HYBRID AND PLANT DENSITY EFFECTS ON NITROGEN RESPONSE IN CORN

BY

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THESIS

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ABSTRACT

The development of corn (*Zea mays*) hybrids that may be improved for nitrogen use efficiency along with the emphasis on higher plant density for maximum yields of modern hybrids have raised questions about interactions between N rate and plant density for different hybrids. Four corn hybrids (Pioneer 33D49, 33K44, 33W84, and 34F07), chosen to represent a range of responses to N rate and plant density (flex-ear vs. fixed-ear), were planted corn following corn for two years (2011 and 2012) at four sites in Illinois using combinations of three densities (44,460, 83,980, and 123,500 plants/ha) and four N rates (0, 90, 179, and 269 kg N/ha). Weather conditions and grain yields led us to group the data into two sets, consisting of three low-stress and three high-stress environments. Across the three sites that experienced substantial drought stress (Urbana 2011 and 2012, DeKalb 2012), the two lower densities (44,460 and 83,980 plants/ha) produced greater yields (7.4 and 7.0 Mg/ha) than did the highest density (5.2 Mg/ha) across all N rates. There was little yield response to N rates above 90 kg N/ha at the low and high densities, as there was a curvilinear increase until yield plateau at the low density (8.1 Mg/ha at 133 kg N/ha) and the high density (5.9 Mg/ha at 102 kg N/ha). Response to N was greatest at the middle density, as there was a quadratic response with maximum yield at 188 kg N/ha (8.7 Mg/ha). Hybrids responded to density as anticipated, with flex-ear hybrids yielding more than fixed-ear hybrids at the lowest density, and less at the highest density. Across the low-stress environments (DeKalb-2011, Monmouth-2011, and Monmouth-2012), the lowest density (44,460 plants/ha) responded little (+0.3 Mg/ha) to N rates above 90 kg N/ha, while there was greater response to N rates at the middle density (13.5 Mg/ha at 162 kg N/ha) and the high density (13.4 Mg/ha at 174 kg

N/ha). Flex-ear hybrids generated greater yields than fixed-ear hybrids at the low density, and produced greater yields overall, while fixed-ear hybrids better maintained yields between the middle and high densities. No support was found for the idea that increasing corn yields requires increases in both plant density and N rate above rates typically used. These results advance our understanding of N rate-plant density interaction within contrasting environmental conditions, but understanding the complexities of hybrid interactions with N rate and plant density will require additional work.

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LITERATURE REVIEW

Overview of Corn

The introduction of corn (*Zea mays*) to the region that became the United States began at approximately 1000 BC when flint maize was brought from the southern portion of Mexico (Troyer, 1999). Two and a half millennia later, around 1500 AD, dent corn reached this region, and many of the flint x dent crosses that resulted, both through natural and human selection, serve as a parent to inbred lines used in hybrid corn production today (Troyer, 2004). Due to the fact most corn cultivars that were grown at the time were based on tropical lines, the requirement for new cultivars that were adapted to shorter growing seasons and higher drought tolerance were necessary for sustained success in the Midwest (Troyer, 1999). Recent advances in corn germ quality and significant increases in industry prices have led to drastic increases in acreage in the past twenty years. As little as 20 years ago in 1992, U.S. corn acreage totaled roughly 79 million acres, and more recently in 2012, total corn acreage increased considerably to approximately 96 million acres (USDA NASS, 2012).

With the increasing use of corn present day, strong emphasis has been placed on maximizing production to meet industry needs. As breakthroughs in technology continue to advance the agricultural industry, much emphasis has been placed on obtaining higher corn yields though new techniques in plant breeding and genomics. At the same time, crop management strategies constitute as important, if not greater, of a role when it comes to maximizing yields (Egli, 2008). Agronomic strategies that are utilized with the intent of maximizing corn productivity often reflect cultural practices, environmental characteristics, and economic restrictions (Archer et al., 2007). Appropriate nitrogen fertilization serves as the principal factor of nutrient management in high-yielding corn production systems. Judging its response among variable conditions, such as varying plant densities and diverse hybrids, will allow for a broader understanding of methods to be more economically efficient while escalating yields.

Nitrogen Management

Stanger and Lauer (2008) supported the idea that nitrogen is the crop input investment that provides greatest potential for financial return on investment. Management decisions pertaining to proper nitrogen application levels can have costly implications. Too little nitrogen can result in yield reduction, inferior grain quality, and reduced profitability (Sawyer et al., 2006). Furthermore, when an abundance of nitrogen is applied, corn yield and quality typically do not suffer, but costs may exceed returns and detrimental environmental consequences are likely to ensue (Sawyer et al., 2006).

Variability in nitrogen sources, application methods, previous crops, timing of application, and environmental conditions can result in inconsistencies associated with nitrogen availability (Kyveryga et al., 2007). New techniques are being used to counteract such inconsistency, including the use of variable rate technology (VRT). Modern advancements, such as field mapping with crop canopy reflectance sensors that collect values for normalized difference vegetative index (NDVI), with the use of visible (VIS) and near-infrared (NIR) wavelengths, can permit more accurate rates for in-season nitrogen applications (Kitchen et al., 2010). The visible light reflectance measures photosynthetic health along with the near-infrared wavelength which processes the plant’s structure and ability to assimilate carbon (Kitchen et al., 2010). Nevertheless, many growers apply nitrogen prior to planting, thus limiting the application of VRT for N. Major reasons for this include the need to apply N only once and the ability to apply

N without concern for weather-related delays in application. Future considerations may focus on readjusting this concept, to more appropriately use these progressive technologies, resulting in better utilization of applied nitrogen (Kyveryga et al., 2007).

In recent years, endorsements for the use of greater N rates, which can lead to nitrogen over application, have been heavily scrutinized due to negative environmental impacts pertaining to water source pollution (Sawyer et al., 2006). Leaching of nitrate into subsurface tile lines has led to surface water degradation, through the reduction of oxygen levels in the water. Nitrate contamination can be associated with N over application or wrongly-timed N application, from either commercial N fertilizer or animal manure applications (Dinnes et al, 2002). These application issues are commonly linked with the corn-following-corn crop sequence, lack of nitrification inhibitors when applying N fertilizers before the growing season, improper N mineralization crediting, and inefficient cultural practices (Dinnes et al, 2002). Applying adequate nitrogen can decrease negative environmental impacts while still maintaining high yield productivity. From strictly a crop production standpoint, nitrogen over application expenses are less than potential lost yield costs in regions of nitrogen under-application (Stanger and Lauer, 2008). As a result, typical crop management strategies result in excess N fertilization to ensure maximum crop production.

Nitrogen recommendations have been made available through various publications by researchers since crop production became commercialized. These recommendations typically call for increasing nitrogen rates for greater yield production in corn. Results from a nitrogen rate study conducted in Illinois and Ohio (Shepard et al., 2011) reinforces that there is a limit in which no yield benefit is achieved as N rate increases. Across five N rates (0, 67, 134, 202, 269 kg N/ha) and all hybrids over two years, yields increased curvilinearly as N rate increased, before leveling off at 202 kg N/ha. Derby et al. (2005) evaluated six N rates (0, 45, 90, 135, 180, 225 kg N/ha) with similar results, with grain yields leveling off at the higher N rates. Grain yields increased by 0.26 Mg/ha from 135 to 180 kg N/ha, and there was no significant increase from 180 to 225 kg N/ha.

Proper nitrogen management is one of the most important factors in corn production. Yield based N recommendations were traditionally used in Illinois and much of the Midwest, before the introduction of the Maximum Return to N (MRTN) in the mid-2000's (Sawyer et al., 2006; Fernández et al., 2009; Hernandez and Mulla, 2008). Unlike yield based recommendations, the MRTN approach does not incorporate a correlation between yield and the required N rate. Instead it is an economic approach that considers expected corn price, the price of N based on the desired product for use, the soil yield potential of a selected region based on actual N responses, and the projected crop rotation (Fernández et al., 2009). This approach was implemented using N response data that can lead to recommendations of economically optimum N rates, which as a result, maximize financial returns to the grower. While the MRTN method can be used to rationalize high N rates, these rates may not necessarily be appropriate. In certain incidences, ratio increases of corn price to price of N can justify greater N rates without financial impact. Increased rates of N may lead to subsequent reduction of nitrogen use efficiency (NUE), as there may be little to no additional yield increase from supplemental N.

NUE, defined as the yield of grain per unit of available N in the soil (Hirel et al, 2007), can be separated into two processes. Uptake efficiency is the ability of the plant to remove N from the soil as nitrate and ammonium ions, and utilization efficiency is the ability to use N to produce grain yield (Hirel et al, 2007). Improvement of NUE through the use of superior hybrids and more evolved crop management has raised questions about suitable nitrogen management. This topic will take on even more importance in upcoming years as nitrogen utilization hybrids likely become commercialized, and will require more evolved N management programs. Proper N management of these hybrids will likely change grower expectations, through either the use of a specific N level with the expectation of higher yields, or reducing the N level to achieve a target yield (Moose and Below, 2009).

Enhanced nitrogen management of corn hybrids starts with better understanding nitrogen nutrition, and what kind of influence cultural practices have on altering NUE. A study in Argentina (Barbieri et al, 2008) indicated that decreasing row spacing can increase NUE in corn. The experiment consisted of three row spacings (70, 52, 35 cm) across three N rates (0, 90, 180 kg N/ha), over two years. Averaged across both years and all N rates, the 52 cm row spacing responded with a 2.05 kg/kg higher NUE of grain yield per unit of available N over the 70 cm row spacing. The 35 cm spacing offered no significant benefit over the 52 cm spacing, both of which had an NUE of 32.9 kg/kg N. These results demonstrated a 7% NUE advantage for using 52 cm or 35 cm row spacing over 70 cm row spacing. It is probable that additional light interception created from the decreased row spacing, at the identical plant density, increased plant metabolism which generated greater nitrogen utilization in the plant.

Timing of nitrogen application has also been found to influence NUE. Vetsch and Randall (2004) and Scharf et al. (2002) recognize that nitrogen application is generally most beneficial as a side-dress treatment several weeks after planting to minimize nitrogen losses attributed to leaching and denitrification. However, modern practices (post-emergence herbicide treatments, etc.) and increases in average farm size have led to alternate strategies, such as fall-applied anhydrous ammonia, to offset time limitations that may constrain nitrogen side-dress applications in the spring. In a study conducted in Minnesota, Vetsch and Randall (2004) applied N as anhydrous ammonia without a nitrification inhibitor (123 kg N/ha) as fall-injected, in-row treatments with a strip-till unit, or as a pre-plant, spring-applied, mid-row treatment across four tillage systems (no-till, strip-till, one-pass field cultivation, and chisel plow). Across three years, advantages were found for spring-applied NH_3 over fall-applied NH_3 in grain yield (+0.8 Mg/ha), total N uptake (+15 kg/ha), and apparent N recovery (+12%). These results provide indication that spring-applied nitrogen demonstrates greater response to N. In an additional study, Binder et al. (2000) concluded that spring N applications applied prior to or at the V6 growth stage are generally more beneficial than applications in later growth stages.

Vetsch and Randall (2004) evaluated four tillage systems in the aforementioned N timing x tillage study. Across all nitrogen treatments, tillage effects (no-till, strip-till, one-pass field cultivation, and chisel plow) were significant with the CP treatment holding the advantage over the next best treatment (ST) in both grain yield (+.3 Mg/ha) and total N uptake (+5 kg/ha). NT lagged behind CP in grain yield by .5 Mg/ha and total

N uptake by 17 kg/ha. These results indicate use of a reduced tillage system can provide apparent NUE improvement over no tillage, though NUE was not directly measured.

Though NUE and nitrogen responsiveness are strongly correlated, N responsiveness, defined as the level of N that maximizes yield, differs from NUE, the yield per unit of available N (Sawyer et al., 2006; Hirel et al, 2007). Nitrogen source, method of application, environmental conditions, and hybrid selection are all factors that can significantly impact response from nitrogen on a year-to-year basis (Gagnon and Ziadi, 2010; Subedi and Ma, 2005). Understanding appropriate nitrogen use levels are important, as abundant soil available nitrogen may be available, but yield may be unaffected (Isfan et al., 1995).

Andraski and Bundy (2008) evaluated various nitrogen sources, across a number of residue levels, in no-till corn. Ammonium nitrate (AN), granular urea, and urea ammonium nitrate (UAN) were broadcast over treatments within one week of planting across four years. At 90 kg N/ha, averaged across all years, AN (9.2 Mg/ha) out-yielded Urea (8.0 Mg/ha) and UAN (7.7 Mg/ha) treatments, indicating a greater nitrogen responsiveness to AN as opposed to other N sources. According to the USDA (2010), nitrogen solutions (UAN 28, UAN 32, etc.) accounted for approximately 41% of nitrogen consumption in corn production, within the United States. Urea (19%), anhydrous ammonia (15%), ammonium sulfate (5%) and ammonium nitrate (3%) trailed UAN nitrogen solutions in consumption, despite yield levels of nitrogen treatments in the previous study, which can likely be attributed to fertilizer expenses and availability (USDA, 2010).

The nitrogen application method can also have an influence on the level of N response in corn. Nelson et al. (2011) evaluated four nitrogen sources (UAN, AN, urea, urea + agrotain) at 170 kg N/ha applied at four plant heights (30, 69, 90, 120 cm) with both between-row and broadcast treatments. Between-row applications resulted in yield advantages as opposed to broadcast applications on average, per treatment, for UAN (+2,265 kg/ha) and AN (+1,015 kg/ha). The lone nitrogen source that demonstrated a yield advantage with a broadcast application was urea (+260 kg/ha). Urea + agrotain did not demonstrate a significant advantage toward either application method. As this study investigated "rescue nitrogen applications" in corn, in which N was applied preplant-V10, yield differences in between-row vs. broadcast application are likely related to differences associated with nitrogen form. Urea (granular), as opposed to UAN and AN (liquid), did not cause the level of injury to the crop that was experienced with liquid N broadcast applications between V5-V10 (Nelson, et al., 2011).

As an insurance measure, producers may choose to over-apply nitrogen, in an attempt to counteract environmental conditions, to protect against reductions in yields (Solari et al., 2008). Corn response to nitrogen may be prone to variability dependent on specific environmental characteristics, such as soil qualities (Tremblay et al., 2012). Tremblay et al. (2008) found that soil texture (fine vs. medium/coarse textures) had profound effects on determined N responsiveness. Fine textured soils (clay, silty clay, silty clay loam, and clay loam) improved corn yields, with a much higher response ratio, by a factor of 2.7, as opposed to corn yields in medium/coarse soils (loam, silt loam, sandy loam, sandy clay loam, and loamy fine sand) which only saw an increase by a factor of 1.6. By understanding that finer soil textures have better nitrogen responsiveness, fertilization requirements can be adjusted accordingly to maximize productivity. Nitrogen response as a factor can be improved by refining cultural strategies and by better understanding environmental characteristics that can have profound effects on yield efficiency (Halvorson et al., 2005).

Over 50 years of continuous corn, Bundy et al. (2011) found that yields doubled from 2.57 Mg/ha in 1957, to 5.09 Mg/ha in 2007 at 0 kg N/ha. These increases are likely due to both improved management and hybrid corn advancements. Steady yield gains were demonstrated, with the highest totals (14.11 Mg/ha at 168 kg N/ha; 14.43 Mg/ha at 252 kg N/ha) coming in the most recent years. The yields in recent years did not require greater N fertilization to obtain greater yields, indicating an apparent improvement in NUE. While it may not be possible to distinguish exactly what percentage of the increased NUE can be attributed to hybrid characteristics or improved crop management through these results, it is clear that a focus should remain on both capacities.

Plant Density

Plant density has functioned as a significant factor in the improvement of corn hybrid yields during the past 70-80 years (Hammer et al., 2009). Modern corn hybrids have demonstrated an ability to tolerate high stress environments, including high plant densities. These “crowded” plant environments increase intra-specific competition, due to the limited resource availability (Boomsma et al., 2009). Additionally, variability on a plant-to-plant basis, related to variability in inter-row spacing and plant height, have significant effects on yield within elevated plant densities (Boomsma et al., 2009). Additional increases in plant densities could potentially lead to greater yields with the continual evolution of stress-tolerant crops. Though many believe these yield improvements can be attributed to enhanced hybrid genetics, agronomic strategies, including those such as increased plant density that were enabled by genetic improvements, have also factored into yield progression (Tollenaar and Wu, 1999).

With recent increases in corn prices, producers have shown interest in improvement of agronomic strategies, including greater plant densities, to optimize corn yields to maximize profitability. Van Roekel and Coulter (2012) evaluated phenotypic responses and yield components associated with plant density and row width interactions. Over densities ranging from 40,700 to 108,700 plants/ha, yields of three hybrids with differing relative maturities (95, 101, 105 days) were assessed at two row widths (51 and 76 cm). Observed grain yields peaked at 11.0 Mg/ha at both 81,500 and 95,100 plants/ha, while additional yields regressed gradually, reaching a minimum of 8.8 Mg/ha at 40,700 plants/ha. In this study, the LAI was at its maximum value (6.5 m^2m^{-2}) at the highest plant density (108,700 plants/ha), but was slightly lower at the densities producing higher yields (81,500 and 95,100 plants/ha), to values of 6.3 m^2m^{-2} and 5.9 m^2m^{-2} respectively. These results indicate plant densities in the range of 81,500-95,100 plants/ha are most economical. Widdicombe and Thelen (2002) established similar results, with 81,000 plants/ha (11,555 kg/ha) and 90,000 plants/ha (11,683 kg/ha) yielding more than lower plant densities (56,000, 65,000, and 73,000 plants/ha), though no higher densities were evaluated.

Plant density response has been found to differ, dependent on hybrid selection and the specific phenotypic traits the crop is meant to exhibit (Stanger and Lauer, 2006). Stanger and Lauer (2006) found that Bt hybrids yielded 6.6% more than traditional non-Bt hybrids across a variance of plant densities extending from 54,000 to 104,000 plants/ha. Approximately 22% more lodging occurred in the non-Bt hybrids, which probably accounted for at least some of the difference in yield. Subedi et al. (2006) compared two hybrids, one deemed as leafy and one as non-leafy, to evaluate how yield and harvest index (HI) responded to N rate and plant density. The leafy hybrid exhibited a decrease in HI values from 0.49 to 0.46 as plant density increased from 60,000 to 90,000 plants/ha. In comparison, the non-leafy hybrid showed an increase in HI from 0.50 at 60,000 plants/ha to 0.52 at 90,000 plants/ha. These results indicate that optimum plant density may differ by hybrid.

Use of proper plant densities is important depending on the various influences that are present. Stanger and Lauer (2006) advise that by introducing increased densities that can create a high stress environment, yields will be reduced when above-optimum rates are used. Aspects extending from hybrid selection, planting date and soil type should influence the determination of a proper plant density.

Stress Tolerance

Corn growth and grain yield can be significantly impacted by stress associated with drought, above average temperatures, and inadequate nitrogen levels (Barker and Sawyer, 2010; Osborne et al., 2002; Monneveux et al., 2006; Cicchino et al., 2010). Drought stress has proven to have significant effects on physiological traits, especially in the week prior to, and the two-week period after, flowering (Monneveux et al., 2006). In addition to drought, extreme heat, which many times can be associated with water-deficit conditions, can have adverse effects on plant metabolism (Cicchino et al., 2010). Water stress can also limit N uptake, leading to deficiency (Barker and Sawyer, 2010; Scharf et al., 2006.) Proper management strategies and recent advancements in technology have led to less stressful plant growing environments, however, sometimes it is nearly impossible to control stress, especially in corn.

Drought stress is an unpredictable circumstance that can have significant adverse effects on a corn crop in a given growing season. During the early stages of vegetative growth, corn is somewhat unaffected by low soil-water conditions, predominantly because water usage remains relatively low in comparison to later corn growth stages (O'Neill et al., 2004). Monneveux et al. (2006) showed evidence that in drought environments, silk emergence is likely to be delayed, grain abortion is expected to occur, and canopy photosynthesis decreases. Decreased canopy photosynthesis can be attributed to leaf curling and stomatal closure, which reduces the plant's transpiration ability in an effort to avoid premature death (O'Neill et al., 2006). Severe drought stress can also result in lower pollination percentages, reduced kernel weight, accelerated leaf senescence, and lack of nitrogen mobilization, which can result in nitrogen deficient symptoms in corn (Monneveux et al., 2006).

Cicchino et al. (2010) examined heat stress effects in corn, and found effects on plant metabolism and on grain yield, which is affected differently depending when the stress occurs. When heat stress occurs immediately prior to tasseling through the silking and pollination periods, grain yield and kernel set can be severely affected. Heat stress applied at V11 to VT produced 13 more kernels per plant compared to stress imposed at VT to R1, but the later stress timing produced heavier kernels by 35 mg. Grain yield was higher by 3 g/plant under the later heat stress compared to the earlier heat stress. Severe heat stress can affect pollen viability, which may be responsible for why fewer kernels were produced under the later timing. Higher overall yield and grain weight for the later stress was likely due to better assimilate partitioning, due to more abundant nutrient reserves. Though heat stress may not be as detrimental as drought stress when proper nutrients and water are available, it is often found simultaneous with drought conditions which can enhance the effects.

It is generally recognized that insufficient nitrogen can lead to significant reductions in yield. This often causes producers to increase N application rates to achieve near-maximum yields (Scharf et al., 2006). Levels of N deficiency can be rapidly assessed through the use of a chlorophyll meter; however, readings may have slight variations attributed to hybrid inconsistencies, growth stage, disease pressure, and levels of light interception (Binder et al., 2000). The SPAD chlorophyll meter processes the transmission of red and near-infrared light in a given leaf. When compared to a well-fertilized control, this output can be used to determine the N deficiency level of a crop (Scharf et al., 2006). The use of technologies such as chlorophyll meters (SPAD) allow producers to properly assess if nitrogen fertilization requirements in corn are being met and if management concepts need to be readjusted.

The ability of modern corn hybrids to tolerate stressful environments has increased. Drought and extreme heat stress often, but not always, occur simultaneously. Such environments are rarely controllable, at least in the absence of irrigation. Thus most growers rely on enhanced genetics in newer corn hybrids to provide some tolerance to such conditions. Nitrogen stress is more easily managed than drought or heat, barring any significant environmental factors, usually through over application. Development of the nitrogen utilization trait in corn hybrids will presumably alter this management.

In summary, yield improvements in corn have been linked with both hybrid progression and improved management strategies. It is clear that nitrogen management has progressed in recent years with more evolved recommendation methods (MRTN). The MRTN approach takes into consideration many aspects of N management (N source, site productivity, price considerations, etc.) that are not considered by yield-based N recommendations. Furthermore, numerous agronomic considerations, extending from soil productivity to hybrid characteristics, should be evaluated when selecting an appropriate plant density. Nevertheless, indefinite environmental conditions like weather can have adverse effects on plant growth, generating varying responses among wide ranges of N rates and plant densities. With a continued focus on improving corn management, more advanced strategies can be used with continual hybrid evolution.

INTRODUCTION

With the possible commercialization of "nitrogen-use-efficient" corn hybrids within the next few years, the hybrid x nitrogen rate question is going to take on more importance. Nitrogen nutrition of NUE hybrids will presumably need to be managed differently than with "normal" hybrids, whether that be using the same rates of N with the expectation of higher yields, or the use of less N with expectation of similar yields. The improvement of NUE continues to evolve as hybrids develop and cultural strategies progress, raising questions of suitable nitrogen management (Bundy et al., 2011).

The question about differential responses of corn hybrids to plant density is also an important one, and one that has been relevant for a long time. Hybrids have long been characterized as to their position along the scale from "fixed-ear" (determinate) to "flex-ear" (indeterminate) types, with the former better able to maintain ear size as plant density is increased, and the latter better able to expand ear size if conditions are very good or plant density is low. Most high-performing hybrids tend to be characterized as "fixed-ear", and with higher densities recommended for high yields.

While a physiological link between ear flex characteristics and N responsiveness has not been well-established, simultaneous measurement of responses to N rate and plant density might prove to be of value in terms of characterizing corn hybrids. Modern hybrids have shown tendencies to withstand higher levels of stress (i.e.- low N, high plant densities), which allow them to better sustain suitable photosynthetic rates, appropriate assimilate supplies, and maintain plant growth rates attributable to enhanced nitrogen and water use efficiency (O'Neill et al., 2004). Responses to density are easier to see with greater consistency than are responses to N rate, which are subject to considerable variation over fields and years (Miao et al., 2006).

Results of a prior study in Illinois showed that two lower plant densities (49,400 and 65,870 plants/ha) required more N to reach optimum yield than two higher plant densities (Nafziger, unpublished). Raising the N rate from 202 to 269 kg N/ha lowered yields at two lower densities (49,400 and 65,870 plants/ha) but not with the two higher densities (98,800 and 115,270 plants/ha). A recent Indiana study (Boomsma et al., 2009) showed that under large ranges of plant density (54,000-104,000 plants/ha) and N rate (0-330 kg N/ha), higher densities required more N. This seems logical, given the prevailing belief that high yields require more plants, and that more plants require more N.

Along with the belief that higher yields require greater rates of N and higher plant densities, the idea that different hybrids respond differently to both N and plant density should be considered. While the concept seems logical, it is unclear whether hybrids are characterized well enough in these regards to call for different N and plant density management by producers. Due to unpredictable supplies of N and water from the soil, it would also be of value in characterizing and managing different hybrids if a connection could be made between N responsiveness and response to plant density.

By better understanding N rate and plant density interactions, it might be possible to develop a system to more easily characterize hybrids – perhaps a “flexibility index” that would have elements of responsiveness to both N rate and plant density. The objectives of this study are to address whether different commercial corn hybrids respond differently to both N rate and plant density, and how consistent such responses might be across years and locations, to answer the question of how differently hybrids respond to plant density, and to determine whether or not nitrogen and plant density responses among hybrids are related to one another.

MATERIALS AND METHODS

Field Experiment

Trials were conducted in 2011 and 2012 at four locations in Illinois (DeKalb, Monmouth, Urbana, and Brownstown) across two years (2011, 2012). Coordinates and soil types were: DeKalb (41° 84’ 37.6584” N, 88° 85’ 47.1821” W) – Elpaso silty clay loam (Fine-silty, mixed, superactive, mesic Typic Endoaquolls); Monmouth (40° 93’ 62.7528” N, 90° 72’ 26.3002” W) – Muscatune silt loam (Fine-silty, mixed, superactive, mesic Aquic Argiudolls); Urbana (40° 4’ 60.5561” N, 88° 23’ 29.8484” W) – Drummer silty clay loam (Fine-silty, mixed, superactive, mesic Typic Endoaquolls) and Brownstown (38° 95’ 17.5817” N, 88° 95’ 70.2839” W) – Cisne silt loam (Fine, smectic, mesic Mollic Albaqualfs) (USDA NRCS, 2013).

Nitrogen applications (main plots) consisted of four rates: 0, 90, 179, 269 kg N/ha, and all used urea ammonium nitrate (UAN) 28 (28-0-0) injected as a side-dress application prior to the V5 growth stage. Within each trial, individual plots consisted of four, 76-cm rows, 7 m in length. Planting rates (subplots) were 43,460, 83,980, and 123,500 plants/ha. Hybrids were assigned to sub-subplots. The four hybrids used were chosen in consultation with personnel from DuPont Pioneer, and were described as having the following characteristics: Pioneer 33D49 - 115 day relative maturity (RM), flex-ear, more responsive to N; Pioneer 33K44 – 114 day RM, flex-ear, less responsive to N; Pioneer 33W84 – 111 day RM, fixed-ear, more responsive to N; Pioneer 34F07 – 110 day RM, fixed-ear, less responsive to N.

All trials were conducted following a corn crop the previous year, and under conventional tillage, which consisted of fall primary tillage with a chisel plow and spring secondary tillage with a field cultivator or soil finisher. Both pre-emergence and post-emergence (applied as necessary) glyphosate applications were made to all trials in both years. Weed control by hand was also used throughout each growing season accordingly, by location.

Grain yield, NUE, SPAD meter measurements, and kernel weight were all variables assessed in this experiment. Grain yield (Mg/ha) was adjusted to 15% moisture upon harvest. We calculated NUE (kg/kg N) values by subtracting yield from yield at zero N, then divided grain yield by the rate of N applied. Single-photon avalanche diode (SPAD) values are a measure of chlorophyll using optical density difference at two wavelengths within the plant tissue assessed. Values were averages from ten readings within the center two rows of each plot, on the leaf subtending the top-most ear, at stage R2 using a Konica Minolta SPAD 502 Chlorophyll Meter (Konica Minolta Sensing Americas, Inc., Ramsey, NJ). Kernel weights were taken from a sample of 250 kernels. Kernel number per plant was obtained by calculation using grain yield, and was converted to number per m^2.

Statistical Analysis

Experimental models were analyzed using the MIXED procedure of SAS (SAS Institute Inc., 2011), taking N rate, plant density, and hybrid as fixed effects. The combination of locations and years (environments), blocks (nested within environments), and all interactions associated with these effects were considered random. Data from Brownstown in 2011 and 2012 were not included in combined analyses due to incomplete data in 2011 and site abandonment in 2012, both attributable to drought stress. The six environments were merged into two data sets as a result of high covariance parameter estimates associated with random effects indicating high random variation, in addition to differences in yield levels. The environments were categorized as either "high-stress" or "low-stress." DeKalb-2012, Urbana-2011, and Urbana-2012 composed the high-stress set, while the low-stress set consisted of DeKalb-2011, Monmouth-2011, and Monmouth-2012. Brownstown-2011 was evaluated as a single environment. Data sets were then reanalyzed to evaluate responses of variables across varying levels of stress.

For each variable, linear, quadratic, and quadratic + plateau regression functions were calculated for N rate and plant density effects, in addition to the N rate x plant density interaction using the MIXED procedure of SAS (SAS Institute Inc., 2011). Quadratic + plateau regression functions were generated using the NLIN procedure of SAS (SAS Institute Inc., 2011). The regression functions were used to distinguish which treatments provided optimum value for each variable. Hybrid and the plant density x hybrid interaction were evaluated using a LSD of 0.10 across all variables.

An analysis of costs and returns for seed and N was conducted, using an N price of $1.57 per kg ($400 per U.S. ton of 28-0-0), a seed price of $0.0035 per kernel ($280 per 80,000-kernel unit), and a corn price of $276 per Mg ($7.00 per bushel).

RESULTS AND DISCUSSION

Weather conditions differed widely among these sites during the 2011 and 2012 growing seasons, resulting in a wide range of stress levels and grain yields. At Brownstown in 2011, root damage from early season rainfall (302 mm in June) followed by mid to late-season dryness severely limited yields. Below-average rainfall (Table 1) and above-average temperatures (Table 2) lowered yields in 2011 at Urbana, and in 2012 at DeKalb and Urbana. At Brownstown in 2012, severe stress resulted in no harvestable yield, and the trial was abandoned.

At Urbana, July temperatures were well above average (+3.0 and +3.8°C) and rainfall below average (-80 and -105 mm) in 2011 and 2012, respectively, resulting in significantly lowered yields both years (5.7 Mg/ha in 2011, 5.8 Mg/ha in 2012). Below-average precipitation (Table 1) in DeKalb in July and August of 2012 (-49 and -50 mm) likely was the reason for reduced yields (8.2 Mg/ha) at this location. In contrast, stress in 2011 at Monmouth and DeKalb and in 2012 at Monmouth was relatively mild, and yields were good at these three sites (11.1 Mg/ha at DeKalb-2011, 11.1 Mg/ha at Monmouth-2011, 10.3 Mg/ha at Monmouth-2012). In addition, early season weather conditions affected corn stand (Table 3) in some environments (DeKalb-2011), although yield was minimally affected.

Table 1. Total monthly precipitation and departure from 30-year (1981-2010) monthly average, for the four trial sites in 2011 and 2012 (Illinois Climate Network, 2013).

Precipitation Totals				
Month	Brownstown	DeKalb	Monmouth	Urbana
	---------------------------------- mm	----------------------------------		
2011				
May	51 (-87)	220 (+104)	172 (+51)	122 (-2)
June	302 (+197)	106 (+1)	175 (+61)	107 (-4)
July	97 (-5)	101 (-10)	53 (-52)	40 (-80)
August	12 (-64)	109 (-2)	12 (-109)	45 (-55)
September	86 (+5)	97 (+14)	73 (-22)	71 (-9)
2012				
May	113 (-25)	81 (-35)	119 (-2)	90 (-34)
June	25 (-80)	19 (-87)	120 (+6)	46 (-64)
July	1 (-101)	62 (-49)	14 (-90)	14 (-105)
August	227 (+151)	61 (-50)	92 (-28)	142 (+42)
September	188 (+107)	39 (-44)	119 (+24)	142 (+63)

Table 2. Monthly mean temperature and departure from 30-year (1981-2010) monthly average, for the four trial sites in 2011 and 2012 (Illinois Climate Network, 2013).

Average Monthly Temperature				
Month	Brownstown	DeKalb	Monmouth	Urbana
	---------------------------------- ° C ----------------------------------			
2011				
May	17.5 (-1.1)	15.1 (-0.1)	16.3 (0.0)	16.9 (0.0)
June	23.4 (-0.5)	21.1 (+0.3)	21.4 (0.0)	22.8 (+0.5)
July	26.6 (+1.3)	24.6 (+1.8)	25.7 (+2.6)	26.8 (+3.0)
August	24.2 (+0.1)	21.2 (-0.6)	22.9 (+0.5)	24.1 (+1.1)
September	17.5 (-2.5)	14.9 (-2.5)	15.8 (-2.3)	17.5 (-1.5)
2012				
May	21.1 (+2.5)	18.4 (+3.2)	19.6 (+3.3)	20.5 (+3.6)
June	23.0 (-0.9)	21.7 (+0.9)	21.9 (+0.5)	22.7 (+0.4)
July	28.2 (+2.9)	24.8 (+2.0)	25.9 (+2.8)	27.6 (+3.8)
August	23.4 (-0.7)	20.9 (-0.9)	21.9 (-0.5)	23.1 (+0.1)
September	18.2 (-1.8)	15.7 (-1.7)	16.5 (-1.6)	17.8 (-1.2)

Table 3. Plant stand as percent of planted seed number, by environment.

	Seeding Rate (plants/ha)		
Environment	44,460	83,980	123,500
	------------------ % Stand -----------------		
Brownstown, 2011	97%	96%	96%
Brownstown, 2012	98%	95%	94%
DeKalb, 2011	92%	91%	89%
DeKalb, 2012	101%	98%	98%
Monmouth, 2011	96%	96%	93%
Monmouth, 2012	99%	97%	95%
Urbana, 2011	99%	98%	97%
Urbana, 2012	100%	98%	98%

Table 4. Analysis of variance for grain yield (Mg/ha) for six environments and grouped into three high-stress environments (DK-12, UR-11, UR-12) and three low-stress environments (DK-11, MN-11, MN-12). Brownstown 2011 (BT-11) is analyzed as a separate environment.

Source	All	High-Stress	Low-Stress	BT-11
N rate (N)	***	***	***	**
Density (D)	**	***	***	*
N*D	***	**	***	NS
Hybrid (H)	**	*	**	NS
N*H	NS	NS	NS	NS
D*H	***	**	**	**
N*D*H	NS	NS	NS	NS

*Significant at p = 0.10

**Significant at p = 0.05

***Significant at p = <0.0001

†NS = Not significant at p = 0.10

Grain Yield

Main effects of N rate, plant density, and hybrid, and plant density x hybrid and N rate x plant density interactions were significant ($p < 0.10$) across six environments for grain yield (Table 4). Response to N was fitted by a quadratic + plateau function (Figure 1), where a yield plateau (9.9 Mg/ha) was reached at 154 kg N/ha. Across N rates and hybrids, yield reached a maximum of 9.3 Mg/ha at a plant density of approximately 80,600 plants/ha (Figure 2). Overall hybrid response indicated that the more N responsive hybrids (33D49, 33W84) yielded significantly higher than those hybrids less responsive to N (33K44, 34F07) (Figure 3).

Evaluation of hybrids across plant densities confirmed that flex-ear hybrids tend to generate higher yields at lower plant densities, as both 33D49 and 33K44 did not show any significant difference between the low and middle densities (Figure 4). Yield of the flex-ear hybrids did not change significantly from the low to the middle density, but dropped from the middle to the high density (-1.2 Mg/ha with 33D49, -1.3 Mg/ha with 33K44). In contrast, the fixed-ear hybrids (33W84, 34F07) produced significantly higher yields (+1.1 and +1.4 Mg/ha, respectively) at the middle density compared to the low density, but yield dropped (-1.3 and -1.0 Mg/ha) from the middle to the high density (Figure 4).

Across all hybrids, yields responded very similarly to N rate above 90 kg N/ha at the low and high densities (Figure 5). Fitted with quadratic + plateau functions, the yield reached a maximum (9.2 Mg/ha) at 136 kg N/ha at the low density, while the yield plateaued at 9.6 Mg/ha at 151 kg N/ha at the high density. The middle density generated the largest response to N and the highest yield, with the yield plateau (10.9 Mg/ha) reached at 164 kg N/ha (Figure 5).

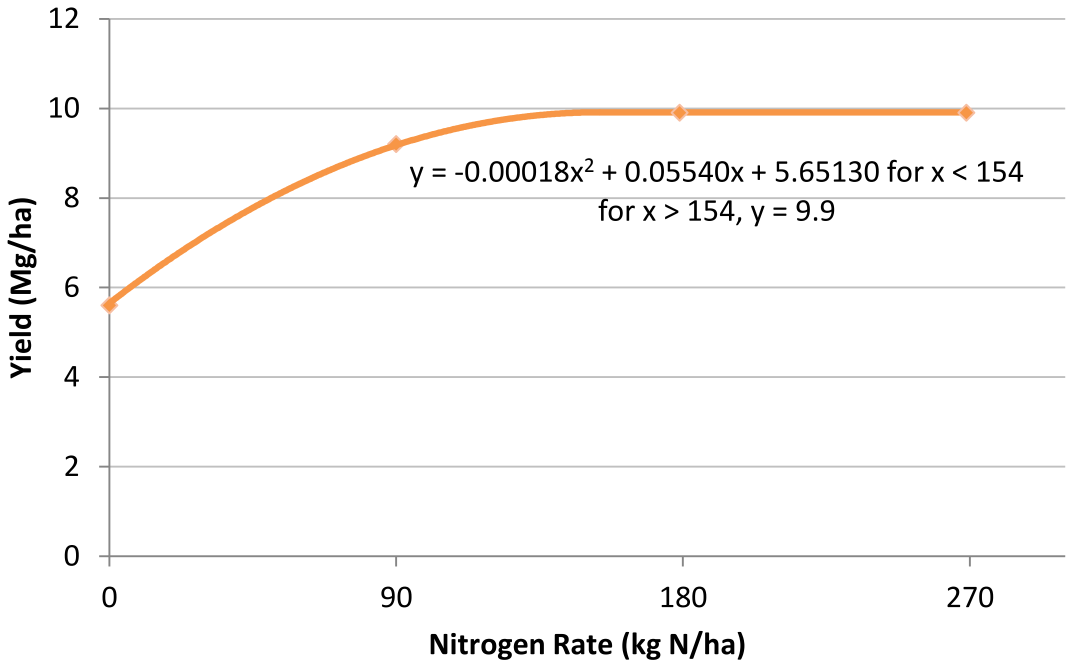

Figure 1: Quadratic + Plateau response function of yields to N rate averaged over four hybrids and three plant densities across all environments.

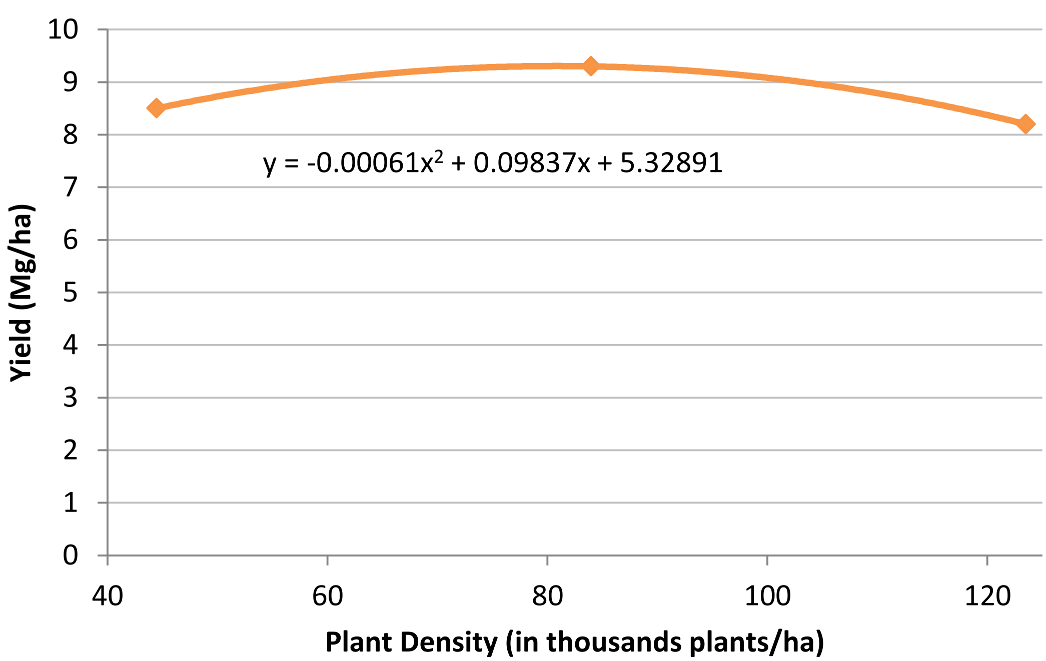

Figure 2: Quadratic response function of yields to plant density averaged over four N rates and four hybrids across all environments.

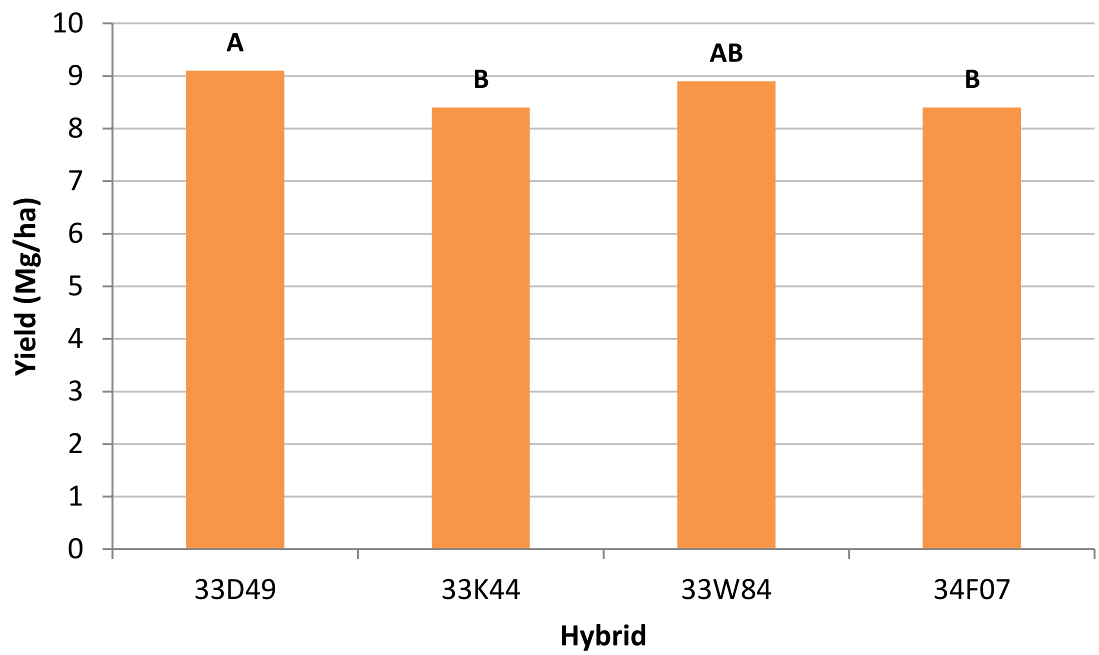

Figure 3: Yields of hybrids averaged over four N rates and three plant densities across all environments. Letters separate means at α = 0.10.

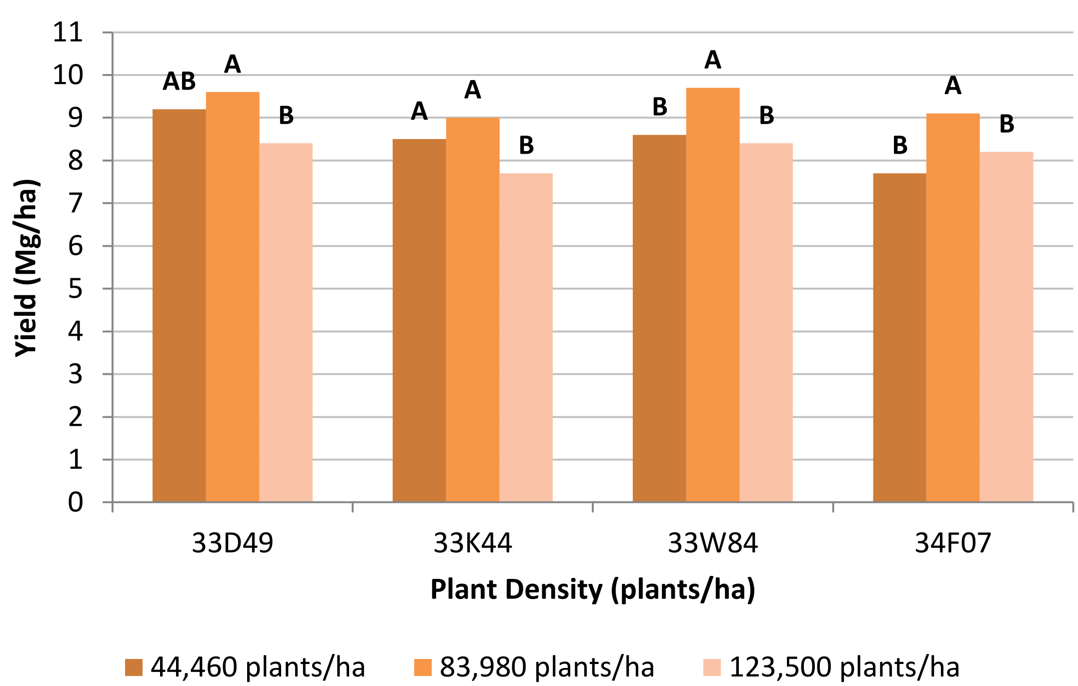

Figure 4: Yield response to plant density and hybrid averaged over four N rates across all environments. Letters separate means within each hybrid at α = 0.10.

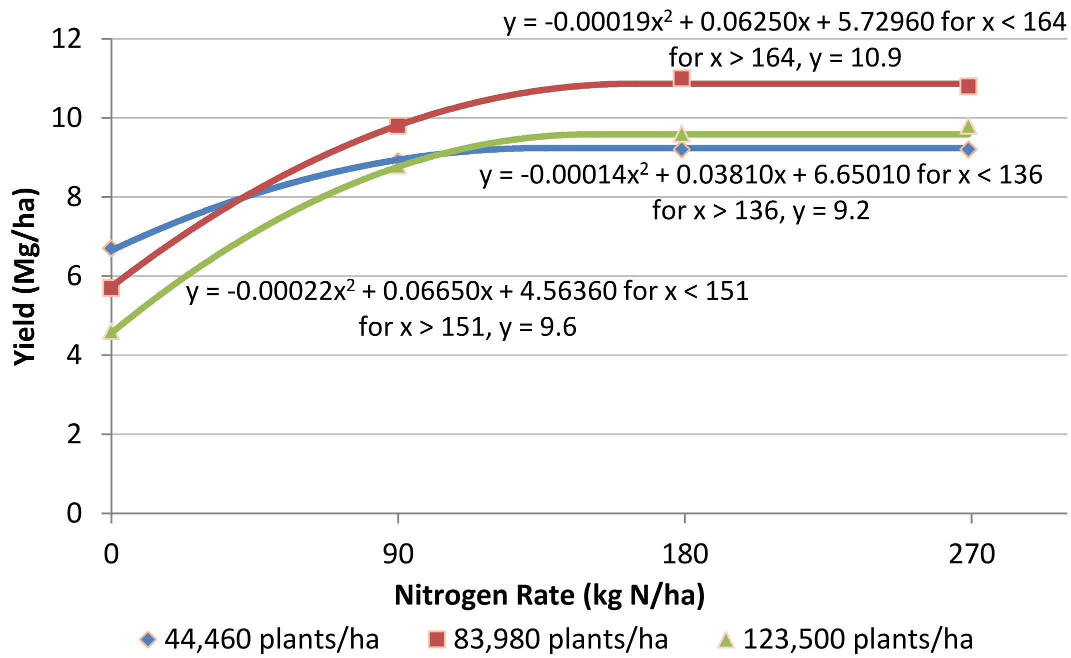

Figure 5: Quadratic + plateau response functions of yield to N rate at three plant densities averaged over four hybrids across all environments.

Hybrid differences were only related to the N responsiveness characteristic, as there was no advantage for selecting either fixed-ear or flex-ear hybrids across all environments. The apparent difference was that flex-ear hybrids responded higher at low densities in comparison to fixed-ear hybrids, likely due to their ability to enhance production under low stress conditions. Weather conditions across all sites certainly minimized any differences that may have been observed between hybrids, as flex-ear hybrids are inclined to react to more ideal conditions with greater yields, and fixed-ear hybrids typically maintain yields better under more stressful conditions. Additionally, N responsiveness was greatest at the middle density, indicating that no yield increase occurred above 164 kg N/ha. The low and high density revealed even lower response to N, as maximum yield levels were achieved at 136 and 151 kg N/ha respectively. These results justify that maximum yields were achieved with response to N below the approximate MRTN rate of 200-240 kg N/ha (Sawyer et al., 2006) and the optimal plant density (80,600 plants/ha) slightly below suggested rates (81,000-95,000 plants/ha) (Van Roekel and Coulter, 2012; Widdicombe and Thelen, 2002).

Results may not represent N rate, plant density, and hybrid responses that would be observed under more ideal growing conditions due, to dissimilarities in weather conditions. As previously mentioned, when hybrids were analyzed across all environments, there was no significant advantage for fixed-ear hybrids vs. flex-ear hybrids. This would not necessarily be the case if these hybrids were evaluated under varying degrees of stress. Much like hybrids, great variations of environmental conditions likely had significance on N response levels and plant density responses. As a result, environments were evaluated in separate data sets to determine if varying stress levels altered responses of different effects.

High-Stress Environments: Urbana 2011 and 2012, DeKalb 2012

In the data set made up of the high-stress environments, main effects of N rate, plant density, and hybrid were significant, as were the N rate x plant density and plant density x hybrid interactions (Table 4). Yields averaged over hybrids and plant densities responded in a way best fit by the quadratic + plateau function, reaching a maximum (7.4 Mg/ha) at 136 kg N/ha (Figure 6). Yield response to plant density fitted to a quadratic function indicated that yield was maximized (7.5 Mg/ha) at approximately 51,000 plants/ha, near the lowest density used, and dropped to 5.2 Mg/ha at 123,500 plants/ha (Figure 7). Drought stress encountered in all environments was likely the reason for the low density produced higher yields than the middle or high density, due to fewer plants competing for restricted water. Hybrids differed as well; the two fixed-ear hybrids

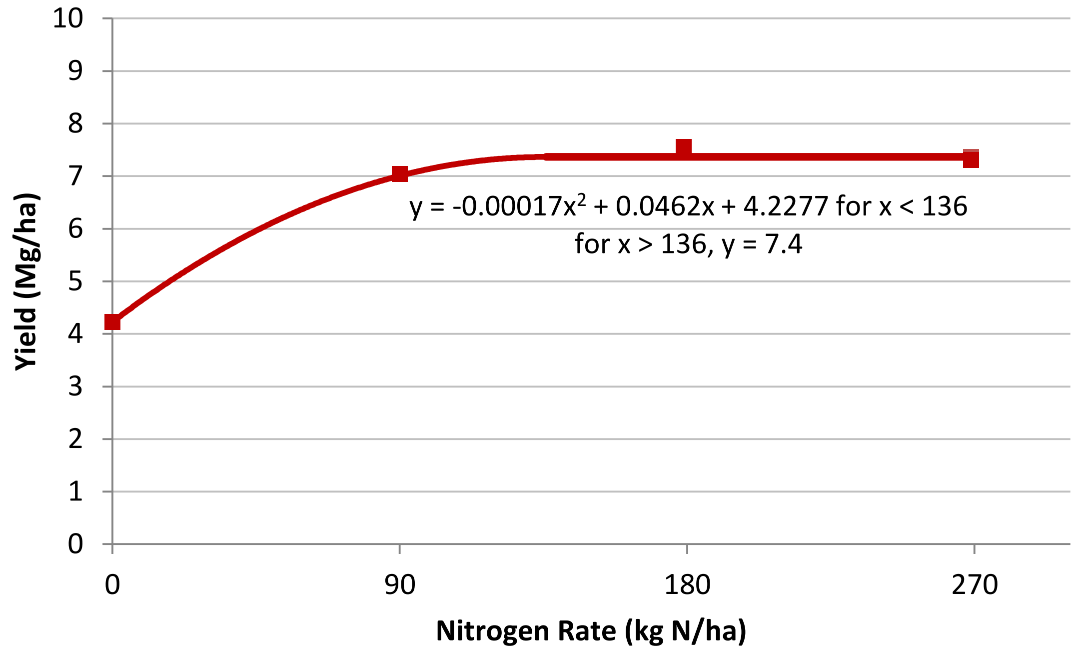

Figure 6: Quadratic + plateau response function of yield to N rate averaged over four hybrids and three plant densities at high-stress environments.

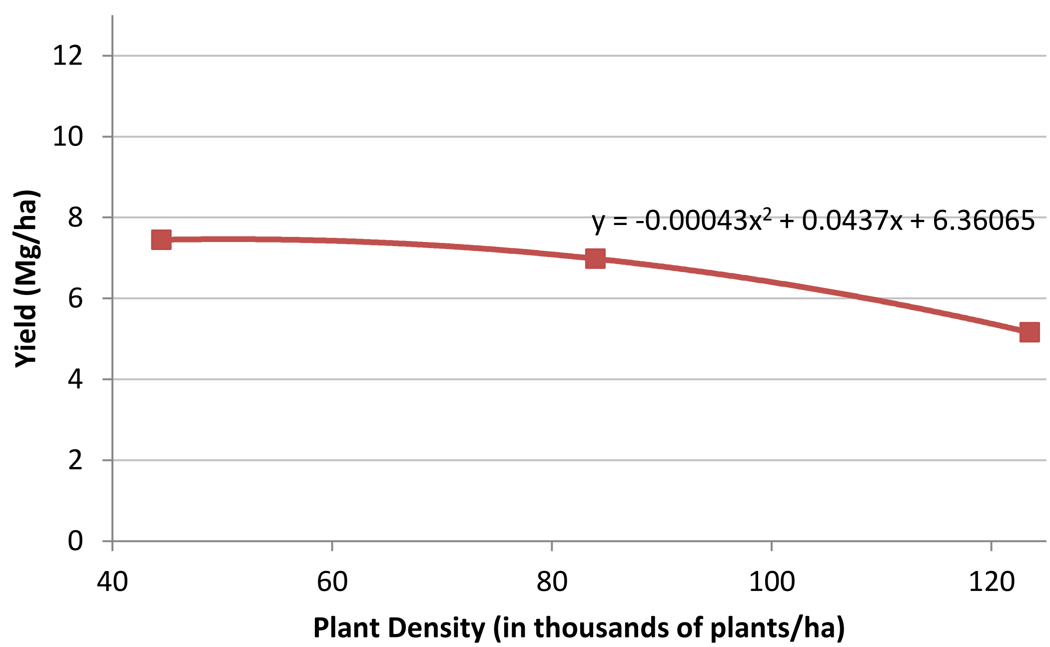

Figure 7: Quadratic response function of yields to plant density averaged over four hybrids and four N rates at high-stress environments.

(33W84, 34F07) produced higher yields (6.9 Mg/ha) than the flex-ear hybrids (6.3 Mg/ha) across all N rates and plant densities (Figure 8). The hybrid 33W84, which is considered more responsive to N, yielded significantly more than 34F07 across all N rates and densities (Figure 8).

The yield response to N averaged across the four hybrids was fitted to a quadratic + plateau function for both low and high densities (Figure 9). Yield reached a plateau (8.1 Mg/ha) at 133 kg N/ha at the low density, and at 102 kg N/ha (5.9 Mg/ha) at the high density. Response to nitrogen was the greatest at the intermediate plant density, which showed a quadratic response to N with highest yield (8.7 Mg/ha) at 188 kg N/ha.
The plant density x hybrid interaction occurred largely because the fixed-ear hybrids (33W84, 34F07) demonstrated little yield change from the low to the middle plant densities, before yields dropped from the middle to high density (Figure 10). Correspondingly, flex-ear hybrids demonstrated a decrease in yield from the low to the middle density, with further decrease from middle to high density (Figure 10).

These results indicate that the low and medium densities were most suitable for greater yields under high-stress conditions. Judging the yield response at each density among a wide range of N rates revealed marginal yield increase above 90 kg N/ha, with the exception of the middle density, which demonstrated increase to 179 kg N/ha. While flex-ear hybrids yielded relatively more than fixed-ear hybrids at low density, they also tend to lose yield faster at higher densities under stress conditions. Fixed-ear hybrids thus had relatively higher yields at the middle (more typical) density, but absolute yields were not so different between the hybrid types at middle and high densities, and it is not clear that either type has much advantage over the other at typical planting densities.

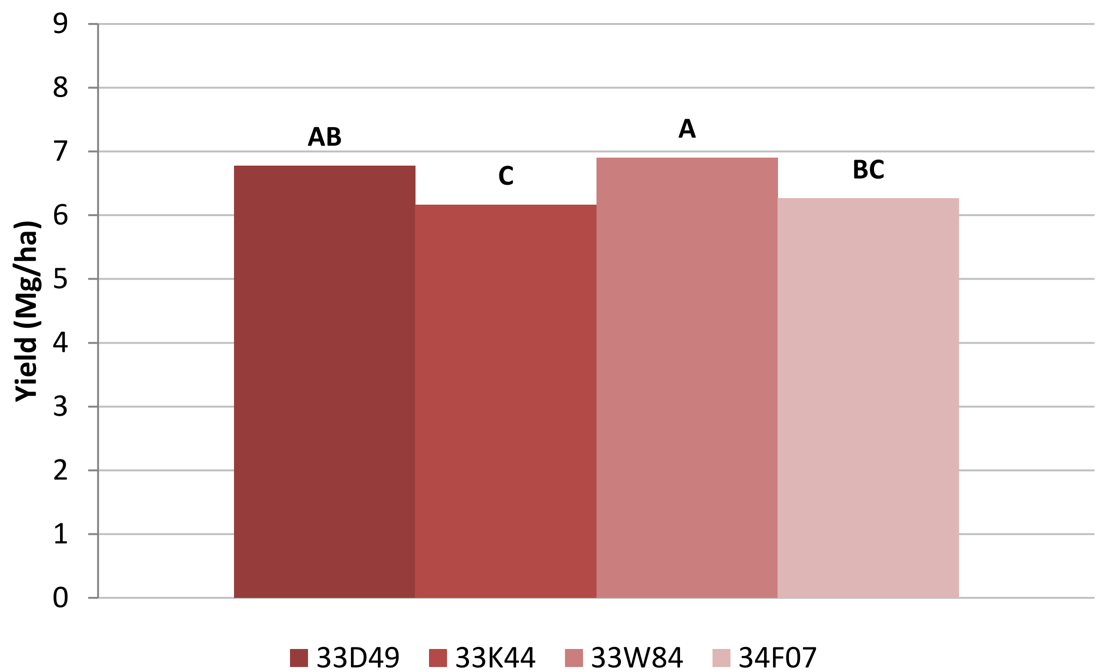

Figure 8: Yield of hybrids averaged over four N rates and three plant densities at high-stress environments. Letters separate means at α = .10.

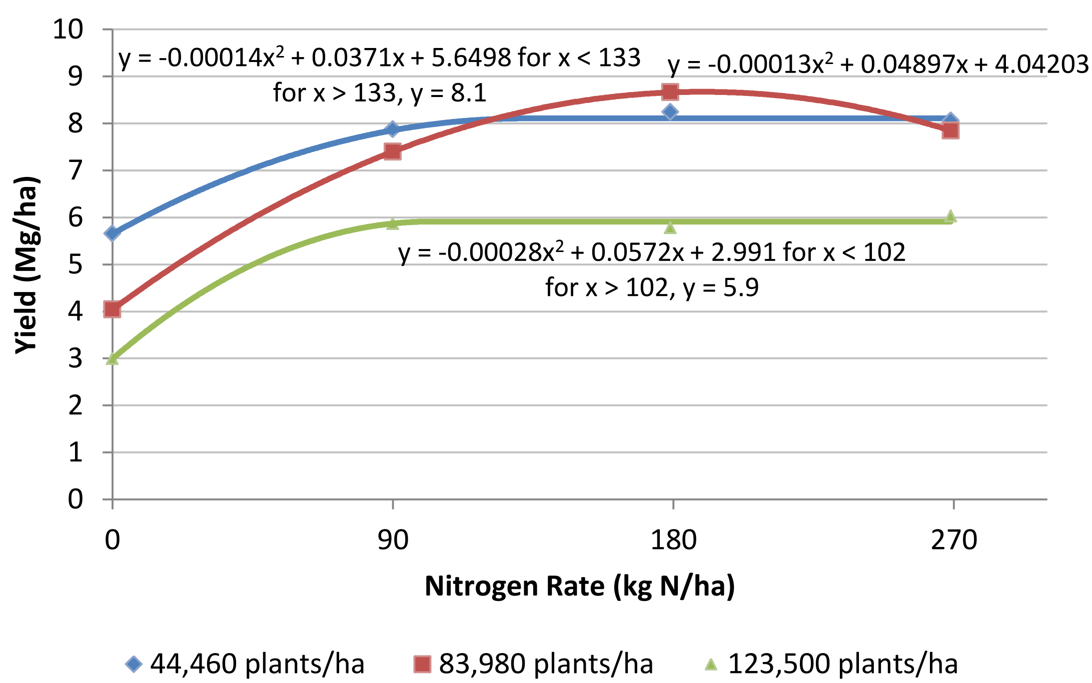

Figure 9: Quadratic + plateau response functions of yield to N rate at low and high densities averaged over four hybrids; quadratic response function of yields to N rate at the middle density averaged over four hybrids, at high-stress environments.

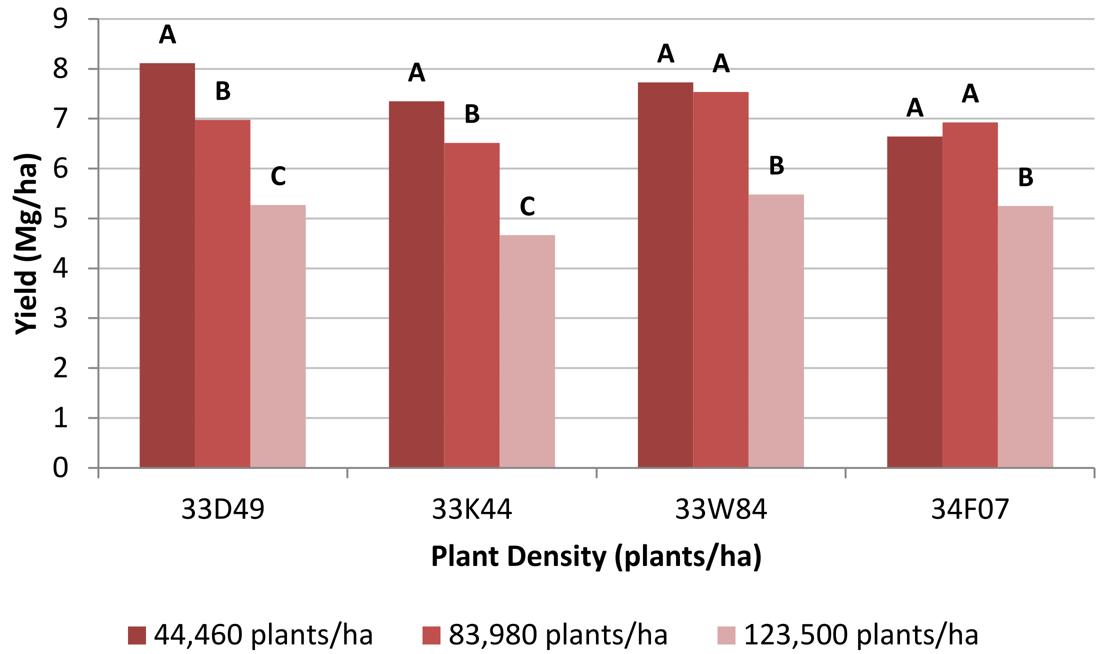

Figure 10: Yield response to plant density and hybrids averaged over four N rates at high-stress environments. Letters separate means within each hybrid at α = .10.

Low-Stress Environments: Monmouth 2011 and 2012, DeKalb 2011

The low-stress environments, with yields averaging about 60% more than the high-stress environments, produced significant N rate, plant density, and hybrid main effects, as well as N rate x plant density and plant density x hybrid interactions (Table 4). Yields increased in a curvilinear fashion as N rate increased, with the maximum yield (across densities and hybrids) of 12.5 Mg/ha reached at 164 kg N/ha (Figure 11), and a flat response thereafter. Across N rates and hybrids, yield reached a maximum (11.8 Mg/ha) at a plant density of about 96,000 plants/ha (Figure 12). Across N rates and densities, flex-ear hybrids (33D49, 33K44) produced greater yields than fixed-ear hybrids (33W84, 34F07) (Figure 13).

Across hybrids, the interaction between nitrogen rate and plant density resulted from different responses to N rate at the two higher densities compared to the response to

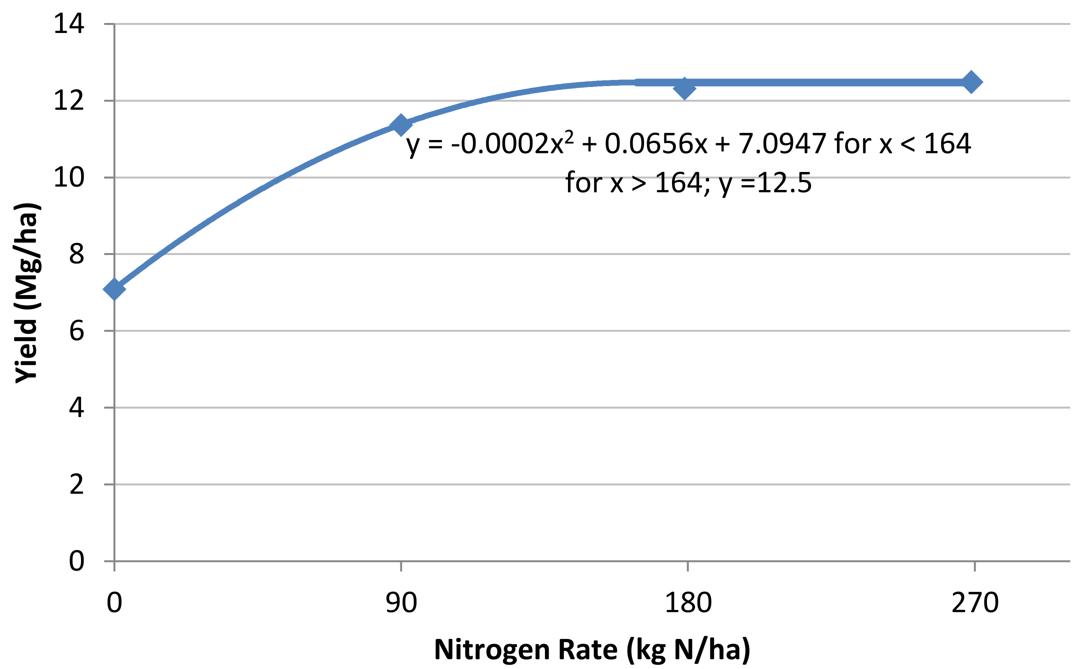

Figure 11: Quadratic + plateau response function of yield to N rate averaged over four hybrids and three plant densities at low-stress environments.

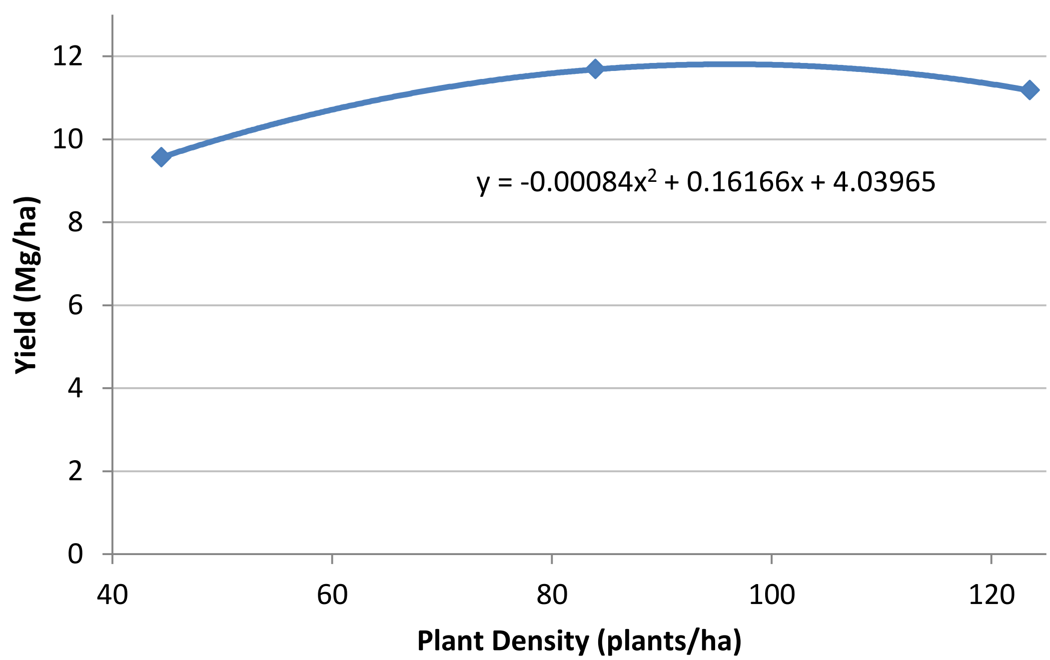

Figure 12: Quadratic response function of yield to plant density averaged over four hybrids and four N rates at low-stress environments.

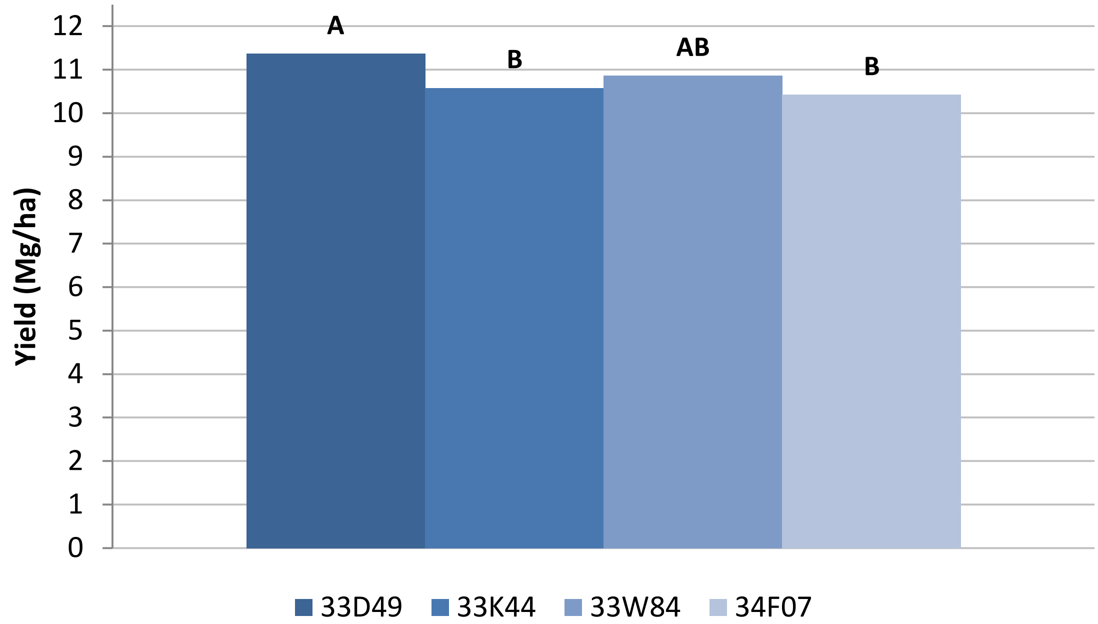

Figure 13: Yield of hybrids averaged over four N rates and three plant densities at low-stress environments. Letters separate means at α = .10.

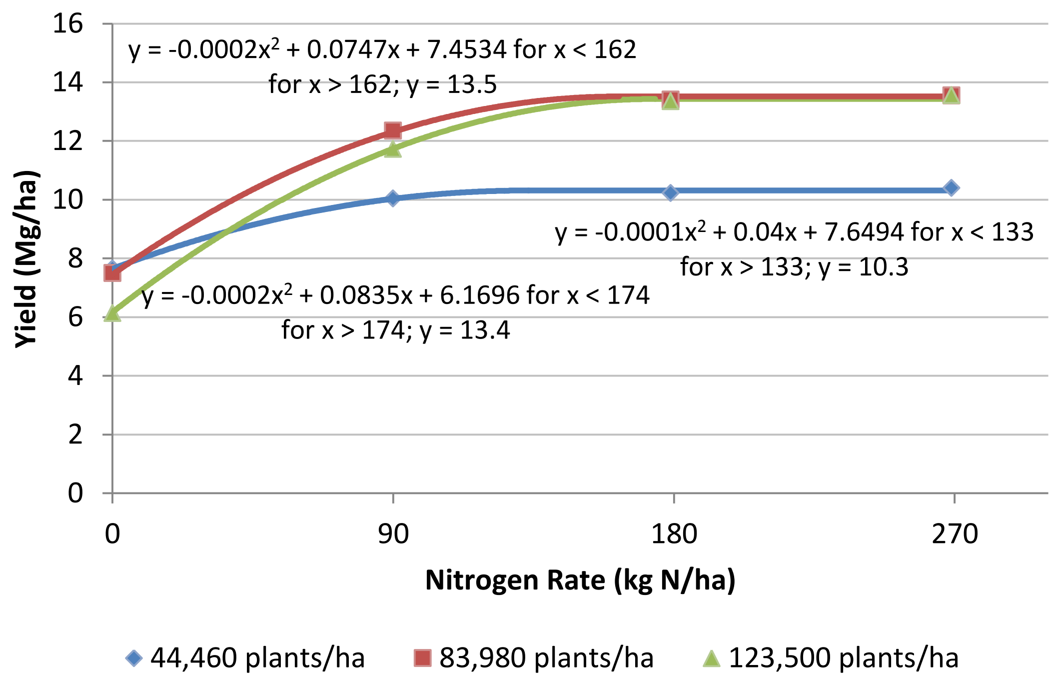

Figure 14: Quadratic + plateau response functions of yield to N rate at all plant densities, averaged over four hybrids, at low-stress environments.

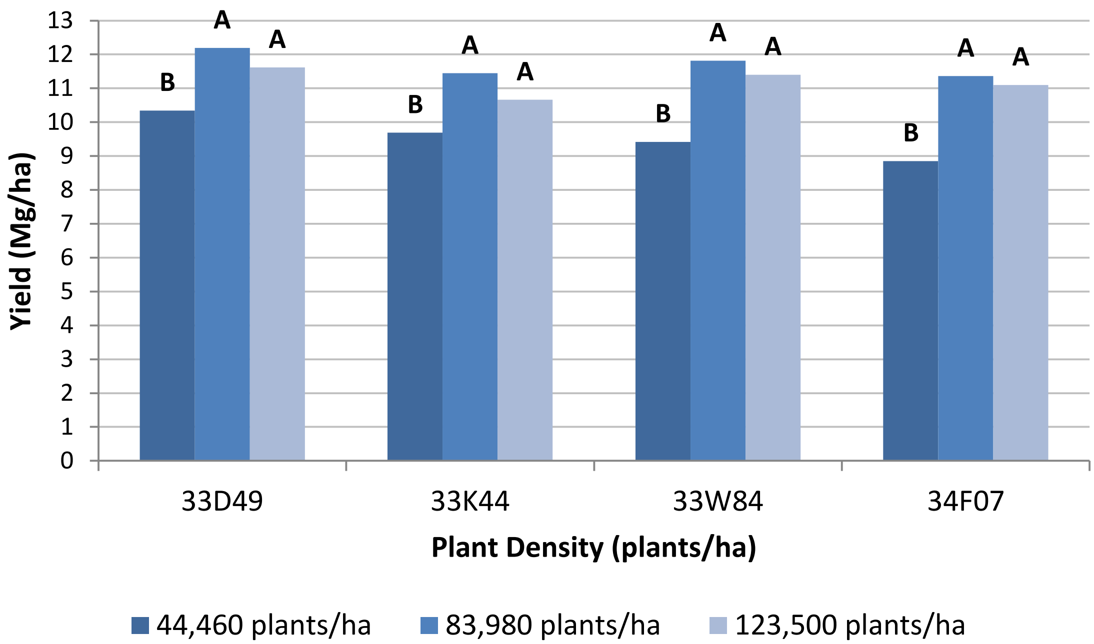

Figure 15: Yield response to plant density and hybrids averaged over four N rates at and Low-stress environments. Letters separate means within each hybrid at α = .10.

lower density (Fig. 14). Yield at the middle density reached a plateau of 13.5 Mg/ha at 162 kg N/ha, while at the highest density yield reached a plateau of 13.4 Mg/ha at 174 kg N/ha (Figure 14). At the lowest density, yield reached a plateau of only 10.3 Mg/ha at only 133 kg N/ha (Figure 14).

A plant density x hybrid interaction occurred, reflecting the fact that the flex-ear hybrids (33D49, 33K44) generated greater yields at the lowest density in comparison to the fixed-ear hybrids (Figure 15). However, both fixed-ear and flex-ear hybrids produced similar yield between the medium and high density, as there was no significant change for any hybrid. The two hybrids deemed more responsive to N (33D49, 33W84) outperformed the other hybrids (33K44, 34F07) at the higher densities, but not consistently at the low density (Figure 15).

Brownstown, 2011

Main effects of N rate and plant density were significant, in addition to the plant density x hybrid interaction at Brownstown in 2011 (Table 4). Yield responded linearly to N rate, reaching a maximum value of 5.1 Mg/ha at the 269 kg N rate (Figure 16). This response was somewhat unusual, as yield plateau will typically occur at a certain N level. It is likely that restricted root growth following heavy rain, along with denitrification, limited the availability of N to the crop, resulting in both low yields and the linear response to N. Increased plant density resulted in lower yields, as the overall yield dropped from 3.6 Mg/ha to 2.4 Mg/ha when transitioning from the low density to the high density (Figure 17). Limited nutrient availability likely led to the more competitive, higher densities producing lower yields. There was a plant density x hybrid interaction, resulting in some inconsistent responses between the two fixed-ear hybrids (33W84 and 34F07) and the flex-ear hybrids (33D49, 33K44) (Figure 18). The low density did produce the highest yields across all hybrids; however, 33D49 and 34F07 were not significantly different at the middle density. Yield responses from Brownstown in 2011 suggest that increases of N rate and reduced plant densities lead to greater yields. Due to missing yield data attributable to weather conditions and the overall lack of significant effects, it seems logical that this data provides little support for conclusions drawn from other environments.

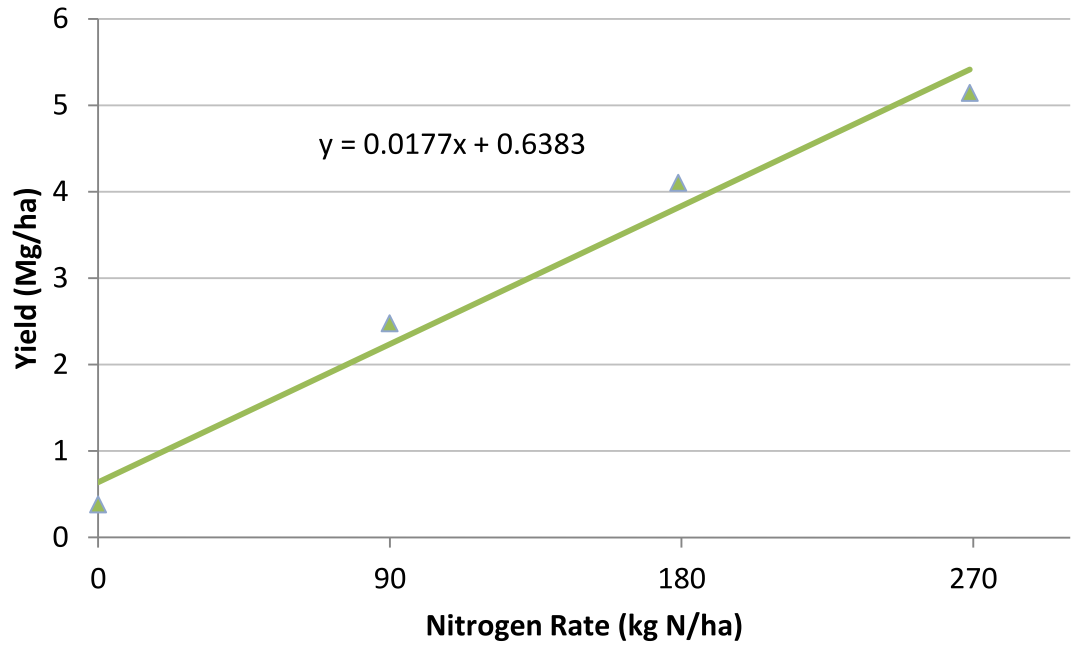

Figure 16: Response function of yield to N rate averaged over four hybrids and three plant densities at Brownstown, 2011.

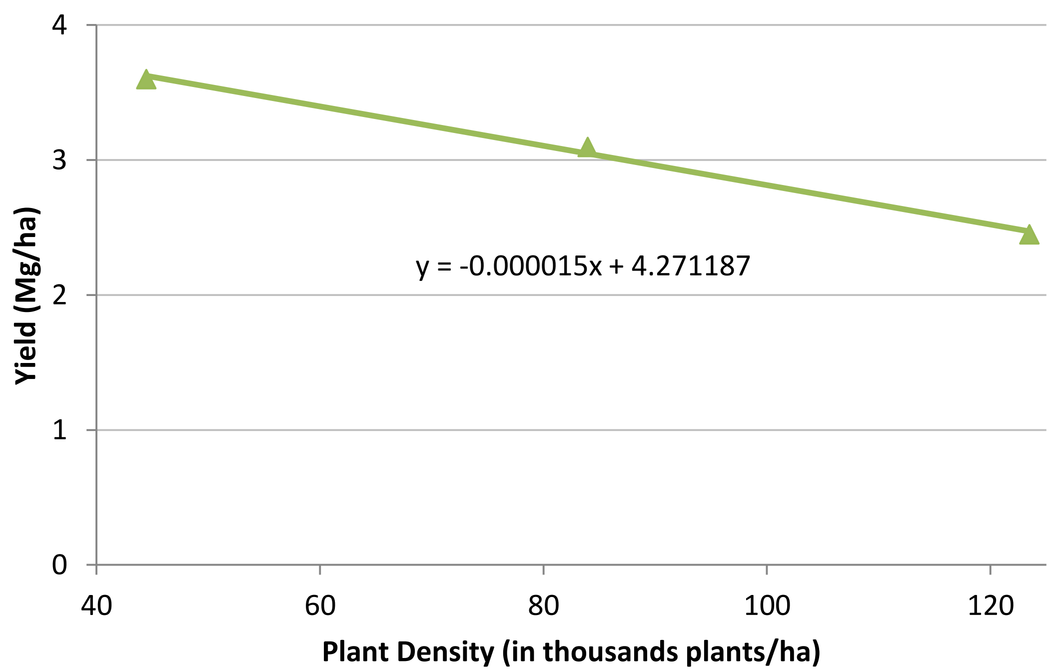

Figure 17: Response function of yield to plant density averaged over four hybrids and four N rates at Brownstown, 2011.

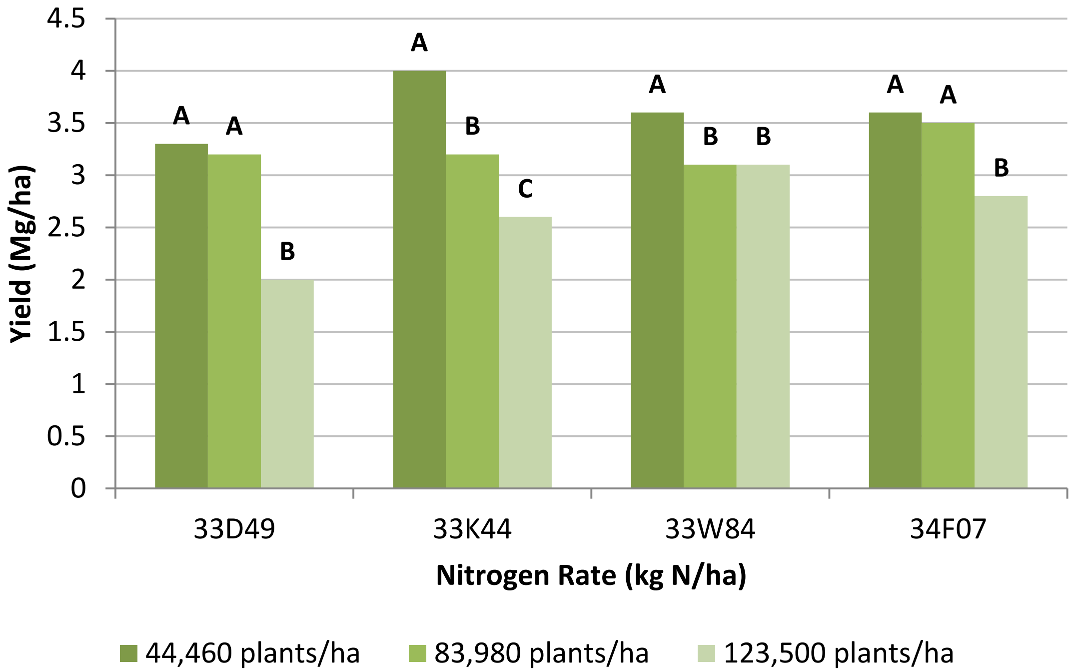

Figure 18: Yield response to hybrids and N rate averaged over three plant densities at Brownstown, 2011. Letters separate means within each hybrid at α = 0.10.

Nitrogen Use Efficiency

Effects of N rate, plant density, and hybrid, as well as N rate x plant density and plant density x hybrid interactions were significant ($p < 0.10$) for NUE, calculated as yielded divided by N rate for all N rates greater than zero (Table 5). There was a curvilinear decrease in NUE as N rates increased, with the highest NUE value of 39.4 kg/kg N at the 90 kg N/ha rate (Figure 19). Plant density response across all N rates and hybrids resulted in the highest NUE value for the middle density (Figure 20). Fitted with a quadratic function, maximum NUE was obtained at 84,900 plants/ha, which was nearly the exact same as the middle density used (83,980 plants/ha).

Fitting of quadratic + plateau functions to all plant densities across three N rates reveals that both the low and high densities used resulted in nearly identical NUE values with each increasing N rate, while the middle density demonstrated the highest NUE values across all N rates (Figure 21). All NUE values across all three plant densities decreased curvilinearly from 90 to 270 kg N/ha. The plant density x hybrid interaction demonstrated that all hybrids produced maximum NUE at the middle density, as the low and high densities did not have significantly different NUE in either 33D49 or 33W84 (Figure 22).

Table 5. Analysis of variance for NUE (kg/kg N) for six environments and grouped into three high-stress environments (DK-12, UR-11, UR-12) and three low-stress environments (DK-11, MN-11, MN-12). Brownstown 2011 (BT-11) is analyzed as a separate environment.

Source	All	High-Stress	Low-Stress	BRN-11
N rate (N)	***	***	***	NS
Density (D)	**	***	***	**
N*D	**	**	***	NS
Hybrid (H)	**	**	**	**
N*H	NS	NS	NS	**
D*H	***	**	***	*
N*D*H	NS	NS	NS	NS

*Significant at p = 0.10

**Significant at p = 0.05

***Significant at p = <0.0001

†NS = Not significant at p = 0.10

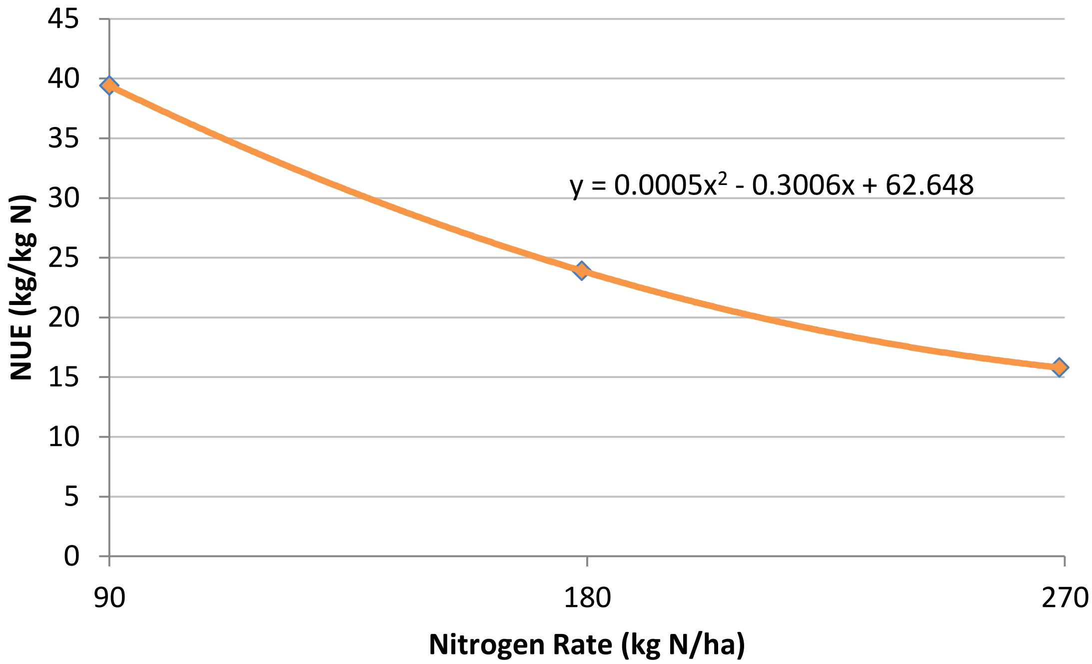

Figure 19: Quadratic function of NUE to N rate averaged over four hybrids and three plant densities across all environments.

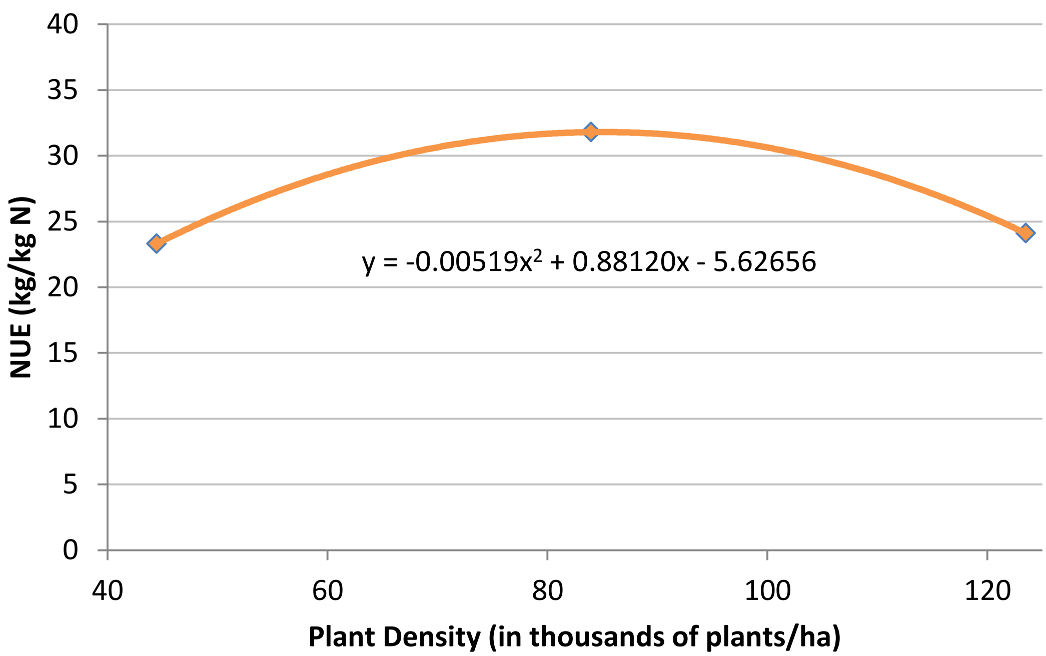

Figure 20: Quadratic function of NUE to plant density averaged over four hybrids and four N rates across all environments.

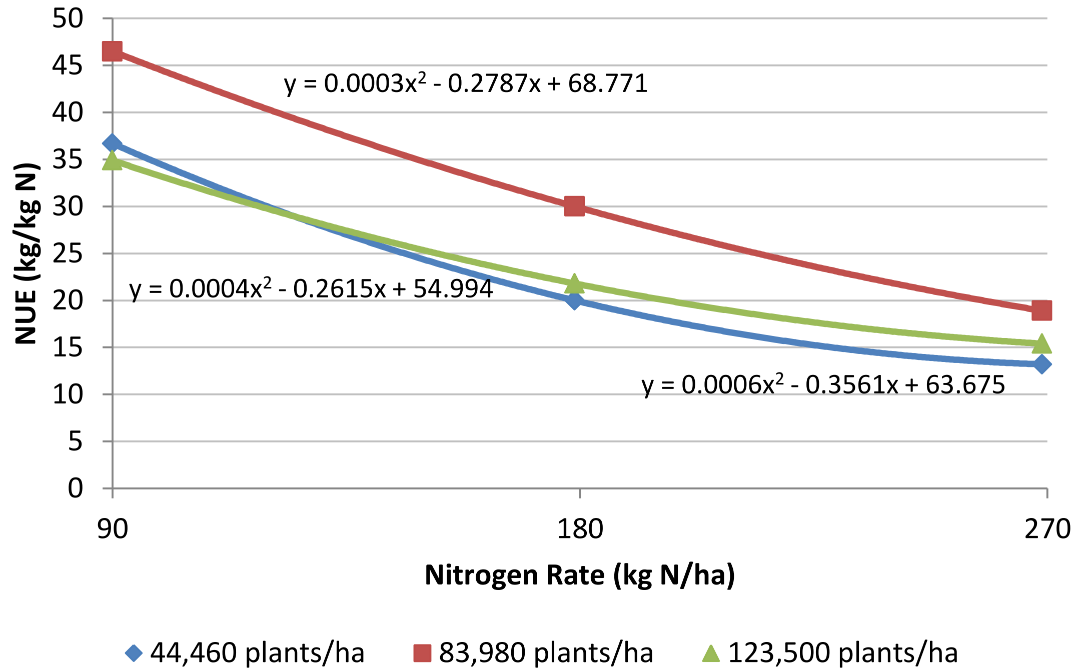

Figure 21: Quadratic functions of NUE to N rate at all plant densities, averaged over four hybrids, across all environments.

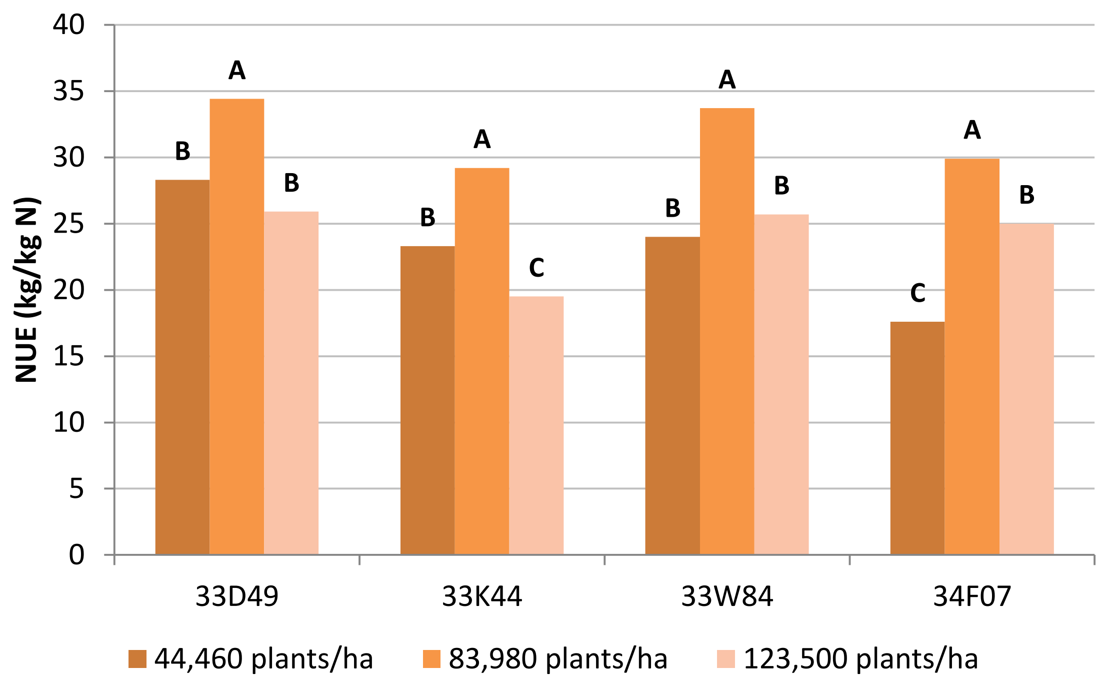

Figure 22: Yield response to plant density and hybrids averaged over four N rates across all environments. Letters separate means across hybrids at $\alpha = .10$.

SPAD Measurement

Yield and SPAD values were highly correlated over N rates within high-stress and low-stress environments (Figure 23). Increases in N rate generally led to increases in relative chlorophyll content, and greater relative chlorophyll content was associated with greater yields. SPAD and yield were positively correlated by plant density for the high-stress environments, as lower plant densities generated greater SPAD values in addition to higher yields (Figure 24). In contrast, the low-stress data were negatively correlated, where decreases in plant density did in fact lead to greater SPAD values, however, yields were reduced as SPAD values increased. There was a SPAD-yield correlation among hybrids across high-stress (high correlation) and low-stress (moderate correlation) environments, as hybrids more responsive to N (33D49 and 33W84) generated higher SPAD values in addition to higher yields (Figure 25). Interestingly, the flex-ear hybrid (33D49) produced higher yields and more relative chlorophyll content in the low-stress environments, in comparison to the high-stress environments, where the fixed-ear hybrid (33W84) produced higher yields and SPAD values when yield and SPAD were correlated.

The high-stress (highly correlated) and low-stress (moderately correlated) data also produced N rate x plant density interactions. The low and middle densities generally produced better yield and SPAD values as N rates increased in the high stress data (Figure 26). Yet, the low-stress data resulted in the middle and high densities producing the highest yields, while the low density developed greater SPAD values as N rate was increased (Figure 27). While low densities favored the formation of the highest SPAD values in both the high-stress and low-stress environments, more desirable growing conditions likely contributed to the middle and high densities yielding greater under low

Table 6. Analysis of variance for SPAD values at R2 for six environments and grouped into three high-stress environments (DK-12, UR-11, UR-12) and three low-stress environments (DK-11, MN-11, MN-12). Brownstown 2011 (BT-11) is analyzed as a separate environment.

Source	All	High-Stress	Low-Stress	BRN-11
N rate (N)	***	***	***	***
Density (D)	***	***	***	***
N*D	***	***	***	**
Hybrid (H)	***	***	***	***
N*H	**	NS	NS	**
D*H	NS	NS	NS	NS
N*D*H	NS	NS	NS	NS

*Significant at p = 0.10

**Significant at p = 0.05

***Significant at p = <0.0001

†NS = Not significant at p = 0.10

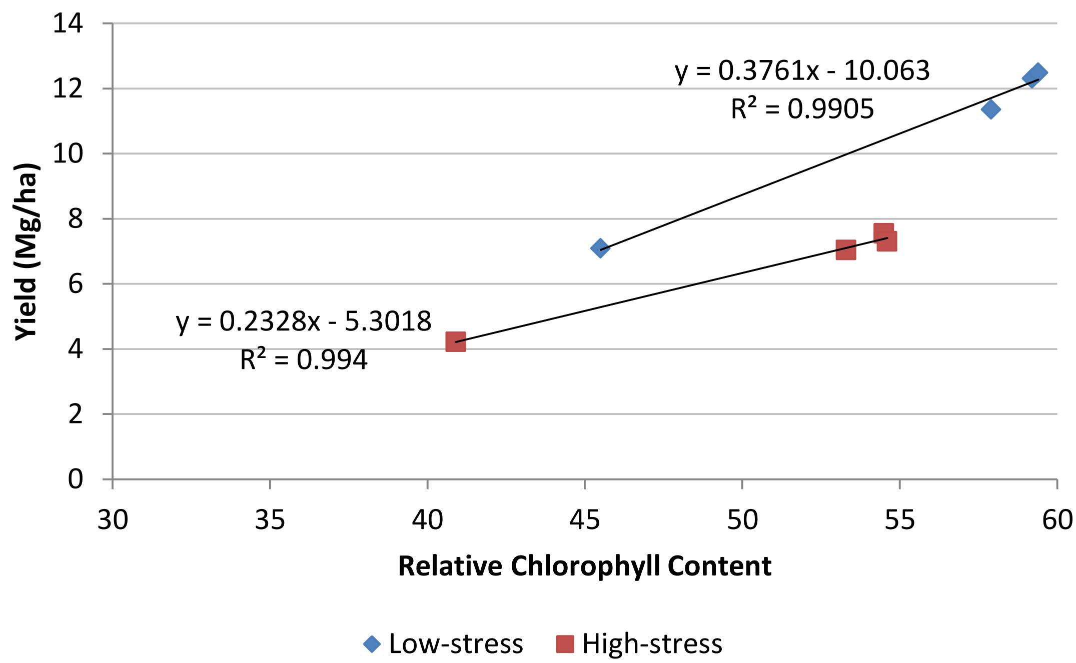

Figure 23: SPAD and grain yield of N rates averaged over three plant densities and four hybrids at high-stress and low-stress environments.

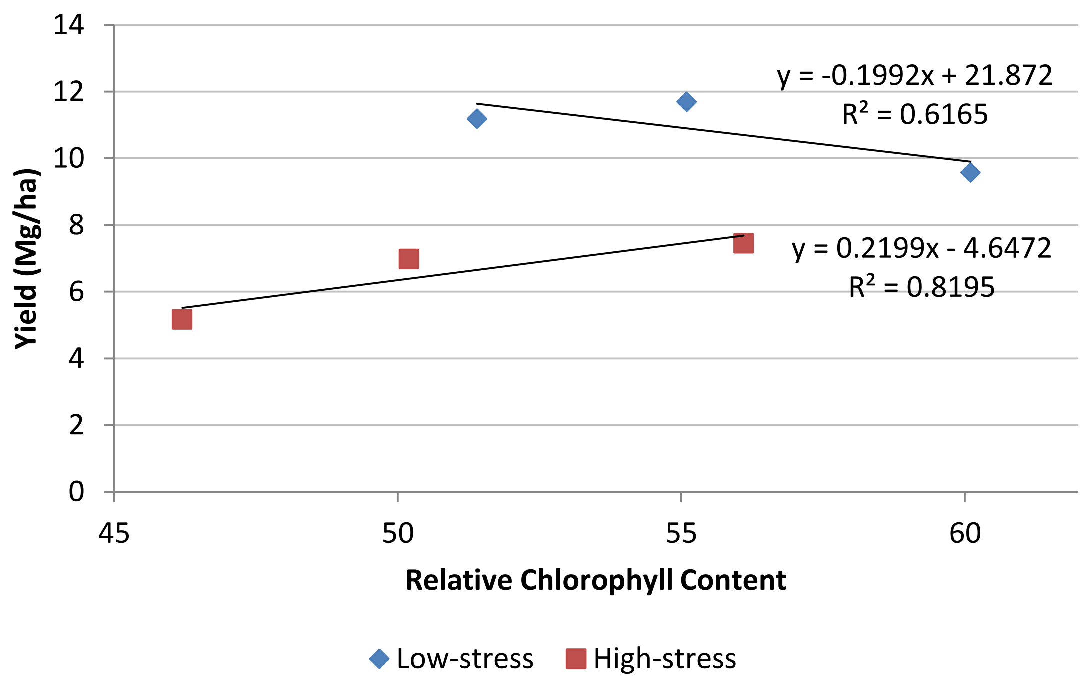

Figure 24: SPAD and grain yield by plant density, averaged over four N rates and four hybrids in high-stress and low-stress environments.

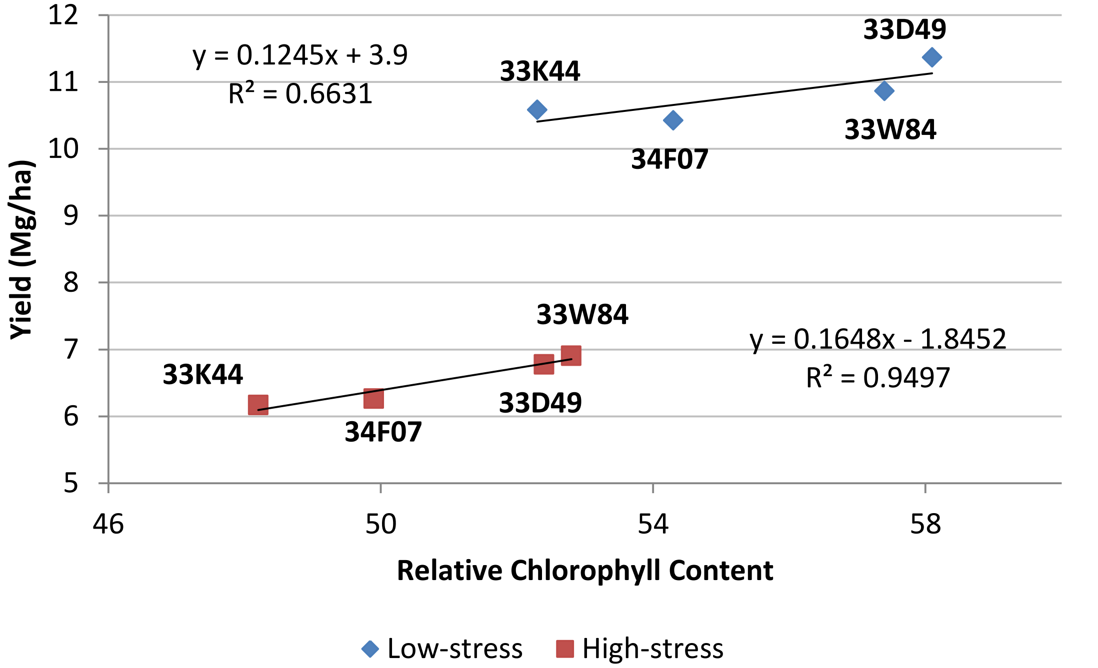

Figure 25: SPAD and grain yield of hybrids averaged over three plant densities and four N rates at high-stress environments and low-stress environments.

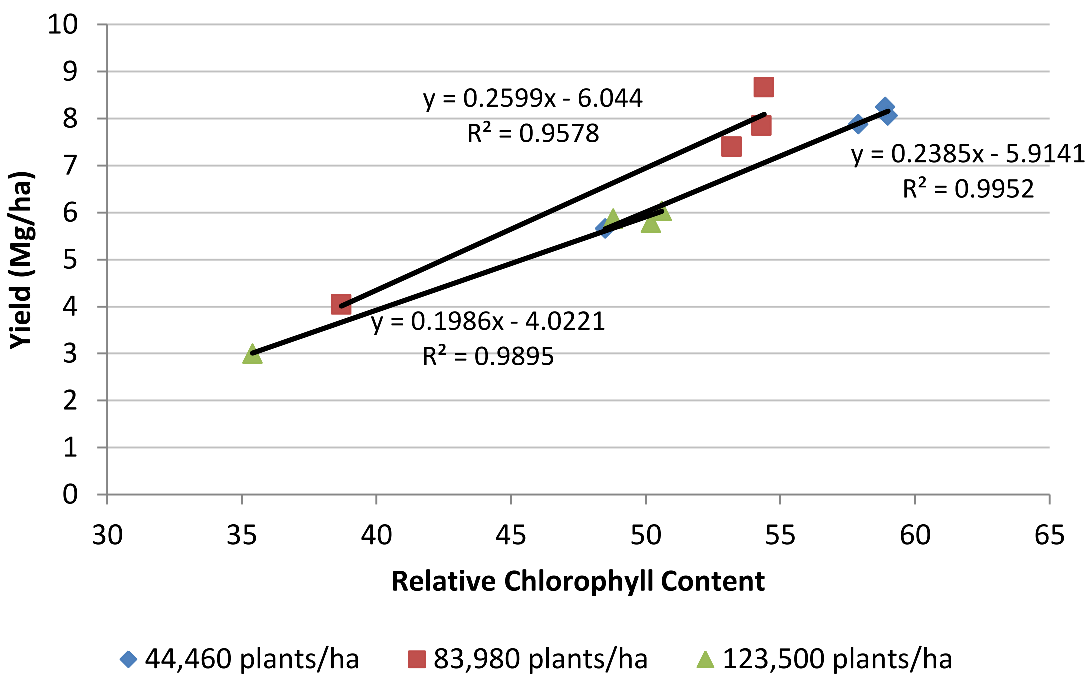

Figure 26: SPAD and grain yield of N rate and plant density averaged four hybrids at high-stress environments.

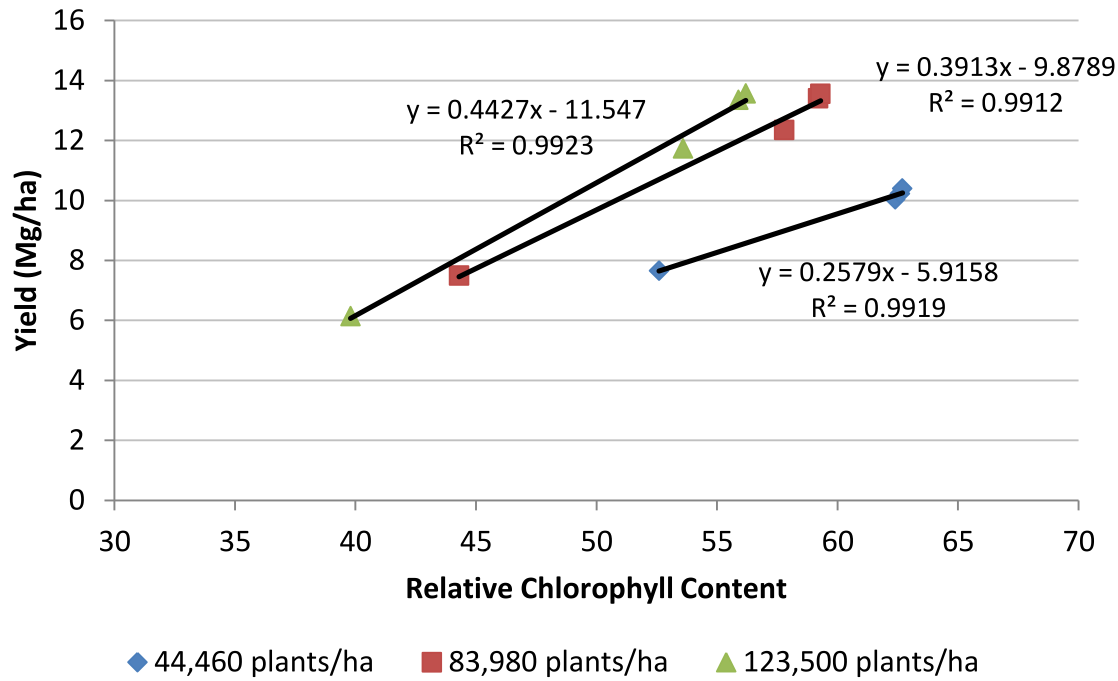

Figure 27: SPAD and grain yield of N rate and plant density averaged four hybrids in low-stress environments.

stress, where the low density was among the highest yielding across N rates under high-stress.

Increasing N rate produced both greater grain yield and SPAD. Greater SPAD values did not necessarily mean greater yields when applied to plant densities. The more favorable environments demonstrated that greater densities led to higher yields, which had lower relative chlorophyll content in comparison to low densities. It is clear that N response and SPAD is strongly correlated with yield response. However, plant density responses did not necessarily follow this same pattern. It is possible that leaf N is not used efficiently under severe water stress, which is increased by having high densities. Additionally, hybrids generated greater SPAD values if they were characterized as being more responsive to N, which was correlated with higher levels of yield.

Kernel Weight and Number

Across high-stress and low-stress data sets, the main effects of N rate, plant density, and hybrid on kernel weight were significant at p = 0.10 (Table 7). Kernel weight was affected by N rate in a positive manner, as weight increased as N rates were raised (Figure 28). Plant density negatively affected kernel weight, as weight decreased with increasing densities (Figure 29). Hybrids responded somewhat simliarly across all environments, as 33K44 (flex-ear, less responsive to N) typically produced significantly higher kernel weights (Figure 30). The only interaction found was the N rate x density interaction, which was found under both high-stress and low-stress environments. As with the main effects, kernel weight increased as N rate increased and as plant density was decreased. The lowest density (44,460 plants/ha) and highest N rate (269 kg N/ha) produced the largest kernels, at 412 mg/kernel under high-stress conditions and 379 mg/kernel under low-stress conditions (Figures 31, 32). Across high-stress environments, the high density produced +17 mg/kernel more than the middle density at 0 kg N/ha, but was significantly lower at all N rates above 90 kg N/ha.

Across varying levels of stress, there were correlations between kernel weight and yield when N rate and plant density were evaluated. As N rate increased, so did yield, but more interesting was the response among environments (Figure 33). The low-stress environments produced greater yields across each N treatment in comparison to the high-stress environments, yet high-stress environments produced considerably higher kernel weights. Plant density correlations between grain yield and kernel weight also revealed differences among stress levels (Figure 34). High-stress resulted in greater kernel weight and yield at the low density. In comparison, low-stress created higher kernel weight at

Table 7. Analysis of variance for kernel weight (mg) for six environments and grouped into three high-stress environments (DK-12, UR-11, UR-12) and three low-stress environments (DK-11, MN-11, MN-12). Brownstown 2011 (BT-11) is analyzed as a separate environment.

Source	All	High-Stress	Low-Stress	BRN-11
N rate (N)	***	***	***	**
Density (D)	***	***	***	**
N*D	**	**	**	NS
Hybrid (H)	***	***	**	**
N*H	**	NS	NS	NS
D*H	**	NS	NS	NS
N*D*H	NS	NS	NS	NS

*Significant at p = 0.10

**Significant at p = 0.05

***Significant at p = <0.0001

†NS = Not significant at p = 0.10

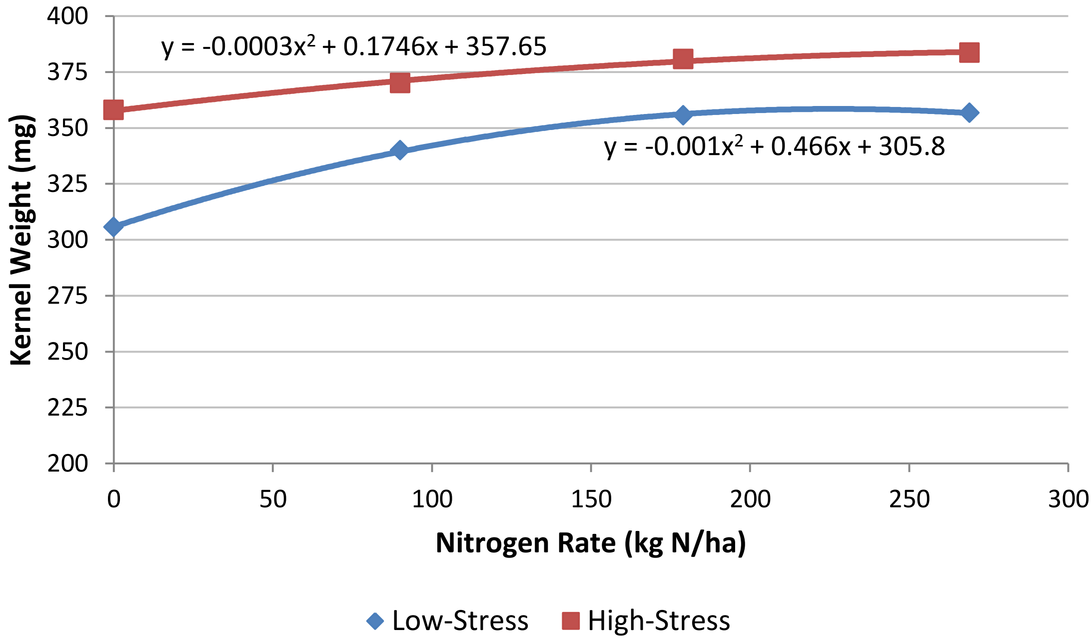

Figure 28: Quadratic response of kernel weight to N rate averaged over four hybrids and three plant densities at high-stress and low-stress environments.

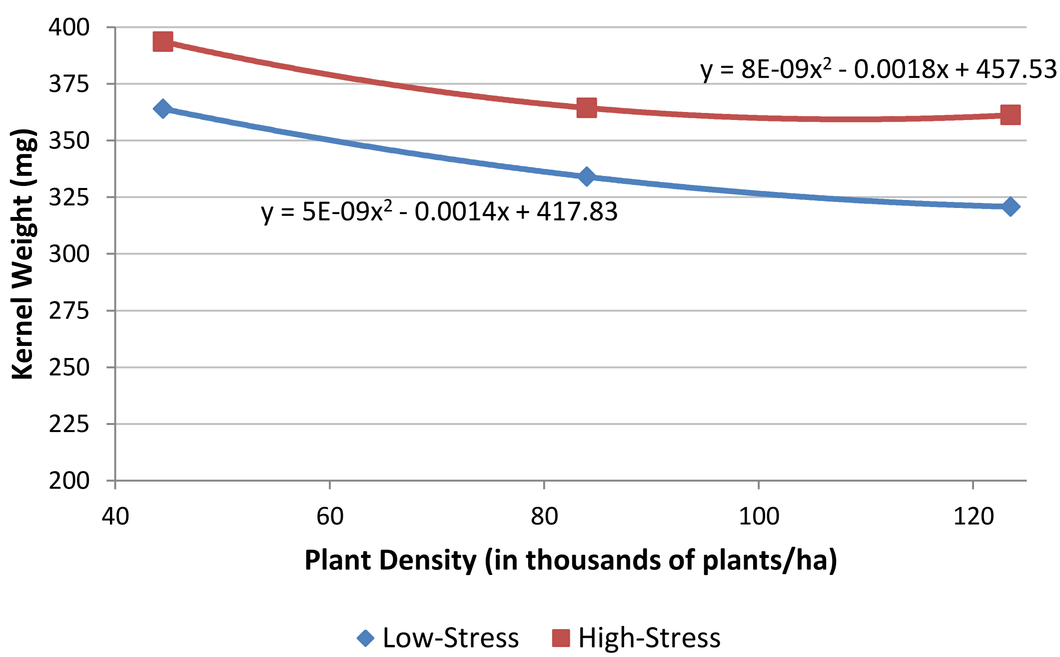

Figure 29: Quadratic response of kernel weight to plant density averaged over four hybrids and four N rates at high-stress and low-stress environments.

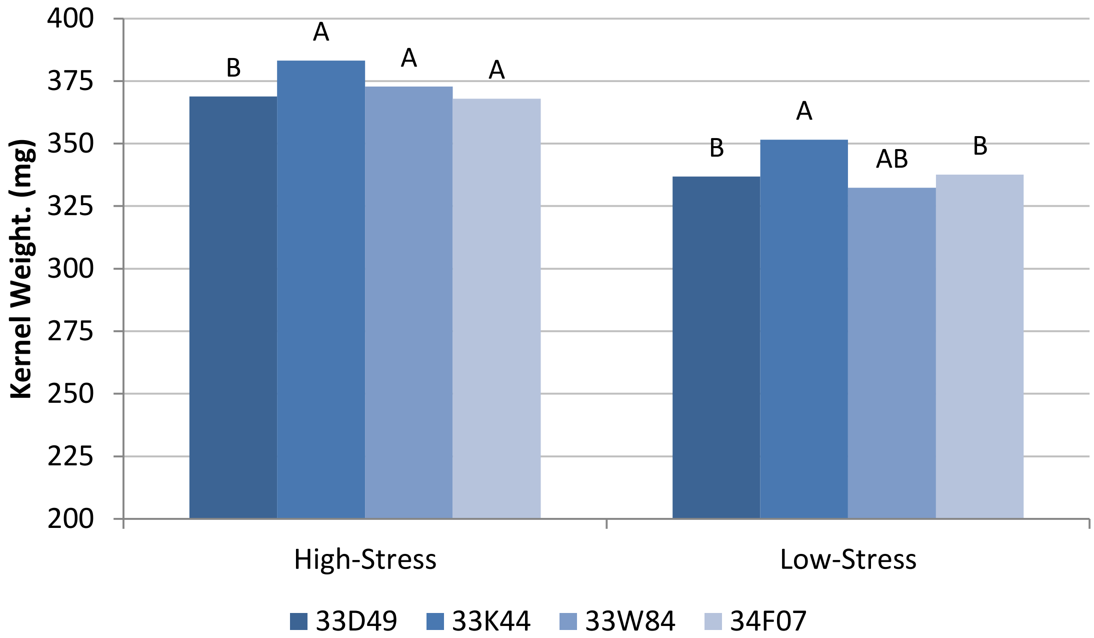

Figure 30: Kernel weight response of hybrids across four N rates and three plant densities at Brownstown – 2011, High-stress environments, and Low-stress environments. Letters separate means among hybrids at α = 0.10.

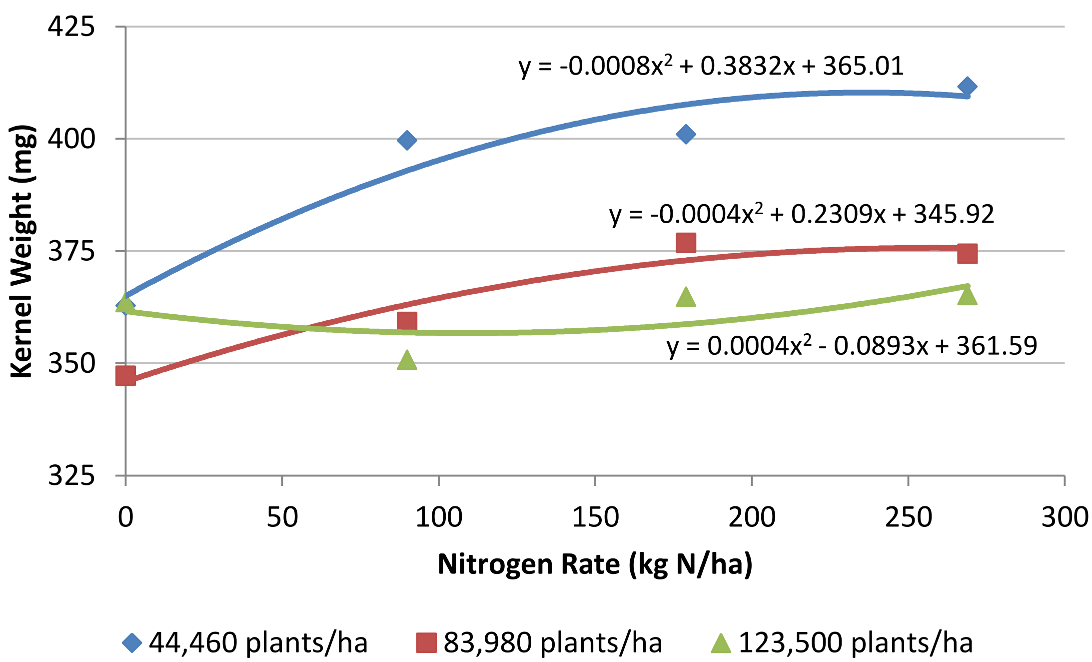

Figure 31: Quadratic response functions of kernel weight to N rate at all plant densities, averaged over four hybrids, at high-stress environments.

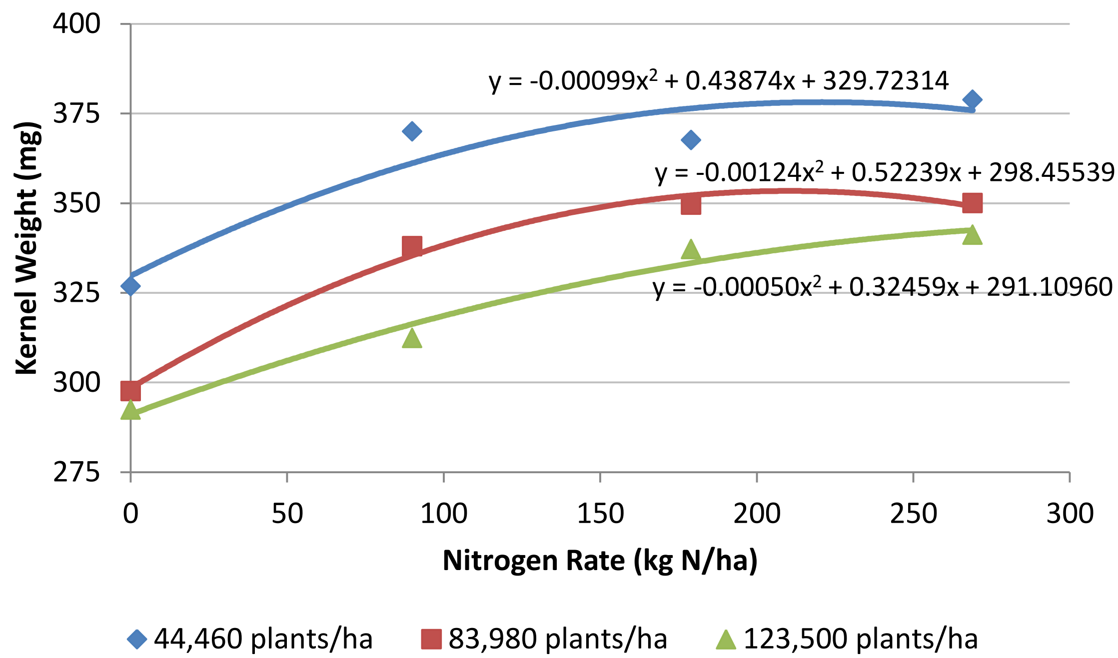

Figure 32: Quadratic response functions of kernel weight to N rate at all plant densities, averaged over four hybrids, at low-stress environments.

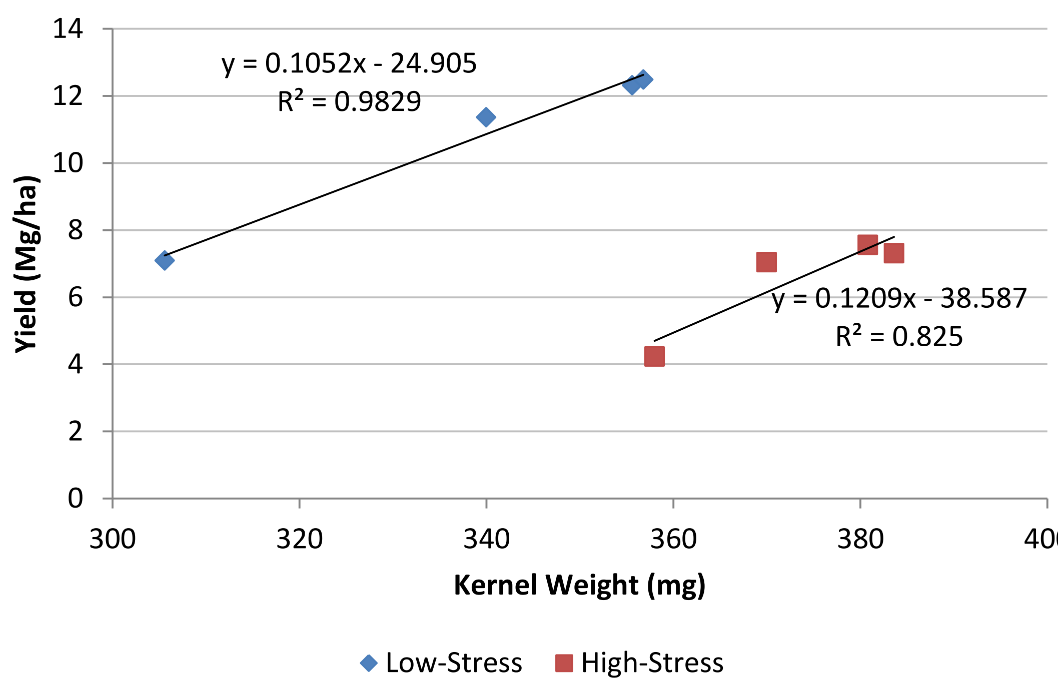

Figure 33: N rate correlation between yield and kernel weight values averaged over three plant densities and four hybrids at high-stress environments and low-stress environments.

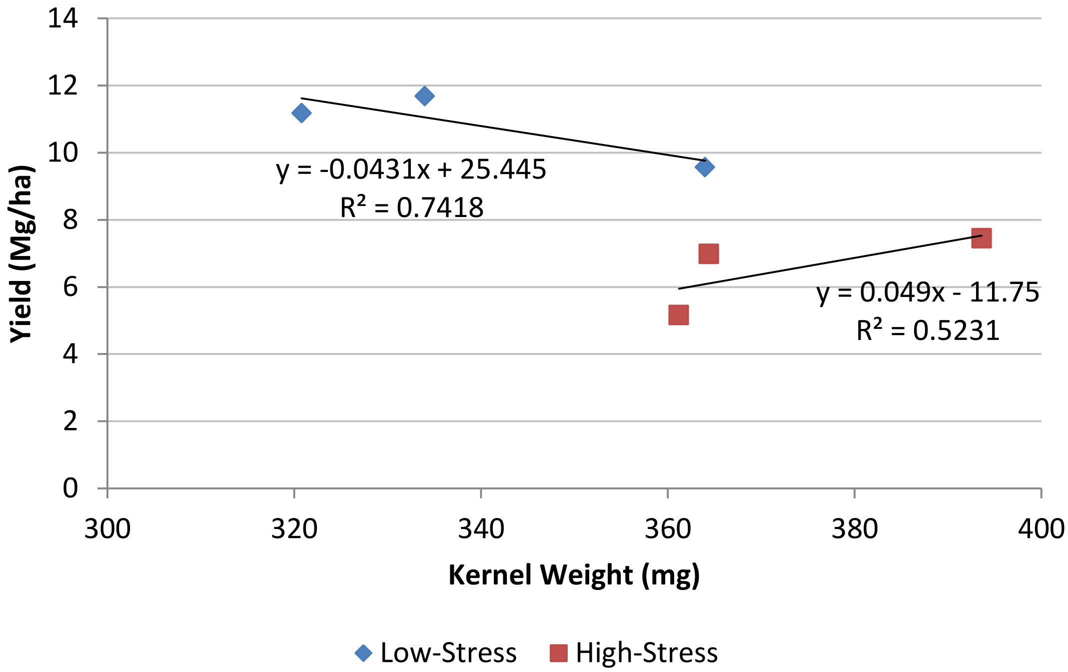

Figure 34: Plant density correlation between yield and kernel weight values averaged over four N rates and four hybrids at high-stress environments and low-stress environments.

the low density as well, but yield was greatest at the high and middle density.

Low-stress environments produced greater yields in comparison to the high-stress environments, but produced lower kernel weight. Calculation of kernel number indicated that low-stress environments produced significantly more kernels (Figures 35 and 36). The high-stress environments seemingly were better able to reassimilate nutrients to existing kernels to protect against yield loss, which resulted in the higher grain weight. While kernel weight is an important yield component, it appears kernel number is better associated with higher yields, based on the comparison of the high-stress and low-stress data.

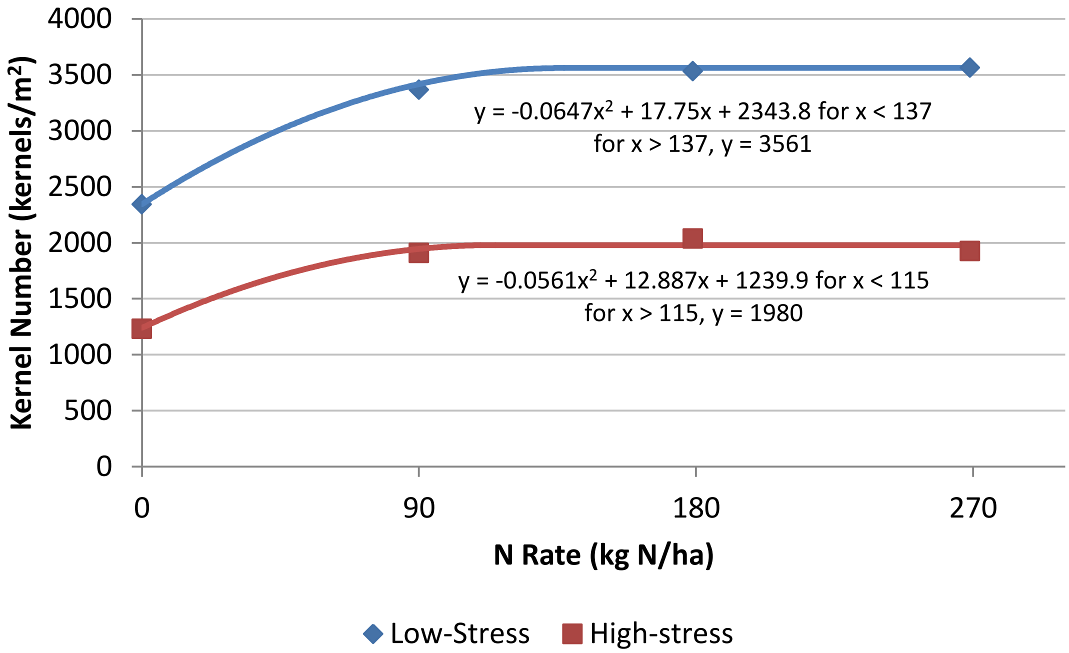

Figure 35: Quadratic + plateau response function of kernel number to N rate averaged over three plant densities and four hybrids at high-stress environments and low-stress environments.

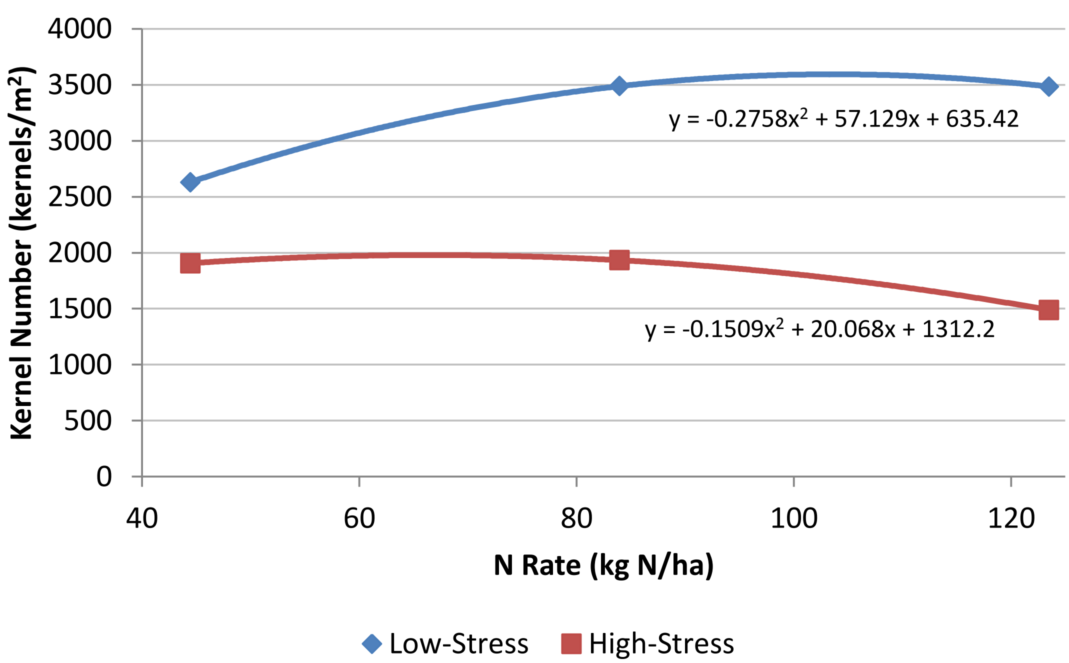

Figure 36: Quadratic response function of kernel number to plant density averaged over four N rates and four hybrids at high-stress environments and low-stress environments.

Economic Analysis

As expected across high-stress environments, the lowest density produced the highest yield and generated the largest net returns, with a maximum return of $1,877 per ha at 90 kg N/ha (Figure 37). The middle density produced a maximum return of $1,816 per ha at 179 kg N/ha, while the highest density generated only $1,045 per ha at an N rate of 90 kg N/ha.

The low-stress environments produced the largest returns at the middle density used (Figure 38). The middle density produced the largest return - $3,126 per ha at 179 kg N/ha. The high density generated lower returns across all N rates, as the largest return ($2,971 per ha) occurred at 179 kg N/ha. Due to much lower yields at the low density, maximum return was only $2,472 per ha, which came at 90 kg N/ha).

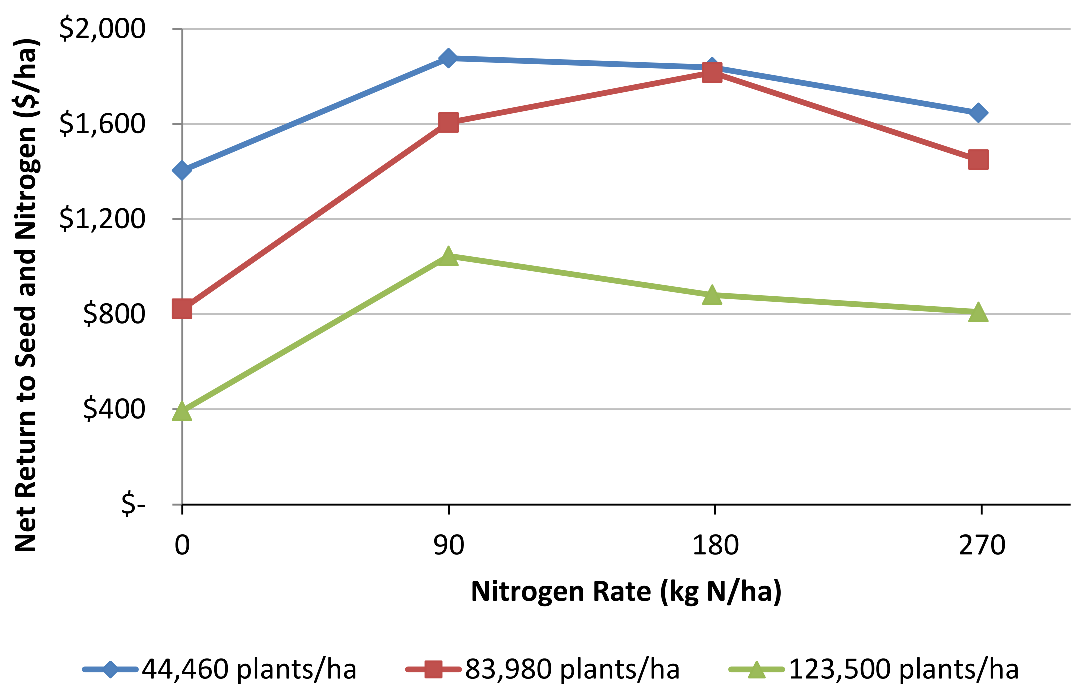

Figure 37: Net return in dollars/ha to seed and nitrogen from yield data reflecting high-stress environments.

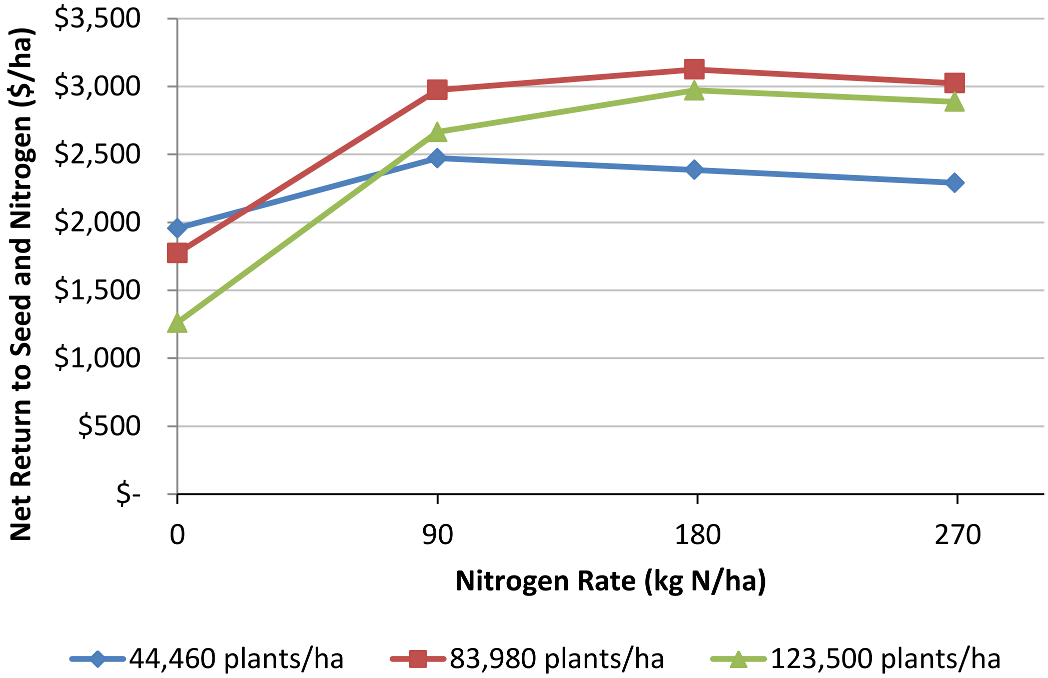

Figure 38: Net return in dollars/ha to seed and nitrogen from yield data reflecting low-stress environments.

SUMMARY AND CONCLUSIONS

Under high-stress conditions, averaged over all plant densities and hybrids, yield increased modestly as N rate increased, but reached a plateau of only 7.4 Mg/ha at only 136 kg N/ha. This is a much lower N rate than would normally be used in Illinois, where suggested N rates are 200 to 240 kg N/ha at current prices (Sawyer et al., 2006). We also saw yields decrease under these conditions as plant density increased, with 2.3 Mg/ha lower yield at 123,500 plants/ha than at 51,000 plants/ha. Hybrids performed as expected under these stress conditions, with fixed-ear hybrids producing higher yields than flex-ear hybrids. Yield response was highest at the middle density, where maximum yield (8.7 Mg/ha) was produced at 188 kg N/ha.

The low-stress growing conditions generated a higher response to N as opposed to the high-stress data, as yield plateau (12.5 Mg/ha) occurred at 164 kg N/ha when a quadratic + plateau function was fitted. This result more closely reflects the MRTN recommendation of 200 to 240 kg N/ha. Maximum yield (11.8 Mg/ha) was obtained at 96,000 plants/ha when plant density response was fitted with a quadratic function. Under these more ideal conditions, flex-ear hybrids produced higher yields in comparison to the fixed-ear hybrids. These results do not necessarily justify recent trends for increasing N rates and plant densities to obtain higher yields.

Across all plant densities and hybrids, yield plateau occurred at different levels of N across high-stress (136 kg N/ha) and low-stress (164 kg N/ha) environments. In addition, when plant density and hybrids were evaluated across varying degrees of stress, high-stress environments typically led to higher yields with lower densities and fixed-ear hybrids. The opposite can be said about low-stress environments, as mid to high densities, and flex-ear hybrids were more favorable for higher yields. Results concerning flex-ear vs. fixed-ear hybrids are in line with assumptions commonly made when evaluated across varying levels of stress. Fixed-ear hybrids may maintain ear kernel number better under higher levels of stress (drought, high plant densities, etc.), whereas flex-ear hybrids will alter yield components (kernel number, kernel weight) corresponding to the growing conditions, where favorable conditions can lead to greater yields. Interestingly, when the N rate x plant density interaction was analyzed across different stress levels, the low density (44,460 plants/ha) responded to the same level of N (133 kg N/ha) when a quadratic + plateau function was fitted, though with different yields, under high-stress (8.1 Mg/ha) and low-stress (10.3 Mg/ha). This comparison indicates that use of low plant densities may involve a constant N rate to maximize yield, even under a wide range of conditions.

These results provide no support for the idea that increases in both plant density and N rate, to levels above those commonly used, are necessary to maximize yields or returns under productive conditions. While combinations of the highest N rate (269 kg N/ha) and the highest density (123,500 plants/ha) did generate yields comparable to those with 83,980 plants/ha and 179 kg N/ha, neither added amount would pay for itself (-$238 at 269 kg N/ha and 123,500 plants/ha; -$155 at 179 kg N/ha and 123,500 plants/ha; -$103 at 269 kg N/ha, 83,980 plants/ha). In this study, returns to seed and nitrogen were highest at 84,000 plants/ha and 180 kg N/ha, under more favorable conditions. 84,000 plants/ha can be regarded as a common plant density used by producers in the U.S. Corn Belt; however, 190 kg N/ha can be viewed as marginally less than the MRTN recommended 200-240 kg N/ha (Sawyer et al., 2006).

Different hybrids generally responded quite similarly to plant density and N rate in this study, even under a variety of growing conditions. While it is possible that further work will reveal more consistent differences that will allow different hybrids to be managed differently, it is also possible that hybrid-specific management of plant density and N rate may not provide large returns when evaluated under variable field conditions.

Continuation of this research would be beneficial towards identifying if additional N rates and plant densities display greater net returns than those examined in this study, across various hybrids. Perhaps, investigating rates approaching 225 kg N/ha in addition to 100,000 plants/ha will help establish a more educated estimate of the economic point of diminishing returns. Rates used in this experiment provide indication of how typical rates interact, as well as how plant density and N rate extremes are capable of affecting costs and production across a variety of environments and hybrids. Results obtained from these data do validate use of “common” rates in farming practices with the use of current corn hybrids.

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APPENDIX

Grain Yield

Table A1. Type III tests of fixed effects for differences in grain yield.

Effect	Type III Tests of Fixed Effects			
All Environments (DEK-2011, DEK-2012, MON-2011, MON-2012, URB-2011, URB-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	69	84.20	<.0001
D	2	46	7.10	0.0021
N*D	6	138	12.40	<.0001
H	3	69	5.72	0.0015
N*H	9	207	1.64	0.1067
D*H	6	138	7.89	<.0001
N*D*H	18	414	1.33	0.1667
Brownstown, 2011				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	8	5.51	0.0240
D	2	6	4.39	0.0668
N*D	6	11	0.04	0.9995
H	3	9	3.76	0.0532
N*H	9	22	2.77	0.0249
D*H	6	18	1.63	0.1966
N*D*H	14	25	0.42	0.9511
High-Stress Environments (URB-2011, URB-2012, DEK-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	33	22.44	<.0001
D	2	22	104.43	<.0001
N*D	6	66	2.99	0.0120
H	3	33	2.67	0.0633
N*H	9	99	1.35	0.2217
D*H	6	66	3.92	0.0021
N*D*H	18	198	0.71	0.8011
Low-Stress Environments (DEK-2011, MON-2011, MON-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	33	125.88	<.0001
D	2	22	67.74	<.0001
N*D	6	66	35.49	<.0001
H	3	33	3.92	0.0169
N*H	9	99	1.11	0.3604
D*H	6	66	5.08	0.0002
N*D*H	18	198	1.39	0.1414

N = Nitrogen Rate
D = Plant Density
H = Hybrid

Table A2. Grain yield in Mg/ha, includes significant results from all data sets, with four N rates (0, 90, 179, 269 kg N/ha), three plant densities (44,460, 83,980, 123,500 plants/ha), and four hybrids.

			Environments			
N Rate	Plant Density	Hybrid	All	BRN, 11	High-St.	Low-St.
---kg N/ha----	--plants/ha--	---Pioneer---	------------------------Mg/ha------------------------			
0			5.6	0.4	4.2	7.1
	44,460		6.7	0.9	5.7	7.7
	83,980		5.7	0.1	4.0	7.5
	123,500		4.6	0.1	3.0	6.1
90			9.2	3.0	7.0	11.4
	44,460		8.9	3.4	7.9	10.0
	83,980		9.8	3.4	7.4	12.4
	123,500		8.8	2.2	5.9	11.7
179			9.9	4.2	7.6	12.3
	44,460		9.2	4.5	8.2	10.2
	83,980		11.0	4.4	8.7	13.4
	123,500		9.6	3.7	5.8	13.3
269			9.9	5.1	7.3	12.5
	44,460		9.2	5.4	8.1	10.4
	83,980		10.8	5.5	7.8	13.5
	123,500		9.8	4.4	6.0	13.6
	44,460		8.5	3.6	7.4	9.6
	83,980		9.3	3.1	7.0	11.7
	123,500		8.2	2.4	5.2	11.2
		33D49	9.1	2.8	6.8	11.4
		33K44	8.4	3.2	6.2	10.6
		33W84	8.9	3.3	6.9	10.9
		34F07	8.4	3.1	6.3	10.4

Table A2. Continued

N. Rate	Plant Density	Hybrid	Environments All	BRN, 11	High-St.	Low-St.
---kg N/ha---	--plants/ha--	---Pioneer---	---------Mg/ha---------			
	44,460					
		33D49	9.2	3.3	8.1	10.3
		33K44	8.5	4.0	7.3	9.7
		33W84	8.6	3.6	7.7	9.4
		34F07	7.7	3.6	6.6	8.9
	83,980					
		33D49	9.6	3.2	7.0	12.2
		33K44	9.0	3.2	6.5	11.4
		33W84	9.7	3.1	7.5	11.8
		34F07	9.1	3.5	6.9	11.4
	123,500					
		33D49	8.4	2.0	5.3	11.6
		33K44	7.7	2.6	4.7	10.7
		33W84	8.4	3.1	5.5	11.4
		34F07	8.2	2.8	5.2	11.1
0						
		33D49	5.8	1.2	4.3	7.3
		33K44	5.6	1.4	4.3	7.0
		33W84	5.8	0.9	4.5	7.1
		34F07	5.4	1.5	4.0	7.0
90						
		33D49	9.6	2.1	7.3	12.0
		33K44	8.8	3.2	6.6	11.1
		33W84	9.3	3.0	7.4	11.4
		34F07	9.0	3.7	7.8	11.0
179						
		33D49	10.4	4.3	7.8	12.9
		33K44	9.8	4.2	7.4	12.2
		33W84	10.1	4.2	7.8	12.5
		34F07	9.5	3.9	7.2	11.8
269						
		33D49	10.5	4.6	7.4	13.3
		33K44	9.4	5.9	6.5	12.2
		33W84	10.4	4.9	8.1	12.5
		34F07	9.5	5.1	7.0	12.0

Nitrogen Use Efficiency

Table A3. Type III tests of fixed effects for differences in NUE.

Effect	Type III Tests of Fixed Effects			
All Environments (DEK-2011, DEK-2012, MON-2011, MON-2012, URB-2011, URB-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	2	46	74.09	<.0001
D	2	46	7.72	0.0013
N*D	4	92	3.39	0.0125
H	3	69	6.67	0.0005
N*H	6	138	1.43	0.2059
D*H	6	138	7.79	<.0001
N*D*H	12	278	1.37	0.1793
Brownstown, 2011				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	2	6	2.15	0.1976
D	2	6	5.53	0.0435
N*D	4	11	0.88	0.5067
H	3	9	6.29	0.0137
N*H	6	18	3.99	0.0103
D*H	6	18	2.88	0.0815
N*D*H	12	25	0.70	0.7365
High-Stress Environments (URB-2011, URB-2012, DEK-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	2	22	21.20	<.0001
D	2	22	85.66	<.0001
N*D	4	44	5.53	0.0011
H	3	33	3.43	0.0281
N*H	6	66	0.81	0.5644
D*H	6	66	2.93	0.0135
N*D*H	12	132	0.56	0.8694
Low-Stress Environments (DEK-2011, MON-2011, MON-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	2	22	72.71	<.0001
D	2	22	203.71	<.0001
N*D	4	44	11.30	<.0001
H	3	33	4.35	0.0109
N*H	6	66	1.19	0.3210
D*H	6	66	7.51	<.0001
N*D*H	12	134	1.41	0.1673

N = Nitrogen Rate
D = Plant Density
H = Hybrid

Table A4. NUE in kg/kg N, includes significant results from all data sets, with four N rates (0, 90, 179, 269 kg N/ha), three plant densities (44,460, 83,980, 123,500 plants/ha), and four hybrids.

			Environments			
N Rate	Plant Density	Hybrid	All	BRN, 11	High-St.	Low-St.
---kg N/ha----	--plants/ha--	---Pioneer---	-----------------------kg/kg N-----------------------			
90			39.4	23.3	31.3	47.4
	44,460		36.7	31.6	40.6	32.6
	83,980		46.5	22	35.2	58
	123,500		34.9	16.2	18.2	51.7
179			23.9	20.8	18.6	29.2
	44,460		20	23.1	22.4	17.5
	83,980		30	22.3	24.8	35.3
	123,500		21.8	16.9	8.7	34.5
269			15.8	17.7	11.5	20.1
	44,460		13.2	18.8	14.3	12.3
	83,980		18.9	19.2	13.5	24.1
	123,500		15.4	15.1	6.7	24
	44,460		23.3	24.5	25.8	20.8
	83,980		31.8	21.2	24.5	39.1
	123,500		24.1	16.1	11.2	36.9
		33D49	29.6	18.6	22.4	36.7
		33K44	24	22.3	17.4	30.5
		33W84	27.8	20	23	32.6
		34F07	24.2	21.4	19.1	29.7

Table A4. Continued

N. Rate	Plant Density	Hybrid	Environments All	BRN, 11	High-St.	Low-St.
---kg N/ha---	--plants/ha--	---Pioneer---	kg/kg N			
	44,460					
		33D49	28.3	22.1	30.2	26.5
		33K44	23.3	28.1	24.4	22.2
		33W84	24	23.7	27.8	20.1
		34F07	17.6	24	20.8	14.5
	83,980					
		33D49	34.4	21.5	24.8	44
		33K44	29.2	21.7	30.9	37.4
		33W84	33.7	15.9	28.3	39.3
		34F07	29.9	25.5	23.9	35.9
	123,500					
		33D49	25.9	12.3	12.3	39.6
		33K44	19.5	17	6.9	31.9
		33W84	25.7	20.4	12.9	38.5
		34F07	25	14.6	12.6	37.5
90						
		33D49	44.2	17.9	34.1	54.4
		33K44	35.2	25.8	26.1	44.2
		33W84	41.3	21.8	34.9	47.8
		34F07	36.8	27.5	30.2	43.2
179						
		33D49	26.3	22.1	20.1	32.4
		33K44	23	20.5	17.7	28.3
		33W84	24.8	21.3	19.8	29.9
		34F07	21.6	19.2	16.8	26.3
269						
		33D49	18.1	15.8	13.1	23.2
		33K44	13.8	20.5	8.3	18.9
		33W84	17.3	16.9	14.2	20.2
		34F07	14.2	17.5	10.2	18.2

SPAD Measurement

Table A5. Type III tests of fixed effects for differences in SPAD.

Effect	Type III Tests of Fixed Effects			
All Environments (DEK-2011, DEK-2012, MON-2011, MON-2012, URB-2011, URB-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	69	212.10	<.0001
D	2	46	491.21	<.0001
N*D	6	138	19.16	<.0001
H	3	69	116.63	<.0001
N*H	9	207	1.97	0.0440
D*H	6	138	1.37	0.2306
N*D*H	18	414	1.33	0.1655
Brownstown, 2011				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	9	72.80	<.0001
D	2	6	62.69	<.0001
N*D	6	18	2.71	0.0471
H	3	9	77.82	<.0001
N*H	9	27	3.51	0.0054
D*H	6	18	0.67	0.6735
N*D*H	18	54	1.00	0.4714
High-Stress Environments (URB-2011, URB-2012, DEK-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	33	58.16	<.0001
D	2	22	382.57	<.0001
N*D	6	66	7.08	<.0001
H	3	33	58.88	<.0001
N*H	9	99	1.12	0.3563
D*H	6	66	0.82	0.5563
N*D*H	18	198	0.71	0.8006
Low-Stress Environments (DEK-2011, MON-2011, MON-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	33	407.87	<.0001
D	2	22	187.38	<.0001
N*D	6	66	14.89	<.0001
H	3	33	67.31	<.0001
N*H	9	99	1.26	0.2706
D*H	6	66	1.09	0.3755
N*D*H	18	198	1.29	0.1973

N = Nitrogen Rate
D = Plant Density
H = Hybrid

Table A6. SPAD in relative chlorophyll content, includes significant results from all data sets, with four N rates (0, 90, 179, 269 kg N/ha), three plant densities (44,460, 83,980, 123,500 plants/ha), and four hybrids.

			Environments			
N Rate	Plant Density	Hybrid	All	BRN, 11	High-St.	Low-St.
---kg N/ha----	--plants/ha--	---Pioneer---	-----------relative chlorophyll content-----------			
0			43.2	35.7	40.9	45.5
	44,460		50.5	40.5	48.5	52.6
	83,980		41.4	35.1	38.7	44.3
	123,500		37.6	31.6	35.4	39.8
90			55.6	50.8	53.3	57.9
	44,460		60.1	54.3	57.9	62.4
	83,980		55.5	49.0	53.2	57.8
	123,500		51.2	49.2	48.8	53.6
179			56.8	56.8	54.5	59.2
	44,460		60.7	58.7	58.9	62.6
	83,980		56.8	56.5	54.4	59.2
	123,500		53.0	55.1	50.2	55.9
269			57.1	58.4	54.6	59.4
	44,460		60.9	60.7	59.0	62.7
	83,980		56.9	58.0	54.3	59.3
	123,500		53.4	56.6	50.6	56.2
	44,460		58.1	53.6	56.1	60.1
	83,980		52.6	49.6	50.2	55.1
	123,500		48.8	48.1	46.2	51.4
		33D49	55.2	52.9	52.4	58.1
		33K44	50.2	46.9	48.2	52.3
		33W84	55.1	52.2	52.8	57.4
		34F07	52.1	49.8	49.9	54.3

Table A6. Continued

N. Rate	Plant Density	Hybrid	Environments All	BRN, 11	High-St.	Low-St.
---kg N/ha---	--plants/ha--	---Pioneer---	-----------relative chlorophyll content-----------			
	44,460					
		33D49	60.1	55.9	57.7	62.4
		33K44	55.4	50.2	53.5	57.2
		33W84	60.3	54.8	58.3	62.2
		34F07	56.5	53.3	54.6	58.4
	83,980					
		33D49	54.9	52.4	51.8	57.9
		33K44	49.4	46.5	47.6	51.3
		33W84	54.3	51.3	51.8	56.9
		34F07	52.0	48.4	49.5	54.5
	123,500					
		33D49	50.8	50.5	47.6	54.0
		33K44	45.9	44	43.4	48.3
		33W84	50.8	50.5	48.4	53.2
		34F07	47.9	47.5	45.6	50.0
0						
		33D49	45.9	38.5	42.8	48.3
		33K44	40.1	29.8	38.1	42.1
		33W84	44.6	38.5	42.5	46.7
		34F07	42.5	36.1	40.0	45.0
90						
		33D49	57.2	52.5	54.3	60.1
		33K44	52.8	47.8	50.9	54.7
		33W84	58.1	52.5	55.9	60.4
		34F07	54.3	50.5	52.1	56.5
179						
		33D49	58.7	60.5	55.9	61.5
		33K44	54.0	53.8	51.7	56.2
		33W84	58.7	57.7	56.2	61.3
		34F07	56.0	55.0	54.1	57.9
269						
		33D49	59.5	60.2	56.5	62.5
		33K44	54.0	56.3	52.0	56.0
		33W84	59.0	60.0	56.6	61.2
		34F07	55.6	57.3	53.5	57.8

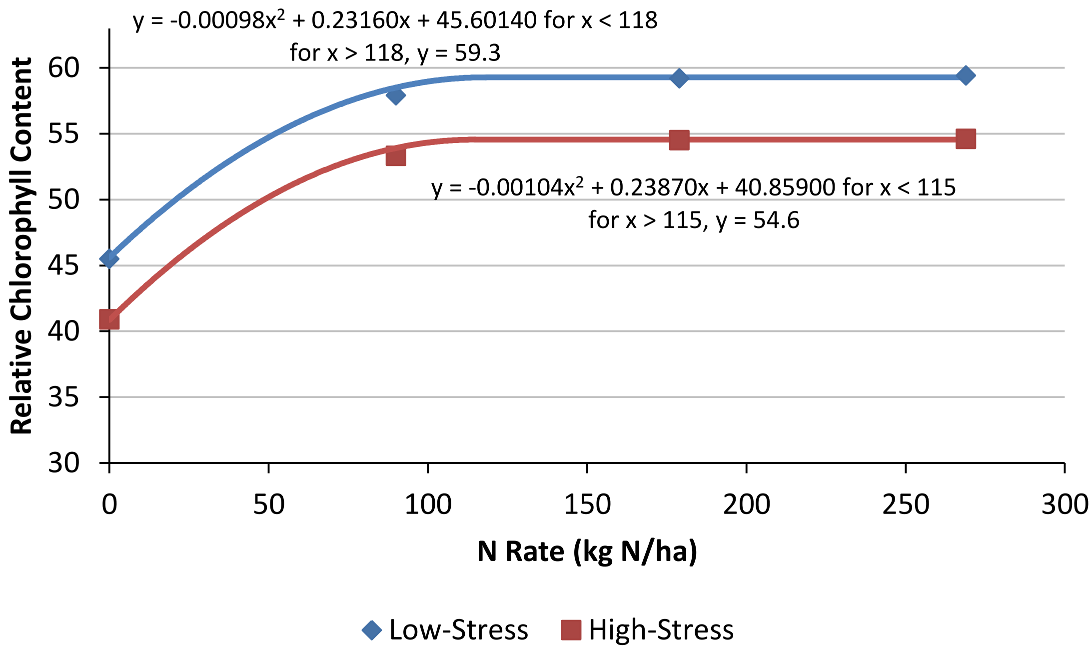

Figure A1: Quadratic + plateau response of SPAD to N rate averaged over four hybrids and three plant densities at high-stress and low-stress environments.

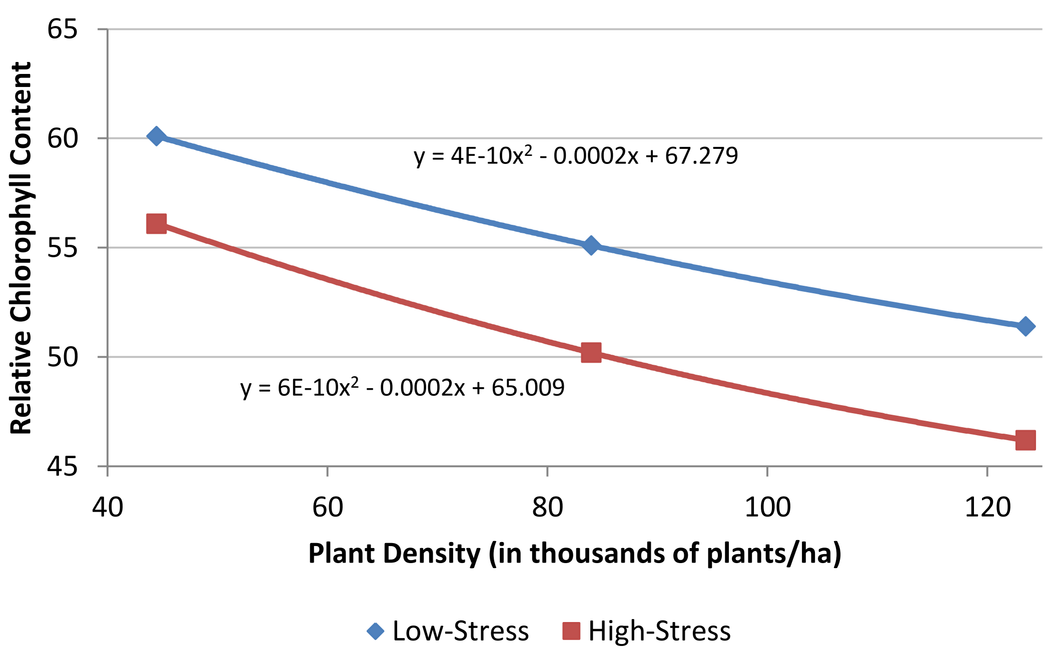

Figure A2: Quadratic response of SPAD to plant density averaged over four hybrids and four N rates at high-stress and low-stress environments.

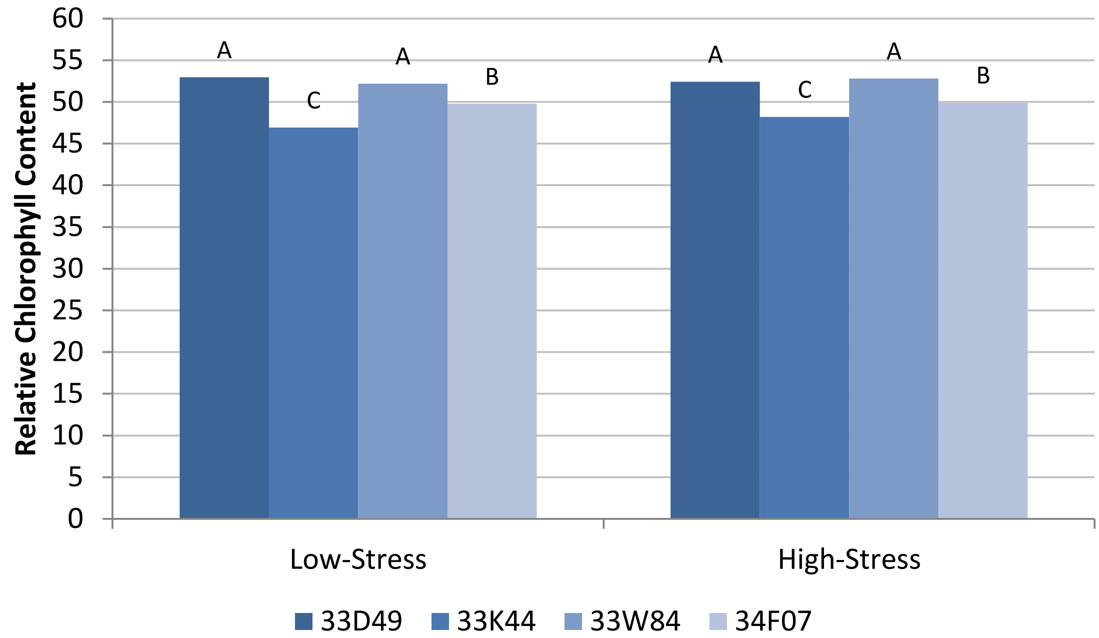

Figure A3: SPAD response of hybrids averaged over four N rates and three plant densities at high-stress and low-stress environments. Letters separate means among hybrids at α = 0.10.

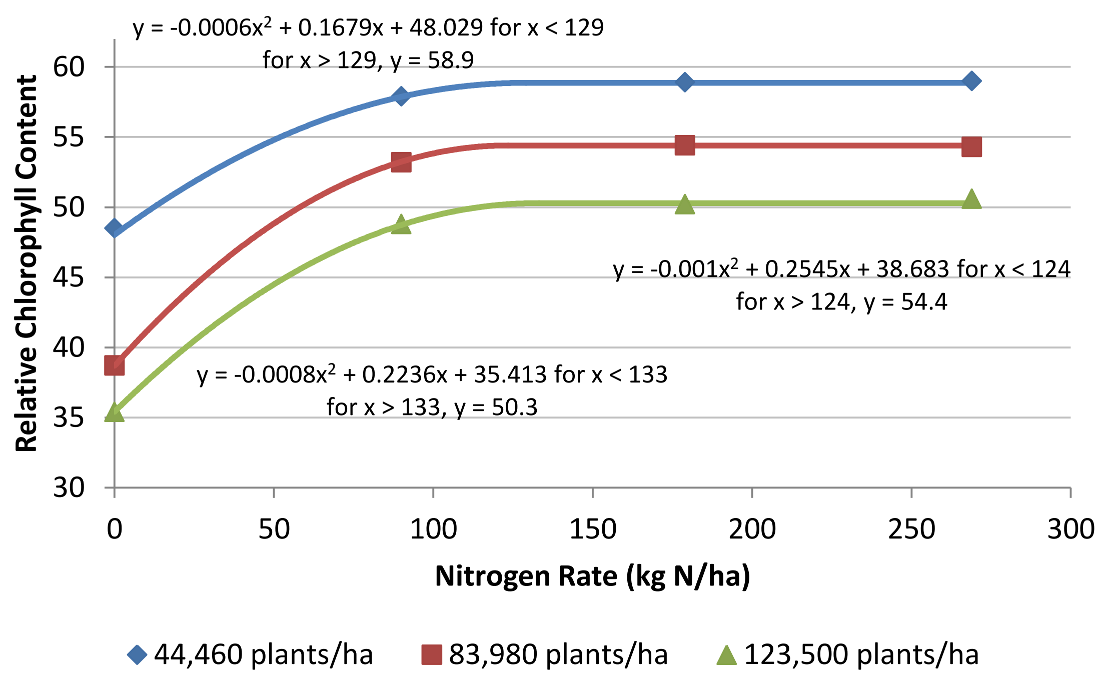

Figure A4: Quadratic + plateau response functions of SPAD to N rate at all plant densities, averaged over four hybrids, at high-stress environments.

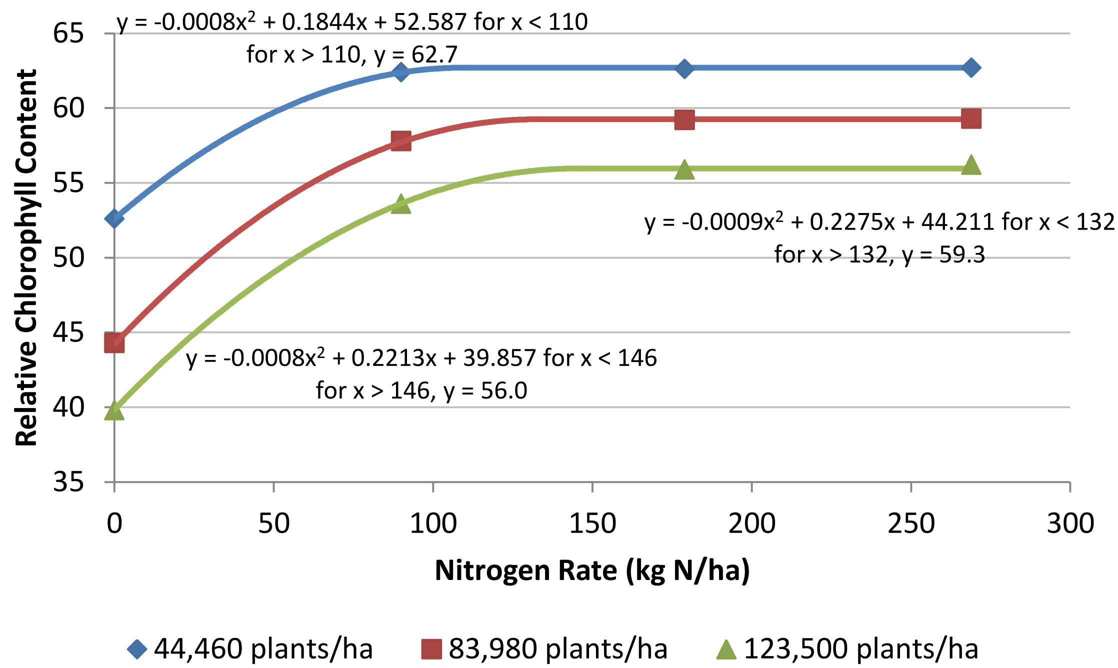

Figure A5: Quadratic + plateau response functions of SPAD to N rate at all plant densities, averaged over four hybrids, at low-stress environments.

Kernel Weight and Number

Table A7. Type III tests of fixed effects for differences in kernel weight.

Effect	Type III Tests of Fixed Effects			
All Environments (DEK-2011, DEK-2012, MON-2011, MON-2012, URB-2011, URB-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	69	52.89	<.0001
D	2	46	250.61	<.0001
N*D	6	138	3.56	0.0026
H	3	69	17.89	<.0001
N*H	9	196	2.53	0.0091
D*H	6	138	2.38	0.0324
N*D*H	18	346	1.23	0.2307
Brownstown, 2011				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	8	4.43	0.0410
D	2	6	7.13	0.0259
N*D	5	11	1.14	0.3970
H	3	9	9.19	0.0042
N*H	9	19	1.95	0.1051
D*H	6	18	0.87	0.5380
N*D*H	12	16	1.04	0.4618
High-Stress Environments (URB-2011, URB-2012, DEK-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	33	12.66	<.0001
D	2	22	112.18	<.0001
N*D	6	66	2.71	0.0204
H	3	33	14.23	<.0001
N*H	9	99	1.57	0.1346
D*H	6	66	1.74	0.1251
N*D*H	18	178	1.65	0.1117
Low-Stress Environments (DEK-2011, MON-2011, MON-2012)				
	---Num DF---	---Den DF---	---F Value---	---Pr > F---
N	3	33	78.61	<.0001
D	2	22	163.39	<.0001
N*D	6	66	2.54	0.0284
H	3	33	6.86	0.0010
N*H	9	99	1.17	0.3267
D*H	6	66	0.98	0.4468
N*D*H	18	150	0.79	0.7144

N = Nitrogen Rate
D = Plant Density
H = Hybrid

Table A8. Kernel weight in mg, includes significant results from all data sets, with four N rates (0, 90, 179, 269 kg N/ha), three plant densities (44,460, 83,980, 123,500 plants/ha), and four hybrids.

			Environments			
N Rate	Plant Density	Hybrid	All	BRN, 11	High-St.	Low-St.
---kg N/ha----	--plants/ha--	---Pioneer---	mg			
0			330.8	227.2	358.0	305.6
	44,460		345.3	225.6	362.8	326.8
	83,980		323.2	---	347.2	297.6
	123,500		323.9	---	363.6	292.4
90			356.2	227.6	370.0	340.0
	44,460		385.9	239.2	399.6	370.0
	83,980		349.7	221.2	359.2	338.0
	123,500		332.8	221.6	350.8	312.4
179			368.7	245.6	380.8	355.6
	44,460		391.0	261.2	401.0	367.6
	83,980		363.4	240.0	376.8	349.6
	123,500		351.6	235.2	364.8	337.2
269			370.7	260.4	383.6	356.8
	44,460		395.9	285.2	411.6	378.8
	83,980		362.5	254.0	374.4	350.0
	123,500		353.6	241.6	365.2	341.2
	44,460		379.5	252.8	393.6	364.0
	83,980		349.7	242.8	364.4	334.0
	123,500		340.5	237.7	361.2	320.8
		33D49	353.3	232.4	368.8	336.8
		33K44	368.4	251.8	383.2	351.6
		33W84	352.2	252.3	372.8	332.4
		34F07	352.4	254.9	368.0	337.6

Table A8. Continued

N. Rate	Plant Density	Hybrid	Environments All	BRN, 11	High-St.	Low-St.
---kg N/ha---	--plants/ha--	---Pioneer---	mg			
	44,460					
		33D49	380.8	241.2	398.0	362.4
		33K44	395.1	252.8	409.2	379.6
		33W84	371.3	255.6	386.4	354.8
		34F07	370.9	262.4	381.6	358.8
	83,980					
		33D49	345.0	225.6	358.0	330.8
		33K44	361.3	248.8	377.2	344.0
		33W84	346.1	249.2	363.2	326.8
		34F07	346.4	249.2	359.6	334.0
	123,500					
		33D49	334.2	215.6	350.0	317.2
		33K44	348.9	244.4	363.6	331.2
		33W84	339.0	242.8	368.4	315.6
		34F07	339.8	244.4	362.4	319.6
0						
		33D49	326.3	222.4	349.6	302.4
		33K44	335.1	227.6	356.4	310.4
		33W84	329.4	228.4	364.0	302.0
		34F07	332.32	228.8	364.0	308.0
90						
		33D49	352.0	209.6	365.2	336.0
		33K44	369.6	221.6	383.6	352.8
		33W84	350.7	234.0	366.8	332.0
		34F07	352.3	244.8	364.4	339.6
179						
		33D49	368.0	236.4	380.0	354.8
		33K44	386.1	246.4	399.6	371.6
		33W84	360.6	253.6	374.4	345.2
		34F07	360.0	246.0	369.2	350.0
269						
		33D49	367.0	236.0	380.4	354.0
		33K44	383.0	275.2	393.6	371.2
		33W84	367.9	262.8	385.2	349.6
		34F07	364.8	267.2	375.6	352.0

Table A9. Kernel number results for data collected by nitrogen rate and plant density across hybrids for high-stress and low-stress environments.

N Rate	Plant Density	High-Stress	Low-Stress
---kg N/ha---	---Plants/ha---	-------------------kernels/m^2-------------------	
0		1,230	2,343
90		1,909	3,367
179		2,038	3,531
269		1,926	3,563
	44,460	1,906	2,630
	83,980	1,933	3,488
	123,500	1,489	3,484

Economic Analysis

Table A10: Net Return to Seed and Nitrogen ($ per hectare) among four N rates (0, 90, 179, 269 kg N/ha) and three plant densities (44,460, 83,980, 123,500 plants/ha).

Net Return to Seed and Nitrogen

HIGH-STRESS ENVIRONMENTS

	Plant Density		
Nitrogen Rate	44,460	83,980	123,500
-------kg N/ha-------	----------------------$ per hectare----------------------		
0	$1,404	$822	$393
90	$1,877	$1,606	$1,045
179	$1,838	$1,816	$881
269	$1,647	$1,450	$809

LOW-STRESS ENVIRONMENTS

	Plant Density		
Nitrogen Rate	44,460	83,980	123,500
-------kg N/ha-------	----------------------$ per hectare----------------------		
0	$1,957	$1,774	$1,262
90	$2,472	$2,974	$2,665
179	$2,386	$3,126	$2,971
269	$2,291	$3,023	$2,888