critical to continue to achieve greater corn yields under these high plant populations.

Narrower row spacings can be used to increase plant-to-plant spacing within a row to reduce crowding and subsequently reduce competition among individual plants, allowing the crop to better utilize available light, water, and nutrients (Tollenaar and Wu, 1999). Historically, row spacing has decreased since the 1930s (USDA-NASS, 2017c). The large capital investment necessary for narrow row planting and harvesting equipment has greatly slowed their adoption by corn growers. Today, the vast majority of corn in the U.S. is planted in 30” row spacings, with narrow rows generally defined as any row spacing or configuration less than 30” row spacings. The most common narrower row spacings include 20” and 15” rows along with twin rows that are spaced 7.5” apart (22.5” between rows), but are on 30” centers (USDA-NASS, 2017c). At plant populations of 38,000 and 56,000 plants acre^{-1}, planting corn in a 20 inch row compared to a 30 inch row creates 2.8 and 1.9 inches more space between plants, respectively. Less inter-plant competition seen with narrower row spacing has been found to increase yields at a given plant population (Paszkiewicz, 1997; Sharratt and McWilliams, 2005; Widdicombe and Thelen, 2002). Better equidistance between plants often leads to yield enhancements, due to increased photosynthesis and decreased stress during critical yield-determining stages (Andrade et al., 2002; Sharratt and McWilliams, 2005). Conversely, there are also studies that have found no yield difference from reducing the row spacing (Nelson and Smoot, 2009; Tharp and Kells, 2001; Van Roekel and Coulter, 2012). Despite the inconsistent yield responses to narrower row spacings, in the future when plant populations reach 50,000 plants acre^{-1} or more, and the plant-to-plant spacing becomes 4.2 inches or less, decreasing the row spacing will likely be necessary to increase the plant-to-plant spacing. The majority of these previous studies conducted on narrower row spacings in corn evaluated row spacing at plant populations ranging from 24,000 to 36,000 plants acre^{-1} with the top end being 46,000 plants acre^{-1}. The plant-to-plant spacing at these lower plant populations may not warrant a need for reduced row spacings. Evaluating hybrid yield responses to row spacing under higher plant populations and more stressful conditions is needed to aid growers in the decision making process while they consider investing in equipment capable of producing corn in narrower row spacings.

Like planting population, plant architecture is another factor in corn production that has greatly changed over the past several decades. Changes in plant architecture that have accompanied genetic gains in hybrids, such as the reduction in plant and ear heights, increasingly more upright leaves, decreased tassel size, and delayed leaf senescence have been documented (Duvick, 2005b). Furthermore, cultural practices (population and row spacing), aimed at improving light interception have been shown to affect plant architecture and corn growth. Seedlings grown in close proximity to each other express phytochrome-mediated responses by developing narrow leaves, long stems, and less massive roots (Kasperbauer and Karlen 1994). With greater planting populations, crop growth and canopy structure, such as leaf area index, total above-ground biomass, and plant height all increase while tiller number decreases (Tetio-Kagho and Gardner, 1988). Photosynthetically active radiation increases and becomes redistributed toward the top of the canopy when corn is grown in narrower row spacings (Ottman and Welch, 1988) or in a pattern that equalizes the spacing of plants within and between rows (Bullock et al., 1988). These types of spatial planting changes affect the architecture and light dynamics of a corn canopy. Plants grown at higher plant populations and wider row spacings shift leaves in the upper canopy to be more perpendicular to the row (Girardin and Tollenaar, 1994). In summary, many of the plant spacing effects on plant architecture, growth, and development are phytochrome-mediated responses along with plant competition for resources such as water, nutrients, and sunlight. Despite the well documented physiological responses of corn to crowding associated with plant population, little is known about the physiological responses of corn to narrower row spacings, especially with regard to below-ground characteristics.

The objective of this study was to determine the effectiveness of narrower row spacings as a management strategy to reduce plant-to-plant competition under anticipated future higher plant populations, and allow for continued increases in corn yields. Understanding the effects that row spacing and planting population have on corn plant biomass accumulation and architecture, both above- and below-ground, will help determine the physiological causes of any subsequent yield changes.

MATERIALS AND METHODS

Agronomic Practices

Field experiments were conducted in 2017 and 2018 at two locations, one at the University of Illinois Crop Sciences Research and Education Center in Champaign, IL (40.045850 N -88.235709 W), and the second at a collaborating farmer's field near Yorkville, IL (41.363669 N -88.224890 W). These locations have been maintained weed- and disease-free, are level and well-drained, and are well-suited to provide evenly distributed soil fertility, pH, soil organic matter, and water availability. Ten soil cores (0-6" deep) were collected from plot areas prior to planting, thoroughly combined, and assessed for pH, organic matter, and fertility levels (A & L Great Lakes Laboratories, Inc. Fort Wayne, IN). Soil properties and preplant soil nutrient levels for all site-years are shown in Table A.1 of the appendix. Experimental units were plots four rows wide and 17.5 feet in length. Plots were planted on 16 May 2017 and 18 May 2018 at Yorkville and 18 May 2017 and 7 May 2018 at Champaign using a precision plot planter with variable seeding rate and row spacing capability (SeedPro 360, ALMACO, Nevada, IA). At all locations, soybean was the previous crop and conventional deep ripping followed by field cultivation tillage was used. Force 3G insecticide (Tefluthrin (2,3,5,6-tetrafluoro-4-methylphenyl)methyl-(1α,3α)-(Z)-(±)-3-(2chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate) (Syngenta AG, Basel, Switzerland) was applied at planting (0.23 oz acre^{-1}) and Lumax EZ (S-metolachlor [2-

chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] +atrazine (1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine) + mesotrione (2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione) (Syngenta AG, Basel, Switzerland) was applied prior to planting (3.25 qt acre^{-1}) as a pre-emergence herbicide. The post- emergence herbicide program included a tank-mixed application of AAtrex4L (Atrazine 2-chloro-4-ethylamino-6-isopropylamino-s-triazine) (Syngenta AG, Basel, Switzerland) at 1.25 qt acre^{-1}, Armezon (topramezone [3-(4,5-dihydro-isoxazolyl)-2-methyl-4-(methylsulfonyl) phenyl](5-hydroxy-1-methyl-1H-pyrazol-4-yl) methanone) (BASF, Ludwigshafen, Germany) at 0.75 oz acre^{-1}, FS MaxSupreme (ammonium sulfate, hpg polymer, and dimethylpolysiloxane antifoam) (Growmark, Bloomington, Illinois) at 0.8 qt acre^{-1}, and Roundup Powermax (Glyphosate, N-(phosphonomethyl)glycin) (Bayer, Leverkusen, Germany) at 32 oz acre^{-1}.

Management factors evaluated included six contemporary commercial hybrids, two row spacings, and four planting populations. DeKalb hybrids 58-06, 60-67, 60-87, 62-08, 64-34, and 66-40, with 108, 110, 110, 112, 114, and 116 day relative maturities, respectively, were each planted at 38,000, 44,000, 50,000 and 56,000 plants acre^{-1} in both 30 and 20 inch row spacings. In a 30 inch row, the intra-row plant spacing is 5.5, 4.8, 4.2, and 3.7 inches when planting 38,000, 44,000, 50,000, and 56,000 plants acre^{-1}, respectively. Planting in a 20 inch row spacing increases the intra-row plant spacing to 8.3, 7.1, 6.3, and 5.6 inches at 38,000, 44,000, 50,000, and 56,000 plant acre^{-1}, respectively. To all plots, including the border rows, urea ammonium nitrate (UAN; 28-0-0) was broadcast applied preplant at a rate of 280 lbs N acre^{-1}.

Traits Measured

Throughout the growing seasons, various plant measurements were acquired to quantify the effect row spacing and plant population had on plant architecture, growth, and development. A total of 46 phenotypic traits were measured (Table A.2). Canopy coverage was determined at the V5 (five leaf) and V8 (eight leaf) growth stages at Yorkville in 2018 and Champaign in 2017 and 2018 (Canopeo; Mathworks, Inc., Natick, MA) to measure the fraction of ground covered by green vegetation (Patrignani and Ochsner, 2015). All images for canopy coverage measurements were obtained with a digital camera positioned 190 cm above the ground.

Plant heights and stem diameters were measured during the V8 growth stage at Yorkville in 2018 and Champaign in 2017 and 2018 and during R1 (silking stage) at all site-years as a non-destructive assessment of plant growth and biomass accumulation. The heights of the plants at V8 were quantified from the soil surface to the latest fully developed extended leaf, while R1 measurements comprised from the soil surface to the tip of the tassel. Ear heights were obtained by measuring the distance from the soil surface to the base of the ear. Ear-to-plant height ratio and the mean internode lengths below and above the ear were subsequently derived from these measurements. Ear-to-plant height ratio is the height of the ear relative to the total plant height. Stem diameter was quantified on the thinnest area along the minor axis of the first internode just above the soil surface using a caliper. The total number of green leaves on each plant was tallied along with the position number of the ear leaf in relationship to the top of the plant at R1.

At R3 (kernel milk stage), leaf angle was quantified on the leaf directly above the ear leaf by using a protractor to measure the degree of angle between the stem where the leaf attaches to the point on the leaf just before it begins to bend. Ninety degrees would be vertical and parallel to the stem while zero degrees would be horizontal and parallel to the soil surface. Leaf area plant^{-1} was determined by measuring the length and maximum width of the leaf directly above the ear. The product of leaf length and width was multiplied by 0.75 to calculate the area of the leaf directly above the ear which was then multiplied by a factor 9.39 to acquire the average leaf area per plant (Pearce et al., 1975). Plant width was estimated using the Pythagorean Theorem using the leaf angle and leaf length to calculate the potential distance across the rows that the entire plant extends, with the assumption that leaf bending has minimal impact on the calculation. Leaf weight was obtained at the R3 growth stage by manually excising the leaf directly above the ear leaf at the leaf collar from plot border rows. Leaves were placed in a forced air oven at 167 °F for a week, dried to 0% moisture, and weighed to acquire the average weight leaf^{-1}. Leaf area index (LAI), leaf area ratio (LAR), and specific leaf weight (SLW) were derived from these measurements. Leaf area index expresses the ratio of leaf surface area to ground area occupied by the crop. The ratio between the area of leaf material and total plant biomass is referred to as LAR. Leaf thickness, or SLW, is the average leaf weight per unit of leaf area.

Total above-ground plant biomass sampling was conducted at R6 (physiological maturity) and consisted of manually excising three random plants at the soil surface from each of the center two rows of each plot. The plants at R6 were partitioned into grain and stover (including husk) components, and biomass was determined by weighing the total fresh stover then processing it through a chipper (BC600XL, Vermeer Corporation, Pella, IA) to obtain representative stover subsamples. The stover subsamples were immediately weighed to determine aliquot fresh weight, and then weighed again after drying to 0% moisture in a forced air oven at 167 °F, to determine subsample aliquot dry weight and calculate total dry biomass accumulation. Corn ears with husks removed were dried, the grain was removed using a corn sheller (AEC Group, St Charles, IA) and analyzed for moisture content using a moisture reader (Dickey John, GSF, Ankeny, IA). Cob weight was obtained by difference between ear and grain weights, and dry stover and cob weights were summed to calculate the overall R6 stover biomass.

The center two rows of each plot were mechanically harvested for determination of grain yield and harvest moisture, and the yield subsequently standardized to bushels acre^{-1} at 15.5% moisture. Subsamples of the harvested grain were evaluated for yield components (individual kernel weight and kernel number) and for grain quality (oil, protein, and starch concentrations) using near-infrared transmittance spectroscopy (Infratec 1241 Grain Analyzer; FOSS, Eden Prairie, MN). Kernel weight and grain qualities are presented at 0% moisture.

Post-harvest, six consecutive root systems per plot were selected from the center two rows and removed using a shovel to dig 10- 12” diameter around the base of the stalk and 10-12” deep. Excess soil was broken off of the root systems manually and the remaining soil was removed using pressurized water until the roots were clean and free of any soil. The roots were dried to 0% moisture in a forced air oven at 167 °F, cut at the soil line to remove excess stalk, and weighed to obtain the average root weight per plant.

Statistical Analysis

Plots were arranged in a split-plot design with row spacing as the main plot. Hybrid and plant population were randomly assigned as sub-plots with six replications. Measured parameters were analyzed using PROC MIXED (SAS 9.4; SAS Institute, Cary, NC). Row spacing, population, hybrid, and their treatment combinations were included as fixed effects with year, location nested within year, replication nested within the interaction of location and year, and the interaction of row spacing and replication nested within the interaction of location and year as random effects. Unless indicated, fixed effects were considered significant in all statistical calculations if $P \leq 0.05$.

Chapter 1 will focus on the population and/or row spacing effects averaged across the six hybrids. Chapter 2 will focus on the effects of hybrid and the interactions with population or row spacing.

RESULTS AND DISCUSSION

Weather

The 2017 production year experienced relatively dry conditions at both experiment locations. Yorkville and Champaign received 1.5 and 6.0 inches less precipitation during June, July, and August, respectively, compared to the 30-year average (Table 1.1). The Yorkville location received 7 inches of rain in July, resulting in minimal moisture stress throughout much of the growing season. The average temperature of each month was similar to the long-term average for each location.

In 2018, both locations, Yorkville and Champaign, experienced a significantly warmer May than the 30-year average, which resulted in corn that rapidly progressed through the vegetative growth stages early in the growing season (Table 1.1). Also, both the Yorkville and Champaign locations received 2.8 and 3.0 inches more of precipitation during the month of June, respectively, compared to the 30-year average (Table 1.1). Yorkville encountered an additional 2.2 inches of precipitation above normal for the month of May. Despite the above-average precipitation early in the growing season at both locations, later in the growing season (July) tended to be drier than the long-term average, leading to moderate moisture stress during grain fill (Table 1.1).

Early Season Plant Growth and Development

Plant growth can be viewed empirically as the product of internal or genetic factors in combination with external managerial or environmental factors. The goal of crop production is to maximize growth (and yield) through both genetic and environmental manipulations. Many of the in-season crop growth measurements acquired at various growth stages were significantly affected by hybrid (genetic factor), row spacing (management factor), and/or planting population (management factor). Canopy coverage was significantly affected by row spacing, population, and hybrid at both the V5 and V8 growth stages (Table 1.2). Maximizing light interception by achieving complete ground cover as quickly as possible is an important crop production strategy as there is a strong relationship between improved grain yields and increased light interception (Andrade et al., 2002). At both growth stages, each additional 6,000 plants acre^{-1} planted, resulted in 2-3% greater canopy coverage (Table 1.3). When planted in a 20” row spacing compared to a 30” row spacing, corn plants achieved 4% and 5% greater canopy coverage at the V5 and V8 growth stages, respectively, on average across all plant populations (Table 1.3). Greater canopy coverage increases light interception by photosynthetic material translating to higher photosynthetic potential.

Mid-Season Plant Growth and Development

After completion of vegetative growth (R1), plant height and stem diameter differences were not the result of competition for sunlight, but rather directly influenced by assimilate and resource availability. Better plant-to-plant spacing with lower plant populations and narrower row spacings resulted in significantly taller plants with larger stem diameters (Tables 1.2 and 1.3), similar to previous studies that found decreases in plant height and stem diameter at the highest plant populations (Early et al., 1966; Stinson and Moss, 1960; Tetio-Kagho and Gardner, 1988). Photodestruction of auxin at high irradiance levels results in reduced plant height, thus internode elongation from shading is believed to be an auxin response from higher auxin levels. (Leopold and Kriedemann, 1975). However, in this study, the decrease in plant height due to high plant populations is probably associated with limitations of assimilates and resources, such as water and nutrients.

Leaf and Plant Characteristics

At the R3 growth stage, the length and width of the leaf directly above the ear leaf were significantly affected by plant population, while only the leaf width was affected by row spacing (Table 1.2). At a given row spacing, as plant population increased, the leaf length and leaf width were reduced (Table 1.4). However, when averaged across plant population, planting in a 20” row spacing compared to a 30” row spacing maintained or increased leaf width, while leaf length was unchanged (Table 1.4). Greater crowding stress within the row, as when planted in a 30” row compared to a 20” row, resulted in reduced leaf width, consequently allowing more light to penetrate the lower canopy. Better distribution of light in the canopy, by having less light captured by the uppermost leaves, and correspondingly, more light penetrating further down the canopy to the lower leaves increases photosynthetic potential because photosynthetic light use efficiency is greatest at low light levels (Gardner et al., 1985). In addition, enhanced photosynthesis at the ear height increases carbohydrate supply to the developing ear, as the proximity to actively growing organs is a dominating factor in allocation of assimilates (Wardlaw, 1990). Maintenance of carbohydrate supply to the developing embryo is critical for kernel set in corn, and the proximal supply of assimilates from light penetration into the lower canopy may promote an increased number of kernels per ear (Zinselmeier et al., 1999). Similarly, plant population significantly affected leaf angle (Table 1.2). The leaves had a greater leaf angle from horizontal, or a more erect leaf angle, at higher planting populations (Table 1.4). A small reduction in upper leaf photosynthesis, due to vertical leaf inclination, allows more light to penetrate to the lower leaves, resulting in greater potential photosynthesis (Brown, 1984). Interestingly, the leaf angle was significantly greater in the 20” row spacing compared to the 30” row spacing. This phenomenon was likely the result of the decrease in light availability across the row when in the narrower row spacing.

The shorter and narrower leaves caused by increases in plant population and row spacing, corresponded to a decrease in leaf area per plant at R3 (Table 1.4). Leaf area index is closely related to photosynthetic potential as it determines light interception and photosynthetic capacity of the plant. However, on an area basis, there was a significant increase in LAI as plant population was increased and when row spacing was narrowed (Table 1.4). At the highest plant population, reducing the row spacing increased the LAI by 4% (Table 1.4). Although each individual plant had less leaf area, the additional plants at the higher plant populations increased the total leaf area per ground area occupied by the crop. As LAI increases (either through the course of the growing season or by adjusting plant population) the opportunity for plants to intercept more solar radiation also increases. Grain yield increases in response to narrow rows has been found to be closely related to an improvement in light interception during the critical period for grain set (Andrade et al., 2002). Optimum LAI for grain yield was associated with upright leaves compared to a normal canopy structure, indicating that high LAI can become detrimental to producing grain in certain hybrids (Winter and Ohlrogge, 1973). Within each row spacing, leaf area ratio (LAR; a measurement of the leafiness of the plant) significantly increased as plant population increased, indicating that the plants were relatively leafier at higher plant populations (Table 1.4). The weight of the stalks decreased at a greater rate than the leaf area as plant population increased (data not reported), resulting in a higher LAR. Similar results of increasing LAR with corn planted at 24,000 and 40,000 plants acre^{-1} were reported by Amanullah et al. (2007) indicating that under stressful conditions (i.e. higher plant populations) plants put more energy into producing photosynthetic leaf material at the expense of stalk material.

Above-Ground Plant Material

Total above-ground plant biomass accumulation can be used as an indication of the level of plant stress associated with plant spatial arrangement (population and/or row spacing). When averaged across row spacing, for each additional 6,000 plants acre^{-1} the total above-ground weight of each individual plant significantly decreased by approximately 10-11% (Tables 1.2 and 1.5). Competition for resources including sunlight, nutrients, and water reduced the size of each individual plant at the higher plant populations. However, when expressed on an area basis and averaged across both row spacings, planting more plants increased total above-ground biomass, maximizing at 50,000 plants acre^{-1} (Tables 1.2 and 1.5). Similar results of increasing total above-ground biomass as plant population increases up to certain plant population, with greater plant populations decreasing total above-ground biomass accumulated have been reported (Hashemi et al., 2005). In a 30” row spacing, total above-ground biomass significantly increased up to 44,000 plants acre^{-1} while in a 20” row spacing planting 50,000 plants acre^{-1} achieved the greatest total above-ground biomass (Table 1.5). Increased plant-to-plant spacing at the higher densities from planting in narrower row spacings can be used as a method to decrease plant stress. When averaged across site-years, hybrids, and plant populations, decreasing the row spacing from 30” to 20” increased the total above-ground biomass by 0.6 tons acre^{-1} (Table 1.5).

Root Systems

Root systems affect plant growth and crop yields, however, due to the difficulty of studying below-ground material there is little research conducted on root characteristics. In this study, the weights of individual plant root systems were significantly affected by row spacing and plant population (Table 1.2). Management systems that increased plant-to-plant spacing within a row, such as the narrower row spacing and lower plant population, significantly increased root weight per plant (Table 1.5). Plant root mass can be used as an estimate of rooting depth and horizontal root spread. When averaged across row spacing, for every additional 6,000 plants planted acre^{-1} there was a 15-18% decrease in root weight per plant (Table 1.5). When planted in a 20” row spacing compared to a 30” row spacing, the better plant-to-plant spacing resulted in a 22% increase in root weight on average (Table 1.5). Interestingly, the average weight of a plant root system from a 30” row was the same as from a 20” row spacing but at a plant population of 6,000 more plants acre^{-1}. The average horizontal spread of a root system at the lower plant population was roughly 7 inches across the row, suggesting there would be little, if any, below-ground competition in this direction (data not shown). With little across-the-row competition below-ground, within-the-row competition is the main driving force for root mass alterations, and plants of the same species have been shown to avoid each other’s root systems (Raper and Barber, 1970). However, between the two management systems with the most similar plant-to-plant spacing within a row (approximately 5.5”), providing 38,000 plants acre^{-1} and 30” row spacing produced 42% more root weight per plant than the 56,000 plants acre^{-1} and 20” row spacing system (Table 1.5). The significant increase in above-ground competition at 56,000 plants acre^{-1} compared to 38,000 plants acre^{-1} may be the reason for the two management systems' differing root mass. The plants were focusing the majority of their energy and resources into producing above-ground biomass, and thereby, may have been sacrificing below-ground biomass production. On an area basis, there also was a significant effect of both row spacing and plant population on total root biomass per acre (Table 1.5). Surprisingly, at higher plant populations, there was a significant decrease in root biomass production per acre (Table 1.5). Even with more plants acre^{-1} there was less root biomass produced per acre. These results are consistent with Tisdale et al. (1993) who reported greater below-ground biomass at a much lower plant population. Plant spatial arrangement had a significant effect on the shoot biomass/root biomass ratio (Table 1.5). When averaged across plant populations, hybrids, and site-years, the plant shoot biomass/root biomass was significantly greater in a 30" row compared to a 20" row, indicating that the root biomass per acre increased at a greater degree than the increase in total above-ground biomass per acre when moving to a narrower row spacing (Table 1.5). As plant population increased, the shoot biomass/root biomass increased indicating that under competitive conditions plants partition their energy and resources to produce above-ground biomass at the expense of producing below-ground biomass. Greater shoot biomass/root biomass ratios under light competitive conditions have been observed in numerous other studies (Demotes-Mainard and Pellerin, 1992; Edwards and Kamprath, 1974; Hébert et al., 2001; Lambers and Posthumus, 1980). Since the shoot has first access to light, limited light intensity will reduce root growth more than shoot growth. On average, plants produced 25 times more above-ground biomass compared to below-ground biomass and this ratio became even greater under higher plant populations. Therefore, under high plant population systems, plants needed to support more total above-ground biomass per acre with less roots to absorb water and fertilizer.

Grain Yield and Yield Components

When averaged across all treatments and site-years, the experiment produced a mean yield of 282 bu acre^{-1} with significant effects from row spacing, population, and the interaction of row spacing and population (Tables 1.2 and 1.5). On average, growing 44,000 plants acre^{-1} at the 20” row spacing resulted in the greatest grain yield of 294 bu acre^{-1} (Table 1.5). When averaged across hybrids and site-years, the minimum plant population that maximized grain yield in a 30” row spacing was 38,000 plants acre^{-1} but was 44,000 plants acre^{-1} in a 20” row spacing (Table 1.5). At 56,000 plants acre^{-1} yield decreased, regardless of row spacing, to a level below that of plants grown at the lowest plant population of 38,000 plants acre^{-1}. When averaged across all site-years, hybrids, and populations, changing from 30” to 20” row spacings increased yield by 12 bu acre^{-1} (Table 1.5). On average across all hybrids and locations, increasing the plant population from 38,000 to 44,000 or 50,000 plants acre^{-1} increased grain yield by approximately 8 bu acre^{-1} when planted in the 20” row spacing, but there was no significant yield changes across these plant populations when planted in the 30” row spacing (Table 1.5). With greater plant plant populations, the increased yields from planting in the 20” row spacing versus the 30” row spacing became even greater up to 50,000 plants acre^{-1}. When grown at 38,000 plants acre^{-1}, use of the 20” row spacing led to 7 bu acre^{-1} greater yields than the 30” row spacing. However, the yield difference due to row spacing increased to 13 and 17 bu acre^{-1} when corn was grown at 44,000 and 50,000 plants acre^{-1}, respectively (Table 1.5). Increased plant populations provided a priori increase in potential kernel number, which was reflected in the greater yields. Therefore, as grain yield increased with increasing plant populations, the higher yields corresponded to an increase in kernel number per land area, with kernel number maximizing at a higher plant population than kernel weight (Table

1.5). On average, across all hybrids, row spacings, and site-years, the grain yield decrease due to changing the plant population from 50,000 plants acre^{-1} to 56,000 plants acre^{-1} was the result of decreases in both kernel number and kernel weight. The higher plant population likely led to greater stress during pollination and grain fill, increasing kernel abortion and decreasing grain fill (Andrade et al., 1999; Kiniry and Richie, 1985). Interestingly, the 12 bu acre^{-1} yield increase from planting corn in a 20” row spacing compared to 30” row spacing was achieved by an increase in kernel number while maintaining kernel weight, suggesting that the greater plant-to-plant spacing in the 20” row spacing reduced stress and kernel abortion (Table 1.5). Additional results including details of the grain yield, yield components, and grain quality for each location and year are presented in the appendix (Tables A.3, A.4, and A.5)

CONCLUSIONS

Plant population and row spacing had significant effects on corn biomass accumulation and development along with corn grain yield. Throughout the life cycle of the plant, higher plant populations and narrower row spacings provided better canopy coverage and greater leaf area to intercept more solar energy. The architecture of the plant significantly changed due to more crowding at the higher plant populations, resulting in increased light penetration into the lower canopy, including reduced leaf width and increased leaf angle.

Planting 44,000 plants acre^{-1} achieved the greatest yield in a 20” row spacing, while only 38,000 plants acre^{-1} was necessary to maximize yields in the 30” row spacing. On average across plant populations, plants in a 20” row spacing yielded 12 bu acre^{-1} more than when planted in a 30” row spacing, however, as plant population increased to 50,000 plants acre^{-1}, the yield differences between row spacings became greater. Planting 56,000 plants acre^{-1} at either row spacing decreased yield, possibly due to limitations of water or other nutrients. These findings suggest that there are upper limits on plant population for current U.S. commercial corn hybrids planted in either a 30” or 20” row spacing to obtain maximum yield without any additional fertilizer, crop protection, or irrigation.

Root systems are a vital part of a plant, however, root architecture is relatively unknown due to the difficulty of studying roots in a soil environment. This study demonstrated the importance of row spacing to help maintain a larger root system under high plant populations. Below-ground biomass supported roughly 25 times more biomass above-ground; and as the plant population increased the total above-ground biomass per acre tended to increase while root biomass per acre tended to decrease. On average, root weight per plant and root biomass per acre were more affected by the planting population and row spacing than were the above-ground measured phenotypic traits. More focus is needed on the below-ground characteristics of a corn plant, especially as pertains to breeding efforts. Understanding how narrow row spacing could mitigate the effects of higher planting population and their interactive effects on the root system will help growers make better agronomic decisions such as fertilizer use and placement.

TABLES

Table 1.1. Monthly weather data between 1 April and 30 September at Yorkville and Champaign, IL in 2017 and 2018. Values presented are the average daily air temperature and the average monthly accumulated rainfall, with deviations from the 30-year average in parentheses (Illinois State Water Survey, 2019).

Site-year	April	May	June	July	August	September
Temperature				^{o}F		
2017						
Yorkville	54 (4)	58 (-3)	72 (2)	74 (0)	70 (-2)	68 (3)
Champaign	57 (5)	61 (-2)	73 (1)	77 (2)	72 (-1)	69 (3)
2018						
Yorkville	40 (-10)	67 (6)	71 (1)	72 (-2)	71 (-1)	66 (1)
Champaign	46 (-6)	72 (9)	75 (3)	75 (0)	75 (2)	71 (5)
Precipitation				Inches		
2017						
Yorkville	6.9 (3.0)	4.7 (0.4)	1.8 (-2.5)	7.0 (2.3)	2.8 (-1.3)	0.1 (-3.0)
Champaign	6.2 (2.6)	5.6 (0.7)	2.5 (-1.8)	2.2 (-2.5)	2.2 (-1.7)	0.8 (-2.3)
2018						
Yorkville	1.0 (-2.9)	6.5 (2.2)	7.1 (2.8)	1.9 (-2.8)	2.8 (-1.3)	2.4 (-0.7)
Champaign	2.5 (-1.1)	4.2 (-0.7)	7.3 (3.0)	3.2 (-1.5)	4.0 (0.1)	4.7 (1.6)

Table 1.2. Test of fixed effects of 46 measured phenotypic traits for corn grown at Yorkville and Champaign, IL in 2017 and 2018.

Phenotypic trait	**Growth stage**	**Row spacing (S)**	**Population (P)**	**S x P**	**Hybrid (H)**	**S x H**	**P x H†**
		P > F					
Canopy coverage	V5	<.0001	<.0001	<.0001	<.0001	0.9515	0.3696
Canopy coverage	V8	<.0001	<.0001	0.3809	<.0001	0.4482	0.9959
Plant height	V8	0.6475	0.2831	0.8410	<.0001	0.9247	0.9985
Stem diameter	V8	<.0001	<.0001	0.8510	0.0038	0.9948	0.9960
Plant height	R1	0.0029	<.0001	0.6978	<.0001	0.5438	0.8212
Stem diameter	R1	<.0001	<.0001	0.4556	<.0001	0.7868	0.7120
Ear height	R1	0.0627	0.0100	0.9309	<.0001	0.1457	0.5920
Ear height/plant height	R1	0.7758	<.0001	0.7712	<.0001	0.3497	0.8170
Ear leaf number	R1	0.0046	0.0140	0.9487	<.0001	0.7410	0.9077
Total leaves	R1	0.0016	0.0003	0.9396	<.0001	0.3152	0.8373
Ear leaf relative position	R1	0.1314	<.0001	0.9937	<.0001	0.3554	0.6975
Number leaves above ear	R1	0.2889	0.7363	0.7937	<.0001	0.4643	0.7789
Number leaves below ear	R1	0.0016	0.0003	0.9396	<.0001	0.3152	0.8373
Leaves above/below ear	R1	0.5727	0.0340	0.9137	<.0001	0.5039	0.6939
Stalk length above ear	R1	0.3047	0.7665	0.7775	<.0001	0.4368	0.7631
Stalk length below ear	R1	<.0001	<.0001	0.5045	<.0001	0.5855	0.8275
Avg. internode length	R1	0.0627	0.0100	0.9309	<.0001	0.1457	0.5920
Avg. internode length above ear	R1	0.0745	0.4594	0.9746	<.0001	0.1561	0.5644
Avg. internode length below ear	R1	0.1130	<.0001	0.4664	<.0001	0.5449	0.2841
Leaf angle	R3	0.1660	0.0003	0.8901	<.0001	0.0962	0.7018
Select leaf length	R3	0.4191	<.0001	0.6597	<.0001	0.0401	0.3358
Select leaf width	R3	0.0335	<.0001	0.1095	<.0001	0.0582	0.0450
Select leaf weight	R3	0.3633	<.0001	0.2015	<.0001	0.3466	0.0597
Leaf area per plant	R3	0.0381	<.0001	0.1427	<.0001	0.0520	0.0102
Leaf area per plant above ear	R3	0.0041	<.0001	0.6317	<.0001	0.8358	0.6829
Leaf area index	R3	<.0001	<.0001	0.0205	<.0001	0.0848	0.0476
Leaf area ratio	R3	0.0069	<.0001	0.1998	<.0001	0.3861	0.0528
Specific leaf weight	R3	0.7913	<.0001	0.9496	<.0001	0.3168	0.4893
Specific leaf area	R3	0.8122	<.0001	0.7330	<.0001	0.4684	0.5543
Plant width	R3	0.0083	<.0001	0.8330	<.0001	0.9594	0.8700
Root weight per plant	R6	<.0001	<.0001	0.1572	<.0001	0.2040	0.0127
Root biomass per acre	R6	<.0001	<.0001	0.8393	<.0001	0.1331	0.0281
Leaf biomass per acre	R6	0.0004	<.0001	0.5417	<.0001	0.2575	0.0269
Stalk biomass per acre	R6	<.0001	0.0014	0.6363	<.0001	0.4884	0.0431
Stover weight per plant	R6	0.0002	<.0001	0.0006	<.0001	0.5680	0.1013
Stover biomass per acre	R6	<.0001	<.0001	0.4727	<.0001	0.4895	0.1548
Total above-ground weight per plant	R6	0.0002	<.0001	0.0017	<.0001	0.6592	0.3965
Total above-ground biomass per acre	R6	<.0001	<.0001	0.7725	<.0001	0.0697	0.0378
Shoot biomass/root biomass	R6	<.0001	<.0001	0.0018	<.0001	0.7428	0.1170
Harvest index	R6	0.0836	<.0001	0.0243	<.0001	0.7384	0.1901
Grain protein concentration	R6	0.1167	<.0001	0.5463	<.0001	0.8699	0.0197
Grain oil concentration	R6	0.8173	<.0001	0.6909	<.0001	0.7946	0.4636
Grain starch concentration	R6	0.6275	<.0001	0.6843	<.0001	0.9307	0.2149
Kernel number per area	R6	<.0001	<.0001	0.0006	<.0001	0.0008	0.0002
Avg. kernel weight	R6	0.8032	<.0001	0.2436	<.0001	0.3199	0.0014
Grain yield	R6	<.0001	<.0001	0.0078	<.0001	0.0163	0.0016

† The interaction between row spacing, population, and hybrid was not significant for any of the phenotypic traits.

Table 1.3. Canopy coverage at V5 and V8, R1 stem diameter, and R1 plant height as influenced by management system for corn averaged across six hybrids and two locations in 2017 and 2018.

Row spacing	**Population (plants acre^{-1})**				**Mean**
	38,000	**44,000**	**50,000**	**56,000**	
			V5 canopy coverage, %		
30”	29 f	30 e	32 d	34 c	31 B
20”	31 de	33 c	37 b	39 a	35 A
Mean	30 D	32 C	34 B	37 A	
			V8 canopy coverage, %		
30”	71 f	73 e	76 d	78 c	75 B
20”	75 d	78 c	81 b	84 a	80 A
Mean	73 D	76 C	79 B	81 A	
			R1 stem diameter, cm		
30”	20.5 b	19.7 c	19.0 d	18.2 e	19.4 B
20”	21.6 a	20.6 b	19.8 c	19.1 d	20.3 A
Mean	21.0 A	20.2 B	19.4 C	18.6 D	
			R1 plant height, cm		
30”	264 bc	262 de	260 e	258 f	261 B
20”	269 a	266 b	264 cd	263 cde	266 A
Mean	267 A	264 B	262 C	260 D	

Mean separation letters (lower case) compare population and row spacing treatment interactions for each trait. Upper case letters compare the main effect of population or row spacing within a trait. Similar letters are not statistically different at α = 0.05.

Table 1.4. Leaf length, leaf width, leaf angle, leaf area per plant, leaf area index, and leaf area ratio as influenced by management system for corn averaged across six hybrids and two locations in 2017 and 2018.

Row spacing	Population (plants acre^{-1})				Mean
	38,000	44,000	50,000	56,000	
			Leaf length, cm		
30”	85.6 ab	85.3 b	84.5 c	83.0 d	84.6 A
20”	86.0 a	85.3 b	84.5 c	83.3 d	84.8 A
Mean	85.8 A	85.3 B	84.5 C	83.2 D	
			Leaf width, cm		
30”	9.8 b	9.6 c	9.3 d	9.1 e	9.46 B
20”	10.0 a	9.7 c	9.3 d	9.1 e	9.53 A
Mean	9.9 A	9.6 B	9.3 C	9.1 D	
			Leaf angle†, degrees		
30”	67.0 d	67.1 cd	67.3 cd	67.7 abc	67.3 B
20”	67.5 bcd	67.7 abc	68.0 ab	68.2 a	67.8 A
Mean	67.2 B	67.4 B	67.6 AB	67.9 A	
			Leaf area plant^{-1}, cm^2 plant^{-1}		
30”	5923 b	5760 c	5539 d	5320 e	5636 B
20”	6042 a	5806 c	5559 d	5353 e	5690 A
Mean	5983 A	5783 B	5549 C	5336 D	
			Leaf area index		
30”	5.7 f	6.3 d	6.8 c	7.1 b	6.5 B
20”	5.8 e	6.4 d	7.0 b	7.4 a	6.7 A
Mean	5.8 D	6.3 C	6.9 B	7.3 A	
			Leaf area ratio, cm^2 g^{-1}		
30”	50 e	54 cd	56 b	58 a	54 A
20”	48 f	52 d	55 bc	58 a	53 B
Mean	49 D	53 C	55 B	58 A	

† 90 degrees is vertical.

Mean separation letters (lower case) compare population and row spacing treatment interactions for each trait. Upper case letters compare the main effect of population or row spacing within a trait. Similar letters are not statistically different at $\alpha = 0.05$.

Table 1.5. Total above-ground plant weight, total above-ground biomass, root weight per plant, root biomass, shoot biomass/root biomass, kernel weight, kernel number, and grain yield as influenced by row spacing and population for corn averaged across six hybrids and two locations in 2017 and 2018. Grain yield is presented at 15.5% moisture, kernel weight is presented at 0% moisture.

Row spacing	**Population (plants acre^{-1})**				**Mean**
	38,000	**44,000**	**50,000**	**56,000**	
	Total above-ground plant weight, grams plant^{-1}				
30”	274 b	246 d	222 f	200 g	236 B
20”	287 a	256 c	227 e	203 g	243 A
Mean	280 A	251 B	225 C	201 D	
	Total above-ground biomass, tons acre^{-1}				
30”	11.7 e	12.0 d	12.1 d	11.9 d	11.9 B
20”	12.3 c	12.6 b	12.8 a	12.5 b	12.5 A
Mean	12.0 C	12.3 B	12.4 A	12.2 B	
	Root weight per plant, grams root^{-1}				
30”	12.2 b	10.2 c	8.6 d	6.8 e	9.4 B
20”	14.6 a	12.5 b	10.3 c	8.6 d	11.5 A
Mean	13.4 A	11.4 B	9.4 C	7.7 D	
	Root biomass, tons acre^{-1}				
30”	0.52 cd	0.49 d	0.47 e	0.41 f	0.47 B
20”	0.63 a	0.61 a	0.58 b	0.53 c	0.59 A
Mean	0.58 A	0.55 B	0.52 C	0.47 D	
	Shoot biomass/root biomass, tons acre^{-1}/ tons acre^{-1}				
30”	24.0 de	26.1 c	27.8 b	32.8 a	27.7 A
20”	20.8 f	21.8 f	23.7 e	25.4 cd	22.9 B
Mean	22.4 D	24.0 C	25.7 B	29.1 A	
	Kernel weight, miligrams kernel^{-1}				
30”	271 a	263 b	256 c	251 de	260 A
20”	273 a	262 b	254 cd	249 e	259 A
Mean	272 A	263 B	255 C	250 D	
	Kernel number, kernels m^{-2}				
30”	5484 e	5683 cd	5763 c	5713 c	5661 B
20”	5575 de	5976 b	6146 a	5999 b	5924 A
Mean	5529 C	5829 B	5954 A	5856 B	
	Grain yield, bu acre^{-1}				
30”	279 cd	281 bc	276 d	268 e	276 B
20”	286 b	294 a	293 a	280 cd	288 A
Mean	282 B	287 A	285 AB	274 C	

Mean separation letters (lower case) compare population and row spacing treatment interactions for each trait. Upper case letters compare the main effect of population or row spacing within a trait. Similar letters are not statistically different at $\alpha = 0.05$.

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CHAPTER 2: DO CERTAIN PHENOTYPIC TRAITS CORRESPOND TO INCREASED YIELD AT INCREASED PLANTING POPULATIONS AND NARROWER ROW SPACINGS IN CORN HYBRIDS?

ABSTRACT

Corn (*Zea mays* L.) hybrids differ in their yield response to plant population and/or row spacing. The objective of this study was to identify the phenotypic traits of plant population and row spacing yield-responsive hybrids to help breeders select for hybrids to be placed in these management systems. In 2017 and 2018, six commercial hybrids were planted at 38,000, 44,000, 50,000, and 56,000 plants acre^{-1} in a 30" and 20" row spacing at two locations in Illinois. In general, the more recently released hybrids and full-season hybrids tended to have greater yields in response to both higher planting population and narrower row spacing. Of the 46 measured phenotypic traits, those related to above-ground biomass had more plasticity than many of the leaf traits (i.e. total leaves, leaf length, leaf angle, etc.) in response to plant spatial arrangement, but below-ground traits had even greater plasticity. While the hybrids had inherently distinct phenotypic traits, there was no difference between hybrids in the plasticity of their above- and below-ground traits in response to plant population and/or row spacing alterations. Stepwise multiple logistic regression was used to identify the key phenotypic traits (predictors) of hybrids with increased yield in response to greater planting populations and narrower row spacing. These key traits for increased yields were related to capturing more sunlight (leaf angle, leaf width, leaf length, and leaf area per plant), plant size (stover biomass per acre, total above-ground biomass per acre, and plant width), and root weight per plant.

INTRODUCTION

Corn grain yields have dramatically increased over time, as have plant populations. Greater yields rely on decreasing plant stresses via genetic selection that promotes tolerance to increased seeding rate. The genetic basis for yield increases to plant population increases over the decades has been driven by better hybrid stability or tolerance over a variety of environments and not yield potential on a per-plant basis (Carlone and Russell, 1987; Duvick, 1997; Gonzalez et al., 2018; Hammer et al., 2009; Sangoi et al., 2002; Tokatlidis and Koutroubas, 2004). Genetic yield gain occurs as a result of adaptation to continual increases in plant population and tolerance to stressful environments.

Hybrid selection is a critical management decision made by farmers because for any given year the spread in grain yield among current commercial hybrids that year can be greater than 100 bu acre^{-1}. In addition, it has been well documented that hybrids vary substantially in their response to management factors such as plant population. Some hybrids exhibit a positive yield response to higher plant populations while other hybrids yield less or have no yield response to higher plant populations (Assefa et al., 2018; Duvick and Cassman, 1999; Gonzalez et al., 2018; Grassini et al., 2011; Hashemi et al., 2005; Mastrodomenico et al., 2018; Monneveux et al., 2006). The hybrid difference in yield response to row spacing has not been well documented.

Hybrid relative maturity can be used as a comparative measurement to determine when hybrids will reach physiological maturity for a particular geographical region. Short-season hybrids require fewer growing degree days to reach maturity as compared to a full-season hybrid. Optimal planting population is usually greater for shorter-season hybrids than for full-season hybrids because of their more upright leaves and shorter plant stature (Beech and Basinski, 1975; Brown et al., 1970; Edwards et al., 2005). Location and relative maturity may also play large roles in whether narrower row spacings would lead to greater yields compared to wider row spacing. Full-season hybrids grown in the northern corn belt and short-season hybrids grown in the southern U.S. may yield more in narrower row spacings because those hybrids would have limited time and heat units to reach maximum radiation interception prior to flowering (Lee, 2006). Having a better understanding of the relationship between relative maturity and the hybrid physiological and yield responses to row arrangement will aid in selecting hybrids that will yield more in specific geographical regions and/or with different management systems.

Corn hybrids differ in their plant architecture such as plant height, ear height, leaf orientation, leaf area, and leaf area distribution (Edmeades and Lafitte, 1993; Maddonni and Otegui, 1996; Stewart and Dwyer, 1993). Additionally, the respsonse of a hybrid to increases in planting population may be dependent on the hybrids' plasticity of phenotypic traits (Sarlangue et al., 2007). Breeding efforts have already been made to select hybrids that possess characteristics associated with tolerance to higher planting populations, however, there has been little movement toward selecting hybrids for narrower row spacings (Duvick et al., 2004a). Hybrids with high biomass plasticity and high reproductive partitioning may have a lower optimal planting population to maximize yields compared to hybrids with low biomass plasticity and with low reproductive partitioning. Plant population tolerance also involves multiple factors relating to plant architecture, photosynthetic potential, and source-sink relationship. Stress-tolerant hybrids have more efficient capture and use of resources by increased interception of incident radiation and greater uptake of nutrients (Tollenar and Wu, 1999). Increased leaf longevity, a more active root system, and a higher ratio of assimilate supply by the leaf canopy to assimilate demand by the grain during the grain filling period can be attributed to the more efficient accumulation and use of resources. Therefore, the objective of this study was to identify the phenotypic traits that enable hybrids to have greater yields at increased planting populations and narrower row spacings, that in turn, can accelerate breeder efforts to obtain more stress-tolerant hybrids grown in more intensive management systems.

MATERIALS AND METHODS

Agronomic Practices

The agronomic practices were the same as stated in Chapter 1. The experiment was conducted at Yorkville and Champaign, IL in 2017 and 2018. Briefly, management factors evaluated included two row spacings, four planting populations, and six commercial DeKalb hybrids. Hybrids 58-06, 60-67, 60-87, 62-08, 64-34, and 66-40 were selected as they represent a wide range of maturities from 108-116 day.

Traits Measured

The parameters measured, including plant growth, development, and phenotypic traits of each hybrid were the same as stated in Chapter 1. The plasticity of each individual trait in response to plant population was calculated by taking the average of the absolute difference, on a percentage basis, between each increase in plant population in a 30” row and in a 20” row spacing. The same method was used to calculate the plasticity in response to row spacing except the average absolute difference between measurements at the 30” and 20” row spacings at each given plant population was used. Above-ground hybrid plasticity in response to plant population was calculated by taking the average absolute difference in response to plant population for each trait and then averaging it across all the above-ground traits which includes all 46 measured traits with the exception of individual root weight, root biomass, and shoot:root ratio. The same method was used to calculate above-ground hybrid plasticity in response to row spacing. Below-ground hybrid plasticity in response to plant population or row spacing was derived using the same method with the exception of only averaging across the two below-ground traits measured (individual root weight and root biomass).

Statistical Analysis

Plots were arranged in a split-plot design in a randomized complete block design (RCBD) with row spacing as the whole plot. Hybrid and plant population were randomly assigned in a factorial arrangement to the sub-plots with six replications. Measured parameters were analyzed using PROC MIXED (SAS 9.4; SAS Institute, Cary, NC). Row spacing, population, hybrid, and their treatment combinations were included as fixed effects with year, location nested within year, replication nested within the interaction of location and year, and the interaction of row spacing and replication nested within the interaction of location and year as random effects. Unless indicated, fixed effects were considered significant in all statistical calculations if $P \leq 0.05$.

Stepwise multiple logistic regression was used to identify the key phenotypic traits (predictors) that differentiate hybrids with positive yield responses (favorable event = 1) to increased plant population and decreased row spacing versus hybrids that have a negative or no response to plant spatial arrangement (non-favorable event = 0). The logistic regression model can be used to predict the probability of a hybrid having a positive yield response to plant population and row spacing given a set of measured traits. Forty-five phenotypic traits (all measured traits except grain yield) were analyzed using PROC LOGISTIC (SAS 9.4; SAS Institute, Cary, NC) to create a logistic regression model. Default values of $\alpha = 0.05$ were specified for both the selection level entry and selection level removal arguments.

Pearson’s correlation coefficient was used to evaluate the linear association between grain yield and measured parameters across all treatments and within each rotation, using the CORR procedure of SAS (SAS 9.4; SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Grain Yield Responses

Corn hybrids varied greatly in their response to increased planting population and narrower row spacings, with changes in grain yield, crop growth, plant architecture, and other phenotypic traits. There was a significant effect of hybrid and the interaction of hybrid and population along with hybrid and row spacing on grain yield (Table 2.1). At the lowest plant population of 38,000 plants acre^{-1} in a 30” row spacing, the two highest yielding hybrids were 62-08 and 66-40 yielding 285 and 291 bu acre^{-1}, respectively (Table 2.2). Both hybrids are high-yielding, however, their yield responses to increased plant population were different. In a 30” row spacing, as plant population increased from 38,000 to 44,000 plants acre^{-1}, hybrid 62-08 tended to produce 6 bu acre^{-1} less grain yield, while hybrid 66-40 tended to produce 5 bu acre^{-1} more (Table 2.3). Similarly, in a 20” row spacing at the lowest plant population of 38,000 plants acre^{-1}, hybrids 62-08 and 66-40 were two of the highest yielding hybrids and their yield responses when increasing plant population were statistically different (Table 2.2 and 2.3). When averaged across all yield responses to increased plant population in both a 30” and 20” row, one hybrid had a negative yield response (62-08) while two hybrids had a positive yield response (64-34 and 66-40) (Table 2.3).

Many of the hybrids produced greater yields in response to narrower row spacings, however, there was a significant hybrid by row spacing interaction (Table 2.1). Some hybrid yields, such as of 58-06, were unaffected by row spacing changes when planting 38,000 or 44,000 plants acre^{-1}

(Table 2.4). Other hybrids, such as 64-34, exhibited a high yield response to row spacing, yielding 11 or 12 more bu acre^{-1} when planted in 20” versus 30” rows at a plant population of 38,000 or 44,000 plants acre^{-1}, respectively (Table 2.4). When averaged across all row spacing yield responses, all hybrids had a significant positive response to being planted in a narrower row (Table 2.4). Notably, hybrids 60-87, 64-34, and 66-40 all averaged a 16 bu acre^{-1} yield increase in response to narrower row spacings (Table 2.4). Two of the three most recently released hybrids (60-87 and 64-34) tended to be more yield responsive to increased plant populations and narrower row spacings. These results highlight the concept that corn breeders have been selecting for traits that are advantageous to higher plant populations and narrower rows when selecting for high yield (Borras et al., 2007; Hammer et al., 2009; Valentinuz and Tollenaar, 2004). The full-season hybrids also tended to be more yield-responsive to plant spatial arrangement suggesting that those hybrids have a longer growing season to respond to management strategies, which is similar to results found by Farnham (2001) but contradicts findings from Lindsey and Thomison (2016).

Phenotypic Trait Responses

Many of the phenotypic traits measured were significantly affected by plant population or row spacing (Table 2.1). Of the 46 phenotypic traits, plant population or row spacing had a significant effect on 42 or 26 of the traits, respectively (Table 2.1). The plasticity, or average absolute response on a percentage basis, of each trait to plant population or row spacing was significantly different (P = <0.0001) (Table 2.5). Three of the top four traits found to be most responsive to plant population increases were below-ground related traits; namely, root biomass per acre, shoot biomass/root biomass, and root weight per plant had average absolute responses of 18.2, 18.1, and

16.7% change, respectively (Table 2.5). Plant root architectures have been shown to be highly responsive to management in other studies (Hodge, 2004; Yu et al., 2014).

Traits that encompass total above-ground biomass per acre such as stalk biomass, stover biomass, and grain yield were included in the top ten most responsive traits. Grain quality, including starch and protein concentrations, was mostly unaffected by changes in plant population (Table 2.5). In addition, many of the leaf-related phenotypic traits such as total leaves, ear leaf number, leaf length, and leaf angle tended to stay the same, regardless of planting population (Table 2.5). Since row spacing affects the plant-to-plant spacing within a row, like plant population, many traits showed similar variability in response to the two plant arrangement changes (Table 2.5). Other studies looking at phenotypic trait responses to plant population and/or row spacing found that the traits had different responses to plant spatial arrangement with some traits being highly responsive and other traits being less responsive (Boomsma, et al., 2009; Ottman and Welch, 1989; Van Roekel and Coulter, 2012).

Also, traits that are expressed later in the growing season, at R6 or final harvest, tended to have a greater degree of plasticity than traits that are expressed early in the growing season. Eight of the top ten traits with greater response to plant population changes were measured at R6 or later and eight of the ten least plastic traits were measured before the R6 growth stage (Table 2.5). Similarly, in response to row spacing alteration, six of the top ten traits with the most plasticity and eight of the ten traits with the least plasticity were measured at R6 or later and before R6, respectively. As the growing season progressed, plants had more time to change or adjust physiologically, supporting the finding that the full-season hybrids tended to be more yield-responsive to plant spatial arrangement.

For 12 of the 46 phenotypic traits measured, their expression was dependent upon the interaction between the hybrid and its planted population while only three of the traits were affected by the combination of hybrid and row spacing (Table 2.1). However, hybrid did not significantly affect the overall plasticity in response to either plant population or row spacing when the above- or below-ground traits were grouped (Table 2.6). In other words, each hybrid's phenotypic characteristics (above- or below-ground) generally responded similarly to plant population and row spacing variations (Table 2.6). Many other reports have indicated, in general, little difference in hybrid phenotypic responses to plant spatial arrangement with the exception of grain yield and yield components (Maddonni et al., 2001; Novacek et al., 2013; Robles et al., 2012; Stinson and Moss, 1960).

Phenotypic Characteristics of Yield Responsive and Non-Responsive Hybrids

Since the above- and below-ground phenotypic traits of the hybrids all responded similarly to plant population and row spacing changes, grain yield responses to plant spatial arrangement were the result of the differing innate phenotypic characteristics of the hybrids rather than a hybrid's capacity for greater phenotypic changes. When averaged across all plant populations and row spacings, hybrid had a significant effect on all 46 measured phenotypic traits (Table 2.1), supporting the concept that the selected hybrids were genetically different. For the stepwise multiple regression analysis, hybrids 58-06, 60-67, and 62-08 were grouped as being less yield responsive to plant spatial arrangement and were denoted with a 0, or non-favorable event. Likewise, hybrids 60-87, 64-34, 66-40 were denoted with a 1, or favorable event, as these hybrids were grouped as having high positive yield responses to increased plant population and decreased row spacing. This analysis found that 14 of the 45 phenotypic traits were associated with predicting if a given hybrid would be yield responsive or non-responsive to plant spatial arrangement (Table 2.7). Within a given hybrid, these 14 traits can be measured, and in turn, predict if that hybrid would have a positive yield response to increased plant populations and narrower row spacings using the model:

$$Y = \frac{1}{(1 + e^{-x})}$$

where x equals the sum of the intercept and the product of the coefficient estimates and the respective trait value; Y is a value between 0 and 1 and is the probability that a specific hybrid will be a yield-responsive hybrid to plant spatial arrangement changes. The R-square value, or percentage of the variability that is explained by the model, was 44%. It is suspected that the other 56% of the variability would be explained by the genotypic traits of each hybrid. A Hosmer and Lemeshow Goodness-of-Fit P-value of 0.3473 indicates that the model is sufficiently complex with the phenotypic traits that were measured and included in the model (Lemeshow and Hosmer, 1982). The key traits for increased yields were related to capturing more sunlight (leaf angle, leaf width, leaf length, and leaf area per plant), plant size (stover biomass per acre, total above-ground biomass per acre, and plant width), and root weight per plant. The same concept of hybrids having phenotypic traits that are correlated to increased photosynthetic potential has been documented in other studies (Mock and Pearce, 1975; Duvick et al., 2004b).

Correlations between Phenotypic Traits and Grain Yield

Phenotypic traits were correlated to grain yield irrespective of plant spatial arrangement. Total above-ground plant biomass, harvest index, kernel weight, and kernel number are all components of grain yield. Each of these traits was either moderately or strongly positively correlated to grain yield (Table 2.8). Setting a high yield potential with greater kernel number while simultaneously maintaining kernel weight is essential to improve grain yield (Ruffo et al., 2015). Plant height at the R1 growth stage and the average internode length were traits that were moderately negatively and strongly negatively correlated to grain yield, respectively. Hybrids and plant spatial arrangements that tended to reduce plant height and internode length typically translated to higher grain yields. Likewise, leaf length was moderately negatively correlated to grain yield while leaf area was weakly negatively correlated. Similar results were found that showed greater correlation between grain yield and phenotypic traits that facilitate greater light capture and increased supply of assimilate (Mansfield and Mumm, 2013). In addition, root biomass was weakly negatively correlated to grain yield, indicating that hybrids and plant spatial arrangements that reduce below-ground biomass tend to yield greater. A similar result was found when growing corn under stressful conditions leading to a reduction in root size and a negative correlation between grain yield and root size (Gallais and Coque, 2005). The partitioning of resources from below-ground plant material toward above-ground plant material generally translated into higher grain yields. Overall, these correlations demonstrate the importance of the phenotypic traits that are used to both set the yield trajectory toward greater kernel numbers while maintaining kernel weight to produce higher yields.

CONCLUSIONS

All hybrids are genotypically and phenotypically different. Hybrids can also have different yield responses to plant population and row spacing. The results from this study suggest that hybrids that have a positive yield response to increased plant population will also have a greater than average positive yield response to narrower row spacings. These hybrids tended to be the full-season hybrids that utilize more of the growing season. Breeders may have already been selecting for these yield-responsive characteristics in hybrids when selecting for higher grain yields. Key traits related to capturing more sunlight (leaf angle, leaf width, leaf length, and leaf area per plant), plant size (stover biomass per acre, total above-ground biomass per acre, and plant width), and root weight per plant were important predictors of yield-responsiveness to plant spatial arrangement changes. The stepwise multiple logistic regression model can be used with these trait measurements to predict if a new hybrid would have a positive yield response to plant spatial arrangement without actually growing the hybrid at all the different plant populations and row spacings. In addition, this information will aid seed companies in characterizing their hybrids for growers to better position them in the right management system.

TABLES

Table 2.1. Test of fixed effects of 46 measured phenotypic traits for corn grown at Yorkville and Champaign, IL in 2017 and 2018.

Phenotypic trait	**Growth stage**	**Row spacing (S)**	**Population (P)**	**S x P**	**Hybrid (H)**	**S x H**	**P x H†**
		P > F					
Canopy coverage	V5	<.0001	<.0001	<.0001	<.0001	0.9515	0.3696
Canopy coverage	V8	<.0001	<.0001	0.3809	<.0001	0.4482	0.9959
Plant height	V8	0.6475	0.2831	0.8410	<.0001	0.9247	0.9985
Stem diameter	V8	<.0001	<.0001	0.8510	0.0038	0.9948	0.9960
Plant height	R1	0.0029	<.0001	0.6978	<.0001	0.5438	0.8212
Stem diameter	R1	<.0001	<.0001	0.4556	<.0001	0.7868	0.7120
Ear height	R1	0.0627	0.0100	0.9309	<.0001	0.1457	0.5920
Ear height/plant height	R1	0.7758	<.0001	0.7712	<.0001	0.3497	0.8170
Ear leaf number	R1	0.0046	0.0140	0.9487	<.0001	0.7410	0.9077
Total leaves	R1	0.0016	0.0003	0.9396	<.0001	0.3152	0.8373
Ear leaf relative position	R1	0.1314	<.0001	0.9937	<.0001	0.3554	0.6975
Number leaves above ear	R1	0.2889	0.7363	0.7937	<.0001	0.4643	0.7789
Number leaves below ear	R1	0.0016	0.0003	0.9396	<.0001	0.3152	0.8373
Leaves above/below ear	R1	0.5727	0.0340	0.9137	<.0001	0.5039	0.6939
Stalk length above ear	R1	0.3047	0.7665	0.7775	<.0001	0.4368	0.7631
Stalk length below ear	R1	<.0001	<.0001	0.5045	<.0001	0.5855	0.8275
Avg. internode length	R1	0.0627	0.0100	0.9309	<.0001	0.1457	0.5920
Avg. internode length above ear	R1	0.0745	0.4594	0.9746	<.0001	0.1561	0.5644
Avg. internode length below ear	R1	0.1130	<.0001	0.4664	<.0001	0.5449	0.2841
Leaf angle	R3	0.1660	0.0003	0.8901	<.0001	0.0962	0.7018
Select leaf length	R3	0.4191	<.0001	0.6597	<.0001	0.0401	0.3358
Select leaf width	R3	0.0335	<.0001	0.1095	<.0001	0.0582	0.0450
Select leaf weight	R3	0.3633	<.0001	0.2015	<.0001	0.3466	0.0597
Leaf area per plant	R3	0.0381	<.0001	0.1427	<.0001	0.0520	0.0102
Leaf area per plant above ear	R3	0.0041	<.0001	0.6317	<.0001	0.8358	0.6829
Leaf area index	R3	<.0001	<.0001	0.0205	<.0001	0.0848	0.0476
Leaf area ratio	R3	0.0069	<.0001	0.1998	<.0001	0.3861	0.0528
Specific leaf weight	R3	0.7913	<.0001	0.9496	<.0001	0.3168	0.4893
Specific leaf area	R3	0.8122	<.0001	0.7330	<.0001	0.4684	0.5543
Plant width	R3	0.0083	<.0001	0.8330	<.0001	0.9594	0.8700
Root weight per plant	R6	<.0001	<.0001	0.1572	<.0001	0.2040	0.0952
Root biomass per acre	R6	<.0001	<.0001	0.8393	<.0001	0.1331	0.1877
Leaf biomass per acre	R6	0.0004	<.0001	0.5417	<.0001	0.2575	0.0269
Stalk biomass per acre	R6	<.0001	0.0014	0.6363	<.0001	0.4884	0.0431
Stover weight per plant	R6	0.0002	<.0001	0.0006	<.0001	0.5680	0.1013
Stover biomass per acre	R6	<.0001	<.0001	0.4727	<.0001	0.4895	0.1548
Total above-ground weight per plant	R6	0.0002	<.0001	0.0017	<.0001	0.6592	0.3965
Total above-ground biomass per acre	R6	<.0001	<.0001	0.7725	<.0001	0.0697	0.0378
Shoot biomass/root biomass	R6	<.0001	<.0001	0.0018	<.0001	0.7428	0.1170
Harvest index	R6	0.0836	<.0001	0.0243	<.0001	0.7384	0.1901
Grain protein concentration	R6	0.1167	<.0001	0.5463	<.0001	0.8699	0.0197
Grain oil concentration	R6	0.8173	<.0001	0.6909	<.0001	0.7946	0.4636
Grain starch concentration	R6	0.6275	<.0001	0.6843	<.0001	0.9307	0.2149
Kernel number per area	R6	<.0001	<.0001	0.0006	<.0001	0.0008	0.0002
Avg. kernel weight	R6	0.8032	<.0001	0.2436	<.0001	0.3199	0.0014
Grain yield	R6	<.0001	<.0001	0.0078	<.0001	0.0163	0.0016

† The interaction between row spacing, population, and hybrid was not significant for any of the phenotypic traits.

Table 2.2. Grain yield as influenced by row spacing, population, and hybrid for corn grown at Yorkville and Champaign, IL in 2017 and 2018. Grain yield is presented at 15.5% moisture.

	30”				**20”**			
	Population (1000 plants acre^{-1})							
Hybrid†	**38**	**44**	**50**	**56**	**38**	**44**	**50**	**56**
	bu acre^{-1}							
58-06	265	265	258	251	265	270	268	260
60-67	271	274	272	263	280	286	286	272
60-87	278	282	279	270	289	300	298	285
62-08	285	279	276	270	293	291	287	279
64-34	281	288	287	279	292	300	308	298
66-40	291	296	286	277	296	317	314	287

† Hybrid x Row spacing x Population interaction LSD (α=0.05) = 10.

Table 2.3. Grain yield response to population as influenced by hybrid for corn grown at Yorkville and Champaign, IL in 2017 and 2018. Grain yield is presented at 15.5% moisture.

	30”			**20”**			
	Population (1000 plants acre^{-1})						
Hybrid	**44-38†**	**50-38**	**56-38**	**44-38**	**50-38**	**56-38**	**Mean**
	Δ bu acre^{-1}						
58-06	0	-7	-14*	5	3	-5	-3
60-67	3	1	-8	6	6	-8	0
60-87	4	1	-8	11*	9	-4	2
62-08	-6	-9	-15*	-2	-6	-14*	-9*
64-34	7	6	-2	8	16*	6	7*
66-40	5	-5	-14*	21*	18*	-9	3*

*Significantly different than zero at α=0.05.

† Difference in yields between the higher population and lowest population.

Table 2.4. Grain yield response to narrowing the row spacing as influenced by hybrid for corn grown at Yorkville and Champaign, IL in 2017 and 2018. Grain yield is presented at 15.5% moisture.

	Population (plants acre^{-1})				
	38,000	**44,000**	**50,000**	**56,000**	
Hybrid	**20”-30”**	**20”-30”**	**20”-30”**	**20”-30”**	**Mean**
	Δ bu acre^{-1}				
58-06	0	5	10*	9	6*
60-67	9	12*	14*	9	11*
60-87	11*	18*	19*	15*	16*
62-08	8	12*	11*	9	10*
64-34	11*	12*	21*	19*	16*
66-40	5	21*	28*	10*	16*

*Significantly different than zero at α=0.05.

Table 2.5. The top ten traits with the greatest and least plasticity in response to changes in population or row spacing averaged across hybrids for corn grown at Yorkville and Champaign, IL in 2017 and 2018.

Population		Row spacing	
Trait	**Δ (%)**	**Trait**	**Δ (%)**
Greatest plasticity			
Root biomass per acre	18.2	Root biomass per acre	40.4
Shoot biomass/root biomass	18.1	Root weight per plant	37.2
Stalk biomass per acre	17.8	Shoot biomass/root biomass	25.9
Root weight per plant	16.7	Stalk biomass per acre	25.6
Stover biomass per acre	11.6	V5 Canopy coverage	18.6
Plant width	11.5	Stover biomass per acre	14.7
Kernel number	11.1	Stover weight per plant	13.1
Stover weight per plant	10.0	Leaf area ratio	12.6
V5 Canopy coverage	9.8	Plant width	10.6
Grain Yield	9.5	V8 Stem diameter	9.5
Least plasticity			
Leaf angle	3.0	Ear height/plant height	4.2
Number leaves above ear	3.0	Leaf angle	3.7
Avg. internode length	2.8	Ear leaf number	3.6
Leaf length	2.8	R1 Plant height	3.5
Grain protein concentration	2.7	Leaf width	3.5
Ear leaf relative position	2.6	Total leaves	3.3
Ear leaf number	2.6	Grain protein concentration	3.3
Total leaves	2.5	Ear leaf relative position	2.7
R1 Plant height	2.2	Leaf length	2.4
Grain starch concentration	0.9	Grain starch concentration	0.9
LSD ($\alpha = 0.05$)	0.2	LSD ($\alpha = 0.05$)	2.1

Table 2.6. Averaged variability of above-ground versus below-ground phenotypic traits in response to changes in population or row spacing as influenced by hybrid for corn grown at Yorkville and Champaign, IL in 2017 and 2018

Hybrid	Plasticity above-ground		Plasticity below-ground	
	Population	**Row spacing**	**Population**	**Row spacing**
	%			
58-06	6.8	7.4	23.6	40.0
60-67	6.5	7.0	23.8	36.3
60-87	6.6	7.3	24.7	35.7
62-08	6.5	7.0	24.8	38.3
64-34	6.4	6.6	25.3	45.6
66-40	6.5	6.7	21.6	37.2
LSD (α = 0.05)	NS	NS	NS	NS

Table 2.7. Significant traits as determined by stepwise multiple logistic regression analysis to predict the likelihood of a hybrid being yield-responsive to population and/or row spacing changes based on 45 measured phenotypic traits.

Trait	Coefficient estimate	*P > F*
Intercept	142.4	<.0001
Total above-ground biomass	1.4333	<.0001
Ear leaf number	3.6530	<.0001
Plant width	-1.3508	<.0001
Leaf width	-9.8844	<.0001
V8 stem diameter	-0.3999	<.0001
Root weight per plant	0.1169	0.0005
Ear height	0.0811	<.0001
Leaf angle	-1.3690	<.0001
Leaf area per plant	0.0171	<.0001
Stover biomass per acre	-0.9033	0.0005
Avg. internode length	0.4246	0.0003
Leaf length	-0.9215	0.0005
V8 plant height	0.0773	0.0003
Leaf weight	0.4131	0.0112

Table 2.8. Pearson correlation coefficients between final grain yield and selected corn growth traits.

Trait	**Correlation *r***	***P* > *F***
Harvest index	0.69	<.0001
Avg. kernel weight	0.64	<.0001
Avg. internode length	-0.61	<.0001
Leaf length	-0.59	<.0001
R1 Plant height	-0.57	<.0001
Total above-ground biomass	0.57	<.0001
Kernel number	0.48	<.0001
Root biomass per acre	-0.33	<.0001
Leaf area per plant	-0.32	<.0001

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CHAPTER 3: NITROGEN MANAGEMENT STRATEGIES TO IMPROVE CORN GRAIN YIELD

ABSTRACT

As plant populations steadily increase, adequate fertility and plant nutrition, especially nitrogen (N), become even more important to continue to grow high yielding corn (*Zea mays L.*). The objective of this study was to improve nitrogen use efficiency through better N management allowing growers to produce greater corn yields with less N. In 2017 and 2018, three N sources (urea, UAN, and PCU), two placements (broadcast and banded), and two timings (preplant and V8 growth stage) were evaluated at three locations across Illinois. Unfertilized check plots were used to determine the amount of N supplied from the soil during the entire growing season by measuring total N accumulation and grain yield at the R6 growth stage. There was a large range in total N accumulation and grain yield for the unfertilized check plots across the six site-years ranging from 69-173 lbs of N acre^{-1} and 97-224 bu acre^{-1}, respectively. Site-years that produced corn with low check plot yields tended to yield greater when more of the N was applied upfront at preplant compared to split applications of N. However, site-years with high check plot yields achieved greater yields with split applications of N. The soils at those site-years were able to supply enough N early in the season during kernel number determination and set a high yield potential making the sidedress application more beneficial to maintain that yield potential. When making a split application, sidedressing UAN along the crop row as Y-drop was the best method and source of application. On average across site-years, plants that received banded N at preplant as either urea or PCU accumulated the most N throughout the growing season and produced the highest grain yields. Placing the N in close proximity to the crop row increased nitrogen use efficiency.

INTRODUCTION

Nitrogen (N) is the mineral nutrient that most often limits corn plant growth and yield because plants require relatively high levels of N (Ciampitti and Vyn, 2012). Nitrogen is present in numerous essential plant compounds such as chlorophyll, the compound by which plants use sunlight energy to produce sugars from water and carbon dioxide. It is also a major component of amino acids, the building blocks of proteins. Some proteins act as structural units in plant cells while others act as enzymes, making many of the biochemical reactions on which life is based possible. In addition, N is essential in other compounds that play important physiological roles such as enzymes, nucleic acids, and growth regulators.

Nitrogen exhibits a relatively complex biological cycle in the environment and can go through many transformations in the soil. Soil N exists in three general forms: organic N compounds, ammonium (NH_4^+) ions and nitrate (NO_3^-) ions. The foundation of the nitrogen cycle is the conversion of inorganic to organic N, and vice versa. Soil microbes remove NH_4^+ and NO_3^- from the soil's inorganic available-nitrogen pool, converting them to organic nitrogen in a process known as immobilization. When these organisms die and decompose, excess NH_4^+ can be released back to the inorganic pool, which is called mineralization. Nitrogen can also be mineralized when microbes decompose a material containing more nitrogen than they can use at one time. Although N can exist in two forms that can be used by plants (NO_3^- and NH_4^+), the predominant form available to plants is NO_3^-. This situation occurs because soil bacteria readily convert NH_4^+ to NO_3^- in the process of nitrification. Because NO_3^- does not bind to the negatively charged soil particles, it is more freely available to plant roots than is NH_4^+, but is also susceptible to leaching. Nitrate can be also be lost from the soil to the atmosphere by additional microbial activity in the process called denitrification. In some cases, N can be volatilized from the soil or from the plant as NH_3. The complexity of the nitrogen cycle makes efficient N fertilization challenging for corn growers.

The efficient use of N fertilizers by corn has been a major agronomic interest for many years. There are many agronomic indices for short-term assessment of nutrient use efficiency (Cassman et al., 2002; Novoa and Loomis, 1981). The fertilizer industry and sustainability efforts promote increased nutrient use efficiency of applied fertilizers through the best management practices approach (right source, right rate, right time, and right place) (Bruulsema et al., 2012; Johnston and Bruulsema, 2014). These best management practices focus on keeping nutrients stable and available to the plant to increase nutrient use efficiency, which may be achieved with better fertilizer placement, slow release fertilizers, and/or optimal application timing.

Placement of in-season fertilizer has been limited in the past to broadcasted dry fertilizers, foliar sprays, or liquid fertilizer applications in the center of the interrow. Recently, 360 Yield Center developed a product that allows for the ability to place a liquid nutrient solution on the soil surface directly next to the crop row called Y-drop. With rain or heavy dew, the architecture of the corn plant leaves creates a water funneling system that flows down to the base of the plant and assists in incorporating the fertilizer into the ground. Research has shown that this stemflow can increase water partitioned to the base of plant from incident rainfall by 40-50% (Quinn and Laflen, 1983; Warner and Young, 1989). Placing the nutrients directly in the root zone increases the probability for the plant roots to take up and utilize those nutrients. This placement is especially important for N, as N tends to follow the movement of water vertically in the soil profile as opposed to horizontally (Mthandi et al., 2013). The placement of fertilizer near the growing plant creates a zone of high nutrient concentration directly in the rooting area to increase nutrient use efficiency and decrease nutrient loss. However, fertilizer injury to the plant may become a concern with high fertilizer rates placed in close proximity to the crop.

A number of fertilizer additives (i.e., nitrification and urease inhibitors) or slow and controlled-release N sources have been developed to help improve nutrient use efficiency, particularly for nitrogen. Environmentally Smart Nitrogen (ESN, 44-0-0, Agrium, Inc., Calgary, Canada), a controlled release fertilizer, has been manufactured to potentially improve crop nutrient use efficiency as well as mitigate some of the environmental concerns associated with N fertilization. Environmentally Smart Nitrogen, commonly referred to as polymer-coated urea (PCU), consists of urea with a polymer coating that is permeable to water and gradually releases N in response to increasing temperatures and soil moisture over the growing season (Golden et al., 2011). Some studies indicate that PCU may increase crop yield and reduce or eliminate the need for split-N applications (Blackshaw et al. 2011; Nelson et al., 2009; Wilson et al., 2010; Ziadi et al., 2011). Due to the slow release of the urea fertilizer with the polymer-coating, higher rates of PCU can be applied close to the seed without injury (Beres et al., 2012; McKenzie et al., 2007; Middleton et al., 2004, Qin et al., 2014; Wilson et al., 2009), and therefore would be the source of choice for increasing N fertilizer use efficiency.

The fertility requirements for modern high-yielding corn have been identified (Bender et al., 2013). Nitrogen uptake by corn follows a sigmoidal pattern over time with two-thirds of the total plant uptake acquired by the VT/R1 growth stage (Bender et al., 2013). Prior to the V6 growth stage, corn accumulates less than 25 lbs of N acre^{-1}. From V8 to R1, corn takes up N at a rate of 7 lbs of N acre^{-1} day^{-1} for 21 continuous days. The extreme demand for N during this time is not only because of its function in green tissue formation but N also plays a crucial role in ear and kernel development. Timing N applications to supply sufficient levels of available N during these critical growth stages provides conditions that are suitable for greater nutrient use efficiencies and higher grain yields. Conventionally in the U.S. Corn Belt, there are three main fertilizer application timings, which include the fall, spring, or in-season. Over the last few decades, there has been a shift into more in-season N applications because of new high clearance equipment that can cover more acres quicker, trying to avoid the frequent wet field conditions in the spring, and the spreading of labor away from the busy spring planting season. There has also been a large push from environmental societies for growers to apply the majority of their N in-season when the crop is growing. The negative environmental impacts associated with corn production can be minimized through efficient N management, including accurate N fertilizer recommendations (Fox et al., 1989). Because a greater portion of the N is applied closer to the time of maximum N uptake, in-season application strategies are often considered as being more efficient and environmentally sound. Nitrogen fertilizer application timing on corn has been studied extensively over a variety of environments. Many studies have compared N applications at or before planting to sidedress applications at the V8 growth stage or earlier with variable results. Preplant N applications have been shown to result in greater yields than when the N was sidedressed (Stecker et al., 1993), and in some cases there have been yield decreases when applying N preplant as compared to sidedressing (Bundy et al., 1992; Reeves and Touchton, 1986; Welch et al., 1971). Research has also shown there to be no yield differences from different N application timings prior to the V8 growth stage (Jokela and Randall, 1989; Roth et at., 1995).

The effect of weather on N availability to a corn crop is tremendous. Excessive rainfall early in the growing season can cause N losses, while warm temperatures and moderate rainfall can result in high N mineralization and a N-sufficient crop. Determining the need for and/or amount of sidedressed N can be dependent on these weather conditions and can be aided by various methods of soil testing or plant nutrient status sensing (Barker et al., 2006; Blackmer et al., 1989; Mulvaney et al., 2001; Mulvaney et al., 2006; Piekkielek and Fox., 1992; Solari et al., 2008; Williams et al., 2007). In addition, the weather determines whether an in-season N application can be made. Wet conditions can delay the sidedress application beyond the optimum application date and extremely dry conditions can result in a delay in the availability of the sidedressed N. Keeping sufficient levels of available N in the soil throughout the entire growing season is the challenge that corn growers are faced with today.

The objective of this research was to evaluate various N management strategies to determine the key factors that improve nutrient use efficiency and corn grain yield. Determining the effect that each individual N management decision (source, timing, and placement) plays on the productivity of corn will help growers better increase their profits while reducing the environmental impact.

MATERIALS AND METHODS

Agronomic Practices

In 2017 and 2018, three trials were conducted at the University of Illinois Crop Sciences Research and Education Center in Champaign, IL (40.030886 N -88.140557 W), and at collaborating farmer's fields near Harrisburg (37.432037 N -88.262623 W) and Yorkville, IL (41.363054 N -88.162969 W). These locations have been maintained weed- and disease-free, are level and well-drained, and are well-suited to provide evenly distributed soil fertility, pH, soil organic matter, and water availability. Experimental units were plots four rows wide and 37.5 feet in length with 30 inch row spacing. Plots were planted on 16 May 2017 and 18 May 2018 in Yorkville, 25 April 2017 and 28 April 2018 in Champaign, and 9 May 2017 and 1 May 2018 in

Harrisburg using a precision plot planter (SeedPro 360, ALMACO, Nevada, IA). Corn hybrid DKC64-34 RIB, previously characterized as responsive to N and management, was planted at all sites to target a final stand of 36,000 plants acre^{-1}. At all locations, soybean was the previous crop and conventional deep ripping followed by field cultivation tillage was used. Force 3G insecticide (Tefluthrin (2,3,5,6-tetrafluoro-4-methylphenyl)methyl-(1α,3α)-(Z)-(±)-3-(2chloro-3,3,3-trifluoro-1-propenyl)-2,2 dimethylcyclopropanecarboxylate) (Syngenta AG, Basel, Switzerland) was applied at planting (0.23 oz acre^{-1}) and Lumax EZ (S-metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] +atrazine (1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine) + mesotrione (2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione) (Syngenta AG, Basel, Switzerland) was applied prior to planting (3.25 qt acre^{-1}) as a pre-emergence herbicide. The post- emergence herbicide program included a tank-mixed application of AAtrex4L (Atrazine 2-chloro-4-ethylamino-6-isopropylamino-s-triazine) (Syngenta AG, Basel, Switzerland) at 1.25 qt acre^{-1}, Armezon (topramezone [3-(4,5-dihydro-isoxazolyl)-2-methyl-4-(methylsulfonyl) phenyl](5-hydroxy-1-methyl-1H-pyrazol-4-yl) methanone) (BASF, Ludwigshafen, Germany) at 0.75 oz acre^{-1}, FS MaxSupreme (ammonium sulfate, hpg polymer, and dimethylpolysiloxane antifoam) (Growmark, Bloomington, Illinois) at 0.8 qt acre^{-1}, and Roundup Powermax (Glyphosate, N-(phosphonomethyl)glycin) (Bayer, Leverkusen, Germany) at 32 oz acre^{-1}.

Nutrient Applications

Treatment applications were designed to compare different N fertilizer sources, timing of application, and application methods, and are outlined in Table 3.1. All treatment plots received a total of 180 lbs of N acre^{-1}. Treatments included supplying all of the N upfront, either broadcasted as urea (46-0-0) or PCU using a hand spreader, or banded as PCU 6 inches directly below the crop row using a toolbar fitted with a dry fertilizer applicator (6000 Series Universal Fertilizer Applicator, Dawn Equipment, Sycamore, IL) and real time kenetic (RTK) guidance at preplant. Additionally, split applications received 90 lbs of N acre^{-1} at preplant as broadcasted urea followed by 90 lbs of N acre^{-1} applied at the V8 growth stage either as urea broadcasted using a hand spreader or placed along the crop row, or urea ammonium nitrate (UAN, 28-0-0) poured on the soil surface down the center of the crop row or along the crop row using 2 liter bottles of UAN solution (simulated Y-drop method). Split applications also included 90 lbs of N acre^{-1} banded at preplant as urea or PCU with the remaining 90 lbs of N acre^{-1} of the same source broadcasted using a hand spreader at the V8 growth stage. All broadcasted treatments at planting were incorporated while all sidedress applications were left on the soil surface. All treatments were compared to an unfertilized check.

Parameters Measured

Ten soil cores (0-6” deep) were collected from plot areas prior to planting, thoroughly combined, and assessed for pH, organic matter, and fertility levels (A & L Great Lakes Laboratories, Inc. Fort Wayne, IN) and are reported in Table 3.2.

Total above-ground plant biomass sampling was conducted at R6 (physiological maturity) to quantify total nutrient uptake throughout the growing season and consisted of manually excising three random plants at the soil surface from each of the center two rows of each plot. The plants at R6 were partitioned into grain and stover (including husk) components, and biomass was determined by weighing the total fresh stover then processing it through a chipper (BC600XL, Vermeer Corporation, Pella, IA) to obtain representative stover subsamples. The stover subsamples were immediately weighed to determine aliquot fresh weight, and then weighed again after drying to 0% moisture in a forced air oven at 167 °F, to determine subsample aliquot dry weight and calculate total dry biomass accumulation. Corn ears were dried, the grain was removed using a corn sheller (AEC Group, St Charles, IA) and analyzed for moisture content using a moisture reader (Dickey John, GSF, Ankeny, IA). Cob weight was obtained by difference, and dry stover and cob weights were summed to calculate the overall R6 stover biomass. Dried subsamples were ground using a Wiley Mill (Thomas Scientific, Swedesboro, NJ) to pass through a 2 mm mesh screen. An approximately 50 mg subsample of the ground tissue was randomly selected and evaluated for N level using a combustion-based analyzer (EA1112, CE Elantech, Lakewood, NJ). Nutrient accumulation in the plant was determined using total plant biomass weight and stover N concentration. Nitrogen concentration in the grain was calculated by converting protein concentration in the grain, obtained using near-infrared transmittance spectroscopy (Infratec 1241 Grain Analyzer; FOSS, Eden Prairie, MN), to N concentration by dividing by a factor of 6.25 (Jones, 1941). Total N in the grain was determined using total grain weight and grain N concentration. Total N uptake is the sum of total N in the grain and total N uptake in the stover. Nutrient use efficiencies were calculated for each treatment from the amount of fertilizer applied, total N uptake, and corn grain yield compared to the unfertilized check plot. Yield efficiency was calculated by subtracting the check plot yield from each treatment yield and dividing by the fertilizer N rate applied. Recovery efficiency was calculated by subtracting the total N uptake of the check plot plants from the total N uptake resulting from each treatment and dividing by the corresponding total N rate applied.

The center two rows of each plot were mechanically harvested for determination of grain yield and harvest moisture, and the yield subsequently standardized to bushels acre^{-1} at 15.5% moisture.

Subsamples of the harvested grain were evaluated for yield components (individual kernel weight and kernel number) and for grain quality (protein, oil, and starch concentrations) using near-infrared transmittance spectroscopy. Kernel weight and grain quality are presented at 0% moisture.

Statistical Analysis

Plots were arranged as a randomized complete block design with six replications. Measured parameters were analyzed using PROC MIXED (SAS Institute, Cary, NC). Each site-year was analyzed separately with N treatment included as the fixed effect and replication as random effect. Unless indicated, fixed effects were considered significant in all statistical calculations if $P \leq 0.05$.

The check plot treatment, with no N applied, was first analyzed with all other treatments and was significantly different than all other treatments for all the measured parameters. Each parameter was reanalyzed with the check plot treatment removed to better compare the treatments with the same total rate of N applied. All of the statistical analysis and results displayed are with the check plot treatment removed.

RESULTS AND DISCUSSION

Weather

The 2017 production year experienced relatively dry conditions at all three experiment locations. Yorkville (17YV), Champaign (17CH), and Harrisburg (17HB) received 1.5, 6.0, and 4.0 inches less precipitation from June through August, respectively, as compared to the 30-year average (Table 3.3). Yorkville did receive 7 inches of rain in July, resulting in minimal moisture stress throughout much of the growing season. The average temperature of each month was similar to the long-term average for each location.

In 2018, all three locations experienced a significantly warmer May than the 30-year average which resulted in corn that rapidly progressed through the vegetative growth stages early in the growing season (Table 3.3). Yorkville (18YV), Champaign (18CH), and Harrisburg (18HB) received 2.8, 3.0, and 1.6 inches more precipitation during the month of June, respectively, compared to the 30-year average (Table 3.3). Yorkville encountered an additional 2.2 inches of precipitation above normal for the month of May. Despite the above-average precipitation early in the growing season at all three locations, the weather in July was to be drier than the long-term average creating moisture stress during grain fill (Table 3.3).

After the preplant N application and planting, every site-year received a minimum of 0.5 inches of rain within 5 days except at 17HB and 18CH (Table 3.4). Three of the site-years (17YV, 17CH, and 18YV) received a considerable rainfall event of at least 0.48 inches within 3 days of the N sidedress application. At 17HB and 18HB, it was 9 and 6 days after the sidedress application before there was a rain event of at least 0.5 inches, respectively. In 2018 at Champaign, 0.26 inches of precipitation fell the subsequent day after the sidedress application and a considerable amount of rain after the 7th day following the application (Table 3.4).

Grain Yield

Despite below-average rainfall across all three sites in 2017, final corn grain yield was above the long-term average for each given location averaging 272, 260, and 275 bu acre^{-1} in Yorkville, Champaign, and Harrisburg, respectively (Table 3.5). The average trial yields were greater in 2017 than 2018, the latter which averaged 242, 224, and 192 bu acre^{-1} in Yorkville, Champaign, and Harrisburg, respectively. There was a large range in check plot yields across the six site-years ranging from 97-224 bu acre^{-1} (Table 3.5). The check plot can be used as a proxy for how much N was supplied by the soil. A lower check plot yield indicates that there was an insufficient supply of N from the soil, likely due to low N mineralization and/or high N loss, while a high check plot yield indicates a sufficient supply of N from the soil with high N mineralization and little N loss. Interestingly, the lowest and highest check plot yields were both from the same location but in different years, demonstrating that the soil characteristics (i.e. soil type, organic matter, and residual N) are not the only factors for predicting the amount of mineralizable N. Previous work has found that soil and climatic parameters can explain around 63% of the variability in potentially mineralizable N (Dessureault-Rompré et al., 2010). In 2017, the Harrisburg location had the lowest organic matter containing soil and the second lowest total residual N (NO_3^- and NH_4^+) in the soil of the six site-years, but had the highest check plot yield (Table 3.2 and 3.5). Despite receiving 3.6 inches less precipitation than normal from May through August, the rains were timely with adequate wetter versus drier periods. Drying and wetting cycles have been well-documented to increase N mineralization in the soil with a flush of available N being released following rewetting of a dry soil (Denef et al., 2001a; Denef et al., 2001b; Fierer and Schimel, 2002; Franzluebbers et al., 2000; Mikha et al., 2005; West et al., 1992).

In three (17CH, 18CH, and 18HB) of the six site-years, fertility treatment significantly affected grain yield (Table 3.6). Fertility treatment also had a significant effect on kernel number at 17CH, 18YV, and 18CH and kernel weight at 18CH and 18HB (Table 3.6). The three lowest check plot yielding site-years were 17CH, 18CH, and 18HB, suggesting that the corn plants required more N supplied by fertilizer to maximize yields. Although not statistically significant, applying more of the N upfront at preplant as broadcast urea tended to generate higher yields than when the plants received 50 percent of the N upfront at preplant and 50 percent of the N sidedressed at the V8 growth stage as broadcast urea at those three site-years (Table 3.5). However, when split applying

N as broadcast urea at the V8 growth stage, if the urea was banded at preplant instead of broadcast it tended to increase grain yield by 21 and 15 bu acre^{-1} at 17CH and 18HB, respectively (Table 3.5). Banding urea-containing fertilizer sources below the soil surface has been shown to eliminate ammonia volatilization from those sources (Mengel et al., 1982; Nelson, 1982; Touchton and Hargrove, 1982). Corn grown at these site-years tended to prefer more N upfront to set a high yield potential. The yield potential was increased when the N was concentrated in a band directly below the crop row at preplant. Under-fertilizing corn at an early growth stage hindered plant growth when kernel number was being determined and the sidedress application was not sufficient for the plants to regain lost yield potential. These findings are consistent with other studies that evaluated plant growth and yield components (Andrade et al., 1999; Boomsma et al., 2009; Jung et al., 1972; Russelle et al., 1983). At 18CH, a site-year with low N supplying power, plants yielded 5 bu acre^{-1} less when N fertilizer was banded as urea directly under the crop row at preplant (Table 3.5), and this decrease was associated with visible crop damage (seedling injury, stunting, and poor emergence). Dry conditions during the preplant N application followed by hot and dry conditions after planting likely created conditions that were conducive to ammonia toxicity in the root zone. Toxicity of banded urea on corn has been documented given certain environmental and management conditions (placement of urea, rate of urea, weather patterns, etc.) (Fan and MacKenzie, 1995; Ouyang et al., 1998).

At 17YV, 17HB, and 18YV, there was a sufficient amount of available N supplied from the soil at the early growth stages, and at these sites, the yield potential was not affected by the fertilizer application time and the sidedress application was more beneficial (Table 3.5). Delaying N applications past the V8 growth stage has shown that corn plants can respond to late N applications, however, full yield was not obtained with applications made at silking. (Scharf et al., 2002). A similar phenomenon was documented when trying to rescue N-deficient corn plants with sidedressed N, with greater initial N deficiencies needing earlier sidedressed N to obtain maximum grain yield (Binder et al., 2000). When averaged across all site-years, placing the N closer to the crop row as either urea or UAN tended to increase grain yield by 5 and 12 bu acre^{-1}, respectively, compared to if the same source was broadcast or placed in the center of the row (Table 3.5). The benefit of placing the fertilizer in close proximity to the crop row has been previously reported in other studies looking at N fertilizer placement (Lehrsch et al., 2000; Mengel et al., 1982; Vetsch and Randall, 2000).

When comparing broadcasted preplant-only treatments, corn grain yield responses were dependent on the site-year. Although not statistically significant, corn grown at four of the site-years (17YV, 17CH, 18CH, and 18HB) showed a zero or negative yield response to PCU applications compared to urea while two of the site-years (17HB and 18YV) had a positive yield response (Table 3.5). Previous studies have shown more consistent positive yield responses when using PCU compared to urea (Gagnon et al., 2012; Gordon, 2014; Noellsch et al., 2009; Shoji et al., 2001). The highest yields were achieved when N was banded 6 inches below the soil surface as PCU at preplant. At 17CH, 18CH, and 18HB, grain yield significantly increased by 30, 18, and 14 bu acre^{-1}, respectively, when banding 180 lbs of N acre^{-1} as PCU compared to broadcast urea at preplant (Table 3.5). The other three site-years also showed strong positive yield responses to banding the PCU directly below the row, yielding 10, 12, and 17 bu acre^{-1} greater than the broadcast urea treated plots at 17YV, 17HB and 18YV, respectively. Corn that received the split application of PCU banded at preplant followed by broadcast PCU at the V8 growth stage tended to yield greater than having all the N applied as broadcast urea at preplant (Table 3.5). In particular, corn grown at the 17CH site-year had a significant yield increase of 25 bu acre^{-1} with the split application of PCU (Table 3.5). Placing the N in a concentrated band directly in the root zone at preplant created a high yield environment that continued for the rest of the growing season. Corn plants react to greater N levels in the soil through increased root-synthesized cytokinins, which in turn upregulate response regulator genes (Sakakibara et al., 2006; Takei et al., 2001). Corn plants need to sense enough available N early in the growing season to set a high yield potential and also require available N later in the season to maintain that high yield potential.

Yield Components and Grain Quality

Kernel number and kernel weight are components of grain yield. These yield components can be used to determine when in the life cycle of a plant that an effect on grain yield occurred. In this study, fertility treatment had a significant effect on kernel number at 17CH, 18YV, and 18CH and kernel weight at 18CH and 18HB (Table 3.6). On average across all site-years, split-applications of N tended to reduce the number of kernels m^{-2}, suggesting that those plants did not have a sufficient level of N during the critical period of kernel number determination (Table 3.5). However, when the sidedress application was placed along the crop row as either urea or UAN, kernel number was 124 and 182 kernels m^{-2} greater compared to broadcasting or placing the same N sources down the center of the row, respectively (Table 3.5). The better-placed sidedressed application along the crop row likely reduced N stress during pollination and limited kernel abortion (Andrade et al., 1999; Crozier et al., 2014).

Interestingly, when averaged across site-years, all N treatments tended to increase or have no effect on kernel weight compared to applying all of the N as urea at preplant (Table 3.5). Similar to other reports, fewer kernels m^{-2} but heavier kernels is an indication that the sidedress application of N was beneficial to the plant during grain filling; however, only applying half of the N at preplant was not enough N early in the season during the critical period of kernel number determination (Mueller and Vyn, 2018; Pearson and Jacobs, 1987; Tollenaar et al., 1992). The highest yields achieved with the banding application of N were via an increase in kernel number (Table 3.5). In 17CH and 18YV, banding 180 lbs of N acre^{-1} as PCU preplant significantly increased kernel number by 516 and 383 kernels m^{-2}, while maintaining kernel weight (Table 3.5). The concentrated band of N placed directly below the crop row created conditions for corn plants to set a high yield potential, and the slow-release N source allowed the plants to maintain that high yield by filling those additional kernels, thereby achieving the greatest yields. At 18CH, the visual damage and reduction in grain yield when banding 90 lbs of N acre^{-1} as urea resulted in a significant decrease in kernel number, subsequently reducing the yield potential.

Nitrogen fertilizer treatment had a significant effect on grain protein concentration at all site-years (Table 3.6). In addition, there was a significant effect on grain oil concentration at 18CH and on grain starch concentration at 17CH, 17HB, and 18HB (Table 3.6). In general across all site-years, all N treatments, except when applying all of the N as broadcast PCU at preplant or applying half of the N as urea and half as UAN placed down the center of row, tended to result in a higher protein concentration in the grain compared to when all of the N was broadcast as urea at preplant (Table 3.7). At 17CH, 17HB, and 18CH, banding N at preplant as either urea or PCU significantly increased protein concentration in the grain by 0.47-0.97% compared to broadcast urea at preplant (Table 3.7). Similarly, at 18YV and 18HB, split-applying urea with half of the urea broadcasted at preplant, and half sidedressed either broadcast or placed along the crop row, significantly increased grain protein concentration, suggesting there was sufficient N available during grain fill (Table 3.7). Treatments that resulted in a significant increase in grain protein concentration subsequently led to a corresponding significant decrease in starch concentration, which is similar to previous reports (Miao et al., 2006; Zhang et al., 1993).

Nitrogen Accumulation

The total N accumulation at the R6 growth stage in the corn plants grown with no N applied can be used to quantify the amount of N supplied by the soil through mineralization at that particular site-year. The amount of N supplied from the soil ranged from 69 lbs of N acre^{-1} at 18CH to 173 lbs of N acre^{-1} at 17HB (Table 3.8). Weather patterns at these individual site-years were just as important for supplying available N as the soil characteristics (soil type, organic matter, and residual N). Given the right wetting and drying periods throughout the growing season, a soil with only 2.2 % organic matter was able to supply 173 lbs of N acre^{-1} through mineralization, and under conditions when little N loss occurred. In most years, plants grown in Illinois soils with no N fertilizer applied, accumulate 60-100 lbs of N acre^{-1} (data not shown).

Nitrogen treatment had a significant effect on grain N content and total N uptake for all site-years and on stover N content at 17YV, 17HB, 18YV, and 18HB (Table 3.9). Total N accumulation tended to correspond to grain yield with increases in total N accumulation resulting in higher grain yields, similar to previous reports (Bergerou et al., 2004; Gentry et al., 2001; Howard and Tyler, 1989). In general, all N treatments, except when applying all of the N as broadcast PCU at preplant or applying half of the N as urea and half as UAN placed down the center of the row, tended to result in 6-13% greater N accumulation in the corn plants compared to all of the N broadcast as urea at preplant. The greater total N accumulation with the split application treatments were driven by more N in the grain, while N accumulation in the stover remained relatively unchanged (Table 3.8). Greater N accumulation in the grain is an indication that more N was available to the plant during grain fill (Gagnon et al., 2012; Stecker et al., 1993). Treatments that received banded N fertilizer at preplant significantly increased total N accumulation in the plant compared to broadcasting N fertilizer at preplant. Placing the N fertilizer directly in the root zone by banding kept the N available for the plant to utilize throughout the season, increasing both stover N content and grain N content. Plants receiving banded N were likely healthier, and possessed a more robust root system, aiding the plants to continually accumulate N throughout the entire growing season (Anderson, 1987; Durieux et al., 1994; Granato and Raper, 1989;).

Nutrient Use Efficiency

Nutrient use efficiency calculations make use of the unfertilized check plots as a reference point, which utilizes the rate of fertilizer applied, the average N accumulation and final grain yield. Yield efficiency, or the increase in grain yield for each additional pound of N applied per acre, and recovery efficiency, the percentage of the applied N that is accumulated in the plant, are directly impacted by the check plot. The N acquired by the unfertilized check plot plants is supplied from the soil through mineralization. Site-years that produced plants with high yields and high N accumulation in the check plots were the least efficient at utilizing the applied fertilizer and had the lowest yield efficiency and recovery efficiency (Table 3.10). As the N-supplying power of the soil increases, the efficiency of the applied fertilizer decreases significantly and management factors to increase efficiency become more important. When averaged across the N treatments, plants at the Harrisburg location in 2017 were 18-35% less efficient at recovering fertilizer N compared to those at Harrisburg in 2018 (Table 3.10). Fertility treatment significantly affected yield efficiency at 17CH, 18CH, and 18HB and recovery efficiency at all of the site-years (Table 3.9). On average, plants that received better N fertilizer placement at preplant from a banding application had significantly higher yields and recovery efficiencies (Table 3.10). This finding from banding fertilizer is evidence that N placement can be used as a method to improve nutrient use efficiency by helping the plant recover more of the applied N from the soil; thereby producing higher yields from each pound of N applied per acre (Roberts, 2008; Maddux et al., 1984; Mengel et al., 1982). This trend was more apparent at the site-years that exhibited check plot plants with lower than average yields and N accumulation. (Table 3.10).

CONCLUSIONS

The results from this study document the importance of proper N management and the large roles that soil characteristics and weather play in determining the best management practice. A large range in N accumulation and grain yield in the unfertilized check plots demonstrated a difference in N-supplying power of the soil between site-years. In environments with high soil-N availability, there tended to be sufficient N for the plant through the V8 growth stage, and thus a sidedress application was more beneficial than supplying all of the N fertilizer upfront. Interestingly, supplying only half of the N fertilizer in a concentrated band directly in the root zone provided enough N for the corn plant so that N was not limiting growth up through the sidedress application timing. Overall, plants that received banded N at preplant as either urea or PCU accumulated the most N throughout the growing season and produced the highest grain yields. Nitrogen treatments that placed the N in closer proximity to the crop row tended to increase both nitrogen fertilizer yield efficiency and recovery efficiency.

TABLES

Table 3.1. Treatment application schedule to evaluate the effect of nitrogen source, application method, and timing on corn grain yield and nutrient use efficiency at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018. All treatments received a total of 180 lbs of N acre^{-1}, excluding the unfertilized check treatment, either 100% applied preplant, or split as 50% preplant plus 50% sidedress.

Treatment Timing	
Preplant	**Sidedress †**
No N Applied	-‡
Urea Broadcast	-
Urea Broadcast	Urea Broadcast
Urea Broadcast	Urea Next To Row
Urea Broadcast	UAN Middle of Row
Urea Broadcast	UAN Next To Row
Urea Banded	Urea Broadcast
PCU Broadcast	-
PCU Banded	-
PCU Banded	PCU Broadcast

† Sidedress application was made at the V8 growth stage.
‡ -, indicates no application was made.

Table 3.2. Preplant soil properties and Mehlich 3-extraction-based mineral test results for Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018.

	Location					
	Yorkville		**Champaign**		**Harrisburg**	
	Year		**Year**		**Year**	
Soil property	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
Soil Type	Graymont Silt Loam	Drummer Silty Clay Loam	Flanagan Silt Loam	Flanagan Silt Loam	Harco Silt Loam	Harco Silt Loam
OM, % †	4.6	4.4	3.3	2.9	2.2	2.3
CEC, meq/100g	22.2	31.9	21.1	17.6	12.1	13.8
pH	6.3	6	6.1	6.3	6.4	6.1
NO_3^-, ppm	38.5	25.8	14.5	8.5	8.0	9.2
NH_4^+, ppm	3.6	5.8	3.2	2.5	5.3	5.5
P, ppm	70	252	91	36	28	28
K, ppm	225	271	212	138	110	135
Ca, ppm	2585	3918	2617	2220	1860	1947
Mg, ppm	613	815	469	455	161	160
S, ppm	9	13	8	6	7	10
Zn, ppm	2.7	11.5	1.9	1.4	0.9	0.7
B, ppm	0.5	0.9	0.6	0.4	0.2	0.1
Mn, ppm	39	13	20	58	50	38
Fe, ppm	133	235	142	137	121	153
Cu, ppm	1.9	6.6	2.1	1.9	1.7	2.1

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

Table 3.3. Monthly weather data between 1 April and 30 September at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018. Values presented are the average daily air temperature and the average monthly accumulated rainfall, with deviations from the 30-year average in parentheses (Illinois State Water Survey, 2019).

Site-year	**April**	**May**	**June**	**July**	**August**	**September**
Temperature			^{O}F			
2017						
Yorkville	54 (4)	58 (-3)	72 (2)	74 (0)	70 (-2)	68 (3)
Champaign	57 (5)	61 (-2)	73 (1)	77 (2)	72 (-1)	69 (3)
Harrisburg	59 (3)	66 (0)	74 (-1)	79 (1)	72 (-5)	69 (0)
2018						
Yorkville	40 (-10)	67 (6)	71 (1)	72 (-2)	71 (-1)	66 (1)
Champaign	46 (-6)	72 (9)	75 (3)	75 (0)	75 (2)	71 (5)
Harrisburg	50 (-6)	73 (7)	78 (3)	78 (0)	76 (-1)	72 (3)
Precipitation			Inches			
2017						
Yorkville	6.9 (3.0)	4.7 (0.4)	1.8 (-2.5)	7.0 (2.3)	2.8 (-1.3)	0.1 (-3.0)
Champaign	6.2 (2.6)	5.6 (0.7)	2.5 (-1.8)	2.2 (-2.5)	2.2 (-1.7)	0.8 (-2.3)
Harrisburg	14.4 (9.9)	5.8 (0.4)	1.9 (-2.6)	2.0 (-1.7)	3.6 (0.3)	1.0 (-2.1)
2018						
Yorkville	1.0 (-2.9)	6.5 (2.2)	7.1 (2.8)	1.9 (-2.8)	2.8 (-1.3)	2.4 (-0.7)
Champaign	2.5 (-1.1)	4.2 (-0.7)	7.3 (3.0)	3.2 (-1.5)	4.0 (0.1)	4.7 (1.6)
Harrisburg	5.3 (0.8)	5.0 (-0.1)	6.1 (1.6)	3.1 (-0.7)	5.0 (2.0)	7.8 (4.7)

Table 3.4. Daily rainfall accumulation two weeks after the preplant or sidedress N application at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018. (Illinois State Water Survey, 2019).

Days after N application	**Site-year**											
	2017 Yorkville		**2017 Champaign**		**2017 Harrisburg**		**2018 Yorkville**		**2018 Champaign**		**2018 Harrisburg**	
	PP†	**SD**	**PP**	**SD**	**PP**	**SD**	**PP**	**SD**	**PP**	**SD**	**PP**	**SD**
days	Inches											
0	0.00	0.00	0.00	0.04	0.00	0.00	0.17	0.03	0.00	0.00	0.00	0.00
1	0.12	0.48	0.76	1.27	0.00	0.00	0.01	0.00	0.00	0.26	0.00	0.00
2	0.00	0.00	0.16	0.00	0.18	0.00	0.01	0.00	0.00	0.00	1.37	0.00
3	0.14	0.00	0.30	0.09	0.00	0.00	0.98	0.75	0.00	0.00	0.04	0.01
4	0.34	0.00	1.64	0.06	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00
5	0.33	0.00	1.19	0.04	0.00	0.00	0.00	0.05	0.17	0.00	0.04	0.00
6	0.00	0.33	0.02	0.00	0.00	0.07	0.00	1.17	0.01	0.00	0.00	0.72
7	0.35	0.14	0.00	0.16	0.00	0.00	0.00	0.72	0.00	0.19	0.00	0.00
8	0.01	0.01	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	0.00
9	0.00	0.00	1.54	0.01	0.10	0.71	0.00	0.00	0.00	1.36	0.00	0.00
10	0.76	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.99	0.00	0.00
11	0.00	0.02	0.20	0.00	2.27	0.00	0.00	0.70	1.27	1.56	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.71	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.02	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.01	0.00	0.00
Total	2.05	0.98	6.17	1.68	2.57	1.67	1.88	3.60	1.45	4.80	1.45	0.73

† PP, preplant; SD, sidedress.

Table 3.5. Grain yield and yield components (kernel number and kernel weight) as influenced by fertility treatment for corn grown at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018. Grain yield is presented at 15.5% moisture, kernel weight is presented at 0% moisture.

Treatment timing		Grain yield						Kernel number						Kernel weight					
		Year																	
		2017			2018			2017			2018			2017			2018		
		Location																	
Preplant	**Sidedress**	**YV†**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**
		bu acre^{-1}						kernels m^{-2}						mg kernel^{-1}					
No N Applied	-	208	184	224	195	103	97	4340	3833	4763	4364	2957	2300	253	254	249	237	184	223
Urea Broadcast	-	265	256	265	232	222	190	5183	4719	5175	5140	5129	3766	271	288	272	240	230	267
Urea Broadcast	Urea Broadcast	272	253	273	236	213	183	5164	4549	5172	5190	4913	3518	280	295	280	241	231	277
Urea Broadcast	Urea Next To Row	270	253	272	237	234	192	5183	4560	5129	5253	5425	3700	276	294	282	239	229	276
Urea Broadcast	UAN Middle of Row	265	231	274	241	205	188	5096	4375	5180	5309	4890	3684	275	280	281	241	223	271
Urea Broadcast	UAN Next To Row	278	245	277	247	228	199	5324	4606	5363	5442	5151	3740	277	282	274	241	234	282
Urea Banded	Urea Broadcast	279	274	282	241	217	198	5321	4904	5310	5260	4755	3788	278	297	282	244	243	278
PCU Broadcast	-	265	257	277	241	225	181	5132	4585	5490	5305	5157	3634	275	298	268	241	230	264
PCU Banded	-	275	286	277	249	240	204	5346	5235	5366	5523	5043	3967	273	292	275	240	254	273
PCU Banded	PCU Broadcast	277	281	282	253	232	195	5414	4999	5476	5585	5108	3787	271	298	274	241	241	274
LSD ($\alpha = 0.05$)		NS‡	22	NS	NS	17	14	NS	358	NS	288	302	NS	NS	NS	NS	NS	12	8

† YV, Yorkville; CH, Champaign; HB, Harrisburg.

‡NS, non- significant.

Table 3.6. Test of fixed effects of fertility treatments on grain yield, yield components (kernel number and kernel weight), and grain quality (protein, oil, and starch concentrations) for corn grown at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018.

		Yield component		**Grain quality**		
Site-year	**Yield**	**Kernel number**	**Kernel weight**	**Protein**	**Oil**	**Starch**
	P > *F*					
2017						
Yorkville	0.4025	0.5769	0.3602	0.0284	0.8933	0.3282
Champaign	0.0001	0.0005	0.2095	0.0006	0.6182	0.0010
Harrisburg	0.2086	0.3533	0.2510	0.0107	0.3621	0.0406
2018						
Yorkville	0.0646	0.0445	0.9543	0.0008	0.9005	0.3940
Champaign	0.0053	0.0047	0.0005	0.0008	0.0418	0.2119
Harrisburg	0.0475	0.2903	0.0023	0.0003	0.0928	0.0003

Table 3.7. Grain quality (oil, protein, and starch concentrations at 0% moisture) as influenced by fertility treatment for corn grown at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018.

Treatment timing		**Protein**						**Oil**						**Starch**					
		Year																	
		2017			**2018**			**2017**			**2018**			**2017**			**2018**		
		Location																	
Preplant	**Sidedress**	**YV†**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**
		%																	
No N Applied	-	6.03	5.73	7.12	6.18	5.62	6.78	4.09	4.39	4.38	3.72	4.28	4.44	72.15	72.25	72.10	74.08	73.50	73.20
Urea Broadcast	-	7.98	7.93	7.62	7.47	6.85	8.72	4.09	4.33	4.35	3.67	4.03	4.37	72.10	71.85	71.63	73.93	73.72	72.30
Urea Broadcast	Urea Broadcast	8.60	8.20	8.17	7.88	7.12	9.27	4.06	4.52	4.57	3.63	4.05	4.52	71.80	70.97	71.28	73.67	73.48	71.70
Urea Broadcast	Urea Next To Row	8.15	7.97	7.90	7.88	7.40	9.25	4.15	4.35	4.33	3.70	4.02	4.57	71.70	71.53	71.68	73.75	73.38	71.55
Urea Broadcast	UAN Middle of Row	7.53	7.87	7.97	7.63	6.98	8.95	4.13	4.33	4.46	3.81	3.90	4.38	71.63	71.92	72.27	73.63	73.62	72.35
Urea Broadcast	UAN Next To Row	8.13	7.85	8.03	7.85	7.18	8.98	4.14	4.36	4.51	3.70	4.01	4.53	71.92	72.00	71.87	73.57	73.63	71.85
Urea Banded	Urea Broadcast	8.50	8.42	8.18	7.73	7.50	8.73	4.16	4.41	4.61	3.79	4.26	4.68	71.73	71.52	72.76	73.32	73.22	71.97
PCU Broadcast	-	7.67	7.98	7.78	7.38	7.28	8.37	4.08	4.38	4.61	3.71	4.14	4.42	72.43	71.58	71.56	73.87	73.22	72.75
PCU Banded	-	8.38	8.53	8.13	7.62	7.82	8.60	4.15	4.45	4.46	3.76	4.36	4.53	71.47	71.12	71.67	73.50	72.92	72.08
PCU Banded	PCU Broadcast	8.22	8.40	8.15	7.55	7.50	8.82	4.18	4.50	4.48	3.69	4.18	4.53	72.22	71.03	72.17	73.70	73.25	72.20
LSD ($\alpha = 0.05$)		0.65	0.36	0.33	0.25	0.32	0.37	NS‡	NS	NS	NS	0.27	NS	NS	0.54	0.85	NS	NS	0.46

† YV, Yorkville; CH, Champaign; HB, Harrisburg.

‡NS, non- significant.

Table 3.8. Stover N content, grain N content, and total N uptake as influenced by fertility treatment for corn grown at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018.

Treatment timing		**Stover N Content**						**Grain N Content**						**Total N Uptake**					
		Year																	
		2017			**2018**			**2017**			**2018**			**2017**			**2018**		
		Location																	
Preplant	**Sidedress**	**YV†**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**
		lbs N acre^{-1}																	
No N Applied	-	41	19	52	39	25	21	96	80	121	91	44	50	138	99	173	130	69	72
Urea Broadcast	-	69	42	66	56	49	54	160	154	153	131	115	125	229	195	219	188	164	179
Urea Broadcast	Urea Broadcast	76	39	72	60	49	55	177	157	169	141	115	128	253	196	241	201	165	183
Urea Broadcast	Urea Next To Row	72	36	70	60	44	58	168	152	163	141	131	134	239	188	232	202	176	192
Urea Broadcast	UAN Middle of Row	65	29	71	60	53	54	152	137	165	139	109	127	218	166	236	199	162	181
Urea Broadcast	UAN Next To Row	74	32	72	63	45	58	172	146	168	147	124	135	246	178	240	210	169	193
Urea Banded	Urea Broadcast	77	40	75	61	49	56	180	175	175	141	124	131	257	214	250	202	172	188
PCU Broadcast	-	66	39	70	58	47	49	154	155	163	135	124	114	220	194	233	192	171	163
PCU Banded	-	75	53	73	62	53	57	174	185	171	144	142	133	249	238	244	205	195	190
PCU Banded	PCU Broadcast	74	43	75	62	44	56	173	178	174	145	132	130	247	222	249	207	176	186
LSD ($\alpha = 0.05$)		8	NS‡	5	4	NS	4	19	14	11	9	11	10	26	22	15	12	17	15

† YV, Yorkville; CH, Champaign; HB, Harrisburg.

‡NS, non- significant.

Table 3.9. Test of fixed effects of fertility treatments on R6 plant stover and grain N content, total plant N accumulation, and nutrient use efficiency (yield efficiency and recovery efficiency) for corn grown at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018.

	N Content		**Total N**	**Yield**	**Recovery**
Site-year	**Stover**	**Grain**	**Uptake**	**Efficiency**	**Efficiency**
			P > F		
2017					
Yorkville	0.0332	0.0332	0.0332	0.4025	0.0332
Champaign	0.0534	<.0001	<.0001	0.0001	<.0001
Harrisburg	0.0059	0.0059	0.0059	0.2086	0.0059
2018					
Yorkville	0.0244	0.0244	0.0244	0.0646	0.0244
Champaign	0.6931	<.0001	0.0171	0.0053	0.0171
Harrisburg	0.0087	0.0087	0.0087	0.0479	0.0102

Table 3.10. Yield efficiency and recovery efficiency as influenced by fertility treatment for corn grown at Yorkville, Champaign, and Harrisburg, IL in 2017 and 2018.

Treatment timing		**Yield Efficiency**						**Recovery Efficiency**					
		Year											
		2017			**2018**			**2017**			**2018**		
		Location											
Preplant	**Sidedress**	**YV†**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**	**YV**	**CH**	**HB**
		bu lb^{-1}						%					
Urea Broadcast	-	0.32	0.40	0.23	0.21	0.66	0.52	51	53	25	32	53	60
Urea Broadcast	Urea Broadcast	0.36	0.38	0.27	0.23	0.62	0.48	64	54	38	39	53	62
Urea Broadcast	Urea Next To Row	0.35	0.38	0.27	0.23	0.73	0.53	56	49	33	40	59	67
Urea Broadcast	UAN Middle of Row	0.32	0.26	0.28	0.26	0.57	0.50	44	37	35	38	51	61
Urea Broadcast	UAN Next To Row	0.39	0.34	0.29	0.29	0.69	0.56	60	44	37	44	55	67
Urea Banded	Urea Broadcast	0.40	0.50	0.32	0.26	0.64	0.56	66	64	42	40	57	64
PCU Broadcast	-	0.32	0.40	0.29	0.26	0.68	0.46	46	53	33	34	57	51
PCU Banded	-	0.38	0.56	0.30	0.30	0.76	0.59	62	77	39	42	70	66
PCU Banded	PCU Broadcast	0.38	0.53	0.32	0.32	0.72	0.54	61	68	42	43	59	64
LSD ($\alpha = 0.05$)		NS‡	0.12	NS	NS	0.10	0.08	15	12	8	7	10	8

† YV, Yorkville; CH, Champaign; HB, Harrisburg.

‡NS, non- significant.

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APPENDIX A: SUPPLEMENTAL TABLES

Table A.1. Preplant soil properties and Mehlich 3-extraction-based mineral test results for Yorkville and Champaign, IL in 2017 and 2018.

	Location			
	Yorkville		**Champaign**	
	Year		**Year**	
Soil property	**2017**	**2018**	**2017**	**2018**
Soil Type	Drummer silty clay loam	Drummer silty clay loam	Flanagan silt loam	Flanagan silt loam
OM, % †	4.4	5.3	4.0	3.1
CEC, meq/100g	20.6	22.6	22.3	19.2
pH	5.7	5.8	5.5	6.2
P, ppm	49	215	67	28
K, ppm	198	223	203	123
Ca, ppm	2074	2636	2484	2409
Mg, ppm	659	489	493	432
S, ppm	11.0	9.3	10.0	8.7
Zn, ppm	1.7	9.4	1.2	1.1
B, ppm	0.4	0.6	0.5	0.3
Mn, ppm	15	29	10	41
Fe, ppm	78	209	72	136
Cu, ppm	1.3	5.4	1.4	1.7

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

Table A.2. Growth stage, description, and unit of measurement for the 46 phenotypic traits collected on six hybrids at Champaign and Yorkville, IL in 2017 and 2018.

Phenotypic traits	Growth stage	Description	Unit
Canopy coverage	V5	fractional green canopy coverage using the Canopeo app	%
Canopy coverage	V8	fractional green canopy coverage using the Canopeo app	%
Plant height	V8	height from ground to latest fully developed extended leaf	cm
Stem diameter	V8	stem minor axis of the first internode above the soil surface	mm
Plant height	R1	height from ground to the tip of the tassel	cm
Stem diameter	R1	stalk minor axis of the first internode above the soil surface	mm
Ear height	R1	height from ground to the base of the ear	cm
Ear height/plant height	R1	ratio of ear height to plant height	cm/cm
Ear leaf number	R1	the ear leaf number from the top of the plant	count
Total leaves	R1	total number of green leaves	count
Ear leaf relative position	R1	ratio of ear leaf number to total leaf number	count/count
Number leaves above ear	R1	number of green leaves above the ear	count
Number leaves below ear	R1	number of green leaves below the ear	count
Leaves above/below ear	R1	ratio of leaves above the ear to below the ear	count/count
Stalk length above ear	R1	length of the stalk from the base of the ear to the tip of the tassel	cm
Stalk length below ear	R1	length of the stalk from the ground to the base of the ear	cm
Avg. internode length	R1	average length of all internodes	cm
Avg. internode length above ear	R1	average length of all internodes above the ear	cm
Avg. internode length below ear	R1	average length of all internodes below the ear	cm
Leaf angle	R3	angle of the leaf above the ear leaf, vertical= 90 degrees	degrees
Select leaf length	R3	maximum length of the leaf above the ear leaf	cm
Select leaf width	R3	maximum width of the leaf above the ear leaf	cm
Select leaf weight	R3	weight of the leaf above the ear leaf	g leaf^{-1}
Leaf area per plant	R3	total leaf area of the whole plant	cm^2 plant^{-1}
Leaf area per plant above ear	R3	total leaf area of the leaves above the ear	cm^2 plant^{-1}
Leaf area index	R3	total leaf area index of the canopy	cm^2/cm^2
Leaf area ratio	R3	area of the leaf material per unit whole plant weight	cm^2 g^{-1}
Specific leaf weight	R3	average leaf weight per unit of leaf area	g cm^{-2}
Specific leaf area	R3	average leaf area per unit of leaf weight	cm^2 g^{-1}
Plant width	R3	maximum distance the plant extends across the rows	inches
Root weight per plant	R6	average root system weight per plant	g root^{-1}
Root biomass per acre	R6	weight of the root systems per acre	tons acre^{-1}
Leaf biomass per acre	R6	weight of the leaves per acre	tons acre^{-1}
Stalk biomass per acre	R6	weight of the stalks per acre	tons acre^{-1}
Stover weight per plant	R6	average stalk, leaf, cob, tassel, plus husk weight per plant	g plant^{-1}
Stover biomass per acre	R6	weight of the stover per acre	tons acre^{-1}
Total above-ground weight per plant	R6	average stover plus grain weight per plant	g plant^{-1}
Total above-ground biomass per acre	R6	total above-ground plant weight per acre	tons acre^{-1}
Shoot biomass/root biomass	R6	ratio stover plus grain weight to root weight per area	tons ac^{-1}/tons ac^{-1}
Harvest index	R6	proportion of the total plant weight that is grain weight	%
Grain protein concentration	R6	concentration of protein in the grain, 0 % moisture	%
Grain oil concentration	R6	concentration of oil in the grain, 0 % moisture	%
Grain starch concentration	R6	concentration of starch in the grain, 0 % moisture	%
Kernel number per area	R6	total number of kernels per square meter	kernels m^{-2}
Avg. kernel weight	R6	average weight of each individual kernel	mg kernel^{-1}
Grain yield	R6	total grain yield, 15 % moisture	bu acre^{-1}

Table A.3. Test of fixed effects of grain yield, yield components (kernel number and kernel weight), and grain quality (oil, protein, and starch concentrations) for corn grown at Yorkville and Champaign, IL in 2017 and 2018.

		Yield component		Grain quality		
Source of variation	**Yield**	**Kernel number**	**Kernel weight**	**Oil**	**Protein**	**Starch**
				P > F		
				2017 Yorkville		
Row spacing (S)	0.0004	0.0067	0.6360	0.1588	0.0961	0.3413
Population (P)	<.0001	<.0001	<.0001	0.0029	<.0001	<.0001
S x P	<.0001	<.0001	0.4063	0.1404	0.2166	0.0587
Hybrid (H)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
S x H	0.0007	0.1576	0.0142	0.2723	0.5434	0.5048
P x H	0.0028	<.0001	0.0013	0.0403	0.3526	0.1976
S x P x H	0.0272	0.8446	0.7677	0.4488	0.9046	0.5361
				2017 Champaign		
Row spacing (S)	0.0048	0.1959	0.5090	0.4527	0.5093	0.4344
Population (P)	<.0001	<.0001	<.0001	<.0001	0.0015	0.0013
S x P	0.1877	0.0225	0.1393	0.0575	0.1954	0.0292
Hybrid (H)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
S x H	0.1213	0.0154	0.0438	0.3853	0.9334	0.9466
P x H	0.0032	0.3902	0.6279	0.0376	0.0997	0.5679
S x P x H	0.4441	0.9727	0.9988	0.1184	0.8520	0.9500
				2018 Yorkville		
Row spacing (S)	0.1433	0.0897	0.2559	0.3359	0.4458	0.4334
Population (P)	<.0001	<.0001	<.0001	0.0010	0.0161	<.0001
S x P	0.4573	0.0896	0.1438	0.6658	0.2168	0.0881
Hybrid (H)	<.0001	0.0002	<.0001	<.0001	<.0001	<.0001
S x H	0.3128	<.0001	0.0032	0.1777	0.4511	0.3578
P x H	0.5412	0.0677	0.7230	0.9862	0.5476	0.9582
S x P x H	0.9632	0.9406	0.9887	0.9941	0.9526	0.7798
				2018 Champaign		
Row spacing (S)	0.0148	<.0001	0.0237	0.0026	0.0132	<.0001
Population (P)	0.0009	<.0001	<.0001	0.0001	0.0004	0.0185
S x P	0.7507	0.0061	0.0011	0.3708	0.2082	0.5798
Hybrid (H)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
S x H	0.7122	0.0979	0.0085	0.4428	0.6439	0.7805
P x H	0.0815	0.0152	0.4205	0.3854	0.1786	0.2163
S x P x H	0.9540	0.4438	0.8890	0.6860	0.2768	0.6524

Table A.4. Grain yield and yield components (kernel number and kernel weight) as influenced by population and row spacing averaged across six corn hybrids grown at Yorkville and Champaign, IL in 2017 and 2018. Grain yield is presented at 15.5% moisture, kernel weight is presented at 0% moisture.

				Yield component					
Population	**Yield**			**Kernel number**			**Kernel weight**		
	Row spacing		**Mean**	**Row spacing**		**Mean**	**Row spacing**		**Mean**
	30”	**20”**		**30”**	**20”**		**30”**	**20”**	
plants acre^{-1}	—— bu acre^{-1} ——			—— kernels m^{-2} ——			—— mg kernel^{-1} ——		
				2017 Yorkville					
38,000	304 c	311 b	307 B	5934 f	6065 ef	5999 D	273 ac	273 ab	273 A
44,000	305 c	318 a	312 A	6205 de	6455 c	6330 C	262 bd	262 cde	262 B
50,000	299 d	321 a	310 AB	6276 cd	6874 a	6575 A	254 efg	249 fh	251 C
56,000	291 e	303 cd	297 C	6282 cd	6647 b	6464 B	248 hi	244 gi	246 D
Mean	300 B	313 A		6174 B	6510 A		259 A	257 A	
				2017 Champaign					
38,000	293 bc	301 b	297 B	5352 d	5332 cd	5342 C	293 ab	301 a	297 A
44,000	298 b	312 a	305 A	5582 bc	5739 b	5661 B	286 bcd	289 bc	287 B
50,000	296 b	315 a	306 A	5638 bc	6069 a	5854 A	280 cde	276 def	278 C
56,000	289 c	301 b	295 B	5714 b	5854 b	5784 AB	271 f	274 ef	273 D
Mean	294 B	307 A		5572 A	5748 A		282 A	285 A	
				2018 Yorkville					
38,000	238 abc	245 bc	241 AB	5398 c	5420 c	5409 B	235 ac	240 ab	238 A
44,000	238 abc	256 a	247 A	5550 bc	5974 a	5762 A	227 bd	228 cde	228 B
50,000	231 bc	245 b	238 B	5727 ab	5758 ab	5743 A	214 ef	226 cdef	220 C
56,000	220 d	234 cd	227 C	5513 bc	5606 bc	5559 B	212 f	222 cdeg	217 C
Mean	232 A	245 A		5547 A	5689 A		222 A	229 A	
				2018 Champaign					
38,000	279 cd	287 ab	283 A	5253 d	5513 b	5383 B	283 a	278 abc	280 A
44,000	282 bc	292 a	287 A	5390 bc	5882 a	5636 A	278 ab	265 d	272 B
50,000	279 cd	292 a	285 A	5390 bc	5888 a	5639 A	275 bc	265 d	270 B
56,000	272 d	282 bc	277 B	5313 cd	5910 a	5611 A	273 cd	256 e	264 C
Mean	278 B	288 A		5336 B	5798 A		277 A	266 B	

Mean separation letters (lower case) compare population and row spacing treatment interactions for each trait. Upper case letters compare the main effect of population or row spacing within a trait. Similar letters are not statistically different at $\alpha = 0.05$.

Table A.5. Grain quality (oil, protein, and starch concentrations at 0% moisture) as influenced by population and row spacing averaged across six corn hybrids grown at Yorkville and Champaign, IL in 2017 and 2018.

Population	Grain quality								
	Oil			**Protein**			**Starch**		
	Row spacing		**Mean**	**Row spacing**		**Mean**	**Row spacing**		**Mean**
	30”	**20”**		**30”**	**20”**		**30”**	**20”**	
plants acre^{-1}	%								
2017 Yorkville									
38,000	3.81 ab	3.90 a	3.85 A	8.11 a	8.07 ab	8.09 A	72.74 de	72.59 e	72.66 C
44,000	3.75 bc	3.71 bc	3.73 B	8.05 abc	7.85 e	7.95 B	72.79 cde	73.08 bc	72.94 B
50,000	3.69 cd	3.60 de	3.65 C	8.00 bcd	7.92 cde	7.96 B	73.03 bc	73.05 bcd	73.04 B
56,000	3.58 e	3.52 e	3.55 D	7.98 bcde	7.86 de	7.92 B	73.13 ab	73.42 a	73.28 A
Mean	3.71 A	3.68 A		8.04 A	7.92 A		72.92 A	73.03 A	
2017 Champaign									
38,000	3.92 ab	3.96 a	3.94 A	8.57 a	8.45 ab	8.51 A	71.98 bc	71.97 bc	71.98 B
44,000	3.81 c	3.95 a	3.88 AB	8.41 b	8.38 b	8.39 B	72.44 a	71.86 c	72.15 B
50,000	3.87 abc	3.83 bc	3.85 BC	8.37 b	8.39 b	8.38 B	72.33 ab	72.53 a	72.43 A
56,000	3.78 c	3.82 bc	3.80 C	8.44 b	8.46 ab	8.45 AB	72.43 a	72.41 a	72.42 A
Mean	3.84 A	3.89 A		8.45 A	8.42 A		72.30 A	72.19 A	
2018 Yorkville									
38,000	3.83 a	3.82 a	3.82 A	8.30 a	8.26 ab	8.28 A	73.27 d	73.46 cd	73.36 B
44,000	3.82 ab	3.86 a	3.84 A	8.15 b	8.23 ab	8.19 AB	73.54 bc	73.41 cd	73.48 B
50,000	3.69 c	3.78 abc	3.74 B	8.09 b	8.20 ab	8.15 B	73.79 ab	73.55 bcd	73.67 A
56,000	3.67 c	3.70 bc	3.68 B	8.04 b	8.21 ab	8.12 B	73.86 a	73.71 ab	73.79 A
Mean	3.75 A	3.79 A		8.22 A	8.14 A		73.62 A	73.53 A	
2018 Champaign									
38,000	4.23 a	4.18 ab	4.21 A	8.02 a	7.89 ab	7.95 A	72.82 b	72.94 b	72.88 B
44,000	4.20 ab	4.04 d	4.12 B	7.98 ab	7.72 c	7.85 B	72.86 b	73.21 a	73.04 AB
50,000	4.13 bc	4.06 cd	4.09 B	7.91 b	7.71 c	7.81 B	73.06 ab	73.21 a	73.13 A
56,000	4.13 bc	4.01 d	4.07 B	7.96 ab	7.69 c	7.82 B	72.99 ab	73.20 a	73.10 A
Mean	4.17 A	4.07 B		7.97 A	7.75 B		72.93 B	73.14 A	

Mean separation letters (lower case) compare population and row spacing treatment interactions for each trait. Upper case letters compare the main effect of population or row spacing within a trait. Similar letters are not statistically different at α = 0.05.