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Management Practices for Corn Producers Implementing Early Planting as a Production Strategy

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Management practices for corn producers implementing early planting as a production strategy

By

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Producers choosing to implement an early corn planting management strategy often experience several yield limiting biotic and abiotic factors. Field variability, flooding, sub-optimal soil temperatures which leads to poor nutrient uptake, delayed emergence and reduced root growth can limit grain production. Three separate experiments were conducted to address some of the negative effects associated with early corn planting. Experiment 1 evaluated flooding effects on several morpho-physiological traits including root system architecture during early crop development. Hybrids (DKC 6208, Pioneer 1197) were flooded at planting (V0) and growth stages V1, V2, V3 for 0, 6, 12, 24, 48, 96 hours. Plants flooded at V0 11% suffered the steepest decline in collar height. Plants flooded at V2 10% were more susceptible than plants flooded V1 4%. Overall, there was a linear decline in nutrient concentration if flooding occurred at planting. Tissue Na levels were the most affected by flood duration and K was the least affected. Experiment 2 evaluated biologic compounds developed to increase immobile nutrients P and K to improve fertilizer use efficiency and provide slow developing roots essential nutrients. The effectiveness of microbial products (B-300, QR, Mammoth, EM-

1) with/without starter fertilizer influenced yield, emergence, plant growth, and nutrient uptake. Biologic seed treatments compared to the control, resulted in a positive yield advantage for all treatments. Yields ranged from 37 to 48% higher if biologic compounds were applied. On average, yields increased from 26 to 38% after starter fertilizer was added to the biologic compounds. Phosphorus levels at VT were significantly higher for QR and K content was higher for B300, SF-B300, QR, Mamm, and SF-Mamm compared to the control. Experiment 3 addressed soil physical/chemical properties affecting plant development and there yield plant density relationship. On average, yields significantly increased 40% as plant population increased from 49,400 to 103,740 plants ha^{-1}. Based on the quadratic model agronomically yields would be highest at 61,360 plants ha^{-1}. Correlation analysis among yield and soil physical and chemical properties revealed positive correlations for grain yield, sand% ($r^2 = 0.42$), soil K ($r^2 = 0.17$) soil Na ($r^2 = 0.46$), and soil P ($r^2 = 0.49$).

DEDICATION

The driving force behind my decision to pursue a graduate degree was to strengthen my knowledge of crop science and learn the skills necessary to convey that knowledge, in a practical format, to farmers and agriculturists. Pursuing my doctorate degree would not have been possible without the support of my family. My wife Gaea, daughter Corabel, and entire family and friends at some point sacrificed in some manner which helped make this possible. My late grandfather Ron “Papa” O’Connor was one of my biggest supporters, although he didn’t get to see me finish I know he is watching and proud of me now. It is my hope that the contents of this dissertation may help at least one farmer or serves as a strong foundation for future investigators.

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CHAPTER I

MANAGEMENT PRACTICES FOR CORN PRODUCERS IMPLEMENTING EARLY PLANTING AS A PRODUCTION STRATEGY

Introduction

Crop production and management practices vary from year to year. Farmers face new problems, pests, and abiotic stresses, often multiple times within a single season. Despite these challenges producers start each year with the same goal of obtaining maximum yields and profit for their crops. This is especially true for corn (*Zea mays* L.) producers. Higher seed costs and fertility requirements result in corn producers assuming more financial risk of their initial crop investments compared to several other commodities. Variable costs such as seed, fertilizer, fuel requirements, equipment and even labor are much higher for corn producers. (USDA-ERS, 2016). United States (U.S.) 2015 total operating cost per planted acre for corn was 333.80 dollars whereas soybeans (*Glycine max* L.) was 170.80 and wheat (*Triticum aestivum*) was only 126.33 dollars per acre. (USDA-ERS, 2016).

Although risk is elevated in corn production, potential reward offsets possible liabilities for many producers. Corn contribution margins on a per acre basis are higher than soybeans and wheat making it an appealing commodity for producers (USDA-ERS, 2016). The majority of corn grown in the U.S. is used in livestock feed. As a result, the livestock industry has become dependent on U.S. corn production. Corn is also used to

create an assortment of food and nonfood products, such as corn meal, sweeteners, corn oil, starch and ethanol. Corn is the most abundant crop grown in the U.S. and produced 32 percent of the world's maize crop, as of 2010, making it the global leader in corn production (USDA-ERS, 2016).

One of the major obstacles producers face growing corn is yield reductions attributable to soil moisture stress (Nielsen et al., 2009, 2010; Ma et al., 2012). Some Mid-south producers have implemented management strategies of shifting planting dates forward to help avoid late-season heat and drought stress. Shifting planting dates forward, increases the probability of receiving more favorable weather conditions during the critical precipitation window of corn development.

Shifting planting dates forward minimizes late season stress, and subsequently increases the potential for early season plant stress as well. Planting earlier increases the likelihood of seeds being exposed to wetter soils and cooler temperatures. Shaw (1977) found that seed which remained in cold saturated soil for long periods of time after imbibition and prior to emergence were more likely to encounter destructive microbes resulting in poor seedling growth and development.

Early planting increases the likelihood of producers experiencing sub-optimal growing conditions with cooler soil temperatures and excess moisture during the early stages of corn development. Previous researchers observed comparable growing conditions resulted in poor plant stands, irregular emergence, and delayed plant growth (Gupta et al., 1988; Ford and Hicks, 1992; Bollero et al., 1996). Historically, planting corn too early or in unfavorable growing conditions like those previously mentioned triggered hesitation for many producers. However, development of more stress tolerant

corn hybrids have a greater capacity to withstand cooler, wetter soil conditions (Kucharik, 2008).

Even with new stress tolerant hybrids corn yields are heavily influenced by moisture stress whether it be excessive or insufficient throughout the growing season. Generally speaking corn is no different than other cereal crops in terms of water requirements for grain production and maintaining normal physiological processes. However, corn is more sensitive than many other crops with regards to timing of moisture and moisture requirements at certain growth stages. (Nielsen et al., 2009, 2010; Ma et al., 2012).

In terms of yield dependency regarding water availability the most critical stage in corn development is a two to three week window around tasseling (Shaw and Newman, 2013). The addition of heat and high winds coinciding with drought stress during the critical precipitation window magnify the stress effects resulting in additional yield losses. The greatest yield reduction occurs if moisture stress coincides with the R1 growth phase (silking). Stress during R1-VT interrupts the pollen shed window, decreasing the probability of successful pollen/silk nicking (simultaneous pollen release and silk emergence) (Shaw and Newman, 1991). More often than not, yield variability is attributed to moisture received during corn's critical precipitation window. However, excessive moisture during early stages of corn growth and development also contribute to substantial yield and thus economic losses.

Having minimal control of environmental factors affecting corn growth and development producers do employ management practices that minimize negative abiotic stressors affecting corn. Strategies such as planting date, hybrid selection, population

density, fertility, and weed management. Implementation of such strategies has led to steady increases in grain yields. Traditionally, increase in corn grain yield has been accomplished by adopting new genetic varieties and employing new or improved crop management practices or a combination of the two (Duvick, 2005).

Agricultural producers and their farming practices ultimately control the amount of food grain produced and, to a great extent, shape the global environment (Tilman et al., 2002). However, global population increases of approximately 75 million people worldwide per year and higher average incomes, especially in developing countries, have increased food and feed demand. For many consumers in developing countries salary increases actually reshaped dietary preferences. The outcome has been a consumption increase of staple foods, but also expanded diets to include more meats, dairy products, and vegetable oils. As a result commodity demand for grains and oilseeds used for feeding livestock have also increased (Trostle, 2008).

The downstream effect of increased demand, volatile commodity prices, rising production costs, and technological advancements have also reshaped U.S. production methods. The overall number of farmers has decreased while the size of farm operation has increased. Thus, producers are challenged to not only manage larger areas, but also maintain efficiency while maximizing profit margins and consumption of crop inputs (Varco, 2015).

Tilman (2001) defined terrestrial or useable lands as all land that is not desert, tundra, rock or boreal. He also went on to say that farmers are the primary managers of such lands and about half of the global usable land is at present in pasture, grazing or intensive production agriculture. Unfortunately, the quality and quantity of usable land

available for production agriculture has, and will, continue to decrease as populations increase. Therefore, it is important that we continue to develop and use existing technologies to attain greater levels of efficiency in production agriculture.

For example, implementing site specific crop management precision agricultural practices has helped many producers become more sustainable in their farming operations. At the surface, precision agriculture seems to be a humble concept of increasing farm productivity. Where efficient use of fertility management was once linked to a producer's bottom line has changed considerably. Economics alone is no longer the driving force in crop production. Producers now more than ever have a much greater impact on our future survival.

Globally, agriculture adds substantial and environmentally detrimental amounts of nitrogen and phosphorus to the environment (Vitousek et al., 1997; Carpenter et al., 1998). In fact, many researchers believe that the negative impacts associated with indiscriminate fertilizer application may triple if historical practices are used to achieve another doubling in food production (Tilman et al., 2001; Cassman et al., 1995). The future environmental effects of agricultural practices will influence not only farmers but societal acceptance of their production methods as well.

In order to maximize net benefits of food production we must also understand the costs and the benefits of alternative agricultural practices. For example, current management practices with respect to essential nutrients like phosphorus regularly experience low plant P use efficiency. This is due in part to natural chemical sorption and transformations of P fertilizer applied to soils (Baas et al., 2016). Producers are challenged to find sustainable solutions for delivering P more efficiently to crops and

eliminating the risk of environmental contamination (MacDonald et al., 2011). In some cases, less than 10% of P fertilizer applied to soil is available for plant use. This is a result of the applied P binding to calcium (Ca), aluminum (Al) and iron (Fe) mineral components of the soil or lost all together due to leaching (Doolette & Smernik, 2011, Randriamanantsoa et al., 2013).

In general, roots absorb phosphorus as orthophosphate, and sometimes certain forms of organic phosphorus. Phosphorus moves to the root surface through diffusion. The presence of mycorrhizal fungi however, form a symbiotic relationship with plant roots by extending threadlike hyphae into the soil, which can increase the uptake of phosphorus. This is especially true for acidic soils that are low in phosphorus (McClellan et al., 2013). Exploiting naturally occurring soil microbial communities specifically targeted to mobilize soil bound P may add environmental benefits to current nutrient management by improving crop nutrient uptake and yield productivity (Baas et al., 2016).

Managing inputs efficiently requires an understanding of the importance of each production factor to yield and how those production factors vary spatially across a field (Cox et al., 2007). Crop and soil management zone delineation is an important part of this process. Crop and/or soil management zones are intended to identify within field areas that have the same or similar yield limiting characteristics such that they can be managed independently. Homogenous areas within fields can then be delineated as “management zones” and treated to optimize economic yields (Cox et al., 2007). The objective of precision agriculture is to optimize production efficiency, profitability, and increase sustainability while reducing the negative environmental effects associated with crop production.

Precision agriculture allows producers to make better management decisions based on the spatial and temporal variability within soil and the effects it has on crop growth. (Robert et al., 1996; Duffera et al., 2007). Collecting in season data such as plant emergence, population density, soil productivity, spectral analysis, yield, and plant growth characteristics provides information that can be used to map field variability. Understanding these relationships within individual fields would improve our ability to modify management techniques and production efficiency throughout the field.

CHAPTER II

INTERACTIVE EFFECTS OF FLOODING INTERVALS AND GROWTH STAGES ON CORN EARLY SEASON GROWTH AND DEVELOPMENT

Abstract

Each year early spring rainfall results in significant production losses for corn (*Zea mays* L.) producers in the U.S. Mid-South. This is especially true for producers implementing an early planting management strategy. We evaluated two commercially available hybrids (DKC 6208, Pioneer 1197) and imposed flood treatments at four growth stages (V0, V1, V2, V3) and six flood intervals 0, 6, 12, 24, 48, 96 h. The specific objectives of this study were to determining flooding effects on two corn hybrids with different genetic background at different growth stages by measuring several morpho-physiological traits including root system architecture. Flood duration effects on corn plants flooded at planting (V0) suffered the greatest decline in collar height. Corn plants flooded at V2 were more susceptible to flooding stress than plants flooded at V1. Collar height at V0 declined by 11%, collar height at V1 declined by 4%, collar height at V2 declined by 10%, and collar height at V3 declined by 9% as flood duration increased from 0 to 6 h. Averaged across flood duration DKC 62-08 leaf lengths were 5% longer than PHB 1197. However, after 6 h of flooding PHB 1197 averaged 8% longer leaf lengths compared to DKC 62-08 and 5% longer after 12 h of flooding. Leaf length for PHB 1197 declined linearly after 24 h of flooding. Hybrid DKC 62-08 leaf length

increased 4% as flooding duration increased from 12 to 24 hours and declined linearly, but a slower rate than PHB after 24 h of flooding was imposed. Overall, there was a linear decreasing trend for all of the plant nutrients analyzed when flooding occurred at planting. The rate of nutrient concentration decreasing the fastest was Na. The rate of nutrient concentration falling the slowest was K. Tissue concentration for K was highest 2.86% when flood duration occurred for 24 h and lowest 0.63% when flooding lasted 96 hours.

Introduction

Several studies have been conducted evaluating the impact of flooding on corn. Previous research suggests there are three main factors associated with injury caused by flooding; 1) timing of flooding during the life cycle of corn, 2) frequency and duration of flooding, and 3) air-soil temperatures during flooding (Belford et al., 1985). Any one or combination of these flooding factors greatly influences corn development.

In the event of a flood, soil pores fill with water limiting the amount of available oxygen for plants. Roots that become deprived of oxygen lose the ability to respire. Without respiration, corn plants are not able to release chemical energy needed to fuel cellular activity. As a result of declining oxygen levels and plant respiration it is common to see plants with reduced total root volume, restricted transport of water and nutrients through the roots to the shoot, and an increase in gas accumulation from microorganisms that can become toxic at certain levels (Wesseling, 1974).

If conditions persist and soil remains waterlogged, flooding causes not only above-ground plant cells to die, but plant roots as well. Previous research documented flooding periods in as little as 1-12 h can result in measurable adverse effects on root and leaf growth (Wenkert et al., 1981). In 2011, 70% of yield reductions for crops grown in the United States were attributed to drought or flooding. Mississippi farmers lost an estimated 800 million dollars whereas monetary losses for corn and soybean (*Glycine max*) production in the Midwest totaled more than $1.6 billion (Motavalli et al., 2013).

Fortunately, not all growing seasons experience extreme rainfall totals like those in 2011; however, many researches hypothesize that the frequency for climatic extremes have and will continue to increase resulting in major losses for crop producing regions

(Bailey-Serres et al., 2012). In addressing yield losses due to drought, the agriculture industry has recently developed commercially available corn varieties either engineered by genetic modification or advanced breeding techniques to be more drought tolerant than previous cultivars. Unfortunately, there has been less progress by seed companies in developing flood tolerant corn cultivars targeted for commercial use (Motavalli et al., 2013).

Advancements in technology have allowed increasingly more information to be accumulated on molecular, biochemical, physiological, morphological, anatomical and metabolic responses to flooding and oxygen deficiency in plants (Kennedy et al., 1992; Vartapetian and Jackson, 1997; Baxter-Burrell et al., 2003; Greenway et al., 2006; Mustroph et al., 2006). As a result, plant genes linked to flood tolerance have since been identified in several crops. The goal now is to modify those genes to develop new and improved flood tolerant crops (Ahmed et al., 2013).

Developing flood tolerant corn cultivars thus far has shown much progress; however, additional understanding of both molecular and physiological processes is still needed. (Qiu et al., 2007). Researchers have established that some corn cultivars do have several naturally occurring adaptive mechanisms to counter conditions of excessive soil moisture both under conditions of partial waterlogging or complete submergence. Such mechanisms include formation of air space (aerenchyma) in the root cortex, stem enlargement (hypertrophy), adventitious root formation particularly near the soil surface (Zaidi et al., 2004) and early root tip death (Subbaiah and Sach, 2003). As a result from the inherent genetic variability in maize, with respect to flood tolerance (Sachs et al.,

1996). Identifying growth and physiological trait differences among corn hybrids would be useful for future researchers to develop more flood-tolerant cultivars.

Agronomic management studies have also been conducted to determine the use of different sources and rates of nitrogen (N) fertilizer to promote increased flood tolerance and recovery in interaction with different corn hybrids (Motavalli et al., 2013). Nielson, 2011 credited denitrification, leaching losses as well as reduced crop N uptake to low oxygen levels in soils where flooding occurred. Experiments conducted by Ritter and Beer, (1969) observed lower yield losses in flooded plots when treated with high N fertilizer rates compared to those of low N fertilizer applications. Applying additional N fertilizer enhances and accelerates plant adaptive mechanisms like root re-growth after flooding.

Each year early spring rainfall results in significant production losses for corn producers in the Mid-South. Growing environments that receive excessive moisture in low lying fields or flood prone areas with poorly-drained soils can be a recipe for disaster. This is often true for producers implementing an early planting strategy. Regular flooding that typically occurs in confined areas or regions could become more widespread if the frequency for climatic extremes continue to increase as predicted (Bailey-Serres et al., 2012). More extreme periods of drought and wetter weather periods are predicted to occur more frequently with significantly more rain during the spring and significantly less during the fall (Andresen et al., 2012)

The decision to plant early depends upon a producer's soil type, equipment and especially upon personal risk/reward tolerance. However, today's corn hybrids have greater tolerance to withstand cooler, wetter soil conditions (Kucharik, 2008).

Improvements in corn genetics have resulted in hybrids that are more tolerant to environmental stresses such as temperature and moisture extremes. Identifying growth characteristics resulting from imposed flooding and classifying flood tolerance with respect to different hybrids could provide much needed information for future researchers and producers. Ultimately, selecting hybrids that exhibit flood tolerance could greatly reduce corn production losses in the future. In addition, experimental findings could lead to targeted management practices for areas that are vulnerable to excessive soil moisture conditions, such as low-lying and floodplain areas.

Objectives

This experiment evaluated flooding effects on corn above and below-ground in regards to growth and development. We evaluated two commercially available hybrids (DKC 6208, Pioneer 1197) and imposed flood treatments at four growth stages (V0, V1, V2, V3) and six flood intervals 0, 6, 12, 24, 48, 96 h. Imposing a flooding scenario using full-strength Hoagland nutrient solution allowed us to measure several developmental components of corn growth without fertility being a limiting factor.

The specific objectives of this study were to determining flooding effects on two corn hybrids with different genetic background at different growth stages by measuring several morpho-physiological traits including root system architecture during early crop development.

Materials and Methods

Two commercially available Mid-South adapted corn hybrids DKC 6208, Pioneer 1197, were used for this study. Selection of these hybrids was based partly on the recommendations from local industry seed representatives. Closer assessment revealed they comprised a large footprint of the market share, had similar relative maturity ranges, 112 and 111, and proven yield performance in the region which made them ideal candidates for testing.

Experiments were conducted at the Rodney Foil Plant Science Research Center, Mississippi State University, Mississippi State (33° 28′N, 88° 47′W), Mississippi State, MS, USA. Polyvinyl-chloride schedule 40 foam core pipe was used to create 192 (101.6-mm diameter and 406.4-mm height) individual plant containers for this experiment. Plant

containers were filled with a sand/soil composite material consisting of 3 parts sand and 1 part top soil sandy loam with 87% sand, 2% clay, and 11% silt.

Initially, four seeds were sown 50.8 mm deep in each container and later hand thinned to one plant per container two days after emergence. All plant containers were evenly spaced and grouped into four rows on a concrete pad under miniature plastic covered hoop-houses. The hoop-house was designed to allow natural air to flow freely through the growing plant area, but retain minimal heat. Environmental growing conditions for plants were naturally occurring other than precipitation.

Plants were irrigated with full-strength Hoagland's nutrient solution through an automated computer-controlled drip system throughout the experiment. Amount and duration of irrigation for treatments undergoing a flood scenario were evaluated hourly and supplemental Hoagland's nutrient solution was applied through the same drip system as needed to maintain flood levels. Flooded plants retained a minimum of 38-mm of liquid solution above the soil surface throughout the duration of the specified flood periods. Plants post-flood were watered normally (twice daily) throughout the remainder of the experiment using the same nutrient solution.

Plant Growth and Development

Length to highest collared leaf (CHEIGHT), width of each leaf at the widest point (L1width) (L2width) (L3width) (L4width), length of each leaf from base to tip (L1LENGTH) (L2LENGTH) (L3LENGTH) (L4LENGTH), stalk width measured just below the first leaf (STALKW), canopy area (CAREA) was measured on all plants 18 days after planting just prior to experiment termination. Leaf area (LAREA) was measured using the LI-3100 leaf-area meter (LI-COR, Inc.). Leaf dry weight (LDW),

stem dry weight (SDW) and root dry weight (RDW) were measured from all plants after oven drying at 80°C until a constant weight was reached. Dry weights of each tissue sample was then recorded for analysis.

SPAD 502 chlorophyll meter (Konica-Minolta, Japan) was used to measure leaf absorbance in the red and near-infrared electromagnetic regions. The numerical SPAD value provides a surrogate to the amount of chlorophyll present in leaf tissue and is a nondestructive method to monitor the crop N status. SPAD readings, have been used to predict the N fertilizer demand for top-dressings in rice (*Oryza sativa* L.) (Cabangon et al., 2011), and maize (*Zea mays* L.) (Varinderpal-Singh et al., 2011).

SPAD measurements were taken from the middle portion of the leaf parallel to the mid-vein of the most recently matured leaf at time of collection. Three SPAD readings were taken from each plant and values were averaged for each treatment. Leaf area (LAREA), leaf dry weights (LDW), stem dry weights (SDW), root dry weights (RDW). Specific leaf area (SLA), leaf area ratio (LAR), and root to shoot ratio (RSRATIO) were estimated from the respective measurements in each treatment.

Nutrient Analysis

Individual plants were separated into root, stem and leaf tissue samples, washed free of debris using deionized water and oven dried at 80 °C until a constant weight was reached. Plant dry matter samples were ground using a Wiley Mini-Mill with a 40-mesh screen (Thomas Scientific, Swedesboro, NJ) in preparation for nutrient analyses. Calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), and phosphorus (P) were processed using the methods described by (Donohue and Aho, 1992). Macronutrient concentrations were determined by ICP (Inductively Coupled Plasma) Spectrophotometer.

Calculations

Total plant dry weight was calculated by summing dry weights of the leaf, stem, and root tissues of each plant. Nutrient content within each tissue sample was calculated by multiplying tissue dry weight by tissue concentration for each particular nutrient. Leaf area (LAREA) was measured using the LI-3100 leaf area meter (Li-COR, Inc., Lincoln, NE). Leaf dry weights (LDW), stem dry weights (SDW), root dry weights (RDW) were recorded for each plant component after oven drying. Specific leaf area thickness (SLA) was calculated by dividing the total leaf area by leaf weight per plant. Leaf area ratio (LAR), was calculated by dividing leaf area per plant by the weight per plant. Root to shoot ratio (RS) was calculated by dividing root dry weights by above-ground plant dry weights.

Experimental Design and Data Analysis

The experimental design was a CR design. The treatment design consisted of a complete factorial with germplasm (2 hybrids), flood duration (6 time durations), and flooding events (4 triggers at growth stages) as the three experimental factors. This resulted in 48 different treatment combinations with four replications. Significance of main effects or interactions was determined by using analysis of variance (ANOVA) GLM procedure of SAS (version 9.4; SAS Institute, Cary, NC 2011). Using ANOVA, multiple comparison of least square means were made with the stimulation method at $P < 0.05$. To obtain relative vigor response indices, the measured values from each growth and development parameter were normalized to obtain the slopes in response to flood duration at different growth stages. The control (FTIME 0 h) value from each parameter within a treatment was used as the denominator so that the derived values could be

normalized falling within a relative scale of 0 to 1 as described by Reddy et al. (2003, 2008). Graphical analysis was performed with SigmaPlot 11.0 (Systat Software Inc., San Jose, CA).

Root Imaging and Analysis

Plant roots were separated from the soil using water and 6 mm wire sieve. Careful attention was taken in washing soil and debris from the roots to minimize harm to the root system. Washed roots were then arranged and spread in a tray to minimize root overlap. This was accomplished by floating the roots in 5 mm of water in a 0.3 × 0.2 m Plexiglas tray. The tray was then placed on top of a specialized dual scan optical scanner (Regent Instruments, Inc., Quebec, Canada). Finally, individual root structures from each treatment were scanned using Epson Expression 11000XL scanner (Epson Inc., Long Beach, CA, USA) interfaced with WinRHIZO Pro software system (Version 2009C, Regent Instruments Inc., Canada). Root images were obtained using a greyscale setting at ‘‘high’’ accuracy (resolution 800 by 800 dpi). Root scans were then analyzed for total root length (RLENGTH), root area (RAREA), root surface area (RSURFAREA), average root diameter (RDIAM), root length per volume (RLPV), root volume (RVOLUME), number of tips (RTIPS), number of forks (RFORKS), and number of crossings (RCROSSINGS) WinRHIZO Pro software system.

Results and Discussion.

Plant Growth and Development

Hybrid Main Effects

Above-ground Effects

The above-ground measured main effects with respect to hybrid varied between dependent variables (Table 2.1). There were significant differences between hybrids when analyzing CHEIGHT, L1WIDTH, L1LENGTH, L2WIDTH, L3WIDTH and L3LENGTH. Average CHEIGHT was the only variable where DKC 62-08 out produced PHB 1197 with respect to above-ground measurements collected. On average there was a significant 6% height difference when measuring from the soil surface to the highest collard leaf for DKC 62-08. Hybrid PHB 1197, ended up with a 6% advantage in L1WIDTH, 17% L1LENGTH, 15% L2WIDTH, 18% L3WIDTH, 5% L3LENGTH compared to DKC 62-08.

Below-Ground Effects

The below-ground measured main effects with respect to hybrid also varied between dependent variables (Table 2.2). There were significant differences between hybrids when analyzing RDIAM, RVOLUME, RDW and RSRATIO. Interestingly, there was an opposite trend between the two hybrids when comparing the above-ground measurements. Hybrid DKC 62-08 ended up with a 14% advantage in RDIAM, 11% RVOLUME, 14% RDW and 14% RSRATIO compared to PHB 1197.

Imposed Flood at Growth Stages Main Effects

Above-ground Effects

The above-ground measured main effects with respect to imposed flooding at different vegetative growth stages varied between dependent variables (Table 2.1). There were significant differences between hybrids when analyzing CHEIGHT, L1WIDTH, L2WIDTH, L3WIDTH, L3LENGTH, STALKW, LAREA, LDW, SDW, SLA, and LAR. Regardless of hybrid or flood duration, there was significant 9% reduction in CHEIGHT, following flooding at planting (V0) compared to flooding at the first true leaf (V1). We also observed a significant 11% reduction in L1WIDTH after flooding was imposed at planting compared to the fourth leaf vegetative stage. Interestingly, there was no significant difference between L1WIDTH and L2WIDTH after flooding was imposed at the second or third leaf vegetative stage. Numerically there was a 4% advantage in leaf width after flooding was triggered at the fourth leaf stage compared to the third leaf stage.

On average affecting the vegetative growth stages in order developmentally (V0, V1, V2, V3) there was a 2 to 3% reduction in L3WIDTH as flooding was triggered. Flooding effects on STALKW revealed there was a significant reduction 8% after imposing floods at the V0 stage compared to V3. Surprisingly, there was also 3% less significant reduction of stalk width after flooding was imposed at V2 compared to V3. Leaf area declined anywhere from 2 to 17% in response to flooding. Developmentally LAREA and LDW exhibited similar trends. Measurements for both variables were lowest if flooding was imposed at V0 and slowly increased as flooding was imposed to the next triggered growth stage. We observed a 12% increase in LDW when allowing the corn plants to reach the V1 growth stage and 21% when allowing plants to reach V3 growth

stage before imposing a flood. The flooding effects on SDW were similar to results for STALKW. Intuitively it would make sense that there would be less negative effects on variables when flooding occurred at later vegetative growth stages. For most measured variables this was true, however in the case of both SDW and STALKW we observed a slight decrease when flooding occurred at the second leaf compared to the first leaf.

Previous reviews and published studies demonstrated that root tissues become more tolerant to oxygen less (anoxia) conditions if they are pretreated with intermediate oxygen concentrations (hypoxic pretreatment) (Johnson et al., 1994; Waters et al., 1991; Atwell, 1999). Apparently, metabolic adaptations initiated by hypoxia increase tolerance levels to anoxia. Changes to the overall protein complement was the first metabolic adaptations to be considered (Atwell et al, 2014).

Unlike the previous results SLA and LAR, produced less logical responses towards flooding. In both measurements there was an increase for treatments flooded at planting compared to other growth stages. There was a 6% increase for both variables when comparing flooding effects at growth stages (V0 to V3).

McBurney (1992) describes the relationship between leaf thickness (SLA) being curvilinear and strongly influenced by leaf age and stress history. Atwell et al, (2014) determined that normal protein synthesis is replaced by anaerobic proteins for some plants in anoxic environments. Coincidentally, maize roots have 20 to 22 of these proteins. We speculate that these fermentative enzymes pyruvate decorboxylase (PDC) and alcohol dehydrogenase (ADH), involved in anaerobic carbohydrate catabolism (e.g. sucrose synthase and enzymes responsible for the reversible breakdown of sucrose) and

several glycolytic enzymes (e.g. aldolase) could be contributing factors to the increased SLA and LAR previously observed.

Other plant tissues which survive but do not grow in anoxic environments will produce an initial burst of fermentative activity over a period of 6 to 24 hour before slowing fermentation rates. This type of documented adaptation provides adequate ATP through the conservation of carbohydrates. Stockpiling or rationing the carbohydrates provides an energy source while the plant tissues become acclimated to the anoxic conditions (Raymond and Pradet 1980).

Below-Ground Effects

The below-ground measured main effects with respect to hybrid also varied between dependent variables (Table 2.2). There were significant differences between hybrids after analyzing RAREA, RSURFAREA, RVOLUME, RDW and RSRATIO. Developmentally RAREA, RSURFAREA and RVOLUME reacted similarly in their response to flooding. All three variables were lowest if flooding was imposed at planting and increased moderately 6% if flooding occurred at the third leaf stage (V3). The largest significant difference occurred after flooding was imposed at the first leaf stage and increased the measured variables anywhere from 12 to 16% compared to floods at planting. Based on these results there was a slight advantage for the measured variables when flooding occurred at the first true leaf growth stage.

Measured variables RDW and RSRATIO did not produce similar results. In the case of RDW there was no significant difference between vegetative growth stages involving development of leaves, but there was significantly lower RDW when flooding occurred at planting. The RSRATIO results indicated that there was no significant

difference in the flooding effects if flooding was triggered at planting (V0), V1 or V2. There was however, significantly lower RSRATIO when flooding occurred at the third leaf growth stage (V3).

It is important to point out that oxygen levels in waterlogged conditions can vary depending on other environmental conditions. Nevertheless, water is characteristically an extremely poor medium for gas diffusion. In fact, diffusion of oxygen in waterlogged soils is further impeded by stagnant and/or turbid floodwaters, because this further restricts the availability of light and oxygen. Light or radiance can significantly impact internal oxygen content of submerged plants. Oxygen levels in plant shoots can fluctuate depending on light availability, presence of leaf gas films, and unique leaf traits that facilitate underwater photosynthesis and inward diffusion of oxygen. Consequently, root oxygen content is strongly dependent on photosynthetically derived oxygen from the shoot after the plant is completely submerged or oxygen that diffuses into an emerged shoot. The movement of oxygen from shoot to root is influenced by source sink strength, tissue porosity, and root respiratory demand (Atwell et al, 2014).

There were several interesting results observed while evaluating the above and below-ground flooding effects that occurred at different vegetative growth stages. Interestingly, some of the results did not always follow along with what would be considered a logical response. It is likely that there were several factors affecting the results. That being said, careful consideration was used when triggering the flooding treatments. We feel confident that our flooding treatments occurred evenly and were consistent across treatments.

Imposed Flood Duration Main Effects

Above-ground Effects

The above-ground measured main effects with respect to flood duration varied between dependent variables (Table 2.1). There were significant differences between hybrids after analyzing CHEIGHT, L3LENGTH, STALKW, CAREA, SPAD, LAREA, LDW, and SDW. Collar height (CHEIGHT) was significantly impacted by flood duration. Plant collar height measurements ranged from a 0.25 to 17% reduction in height as a result of flooding duration. Unsurprisingly, the most significant response occurred between a flooding duration of 0 and 96 hours. Although, there was also an interesting increase in CHEIGHT when duration occurred for 24 hours compared to only 12 hours.

L3LENGTH was also significantly impacted by flood duration. However, percentage wise there was less decline in leaf length compared to CHEIGHT as flood duration increased. The numerical difference between the treatments ranged from 0.45 to 9%. Unlike, collar height the most significant response occurred between a flooding duration of 6 and 96 hours (Table 2.8). There was also an unexpected increase in L3LENGTH when duration occurred for 6 hours compared to 0 hours. Although a small difference, there was almost a half percent increase in leaf length attributed to the stress associated with a brief 6 hour flood.

There was a reoccurring pattern between STALKW, CAREA, SPAD, LAREA, LDW, and SDW. Expectedly there was in most cases a significant and often numerical penalty associated with the 96 hour flood treatment for all listed variables compared to the non-flooded control. There were also significant and numerical advantages for treatments that did not receive a flood treatment. Unexpectedly, there was also a

numerical advantage for measured variables that were flooded for 24 hours compared to only 12. Similar to RAREA, RSURFAREA and RVOLUME with respect to flooding at different growth stages and CHEIGHT and L3LENGTH flooded at different intervals, it appears that we once again found an advantage from the stress imposed by a flooding scenario.

Below-Ground Effects

The below-ground measured main effects with respect to flood duration varied between dependent variables (Table 2.2). There were significant differences between measured variables RLENGTH, RAREA, RSURFAREA, RLPV, RVOLUME, RTIPS, RFORKS, RCROSSINGS and RDW and the duration of the flooding scenario. This type of physiologic response of cellular proliferation has been observed in other crops. However, the measurable adaptations will vary across species. This is because plant species have morphological and physiological differences in root and organ systems and unique metabolic responses to flooding stress. Root systems in some plant species have a distinct advantage and ability to form aerenchyma in waterlogged soils (Thomson et al., 1992).

Mathematical models based on oxygen transport rates can accurately predict the maximum length to which adventitious roots can grow in waterlogged soil. Adventitious root length is highly dependent on the amount of aerenchyma formed (Thomson et al., 1992). The trends observed in the above-ground variables were similar to those for below-ground. There was a less of a decline in the measured variables when flooding lasted 0 hours compared to 96 hours. With the exception of number of root tips (RTIPS) there was a significant penalty or reduction for each variable being measured. Similarly,

with the exception of RVOLUME there was a significant advantage or improvement in each variable being measured when flooding treatment was 0 hours.

Generally, waterlogged plants will have shorter more condensed root systems than those grown in well-drained soil. This is because the efficiency of oxygen delivery via aerenchyma does not accommodate normal growth requirements (Thomson et al., 1992; Atwell et al., 2014). Logically, these results are not surprising with the exception of what appears to be a slight growth advantage triggered from the stress imposed by a brief flooding event. Although statistically, there were no significant differences, numerically all of the below-ground variables produced higher values when flooding duration lasted 24 hours compared to 12 hours.

It is plausible to consider this unlikely advantage is possibly a stress induced adaptive characteristic shared between the two hybrids. Additional, documented traits include upward bending of leaves (hyponasty), enhanced shoot elongation, formation of interconnected air-filled voids (aerenchyma), induction of barriers to radial O_2 loss in roots, development of adventitious roots, formation of gas films on leaf surfaces, modifications of leaf anatomy and pressurized gas flow through porous tissues (Jackson & Armstrong, 1999; Colmer, 2003; Mommer & Visser, 2005; Colmer & Pedersen, 2007; Polko et al., 2011; Sauter, 2013). Of these traits mentioned, there is an improved understanding of the developmental plasticity that drives aerenchyma and the formation and elongation of aerial organs. All of these involve ethylene, but the first two also involve generation of reactive O_2 species and are not associated to hormonal fluctuations including abscisic acid and gibberellins.

Nutrient Analysis

The results of the nutrient concentrations in relation to flood duration are presented in Figure 2.1. Overall, there was a linear decreasing trend for all of the plant nutrients analyzed when flooding occurred at planting. The rate of nutrient concentration falling the fastest was Na with a slope of -0.000013 $r^2 = 0.91$ followed by Mg -0.000072 $r^2 = 0.85$. Sodium concentration was highest 0.30% when flood duration occurred for 24 h and lowest 0.06% when flooding lasted 96 h. Magnesium concentrations were also highest 0.09% when flood duration occurred for 24 h and lowest 0.02% when flooding lasted 96 h. The decline of Ca and P tissue concentration responded similarly to flooding duration. The range of Ca concentration was 0.30 at 24 h and 0.06 at 96 hours with a slope of -0.00023 $r^2 = 0.83$. The range of P concentration was 0.35 at 12 h and 0.08 at 96 hours with a slope of -0.00024 $r^2 = 0.79$. The rate of nutrient concentration falling the slowest was K with a slope of -0.0198 $r^2 = 0.80$. Tissue concentration for K was highest 2.86% when flood duration occurred for 24 h and lowest 0.63% when flooding lasted 96 hours.

Hybrid Flood Duration Interactions

Hybrid Relative Vigor Response Indices

Leaf development rates of the third leaf length were significantly ($P < .05$) affected by the interaction between hybrid and flood duration. The decline in leaf length in response to flood duration was more evident for hybrid PHB 1197. Based on all statistical model selection criterions considered and compared with the best linear, exponential, and hyperbola models fitted to the data, the quadratic model best explained the leaf length flood duration relationship for both hybrids (Figure 2.2 A). The quadratic

model fitted to leaf length for DKC 62-08 $r^2 = 0.81$. The quadratic model fitted to the leaf length for PHB 1197 $r^2 = 0.83$. Averaged across flood duration DKC 62-08 leaf lengths were 5% longer than PHB 1197. However, after 6 h of flooding PHB 1197 averaged 8% longer leaf lengths compared to DKC 62-08 and 5% longer after 12 h of flooding. Leaf length for PHB 1197 declined linearly after 24 h of flooding. Hybrid DKC 62-08 leaf length increased 4% as flooding duration increased from 12 to 24 hours and declined linearly, but a slower rate than PHB after 24 h of flooding was imposed.

Plant nutritional assessments between the two hybrids in response to flood duration were derived from SPAD values collected 18 days after planting. Leaf SPAD values were significantly ($P < .05$) affected by the interaction between hybrid and flood duration. The decline SPAD value in response to flood duration was more evident for hybrid DKC 62-08. Based on all statistical model selection criterions considered and compared with the best linear, exponential, and hyperbola models fitted to the data, the Linear model best explained the SPAD flood duration relationship for DKC 62-08. The quadratic model best explained the SPAD flood duration relationship for PHB 1197 (Figure 2.2 B). The linear model fitted to the SPAD values for DKC 62-08 $r^2 = 0.71$. The quadratic model fitted to the SPAD values for PHB 1197 $r^2 = 0.80$.

Root development partially characterized by the number of root forks was significantly ($P < .05$) affected by the interaction between hybrid and flood duration. The deleterious effects of flood duration and the number of root forks was more evident for hybrid DKC 62-08 slope = -0.0000038 compared to PHB 1197 slope = -0.0000069. Based on all statistical model selection criterions considered and compared with the best linear, exponential, and hyperbola models fitted to the data, the quadratic model best

explained the number of root forks flood duration relationship for both hybrids (Figure 2.3 A). The quadratic model fitted to number of root forks for DKC 62-08 $r^2 = 0.82$. The quadratic model fitted to the number of root forks for PHB 1197 $r^2 = 0.91$. The initial response among hybrids in relation to flood duration lasting 6 h decreased the number of root forks 34% for DKC 62-08 compared to 7% for PHB 1197. Both hybrids responded similarly after 24 h of flooding and the number of root forks declined linearly through 48 h. The difference in number of root forks between hybrids after 96 h of flooding was 46% with the advantage again going to PHB 1197.

Root development furthermore characterized by the number of root crossings was significantly ($P < .05$) affected by the interaction between hybrid and flood duration. The damaging effects of flood duration and the number of root crossings was once again more evident for hybrid DKC 62-08 slope = -0.00063 compared to PHB 1197. Based on the statistical model selection criterions considered. The linear model best explained the number of root crossing for DKC 62-08 and quadratic model best explained the number of root crossings flood duration relationship for PHB 1197 (Figure 2.3 B). The linear model fitted to number of root crossings for DKC 62-08 $r^2 = 0.76$. The quadratic model fitted to the number of root crossings for PHB 1197 $r^2 = 0.88$. Although, the rate of decline in number of root crossings was more evident for DKC 62-08 overall. There was a 16% advantage with respect to root crossings for DKC 62-08 over PHB 1197 after flooding lasted 48 hours.

Flood Duration Effects on Root Development

Flood Duration Relative Vigor Response Indices

Averaged across hybrid and growth stage there was a similar trend for root length, root volume, and root area with respect to flood duration. All three root development parameters measured declined linearly as flood duration increased. The decline and vigor in response to flood duration exposed root volume (slope -0.00052) as being the most susceptible to the negative stress associated with flood duration followed by root area (slope -0.00053) and root length (slope -0.00054). Based on all statistical model selection criterions considered and fitted to the data, the linear model best explained the root parameter flood duration relationship (Figure 2.4 A). The linear model fitted to root length $r^2 = 0.85$, root volume $r^2 = 0.90$, root area $r^2 = 0.88$.

The root development characteristics number of root forks and root crossings averaged across hybrids trended similarly with respect to flood duration. Based on all statistical model selection criterions considered and fitted to the data, the linear model best explained the root development flood duration relationship (Figure 2.4 B). The linear model fitted to root forks $r^2 = 0.87$ and root crossings $r^2 = 0.84$. Both root development parameters declined linearly as flood duration increased. The decline and vigor in response to flood duration characterized by the number of root crossings (slope -0.00064) as being more susceptible to flood duration compared to the formation of root forks (slope -0.00067). The decline in number of root forks 15% and root crossings 22% initial response to flood duration 0 to 6 h resulted in the largest difference comparing root development parameters with respect to flood duration.

Flood Duration Effects on Plant Development

Flood Duration Relative Vigor Response Indices

Averaged across hybrid and growth stage there was a similar trend for collar height, length of 3rd leaf, stalk width, and leaf area with respect to flood duration. All of the plant development parameters measured declined linearly as flood duration increased. The decline and vigor in response to flood duration exposed leaf area (slope 0.00044) as being the most susceptible to the negative stress associated with flood duration followed by stalk width (slope -0.00029), collar height and lastly length of the 3rd leaf. Based on all statistical model selection criterions considered and fitted to the data, the linear model best explained all of the plant development flood duration relationships (Figure 2.5). The linear model fitted to collar height $r^2 = 0.94$, length of 3rd leaf $r^2 = 0.98$, stalk width $r^2 = 0.97$, and leaf area $r^2 = 0.90$. Collar height declined by 6% as flood duration increased from 0 to 6 h whereas stalk width declined by 3% at the same flood duration. Conversely, at the same flood duration flood duration increase of 6 to 12 h collar height declined by 2% whereas stalk width declined by 5%.

Growth Stage Flood Duration Interactions

Growth Stage Flood Duration Relative Vigor Response Indices

Collar height response, averaged across hybrid, and imposed at the different growth stages varied with respect to flood duration. While, the overall trend for collar height decreased as flood duration increased. The rate of decline was clearly affected by the growth stage at which the flood was imposed. Flood duration effects on corn plants flooded at planting (V0) suffered the steepest decline in collar height (slope -0.00041). Interestingly, corn plants flooded at V2 (slope -0.00016) were more susceptible to

flooding stress than plants flooded at V1 (slope -0.00013). Based on the statistical model selection criterions considered and collar height response fitted to the data, the linear model best explained growth stages V0, V1, and V2 and flood duration relationships (Figure 2.6 A). The linear model fitted to collar height at V0 $r^2 = 0.93$, collar height at V1 $r^2 = 0.69$, and collar height at V2 $r^2 = 0.76$. Collar height response to flood duration at V3 was best explained by a quadratic model $r^2 = 0.83$. Collar height at V0 declined by 11%, collar height at V1 declined by 4%, collar height at V2 declined by 10%, and collar height at V3 declined by 9% as flood duration increased from 0 to 6 h. Regardless of growth stage the greatest penalty associated with flood duration occurred at the 96 hour flood duration. Collar height at V0 declined by 75%, collar height at V1 declined by 25%, collar height at V2 declined by 30%, and collar height at V3 declined by 18% as flood duration increased from 0 to 96 h.

Leaf development response for 1st leaf width, 3rd leaf length, and specific leaf area (SLA) averaged across hybrid, and imposed at the V0 growth stage varied with respect to flood duration. All three leaf development parameters were significantly ($P < .05$) affected by the interaction between growth stage and flood duration. Plant development parameters leaf width $r^2 = 0.96$ and leaf length $r^2 = 0.98$ declined linearly as flood duration increased. The decline and vigor in response to flood duration suggests leaf width as being the most susceptible to the negative stress associated with flood duration followed by leaf length. Interestingly, the SLA response to flood duration was best explained by a quadratic model $r^2 = 0.97$ and trends positively for each increase in flood duration (Figure 2.6 B).

Conclusion

Soil flooding caused by excessive rain, irrigation, poor drainage or topography can severely impede plant growth and development. This is because most terrestrial plants, including major production crops, are extremely sensitive to excessively wet conditions. Flooding survival tactics in plants vary widely and include several morphological, anatomical, physiological, and molecular changes that can prolong survival, and in some cases, permanent habitation. This research addressed some of the limitations associated with early planting by imposing moisture stress comparable to crop flooding. Our experiment replicated environmental growing conditions that resulted in complex interactions realistic to what a producer might encounter.

We observed several trends with respect to flooding stress. As expected we observed significant differences between hybrids and their stress tolerance towards flooding. However, we did not expect to see such clear across the board physiological differences between hybrids with respect to above and below-ground growth and development. The above-ground variables measured were better for hybrid PHB 1197 the majority of the time, whereas DKC 62-08 typically excelled in the below-ground variables. Logically, these hybrids inherit genetic backgrounds provided different advantages/tolerances in response to flooding. Hybrid DKC 62-08 produced a 14% advantage in RDIAM, 11% RVOLUME, 14% RDW and 14% RSRATIO compared to PHB 1197. Hybrid PHB 1197, produced a 6% advantage in L1WIDTH, 17% L1LENGTH, 15% L2WIDTH, 18% L3WIDTH, 5% L3LENGTH comparatively.

Although the advantages in growth and development between hybrids appeared straightforward the majority of the time. There were also instances where hybrids stress

tolerance varied periodically as flood duration or growth stage interactions were introduced. Averaged across flood duration DKC 62-08 leaf lengths were 5% longer than PHB 1197. However, after 6 h of flooding PHB 1197 averaged 8% longer leaf lengths compared to DKC 62-08 and 5% longer after 12 h of flooding. Leaf length for PHB 1197 declined linearly after 24 h of flooding. Hybrid DKC 62-08 leaf length increased 4% as flooding duration increased from 12 to 24 hours and declined linearly, but a slower rate than PHB after 24 h of flooding was imposed.

The deleterious effects of flood duration and the number of root forks was more evident for hybrid DKC 62-08 slope = -0.0000038 compared to PHB 1197 slope = -0.0000069. The initial response among hybrids in relation to flood duration lasting 6 h decreased the number of root forks 34% for DKC 62-08 compared to 7% for PHB 1197. Both hybrids responded similarly after 24 h of flooding and the number of root forks declined linearly through 48 h. Although, the rate of decline in number of root crossings was more evident for DKC 62-08 overall. There was a 16% advantage with respect to root crossings for DKC 62-08 over PHB 1197 after flooding lasted 48 hours.

Averaged across hybrid and growth stage there was a similar trend for root length, root volume, and root area with respect to flood duration. All three root development parameters measured declined linearly as flood duration increased. The decline and vigor in response to flood duration exposed root volume (slope -0.00052) as being the most susceptible to the negative stress associated with flood duration followed by root area (slope -0.00053) and root length (slope -0.00054). The root development characteristics number of root forks and root crossings averaged across hybrids trended similarly with respect to flood duration. The decline and vigor in response to flood duration

characterized by the number of root crossings (slope -0.00064) as being more susceptible to flood duration compared to the formation of root forks (slope -0.00067).

Averaged across hybrid and growth stage there was a similar trend for collar height, length of 3rd leaf, stalk width, and leaf area with respect to flood duration. All of the plant development parameters measured declined linearly as flood duration increased. The decline and vigor in response to flood duration exposed leaf area (slope 0.00044) as being the most susceptible to the negative stress associated with flood duration followed by stalk width (slope -0.00029), collar height and lastly length of the 3rd leaf. Collar height declined by 6% as flood duration increased from 0 to 6 h whereas stalk width declined by 3% at the same flood duration.

Flood duration effects on corn plants flooded at planting (V0) suffered the steepest decline in collar height (slope -0.00041). Interestingly, corn plants flooded at V2 (slope -0.00016) were more susceptible to flooding stress than plants flooded at V1 (slope -0.00013). Collar height at V0 declined by 11%, collar height at V1 declined by 4%, collar height at V2 declined by 10%, and collar height at V3 declined by 9% as flood duration increased from 0 to 6 h. The decline and vigor in response to flood duration suggests leaf width as being the most susceptible to the negative stress associated with flood duration followed by leaf length.

Determining the negative stress effects flooding caused when applied at different vegetative growth stages provided some interesting results. Our analysis exposed the lack of significant differences between L1WIDTH and L2WIDTH after flooding was imposed at the second and third leaf vegetative stages. Interestingly, the SLA response to flood duration was best explained by a quadratic model $r^2 = 0.97$ and trended positively for

each increase in flood duration. There were however, significant differences between hybrids in RAREA, RSURFAREA, RVOLUME, RDW and RSRATIO when considering growth stage and triggered flooding events.

Flood duration effects for both hybrids revealed no significant differences in RSRATIO and RDW if flooding was triggered at planting (V0), V1 or V2. Additionally, there was no significant difference in RAREA or RVOLUME when flooding was triggered at V1 or V2. Overall, flood duration provided more significant differences between measured variables than growth stage. The flooding response between 0 and 96 hours provided the largest differences. Surprisingly, there was an increase in CHEIGHT when duration occurred for 24 hours compared to only 12 hours. Percentage wise there was less penalty in leaf length compared to CHEIGHT as flood duration increased. The numerical difference between the treatments ranged from 0.45 to 9%.

Understandably, this analysis does provide a basis for speculation. The interpretation requires general agronomic insight, knowledge of plant genetics, plant physiology, meteorology, and soil science as well as subjective judgement. The inherent genes and adaptive stress response via fermentative capability was largely responsible for plant survival and the less explainable advantageous stress response to the 24 hour flood vs 12 hour. The consistent advantage from the stress imposed by a flooding scenario at 24 hours compared to 12 seems unreasonable. However, the increase in measured variables could be explained by or linked to previously published findings. First, roots of corn and wheat survive anoxic conditions more than three times longer when they were exposed first to hypoxic rather than an aerated solution (Johnson et al., 1994; Waters et al., 1991; Atwell, 1999). Consider this hypoxic priming as a trigger for the fermentative enzymes

PDC and ADH. As a result of the pre stress there is a quicker response rate and initiation of the alcoholic fermentation process during anoxic conditions. As previously mentioned corn roots, have 20 to 22 of these fermentative enzymes (PDC and ADH), involved in anaerobic carbohydrate catabolism.

Secondly, previous studies found off-type (mutant) corn lines that were missing the gene encoding ADH isoform (ADH-1), had a 30% to 35% slower reaction rate of the alcoholic fermentation process following hypoxic pre-treatment than those with the ADH gene. Interestingly, only 70% of the mutant lines survived 24 hours of anoxic treatment. However plants having the ADH gene survived 48 hours of anoxic treatments (Drew et al. 1994). That said it is realistic to expect mutant off types and transgenic plants altered by molecular tactics will soon provide some useful insight and increased advantages to flood tolerance.

Utilizing promoter analysis gives the impression that we are getting closer to fully understanding the complex interaction of plant response to flooding. We believe the best options to date still include supplementing fertility to minimize the negative interactions as well as limit exposure when possible. This includes site preparation, planting dates, bed preparation, and irrigation management. Additionally, we believe researchers have narrowed the gap as far as what we know and the complexity of interactions when talking about adaptive traits in flooded/anoxic conditions. Technological advancements such as promoter analysis in combination with conventional breeding trait selection methods, should produce innovative plant species to be further investigated in the upcoming years.

Table 2.1 Significance of *F*-Values for main effects and interactions for flood study above-ground corn growth and development characteristics measured 18 days after planting.

	Main Effects and Interactions						
Dependent variable	**Hybrid (HYB)**	**Growth stage (VSTAGE)**	**Flood Duration (FTIME)**	**HYB*VSTAGE**	**HYB*FTIME**	**VSTAGE*FTIME**	**HYB*VSTAGE*FTIME**
CHEIGHT	**	*	**			*	
L1WIDTH	*	*				*	
L1LENGTH	**						
L2WIDTH	**	*					
L2LENGTH							
L3WIDTH	**	*				*	
L3LENGTH	*	**	**		*	*	
STALKW		**	**				
CAREA			**				
SPAD			**		*		
LAREA		**	**			*	
LDW		**	**			*	
SDW		**	**			**	
SLA		*				*	
LAR		*				**	

LSMeans significant at (α =0.05) ** Significant at <.0001 * Significant at <.05
Length to highest collared leaf (CHEIGHT), width of each leaf at the widest point (L1WIDTH) (L2WIDTH) (L3WIDTH) (L4WIDTH), length of each leaf from base to tip (L1LENGTH) (L2LENGTH) (L3LENGTH) (L4LENGTH), stalk width measured just below the first leaf (STALKW), canopy area (CAREA) was measured on all plants 18 days after planting just prior to experiment termination. (SPAD) measured leaf absorbance using the SPAD 502 chlorophyll meter (Konica-Minolta, Japan). Leaf area (LAREA) was measured using the LI-3100 leaf-area meter (LI-COR, Inc.). Leaf dry weight (LDW), stem dry weight (SDW), specific leaf area thickness (SLA), leaf area ratio (LAR).

Table 2.2 Significance of *F*-Values for main effects and interactions for flood study below-ground corn growth and development characteristics measured 18 days after planting.

Dependent variable	Hybrid (HYB)	Growth stage (VSTAGE)	Flood Duration (FTIME)	HYB*VSTAGE	HYB*FTIME	VSTAGE*FTIME	HYB*VSTAGE*FTIME
RLENGTH			**				
RAREA		*	**				
RSURFAREA		*	**				
RDIAM	*						
RLPV			**				
RVOLUME	*	*	**				
RTIPS			**				
RFORKS			**		*		
RCROSSINGS			**		*		
RDW	**	**	**				
RSRATIO	**	**				**	

LSMeans significant at (α =0.05) ** Significant at <.0001 * Significant at <.05
Total root length (RLENGTH), root area (RAREA), root surface area (RSURFAREA), average root diameter (RDIAM), root length per volume (RLPV), root volume (RVOLUME), number of tips (RTIPS), number of forks (RFORKS), and number of crossings (RCROSSINGS), root dry weight (RDW), root to shoot ratio (RSRATIO).

Table 2.3 Significance of *F*-Values for main effects and interactions for flood study corn nutrient analysis for plants harvested measured 18 days after planting.

Dependent variable	Hybrid (HYB)	Growth stage (VSTAGE)	Flood Duration (FTIME)	HYB*VSTAGE	HYB*FTIME	VSTAGE*FTIME	HYB*VSTAGE*FTIME
Ca		*				*	
K		*	*			**	
Mg		**				**	
Na		*	*			*	
P		*	*			*	

LSMeans significant at (α =0.05) ** Significant at <.0001 * Significant at <.05.
Calcium (Ca), Potassium (K), Magnesium (Mg), sodium (Na), and phosphorus (P).

Table 2.4 Corn hybrid main effects for flood study above-ground variables growth and development characteristics measured 18 days after planting.

Significance P < 0.05	Measured Variable	Hybrid	Significance P < 0.05	Measured Variable	Hybrid
	CHEIGHT cm			**L1WIDTH mm**	
A	12.16354	DKC 62-08	A	9.084688	PHB 1197
B	11.42535	PHB 1197	B	8.495278	DKC 62-08
	L1LENGTH cm			**L2WIDTH mm**	
A	12.45694	PHB 1197	A	13.96368	PHB 1197
B	10.31806	DKC 62-08	B	11.845	DKC 62-08
	L3WIDTH mm			**L3LENGTH cm**	
A	22.01767	PHB 1197	A	30.24698	PHB 1197
B	18.0876	DKC 62-08	B	28.59861	DKC 62-08

LSMeans significant at (α =0.05). Hybrids with the same letter are not significantly different (α =0.05). Length to highest collared leaf (CHEIGHT), width of each leaf at the widest point for leaf 1 (L1WIDTH), leaf 2 (L2WIDTH), and leaf 3 (L3WIDTH), length of each leaf from base to tip of leaf 1 (L1LENGTH) and leaf 3 (L3LENGTH).

Table 2.5 Corn hybrid main effects for flood study below-ground variables root growth and development characteristics measured 18 days after planting.

Significance P < 0.05	Measured Variable	Hybrid	Significance P < 0.05	Measured Variable	Hybrid
	RDIAM mm			**RVOLUME cm^3**	
A	0.53269	DKC 62-08	A	5.44194	DKC 62-08
B	0.45947	PHB 1197	B	4.86835	PHB 1197
	RDW g			**RSRATIO ratio**	
A	0.58427	DKC 62-08	A	0.25102	DKC 62-08
B	0.50198	PHB 1197	B	0.21476	PHB 1197

LSMeans significant at (α =0.05). Hybrids with the same letter are not significantly different (α =0.05). Average root diameter (RDIAM), root volume (RVOLUME), root dry weight (RDW), and root to shoot ratio (RSRATIO).

Table 2.6 Corn growth stage main effects for flood study above-ground variables growth and development characteristics measured 18 days after planting.

Significance P < 0.05	Measured Variable	Vstage	Significance P < 0.05	Measured Variable	Vstage
	CHEIGHT cm			**L1WIDTH mm**	
C	11.0632	0	C	8.22576	0
A	12.1813	1	AB	8.95104	1
B	11.7833	2	CB	8.72042	2
AB	12.15	3	A	9.26271	3
	L2WIDTH mm			**L3WIDTH mm**	
B	12.5122	0	B	19.9114	0
B	12.45	1	B	19.2727	1
AB	12.9102	2	B	19.53	2
A	13.745	3	A	21.4965	3
	L3LENGTH cm			**STALKW mm**	
C	27.5776	0	C	13.6504	0
B	28.9927	1	A	15.2792	1
AB	30.0896	2	B	14.6769	2
A	31.0313	3	A	15.4871	3
	LAREA cm^2			**LDW g**	
C	356.768	0	C	1.21653	0
B	417.868	1	B	1.47927	1
B	432.703	2	B	1.49479	2
A	468.293	3	A	1.68688	3

LSMeans significant at (α =0.05). Vegetative growth stages with the same letter are not significantly different (α =0.05).Length to highest collared leaf (CHEIGHT), width of each leaf at the widest point for leaf 1 (L1WIDTH) leaf 2 (L2WIDTH) and leaf 3 (L3WIDTH), length of leaf from base to tip for leaf 3 (L3LENGTH), stalk width measured just below the first leaf (STALKW). Leaf area (LAREA) was measured using the LI-3100 leaf-area meter (LI-COR, Inc.). Leaf dry weight (LDW).

Table 2.6 continued

Significance P < 0.05	Measured Variable	Vstage	Significance P < 0.05	Measured Variable	Vstage
	SDW g			**SLA $cm^2 g^{-1}$**	
C	0.77021	0	A	307.655	0
B	0.95396	1	BB	288.446	1
B	0.93354	2	B	293.179	2
A	1.11354	3	C	279.646	3
	LAR ratio				
A	186.385	0			
CB	174.952	1			
AB	180.308	2			
C	168.942	3			

LSMeans significant at (α =0.05). Vegetative growth stages with the same letter are not significantly different (α =0.05). Stem dry weight (SDW), specific leaf area thickness (SLA), leaf area ratio (LAR).

Table 2.7 Corn growth stage main effects for flood study below-ground variables root growth and development characteristics measured 18 days after planting.

Significance P < 0.05	Measured Variable	Vstage	Significance P < 0.05	Measured Variable	Vstage
	RAREA cm^2			**RSURFAREA cm^2**	
B	142.997	0	B	449.24	0
A	174.45	1	A	548.052	1
A	168.525	2	A	529.438	2
AB	155.694	3	AB	489.128	3
	RVOLUME cm^3			**RDW g**	
B	4.43985	0	B	0.44729	0
A	5.716	1	A	0.58375	1
A	5.59925	2	A	0.58604	2
B	4.86548	3	A	0.55542	3
	RSRATIO ratio				
A	0.24335	0			
A	0.24646	1			
A	0.2424	2			
B	0.19935	3			

LSMeans significant at (α =0.05). Vegetative growth stages with the same letter are not significantly different (α =0.05). Root area (RAREA), root surface area (RSURFAREA), root volume (RVOLUME), root dry weight (RDW), root to shoot ratio (RSRATIO).

Table 2.8 Corn flood duration main effects for flood study above-ground variables growth and development characteristics measured 18 days after planting.

Significance P < 0.05	Measured Variable	FTIME (hours)	Significance P < 0.05	Measured Variable	FTIME (hours)
	CHEIGHT cm			**L3LENGTH cm**	
A	13.09	0	A	30.43	0
B	12.28	6	A	30.63	6
B	12.08	12	A	30.21	12
B	12.13	24	AB	30	24
C	11.18	48	B	28.73	48
D	10.02	96	C	26.54	96
	STALKW mm			**CAREA cm^2**	
A	16.46	0	AB	82.59	0
AB	15.96	6	A	83.7	6
B	15.25	12	CD	66.8	12
B	15.46	24	CB	68.75	24
C	13.8	48	D	53.63	48
D	11.71	96	D	51.83	96
	SPAD value			**LAREA cm^2**	
A	46.05	0	A	528.7	0
B	42.01	6	B	464.48	6
BC	39.38	12	B	430.37	12
BC	40.21	24	B	457.94	24
DC	37.28	48	C	353.99	48
D	35.36	96	D	277.97	96

LSMeans significant at (α =0.05). Flood durations (FTIME) with the same letter are not significantly different (α =0.05).Length to highest collared leaf (CHEIGHT), width of each leaf at the widest point leaf 3 (L3WIDTH), stalk width measured just below the first leaf (STALKW), canopy area (CAREA) was measured on all plants 18 days after planting just prior to experiment termination. SPAD (SPAD) measured leaf absorbance using the SPAD 502 chlorophyll meter (Konica-Minolta, Japan). Leaf area (LAREA) was measured using the LI-3100 leaf-area meter (LI-COR, Inc.).

Table 2.8 continued

Significance P < 0.05	Measured Variable	FTIME (hours)	Significance P < 0.05	Measured Variable	FTIME (hours)
	LDW g			**SDW g**	
A	1.9	0	A	1.14	0
B	1.63	6	AB	1.09	6
B	1.48	12	C	0.97	12
B	1.61	24	CB	1.02	24
C	1.2	48	D	0.76	48
C	1	96	D	0.68	96

LSMeans significant at (α =0.05). Flood durations (FTIME) with the same letter are not significantly different (α =0.05). Leaf dry weight (LDW), stem dry weight (SDW).

Table 2.9 Corn flood duration main effects for flood study below-ground variables root growth and development characteristics measured 18 days after planting.

Significance P < 0.05	Measured Variable	FTIME (hours)	Significance P < 0.05	Measured Variable	FTIME (hours)
	RLENGTH cm			**RAREA cm^2**	
A	5638.1	0	A	217.54	0
B	4655	6	B	191.38	6
B	3923.5	12	DC	157.62	12
B	4310.2	24	BC	172.88	24
C	3144.7	48	DC	132.39	48
D	2198	96	E	90.71	96
	RSURFAREA cm^2			**RLPV cm/m^3**	
A	683.41	0	A	5781	0
B	601.23	6	B	4685.9	6
DC	495.17	12	DC	3923.5	12
BC	543.11	24	BC	4310.2	24
D	415.9	48	D	3282.6	48
E	284.98	96	E	2198	96
	RVOLUME cm^3			**RTIPS No.**	
A	6.66	0	A	17288	0
AB	6.28	6	B	13769	6
CD	5.02	12	B	12182	12
CB	5.51	24	B	13130	24
D	4.45	48	C	9300	48
E	3.01	96	C	7603	96

LSMeans significant at (α =0.05). Flood durations (FTIME) with the same letter are not significantly different (α =0.05). Total root length (RLENGTH), root area (RAREA), root surface area (RSURFAREA), root length per volume (RLPV), root volume (RVOLUME), number of tips (RTIPS).

Table 2.9 continued

Significance P < 0.05	Measured Variable	FTIME (hours)	Significance P < 0.05	Measured Variable	FTIME (hours)
	RFORKS No.			**RCROSSINGS No.**	
A	42775	0	A	4736.4	0
B	36387	6	B	3687.3	6
C	28151	12	B	3053.6	12
BC	32166	24	B	3493.9	24
D	20046	48	C	2158.7	48
E	11797	96	D	1330	96
	RDW g				
A	0.715	0			
B	0.625	6			
C	0.5472	12			
BC	0.5903	24			
D	0.4656	48			
E	0.3156	96			

LSMeans significant at (α =0.05). Flood durations (FTIME) with the same letter are not significantly different (α =0.05). Number of forks (RFORKS), number of root crossings (RCROSSINGS), root dry weight (RDW).

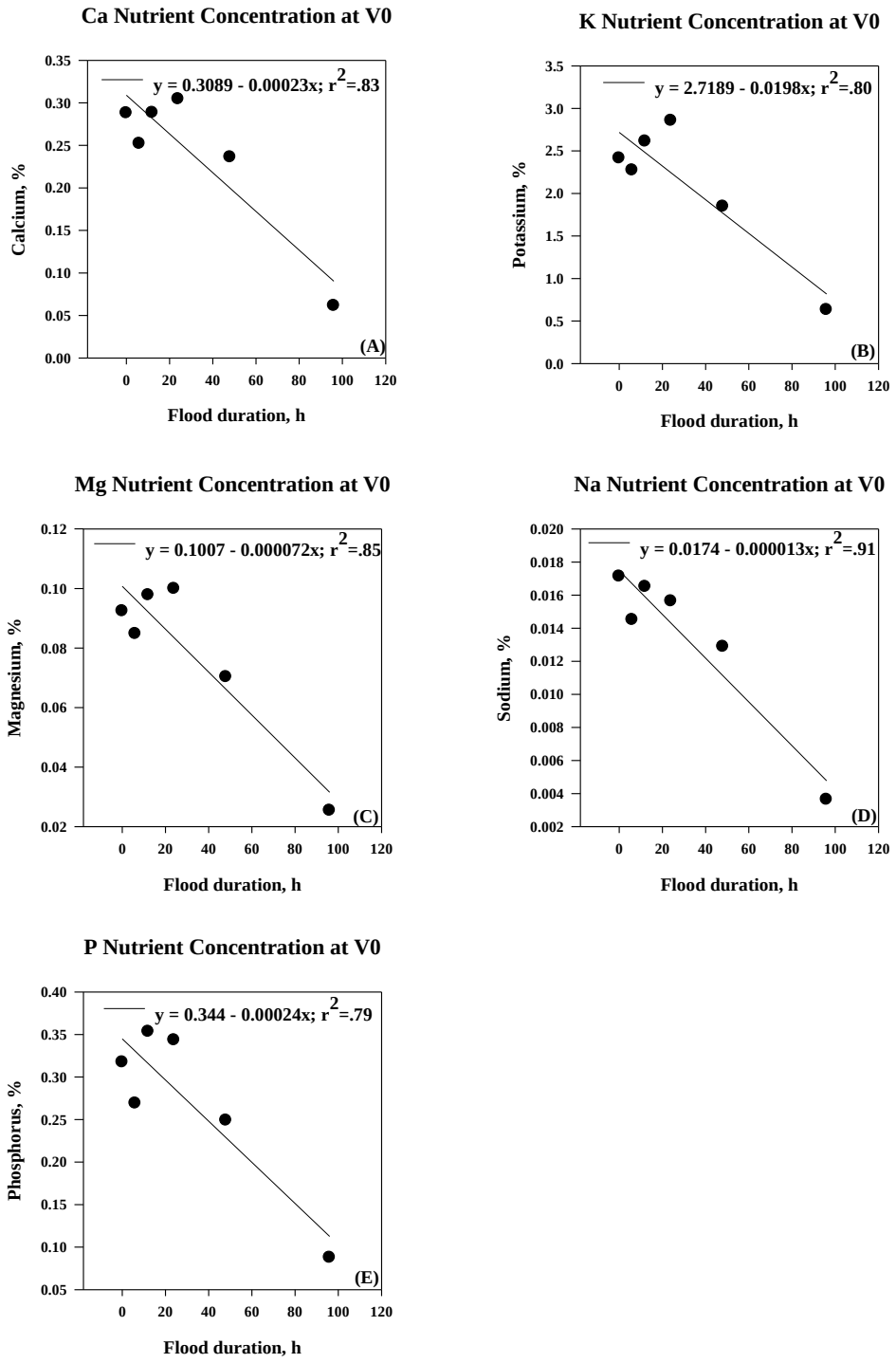

Figure 2.1 Corn flood duration effects on corn tissue nutrient concentration.

Average nutrient concentration Ca, K, Mg, Na and P collected 18 days after planting for hybrids flooded at planting (V0).

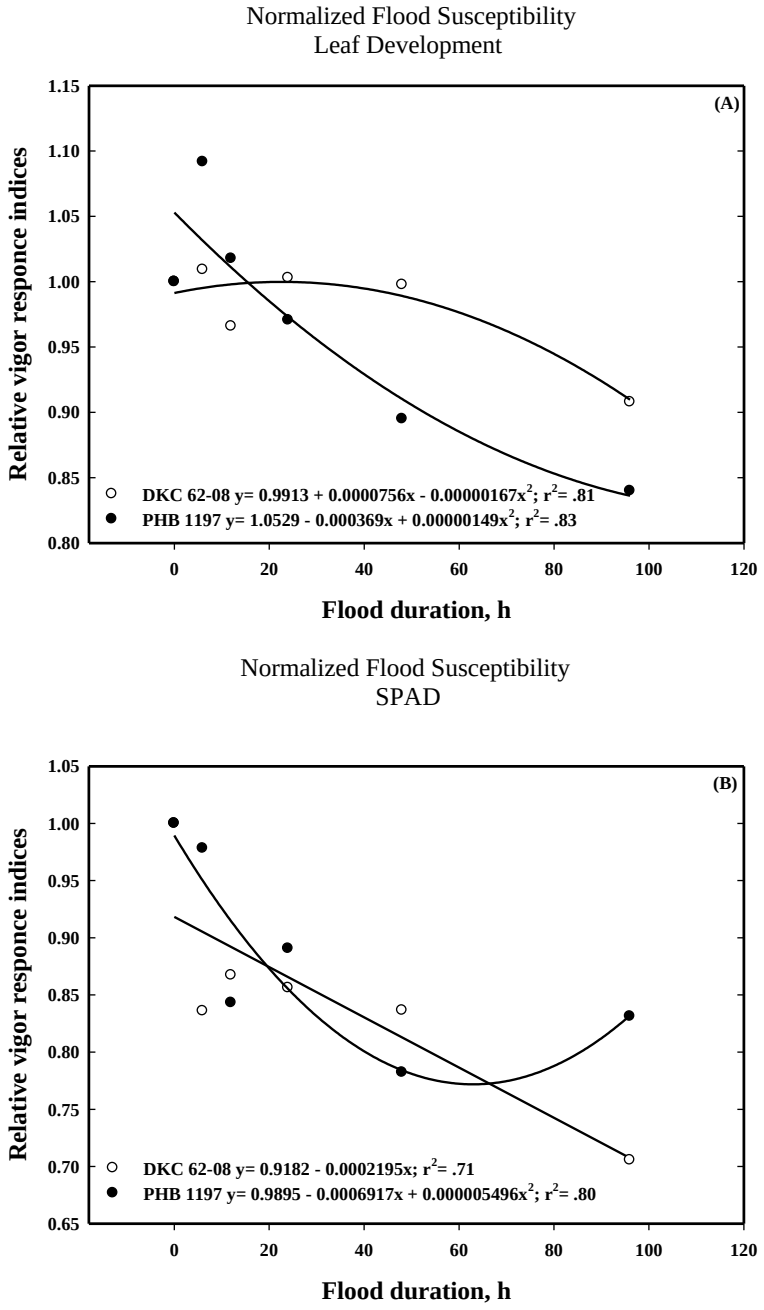

Figure 2.2 Hybrid by flood duration above-ground stress response indices.

Leaf development for hybrids DKC 62-08 and PHB 1197 is the length of leaf from base to tip for leaf 3 (L3LENGTH). SPAD measured leaf absorbance using the SPAD 502 chlorophyll meter collected 18 days after planting just prior to experiment termination.

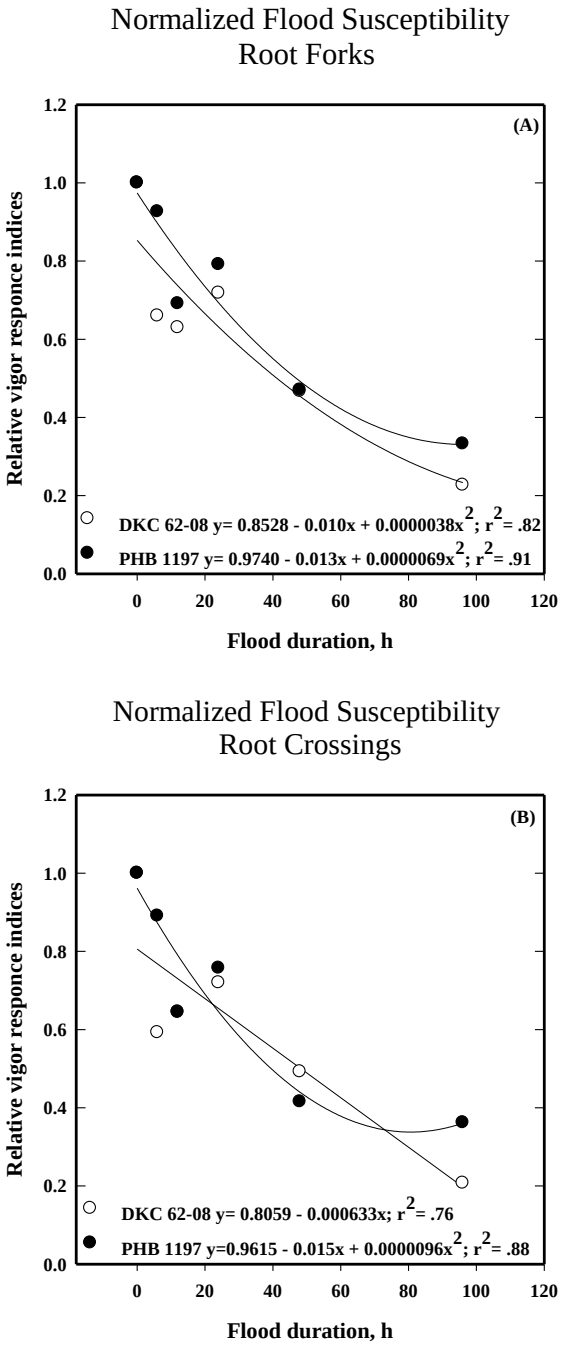

Figure 2.3 Hybrid by flood duration root stress response indices.

The number of root forks and root crossings for hybrids DKC 62-08 and PHB 1197 collected 18 days after planting.

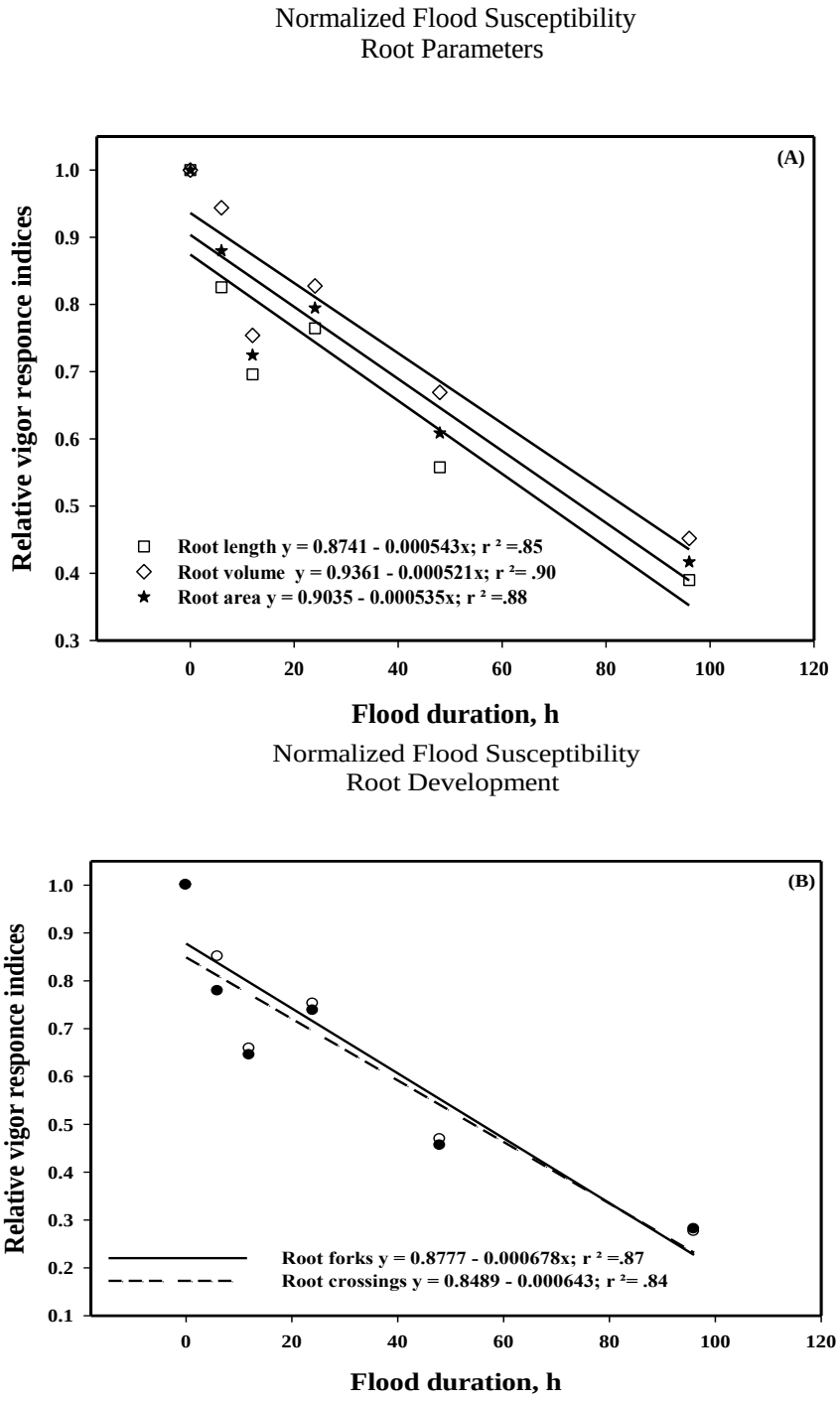

Figure 2.4 Flood duration root stress response indices.

Flood duration effects on root length, root volume, root area, number of root forks and crossings averaged across hybrids collected 18 days after planting.

Normalized Flood Susceptibility
Plant Development

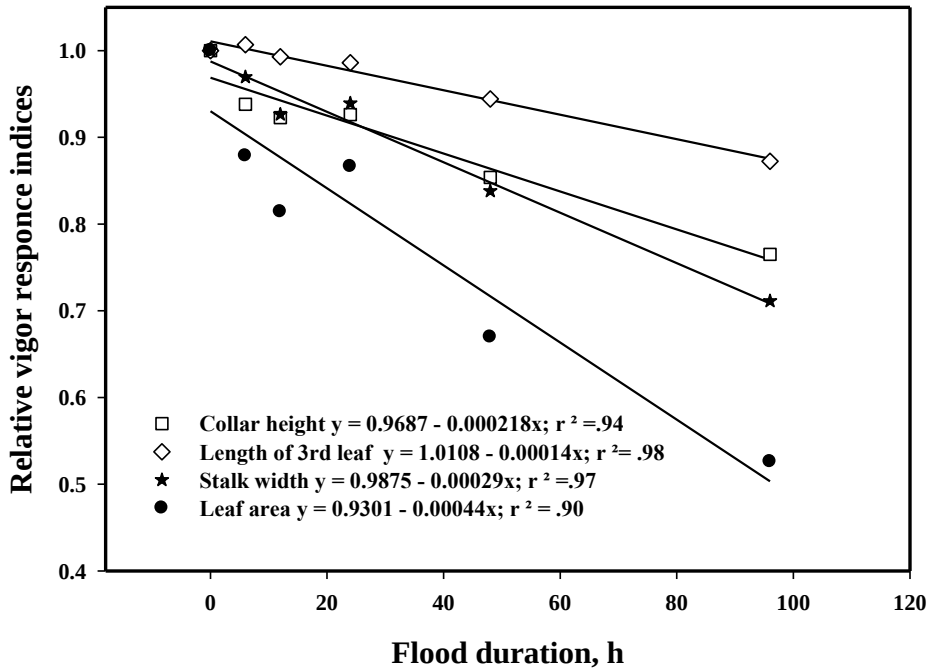

Figure 2.5 Flood duration plant stress response indices.

Flood duration effects on collar height, leaf length, stalk width, and leaf area averaged across hybrids collected 18 days after planting.

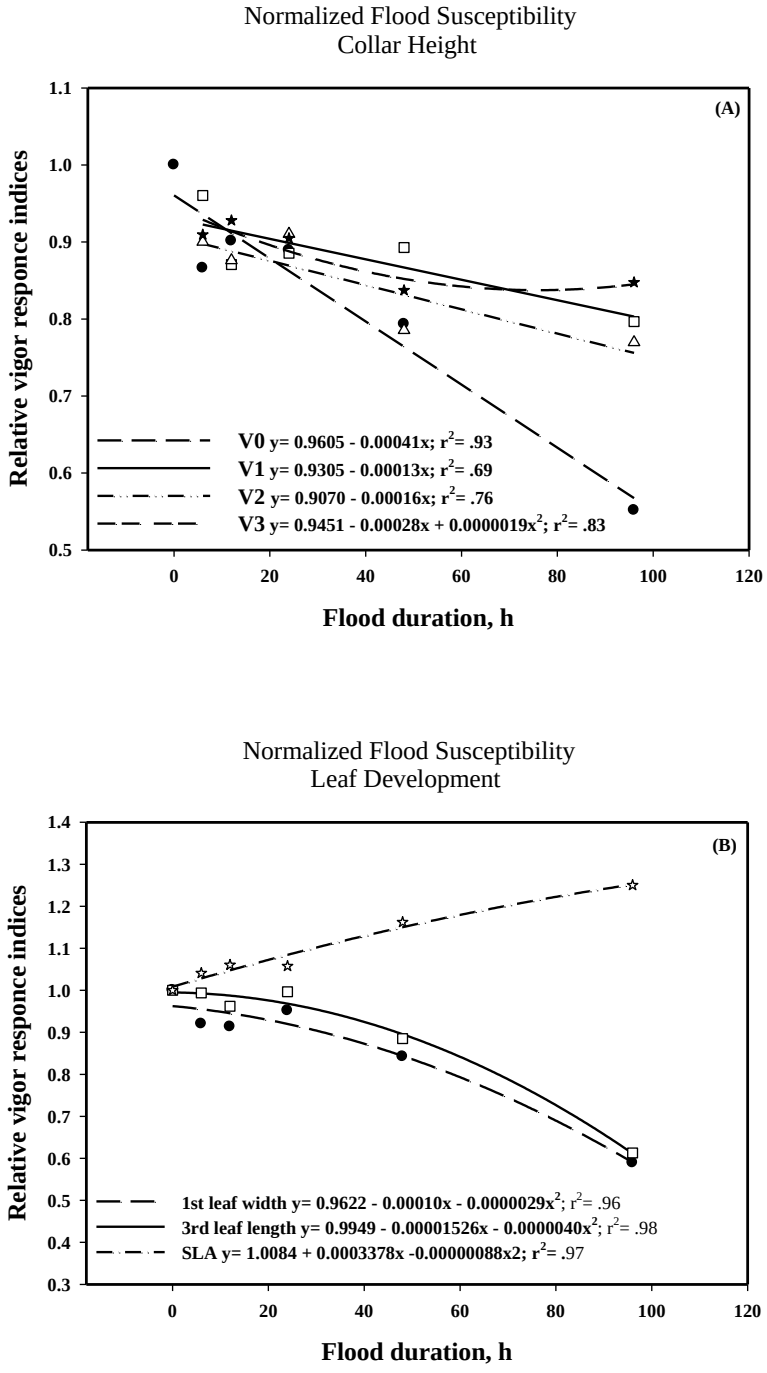

Figure 2.6 Growth stage by flood duration stress response indices.

Flood duration effects on collar height when flooded at planting V1, V2, and V3. Flood duration effects on leaf width, leaf length, and specific leaf area (SLA) flooded at planting. All measured variables were averaged across hybrids and collected 18 days after planting.

CHAPTER III

THE EFFECT OF BIOLOGIC SEED TREATMENTS AND STARTER FERTILIZER ON EARLY SEASON CORN GROWTH AND DEVELOPMENT

Abstract

Production efficiency over the last fifty years has been accomplished through a combination of management practices including irrigation, genetic manipulation, breeding efforts, and an upsurge in fertilizer usage. Producers now face the reality that there is limited and finite supply of suitable production land and plant fertilizers. Strategic placement of soil bacteria developed to increase immobile nutrients like P and K to improve fertilizer use efficiency for producers implementing an early planting strategy and provide slow developing root systems essential plant nutrients. Our objective was to test the efficacy of four commercially available microbial plant enhancing products (B-300, QR, Mammoth, EM-1, untreated check), with and without starter fertilizer. In this study, we evaluated multiple biologic compounds and their effect on grain yield, plant emergence, plant growth and development, and nutrient uptake efficiency. Biologic seed treatments compared to the untreated seed, resulted in a positive yield advantage for all treatments. This was also the case when starter fertilizer was added, yields ranged from 37 to 48% higher if biologic compounds were applied. On average, yields increased from 26 to 38% after starter fertilizer was added to the biologic compounds. There was a significant 7% increase in plant emergence for B300 compared to Mamm. We observed a significant increase in leaf area 16% for corn seed treated with

SF-QR compared to the control. There was also a significant increase 16% in total leaf area for SF-Mamm compared to the control. The addition of biologic treatments alone in many cases, increased leaf area compared to the starter fertilizer seed treatment. We observed a 7% increase in leaf area for B300, 13% QR, 11% Mamm and 6% for EM1. We saw a significant increase in P concentration for QR compared to the control at VT. Nutrient content for B300, SF-B300, QR, SF-QR, Mamm, SF-Mamm and EM1 averaged higher Ca content compared to the control. Nutrient content for B300, SF-B300, QR, Mamm, and SF-Mamm all averaged higher K content compared to the control. Our results indicate, that for the majority of variables measured, the bacterial inoculates and starter fertilizer positively influenced plant growth and development.

Introduction

Corn (*Zea mays* L.) producers are constantly looking for ways to increase yields and production efficiency. Early planting (early March to mid-April) is one technique being utilized by producers to avoid late season drought stress that negatively influences corn production (Mascagni and Boquet, 1996). Early planting provides corn the opportunity to initiate growth earlier, potentially synchronizing corn's reproductive phase to a time that offers more favorable growing conditions. Early planting strategies utilize the beginning of the growing season to take advantage of increased solar radiation, increased rainfall, and reduced day-and nighttime temperatures.

Producers who shift planting dates forward often see benefits of more favorable growing conditions during the latter part of the growing season. Conversely this shift can also result in adverse effects on the front end of plant growth. Early planting exposes seedlings to suboptimal growing conditions. Producers who utilize an early planting strategy will likely plant into cold, wet soils which inhibit seed germination and root development (Gupta et al., 1988; Ford and Hicks, 1992; Bollero et al., 1996).

Consequently, these factors can lead to uneven plant emergence and reduced availability of soil nutrients (Mascagni and Boquet, 1996). The decrease in nutrient availability, especially phosphorus (P), is affected by the buffering capacity of the soil around the plant roots. Despite the abundancy of P in soils, in both organic and inorganic forms, its availability is limited as it occurs mostly in insoluble forms. Average P content in soil is approximately 0.05% (w/w), however poor solubility and fixation to soil results in total plant available (P) to be closer to 0.1% (Illmer and Schinner, 1995).

Besides nitrogen (N) P is considered the most important nutrient element required by plants. In fact, all major metabolic processes in plants including: photosynthesis, energy transfer, signal transduction, macromolecular biosynthesis and respiration require (P) to function normally (Khan et al., 2010). Phosphorus availability during early season plant growth phases and development contributes directly to reproductive organ formation. Additionally, P has been linked to increased root branching and vigor which in turn increases a plants overall vitality and ability to fight disease (Sharma et al., 2013). Ultimately, P deficiencies Affect plant growth, seed formation, and crop maturation in cereals and legumes.

In some situations, soils with high P levels can actually have reduced amounts of available P for early planted corn seedlings (Mascangni and Boquet, 1996). This is due in part to the delayed root growth and decreased ion uptake under poor growing conditions (Salisbury and Ross, 1978). To fully understand nutrient availability for corn seedlings, it is important to recognize root systems, and their complexity of interactions within the soil environment.

Understanding root development and problems associated with root limitations is an important factor in crop production, especially important for producers implementing early planting strategies. Corn is a grass with a fibrous root system. Stunting or restriction of a corn root systems during early season development can cause adverse effects for the remainder of the growing season. Environments that include excessively dry soil, wet soil, cold soil and compacted soil have been linked to negatively impacting root development (Nielsen, 2013).

Root systems are morphologically diverse, and each part of the root system is responsible for a different aspect of plant growth and development (Lynch, 1995). Corn for example has three root systems as it develops from a seedling. The embryonic root system (primary and lateral roots) play a major role in early plant development (Richner et al., 1997). The postembryonic (crown roots) play an essential role by absorbing water and nutrients and supporting the plant as it reaches maturity. Lateral roots also have a significant role in water and nutrient uptake (McCully and Canny, 1988) and greatly influence rooting architecture (Lynch, 1995). However, genetic diversity in corn genotypes can cause roots to vary greatly in their response to environmental conditions, such as temperature and moisture (Stamp et al., 1997).). Environmental adaptations such as these have also been observed in other species. Wheat (*Triticum aestivum* L.) for example will alter the adventitious (nodal) root system to form aerenchyma in a flooded growing environment. This type of response to moisture stress allows wheat plants to survive periods of time in a low oxygen environment (Thomson et al., 1992). Hammer and others (2009) documented yield increases in the U.S. Corn Belt production region that were attributed to increased root system mass.

In optimal growing conditions corn plants have rapid root growth and adequate inorganic and organic P available for root absorption. However, cold, wet soils reduce the rate at which roots grow thus limiting the area for them to absorb either forms of P (Havlin et al., 2005). Fortunately, production techniques can be implemented to mitigate the negative responses to early planting and nutrient availability for corn seedlings. One method consists of banding a liquid starter fertilizer containing N-P or N-P and potassium

(K). Target applications of fertilizer banding has increased the concentration of nutrients around the root zone (Mallarino et al., 2011).

Strategic placement of starter fertilizer increases the availability of relatively immobile nutrients, like P and K, to be taken up by slow developing roots (Barber and Kovar, 1985). However, (P) is a finite resource with substantial resources found only in a limited number of countries (Cordell, 2010; Jasinski, 2013). Some researchers have hypothesized that peak global phosphorus availability will occur in less than three decades (Craswell et al., 2010; Steen, 1998). Because P is a critical nutrient used to maximize plant growth and yield, any reductions in the supply or availability of P fertilizers could severely upset crop production. One solution for alleviating some of our crop dependency of P is to develop sustainable technologies that would improve P use efficiently for plant uptake.

Such technologies include utilizing bacteria specifically developed to mobilize soil nutrients. If successful, such bacteria could help producers limit their inorganic fertilizer dependency and extend our P reserves. The amount of plant available P in the soil has effectively increased when certain soil bacteria are present. (Malboobi et al., 2009; Osorio & Habte, 2014; Tawaraya, Naito and Wagatsuma, 2006). Soil microbes solubilize mineral bound P by secreting organic acids and high-affinity iron chelating siderophores (Richardson et al., 2009; Shropshire & Bordenstein, 2016) and by exuding plant hormones such as auxins (Spaepen, 2015). This type of synergistic relationship between microbial communities and developing plants resulted in increased root growth and P uptake. (Bal et al., 2013; Penrose & Glick, 2003; Rashid, Charles & Glick, 2012).

Although several known species of bacteria are capable of mineralizing soil nutrients there are multiple mechanisms by which microbes solubilize P. Some researchers believe that a conglomerate approach of P-mobilizing bacteria would increase the efficiency of making P available (Baas et al., 2016). Additional studies identified synergistic effects between multiple microbial species (Kim, Jordan & McDonald, 1997; Tarafdar & Marschner, 1995). Therefore, strategically incorporating multiple microbial communities near developing plants may be more effective than a single species or applying conventional fertility alone. By incorporating several microbial species, the number of mechanisms by which soil nutrients can be made available to plants is increased.

Current estimates suggest that food production will need to increase by as much as 70% in order to meet global food security if populations increase to the predicted 9.2 billion people in 2050 (FAO 2016). Food producers will be faced with a challenging dilemma in the years to come. Obviously, our goal is to continue to provide adequate amounts of food for the growing population. However, we must become more efficient with our conventional methods in order to be sustainable, especially for soils prone to binding P. Conventional P application in these soils requires more inputs relative to the P outputs in harvested crops (MacDonald et al., 2011).

Objectives

Exploiting microbial biostimulants offers promising benefits for crop producers by improving microorganism activities to enhance plant growth (Richardson & Simpson, 2011). In this study, we evaluated multiple biologic compounds and their effect on plant emergence, plant development, and nutrient uptake efficiency. Our objective was to test

the efficacy of four commercially available microbial plant enhancing products. We hypothesized that incorporating microbes to conventional production methods could increase plant productivity and efficiency. Likely, the greatest benefit would occur for plants receiving both conventional fertilizer and biostimulants, we further predicted applying microbes alone could also have a positive effect on plant performance.

We investigated whether seed or soil applied bacterial inoculates developed to mobilize soil P could increase plant productivity. Ideally, we would like to use these microbes to reduce nutrient deficiencies in early planted corn due to slow root growth from suboptimal growing conditions. We evaluated two microbial products from Monsanto (B-300, Quick Roots) (Monsanto BioAg, St. Louis, MO) and two liquid bacterial products (Mammoth P) (Growcentia, Fort Collins, CO) (EM-1) (Teraganix INC, Alto TX). Products along with known microorganisms, application rate, and colony forming unites (CFU) can be found on (Table 3.1). Hopefully, results from this study will indicate the potential that microbes have and their ability to enhance plant growth and crop productivity.

Materials and Methods

The 2016 field experiments were conducted at Starkville, MS at the R.R. Plant Science Foil Research Center (33.482117° -88.782767°). Unfortunately, planting for this experiment was much later than we had hoped and took place on May 11, 2016. One commercially available Mid-South adapted corn hybrid DKC 65-20 (DKC Monsanto, St. Louis, MO) was used for this field experiment. All seeds used in the experiment were treated with a standard fungicide/pesticide except for the untreated check. Four biologic treatments were used in combination with the standard fungicide/pesticide treated seed.

Biologics include the following (B-300), (Quick Roots), (Mammoth P), (EM-1). A fertility component consisting of a starter fertilizer comprised of ammonium polyphosphate, 10-34-0 (% N-P_2O_5-K_2O) was banded approximately 50.8 mm parallel to the planted seeds at a depth of 50.8 mm and applied at a rate of 44.83 kg ha^{-1} with a pressure regulated knifing coulter rig. Relative maturity as well as transgenic resistance characteristics and experiment treatment combinations for Dekalb (DKC Monsanto, St. Louis, MO) DKC 65-20 seed can be found in (Table 3.1).

Plots were planted in slight excess of the target treatment density and hand-thinned to the exact desired population of 61,750 plants ha^{-1} prior to plants reaching the fifth leaf collar stage. Plots consisted of four 97-cm rows (.96 m) wide by 6.09 m long. Standard rainfed corn populations for this region are 69,160 plants ha^{-1}, however, planting took place later in the growing season so the population was slightly reduced.

The 2016 Starkville biologic seed treatment experiment was planted in a Longview, fine-silty, siliceous, active, thermic Glossaquic Hapludalfs (USDA-NRCS Soil Survey Division, 2016) soil following a year of fallow in 2015 and wheat in 2014. Pre-plant soil samples were taken for analysis and are presented on (Table 3.2). Mississippi soil test results indicated that levels of extractable nutrients Phosphorus and Potassium were considered low based on the proposed crop goal of producing 13Mg/ha^{-1}. Nitrogen (N) was applied with a four row liquid fertilizer applicator equipped with coulter-knives approximately 20-cm from the center row in a single application of 224 kg/ha^{-1} using a 32% urea ammonium nitrate (UAN) solution. Application of N was applied post-emergent to plants at the 4 to 5 leaf stage.

Weed management consisted of a pre-emergent application of glyphosate (Roundup PowerMax) and Halex GT at recommended, labeled rates. Additional applications of Roudup PowerMax were applied post as needed to control late season weed emergence. Field preparation consisted of using a lister/cultivator to make plant bed/rows and followed by a packer/roller to flatten the tops of the rows to have a wider surface to plant into. Corn was planted 6.25-cm deep using a 4-row John Deere 7100 MaxEmerge vacuum planter (Deere and Co., Moline, IL).

A SPAD 502 chlorophyll meter (Konica-Minolta, Japan) was used to measure leaf absorbance in the red and near-infrared electromagnetic regions. The Numerical SPAD value is closely related to plant nutritional condition and provides a surrogate to the amount of chlorophyll present in leaf tissue. SPAD is a nondestructive method to monitor the crop N status. SPAD readings have been used to predict the N fertilizer demand for top-dressings in rice (*Oryza sativa* L.) (Cabangon et al., 2011), and maize (*Zea mays* L.) (Varinderpal-Singh et al., 2011).

Three SPAD readings were taken from two plants within the middle two rows of each four row plot. The values were then averaged. SPAD measurements were taken from the middle portion of the leaf parallel to the mid-vein of the most matured leaf at time of collection. SPAD was taken at the third leaf stage (V3) and again at tasseling (VT). Plant height was taken by measuring from the ground to the point of the highest collared leaf. The number of collared leaves was also recorded along with the total number of leaves at time of collection. Growth characteristics were taken at (V3) and again at (VT). Measurements were taken from three random plants within the two inner rows and at least 1-m from the edge of the front of the plot.

One meter of biomass was calculated for each plot. A single plant from one of the two outside rows was cut at soil level from each plot and dried in a forced air oven at 75°C until it reached a constant weight. Using one plant as an average representative within one meter, the dry plant sample weight was multiplied by the number of plants within a meter in a given plot to give a total weight for one meter of above-ground biomass g kg^{-1}.

Ear samples were collected from five consecutive plants in the center portion of the outer two rows of each plot prior to harvest. The number of kernel rows (around) and number of kernels per row (long) were counted and averaged for comparison. Yield and test weight were collected using a Kincaid 8-XP small plot combine (Kincaid Equipment Manufacturing, Haven, KS). The middle two rows of each plot were harvested. Yield calculations from the plots were adjusted to 155 g kg^{-1} moisture.

A sub-sample of grain was taken from each plot after yield was calculated to collect 100 kernel weights. Test weight and moisture content of the sample was measured with a Dickey-John GAC 2100 grain moisture tester (Dickey-John Corporation, Auburn, Illinois). Kernel weight was then determined by weighing 100 kernels and adjusting moisture content to 155 g kg^{-1}.

Plant growth and Development

Length to highest collared leaf (CHEIGHT) and length of the longest leaf from base to tip (L1LENGTH) was measured from 10 plants taken from rows one and four at the V3 growth stage. Leaf area (LAREA) was measured using the LI-3100 leaf-area meter (LI-COR, Inc.), leaf dry weight (LDW) and stem dry weight (SDW) were collected for each treatment. Plant samples were weighed after oven drying at 60°C and a constant

weight was reached. Dry weights of each tissue sample was then recorded for analysis. Specific leaf area (SLA, leaf area ratio (LAR) were also calculated for each treatment combination and recorded for analysis.

Nutrient Analysis

Plants were harvested at the (V3) growth stage from rows one and four and again at (VT). Plants in each plot were harvested by cutting at soil level, washed free of debris using deionized water and oven dried at 60 °C until a constant weight was reached. Plant dry matter samples were ground using a Wiley Mini-Mill with a 40-mesh screen (Thomas Scientific, Swedesboro, NJ) in preparation for nutrient analyses. Macro nutrients Calcium (Ca), Potassium (K), Magnesium (Mg), Sodium (Na), Phosphorus (P) and micro nutrients Boron (B), Copper (Cu), Iron (Fe), Manganese (Mn), Molybdenum (Mo), and Zinc (Zn) were processed using high temperature oxidation dry ashing. A 0.5 g sub-sample was put in a ceramic crucible at 500ºC for 4 hours. Next the ash was dissolved in 10.0 mL of 6 M HCl for 1 hour and an additional 40 mL of a double-acid solution of 0.0125 M H2SO4 and 0.05 M HCl for another hour. The remaining sample was then filtered through a Whatman No.2 paper (Southern Coop. Ser.1983). The filtrate was measured by emission spectroscopy on an inductively coupled plasma spectrophotometer (ICP). Methods described by Donohue and Aho (1992).

Calculations

Total plant dry weight was calculated by summing dry weights of the leaves and stems of each plant. Nutrient content within each tissue sample was calculated by multiplying tissue dry weight by tissue concentration for each particular nutrient. Total

plant nutrient content in each plant was estimated by summing total nutrient content from leaves and stem tissue. Average plant nutrient concentration was calculated by dividing the total nutrient content by the total plant dry weight. Leaf area (LAREA) was measured using the LI-3100 leaf area meter (Li-COR, Inc., Lincoln, NE). Leaf dry weights (LDW), stem dry weights (SDW) were weighed for each plant component after oven drying and a constant weight was reached. Specific leaf area thickness (SLA) was calculated by dividing the total leaf area by leaf weight per plant. Leaf area ratio (LAR) was calculated by dividing leaf area per plant by the weight per plant.

Experimental Design and Data Analysis

The experimental design was a completely randomized design with four replications. The two treatment factors consisted of five seed treatments of microbial compounds (none, B-300, QR, Mammoth, EM-1), and two fertility component (with starter fertilizer, without starter fertilizer) experimental factors. Significance of main effects and interactions was determined by using analysis of variance (ANOVA) GLM procedure of SAS (version 9.4; SAS Institute, Cary, NC 2011). Where indicated by ANOVA, multiple comparison of least square means were made with the stimulation method at $P < 0.05$. The CORR procedure in SAS was used to determine the correlation between physiological measurements collected, and then analyzed using regression. Graphical analysis was performed using SigmaPlot 11.0 (Systat Software Inc., San Jose, CA).

Results and Discussion

Grain Yield, Attributes and Plant Emergence

Grain Attributes

The addition of starter fertilizer and microbial biostimulants produced varied results with respect to grain test weight (TW) (Table3.3). We observed a significant increase in grain TW for corn seed treated with EM1, QR, SF-QR, and B300 compared to the untreated corn seed (Table 3.3). After starter fertilizer was applied to the untreated corn seed there was a 4% increase in TW. There was also an increase in TW after starter fertilizer was used in combination with QR. There was a 4% reduction in TW after starter fertilizer was used in combination with B300. Overall, there was no significant differences among microbial seed treatments. There were also no significant differences with the addition of starter fertilizer used in combination with biologic seed treatments.

Seed Moisture

The addition of starter fertilizer and microbial treatments produced diverse results with respect to seed percent moisture (SMOIST). We observed a significant increase in grain SMOIST after corn seed was treated with B300, SF-B300, QR, Mamm, SF-Mamm, and EM1 compared to the untreated corn seed (Table 3.3). After starter fertilizer was used with EM1 there was a 5% increase in SMOIST. There was also a 3% increase in SMOIST after starter fertilizer was used in combination with Mamm. There was a 4% increase in SMOIST after starter fertilizer was used with the untreated corn seed.

Grain Yield

Although growing conditions were less than ideal, we did capture some yield differences attributed to both SF and seed treatments (Table3.3). There was a significant yield advantage for SF-Mamm 50% compared to SF-QR. Yields were also significantly improved when comparing SF-Mamm 44% and SF-B300. Starter fertilizer applied to the untreated corn seed increased grain yield by 32%.

Biologic seed treatments compared to the untreated seed, resulted in a positive yield advantage for all treatments. This was also the case when starter fertilizer was added, yields ranged from 37 to 48% higher if biologic compounds were applied. With the exception of SF-B300, yield increased from 26 to 38% after starter fertilizer was added to the biologic compounds. The addition of starter fertilizer increased the yield of QR by 9%, and 11% for EM1 respectively.

Overall, grain yields varied with respect to treatments, however yields were lower than average because of extended periods of drought. This was especially true during the reproductive phase. There was span of several weeks where rainfall was nonexistent, and this coincided with the tasseling and grain filling stage of corn development. Due to irrigation limitations there was little that could be done to eliminate the environmental stress associated with high temperatures and reduced rainfall. Therefore, it is highly likely that the negative environmental stress affected our yields, but also the ability to capture subtle differences among treatments. Despite the negative environmental factors, we do feel we were able to capture some of the positive aspects of starter fertilizer and biologic seed treatments at least with respect to percent difference of our treatments compared to the control. Averaged across treatment groups (Biologic only) and (SF-

Biologic) averaged 44% higher yields than the untreated seed and 26% higher than the SF-untreated seed.

Kernel Weight (100 seed)

Overall, seed weights appeared to have less of a response between biologic compounds and starter fertilizer applications (Table3.3). There was a significant difference observed between SF-EM1 and the untreated seed. The addition of starter fertilizer and biologic compound resulted in a 15% increase in seed weights. There was also a significant difference between QR and the untreated seed that resulted in a 16% increase in seed weights. Across treatments average seed weight was 34.62 grams per 100 seed.

Plant Emergence

The addition of starter fertilizer and microbial biostimulants produced marginal differences with respect to plant emergence (STANDCT) (Table3.3). Based on germination percentages all of the experimental plots had better than a 95% germinate rate. However, there was a significant 7% increase in plant emergence comparing B300 to Mamm without the addition of starter fertilizer. There was also a significant 5% increase in plant emergence when SF-QR was used compared to Mamm alone. Overall, all plots emerged uniformly and we observed very few differences among treatments while evaluating emergence. Some of that could be contributed to the hybrid genetics and high germination rates. Additionally, the experiment was planted much later than we would have liked so the soil temperatures conditions facilitated emergence for early season crop growth.

Plant Growth and Development at the V3 Growth Stage

Leaf Length V3

There were no significant differences between treatments when starter fertilizer or combination of starter fertilizer with a microbial biostimulant with respect to leaf growth at the V3 growth stage (V3LEAF) (Table 3.4). With the exception of SF-B300, all treatment leaf lengths were higher than the mean 33.67cm. There was a 7% increase in leaf length for SF-QR vs QR and a 6% increase for SF-Mamm vs Mamm. Similarly, SF-QR and SF-Mamm also produced marginally longer leaf lengths 2% to 5% compared to the untreated seed.

Leaf Collar Height V3

There were no significant differences observed between treatments for leaf collar heights (V3COLLAR) (Table 3.4). With the exception of SF-EM1, and the untreated seed with and without starter fertilizer all treatments leaf collar heights were higher than the mean 7.52 cm. While evaluating the effects of starter fertilizer with biologic treatments we again saw a positive response with starter fertilizer used in conjunction with QR. There was a 4% increase in collar height for SF-QR vs QR alone. With the exception of SF-B300 all treatments averaged higher collar heights than the untreated seed with and without starter fertilizer.

Total Leaf Area V3

Despite numerical differences there were no significant differences observed between treatments for total leaf area (V3LAREA) (Table 3.4). Similar to previous results for other measured variables. We saw an increase in leaf area comparing

treatments to the untreated seed. Additionally, there were higher leaf area values after SF was added to the different biologic compounds. With the exception of EM1 all biologic treatments responded positively to starter fertilizer. Leaf area increases ranged from 7% to 16% higher as a result of the starter fertilizer-biologic combination. Using the biologic treatments alone in many cases, increased leaf area compared to the starter fertilizer seed treatment. There was a 4% increase in leaf area for Mamm and 1% for EM1 compared to F-Seed.

Stem Weights V3

Like leaf length and leaf area there were no significant differences observed between treatments for total stem weight (V3STEMWT) (Table 3.4). Evaluation of the effects of starter fertilizer with biologic treatments we again saw a positive response to starter fertilizer added to biologic seed treatments. The addition of starter fertilizer increased stem weights for all treatments. The observed increase ranged from half a percent up to 18%. Similar to previous results we saw a positive interaction between QR and starter fertilizer. On average SF-QR increased stem weights by 18% when compared to QR alone.

Leaf Weights V3

The addition of starter fertilizer and microbial biostimulants produced varied results with respect to leaf weight (V3LEAFWT) (Table3.4). We observed a significant increase in leaf weight to corn seed treated with SF-Mamm compared to B300. Starter fertilizer applied to the untreated corn seed had an 8% increase in leaf weight. There was also an increase in leaf weight after starter fertilizer was used in combination with all

biologic compounds. Stem weight increases ranged from 0.5 % B300, 18% QR, 11% Mamm, 4% EM1 and 8% after fertilizer was added to the untreated seed. Overall, there were no significant differences between microbial seed treatments other than those previously mentioned. There were also no significant differences for starter fertilizer used in combination with biologic seed treatments.

Plant Growth and Development at the VT Growth Stage

Total Leaf Area VT

Analysis of the VT leaf area (VTLAREA) produced many numerical and significant differences between treatments (Table 3.5). We observed a significant increase in leaf area 16% for corn seed treated with SF-QR compared to SF-EM1 and the untreated seed. There was also a significant increase 16% in total leaf area for SF-Mamm was compared to the untreated seed and SF-EM1. Starter fertilizer applied to the untreated corn seed increased in leaf area by 3%. There was also an increase in leaf area after starter fertilizer was used in combination with QR and Mamm treatments. Leaf area increases averaged 2-3% respectively. Using the biologic treatments alone in many cases, increased leaf area compared to the starter fertilizer seed treatment. There was a 7% increase in leaf area for B300, 13% QR, 11% Mamm and 6% for EM1 compared to F-Seed.

Number of Leaves VT

There were no significant differences observed between treatments for number of leaves (VTNUMLF) (Table 3.5). With the exception of SF-Mamm, and the untreated seed all treatments produced leaf numbers higher than the mean of 14.3. While evaluating the effects of starter fertilizer with biologic treatments we saw a positive response to starter fertilizer was used in conjunction with B300. With the exception of SF-Mamm all treatments averaged more leaves than the untreated seed.

Stem Weights VT

The addition of starter fertilizer and microbial biostimulants produced varied results with respect to stem weights (VTSTEMWT) (Table3.5). We observed a significant increase in stem weight in corn seed treated with SF-QR and SF-Mamm compared to the untreated seed both with and without starter fertilizer. There was also an increase in stem weights when starter fertilizer was used in combination with all biologic compounds besides QR. Stem weight increases ranged from 14% B300, 7% Mamm, and 27% for EM1 when fertilizer was added to the biologic compound. Using the biologic treatments alone in many cases, increased leaf area compared to the starter fertilizer seed treatment. There was a 10% increase in stem weights for QR, 17% Mamm and 6% for EM1 compared to the untreated seed with starter fertilizer.

Leaf Weights VT

Analysis of the VT leaf weight (VTLEAFWT) produced several numerical and significant differences between treatments (Table 3.5). We observed a significant increase in leaf weight 21% for corn seed treated with SF-QR compared to the untreated

seed. Starter fertilizer applied to the untreated corn seed resulted in a 9 % increase in leaf weight. There was also an increase in leaf weight after starter fertilizer was used in combination with all biologic compounds with the exception of B300. Leaf weight increases ranged from 13% QR, 0.5% Mamm, and 8% EM1 after starter fertilizer was used along with the biologic compounds. Overall, there were no significant differences among microbial seed treatments. There were also no significant differences for starter fertilizer used in combination with biologic seed treatments.

Plant Height VT

The addition of starter fertilizer and microbial biostimulants produced varied results with respect to plant heights (VTPHEIGHT) (Table3.5). We observed a significant increase 13% in plant height in corn seed treated with Mamm compared to the untreated control. There was also a significant increase 13% in plant height comparing Mamm to SF-B300. With the exception of B300, SF-B300 and SF-QR all treatment plant heights were higher than the mean 180.34 cm.

SPAD VT

Despite numerical differences there were no significant differences observed among treatments for SPAD (VTSPAD) (Table 3.5). Similar to previous results for other measured variables. We saw an increase in SPAD values after SF was added to the different biologic compounds. SPAD values ranged from 31.5 to 40.56. There was an 8% increase in SPAD value if SF was added to B300 and 4% if added to EM1.

Percent Tassel VT

Analysis of the tassel percentages (VTPERCTAS) was as a means of measuring crop growth/maturity as a result of environmental interactions from the different treatment combinations. The number of plants tasseled was estimated by averaging the first 3 days of tassel percentages for each plot after the first tassel emerged. We observed several numerical and significant differences among treatments and tassel percentages (Table 3.5). We observed a significant increase in tassel percentages 41% for corn seed treated with SF-QR compared to the untreated seed. We also observed a significant increase in tassel percentages 40% for corn seed treated with EM1 with and without starter fertilizer compared to the untreated seed. Tassel percentages increased after starter fertilizer was used in combination with biologic compounds B300 and Mamm. Percent tassel increased 50% for SF added to the B300 compound and 21% after added to Mamm treatment. Overall, there were no significant differences among microbial seed treatments.

Soil Physical and Chemical Properties

Overall, soil physical and chemical properties were evenly represented throughout the field experiment (Table 3.6). We purposely sampled and analyzed each experimental plot throughout the field. Other than a slight difference in sand content for SF-QR compared to EM1 there were no significant differences with regards to sand percentages among other treatments. The SF-EM1 treatments were planted in areas of the field that contained higher silt content than EM1, but overall soil physical differences were consistent among treatments. We observed no significant differences when evaluating

soil clay content. There were also no significant differences between soil pH. Soil pH levels ranged from 5.77 to 6.43 with an average of 6.09.

Across treatments there were no significant difference between soil calcium or sodium content. There were significant differences favoring the control treatment for soil potassium content over SF-EM1 and SF-QR. There were also significant differences favoring the control treatment for soil magnesium over SF-QR and SF-Mamm. Soil phosphorus levels over all showed little differences among treatments, other than QR being significantly greater than SF-B300. Total nitrogen was significantly greater for F-seed treatment compared to EM1, SF-B300, and B300. Total carbon varied slightly across treatments, however there were no significant differences observed.

Plant Nutrient Analysis

Nutrient Analysis at V3

Plant nutrient concentrations at the V3 growth stage varied slightly across treatments. The addition of starter fertilizer and or microbial biostimulants produced minimal significant differences among treatments for the nutrients measured (Table3.7). Other than SF-Mamm compared to B300 there were no significant differences for calcium concentration. Other than B300 compared to the untreated seed there were no significant differences observed between potassium content. There were no significant differences between treatments and nutrient concentrations for magnesium, sodium, phosphorus, boron, zinc, iron or manganese. We did observe some significant differences in copper and molybdenum content, however the nutrient levels were minute.

Nutrient analysis at VT

Similarly, plant nutrient content at the VT growth stage varied slightly across treatments. The addition of starter fertilizer and or microbial biostimulants produced minimally significant differences among treatments of the nutrients measured (Table3.8). There were no significant differences between treatments and nutrient content for calcium, potassium, magnesium or sodium. There was a significant difference between treatments and nutrient content for phosphorus. We observed an increase in P content when QR was used compared to the control.

Conclusion

In this study, we evaluated multiple biologic compounds and their effect on plant emergence, plant development, and nutrient uptake efficiency. Our objective was to test the efficacy of four commercially available microbial plant enhancing products. We hypothesized that microbial biostimulants used in addition to conventional fertility management would increase plant productivity and nutrient use efficiency. We further predicted that applying nutrient mobilizing bacteria could have a positive effect on plant performance and growth.

Because early planted corn is typically subjected to cool, wet, less than ideal growing environments, corn has a tendency to suffer at the beginning of the growing season. Our goal was to find one or more microbial biostimulants that would minimize nutrient deficiencies in slow developing corn roots. Utilizing soil bacteria to increase nutrient mobilization would benefit crop growth and also increase production efficiency for producers. Strategically incorporating soil microorganisms into our conventional farming strategies could also extend our long term fertilizer resources.

In order to maximize net benefits of food production we must understand the costs and the benefits of alternative agricultural practices. The future environmental effects of agricultural practices will influence not only farmers but societal acceptance of their production methods as well. Producers are now more than ever challenged to find sustainable solutions in delivering plant nutrients more efficiently to crops and eliminating the risk of environmental contamination. We evaluated two microbial products from Monsanto (B-300, Quick Roots) and two liquid bacterial products (Mammoth P and EM-1) that were commercially available.

Our results indicate, that for the majority of variables measured, the bacterial inoculates and starter fertilizer positively influenced plant growth and development. We observed a significant increase in grain TW when corn was treated with EM1, QR, SF-QR, and B300 compared to the untreated corn seed. There was significant increase in grain SMOIST when corn seed was treated with B300, SF-B300, QR, Mamm, SF-Mamm, and EM1 when compared to the untreated corn seed.

All biologic treatments compared to the untreated seed had a positive yield advantage. As a result of starter fertilizer, grain yield increased by 32% over the untreated corn seed. With starter fertilizer added to the biologic treatments, yield increased from 37 to 48%. There was a significant yield advantage for SF-Mamm 50% when comparing SF-QR. Yields were also significantly improved comparing SF-Mamm 44% and SF-B300.

The addition of starter fertilizer and microbial treatments sometimes had little effect on measured variables. Seed weights, for example responded similarly across all treatments. The addition of starter fertilizer and biologic compounds, on average, resulted in a 15% increase in seed weight. There was however a significant difference observed between SF-EM1 and the untreated seed. The addition of starter fertilizer and microbial biostimulants produced marginal differences with respect to plant emergence. Based on germination percentages all of the experimental plots had 95% or better germination rates.

Several components of corn growth and development are influenced or determined by the genetic background of the hybrid. However, environmental stress is always a factor. For example corn ear length (kernels per row) is largely based on a hybrid's genetics, but can be significantly altered by environmental stresses.

Environmentally, kernels per row potential is highly dependent on growing conditions prior to silking. Actual kernels per ear are determined by conditions during and after silking. Hybrid genetics is instrumental in determining the potential number of rows per ear whereas environmental factors have less influence. Yet, the amount of water received as well as varying environmental factors will affect the number of kernels per row.

In context, fertility or nutrient availability could be classified as a type of environmental stress. Research investigating the influence of nitrogen timing determined early season stress greatly influenced ear development. A deficiency in nitrogen before V8 caused an irreversible decrease in ear diameter and ear length as well as kernels per ear. Even when nitrogen was supplied later in the season, the ears were not able to regain what had been lost in yield. This is because the ear parameters were set earlier in the growth cycle.

Given the genetic tendencies of our hybrid, there were no significant differences observed between treatments for number of leaves. However, treatments with SF-QR and SF-Mamm on average produced 2% to 5% longer leaves than the untreated control. We also recorded a 4% increase in collar height for SF-QR. Leaf area increases ranged from 7% to 16% higher as a result of the starter fertilizer-biologic combination. We observed a significant increase in leaf weight after corn seed was treated with SF-Mamm. On average SF-QR increased stem weights by 18% compared to QR alone.

Starter fertilizer added to the untreated corn seed increased leaf weight by 8%. Leaf area improved by 16% for corn seed treated with SF-QR compared to the untreated seed. Our results found significant increases in stem weight for SF-QR and SF-Mamm compared to the untreated seed with and without fertilizer. We observed a significant

increase in leaf weight 21% for corn seed treated with SF-QR compared to the untreated seed. There was a significant increase 13% in plant height when corn seed was treated with Mamm compared to the untreated seed.

Numerical SPAD values increased after SF was added to the different biologic compounds. We even observed a significant increase in tassel percentages 41% when corn seed was treated with SF-QR compared to the untreated seed. Despite the lack of significant differences in plant nutrient concentrations at the V3 growth stage. There was a significant difference between treatments and nutrient concentrations while evaluating phosphorus at the VT growth stage. We saw an increase in P concentration for QR compared to the control. We also saw several numerical advantages in nutrient content for all treatments compared to the control. Nutrient content for B300, SF-B300, QR, SF-QR, Mamm, SF-Mamm and EM1 all averaged higher Ca content compared to the control. Nutrient content for B300, SF-B300, QR, Mamm, and SF-Mamm all averaged higher K content compared to the control. Phosphorus tissue content also averaged higher when starter fertilizer and or biologic compounds were used.

In this study we showed that the microbial communities found in B-300, Quick Roots, Mammoth P and EM-1 have the potential to improve plant productivity. These results also suggest that microbial-plant interactions vary across several growth and developmental stages. Naturally, the environment and stress play a critical role in plant development. However the microbial communities seem to have an influence in controlling plant growth in a variety of ways. We believe the extent of the response and significance will greatly depend on production practices. Our experiment incorporated

conventional starter fertilizer practices and inoculation with biological treatments and we saw a positive response.

These results indicate the potential and need for future development of microbial seed inoculation to increase yields and production efficiency. The results show that a starter fertilizer application is not the only management practice to consider when incorporating an early planting strategy. Obviously, selecting the proper maturity and hybrid is critical. However, having a good seed treatment (fungicide, pesticide, biologic) provides added value and minimizes some of the stress. In order to confirm the results from this study, a follow up study setup and conducted in the same manner should be completed. It would also be beneficial to conduct a rate response partner study completed in the field and green house setting. The environmental conditions for this experiment likely had a negative effect on the plants at VT/R1 and it would be useful to see the full effects of rate increases and response in a controlled growing environment with growth limiting conditions.

Table 3.1 Description of hybrid and microbial biostimulants used in the seed treatment starter fertilizer experiment at Starkville, MS 2016.

Seed Treatment Starter Fertilizer Experiment				
Brand	**Hybrid**	**Technology Trait(s)**	**Maturity Days (RM)**	**(GDU) Black Layer**
DEKALB	DKC 65-20	DGVT2RIB RR2	115	2875

Product	**Family**	**Genus/Species**	**CFU/mL**
B-300	*Proprietary*	Proprietary	.0005 Seed
Quick Roots	*Bacillaceae*	*Bacillus amyloliquefaciens*	.0005 Seed
EM-1	*Lactobacillaceae*	*Lactobacillus plantarum*	1M
	Lactobacillaceae	*Lactobacillus casei*	1M
	Lactobacillaceae	*Lactobacillus fermentum*	1M
	Lactobacillaceae	*Lactobacillus delbrueckii*	1M
	Bacillaceae	*Bacillus subtilis*	1M
	Saccharomycetaceae	*Saccharomyces cerevisiae*	1M
	Bradyrhizobiaceae	*Rhodopseudomonas palustris.*	1M
Mammoth P	*Enterobacteriaceae*	*Citrobacter freundii*	60M
	Enterobacteriaceae	*Enterobacter cloacae*	80M
	Pseudomonadaceae	*Pseudomonas putida*	20M
	Comamonaceae	*Comamonas testosteroni*	40M

Technology Traits
DG DroughtGard®
VT2: Genuity® VT Triple PRO®
RIB: Refuge in bag
RR2: Roundup Ready® Corn 2
Relative maturity (RM)
Growing degree units (GDU)
Colony forming unites (CFU)

Table 3.2 Experimental field pre plant soil sample analysis.

Extractable Nutrient Levels					
pH	**Ca**	**K**	**Mg**	**Na**	**P**
	---------- mg kg^{-1}----------				
6.0	1114	54	43	7	16

Soil analysis conducted at Mississippi State University.

Table 3.3 Least significant differences for grain quality, yield and emergence data.

Treatment	TW	SMOIST	YIELD	YIELD	KERWT	STANDCT
	kg/hL	%	Mg/ha	bu/ac	g	plant No.
B300	72.91 a	15.80 ab	3.77 abc	60.14 abc	35.85 ab	41.25 a
SF-B300	70.12 ab	15.88 ab	2.68 bc	42.75 bc	33.19 ab	39.38 abc
QR	72.41 a	15.50 ab	4.40 abc	70.17 abc	37.08 a	39.88 abc
SF-QR	72.53 a	14.88 abc	4.78 a	76.23 a	35.61 ab	40.13 ab
Mamm	71.68 ab	15.58 ab	4.35 abc	69.30 abc	36.00 ab	38.06 c
SF-Mamm	71.43 ab	16.00 a	4.27 abc	68.07 abc	32.87 ab	38.94 bc
EM1	72.25 a	14.68 abc	4.58 ab	72.91 ab	36.11 ab	39.69 abc
SF-EM1	71.75 ab	15.48 ab	5.09 a	81.17 a	36.73 a	39.06 bc
Seed	68.53 b	14.30 bc	2.38 c	37.84 c	31.05 b	39.31 abc
F-Seed	71.25 ab	13.68 c	3.14 abc	49.95 abc	31.71 ab	39.25 bc

Seed treatments B300 = Monsanto proprietary microbial seed treatment, QR = Quick roots Monsanto microbial seed treatment, Mamm = Mammoth P microbial inoculant, EM1 microbial inoculant. Seed = untreated corn seed no fertilizer no biologic compound, F-Seed untreated corn seed with starter fertilizer. Treatments with the abbreviation SF in front designates the addition of starter fertilizer in addition to the microbial treatment. Grain quality, yield and emergent data were averaged across the four reps within each treatment area. TW = grain test weight, SMOIST = seed moisture percent at harvest, Mg/ha = grain yield Mg ha^{-1}, bu/ac = grain yield bu/ac, KERWT = kernel weight of 100 seed (g), STANDCT = treatment emergent/total number of plants emerged for each four row plot. Means followed by the same letter are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

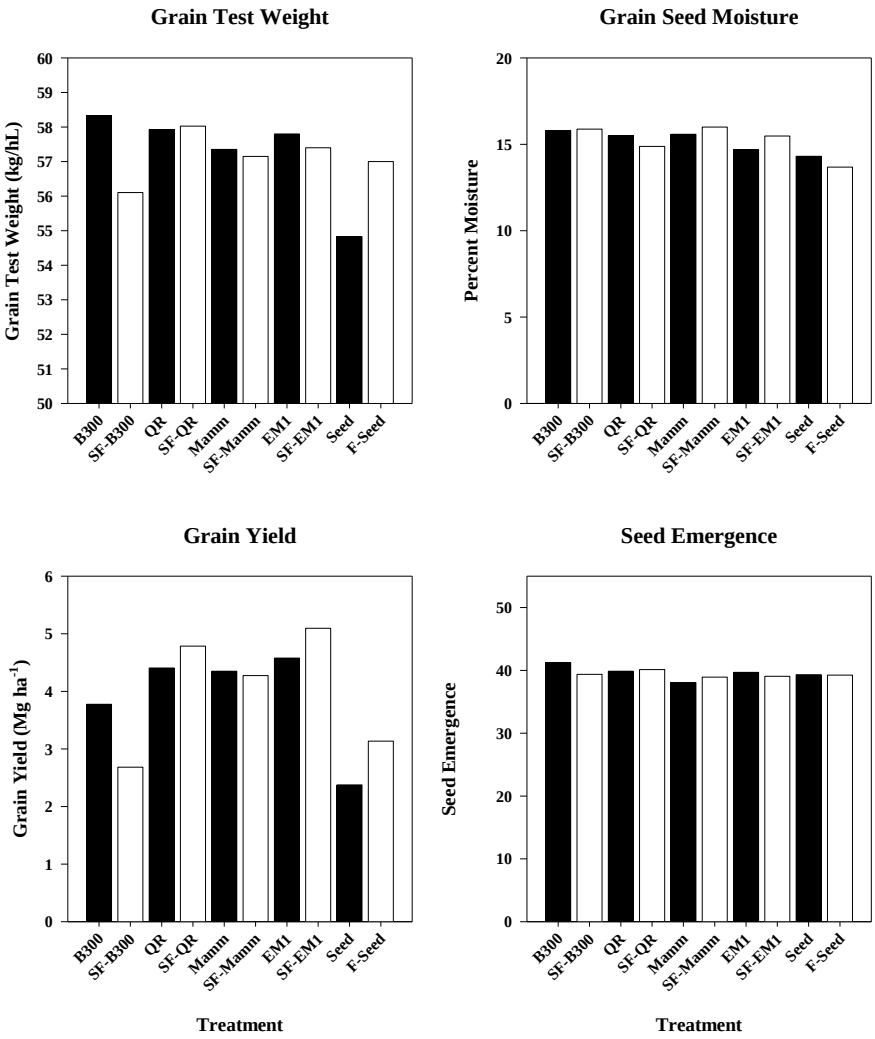

Figure 3.1 Grain yield, yield attributes and plant emergence

Seed treatment starter fertilizer relationship between grain test weight, seed moisture, grain yield and seed emergence at Starkville 2016.

Table 3.4 Least significant differences for V3 crop growth and development.

Treatment	V3LEAF	V3COLLAR	V3LAREA	V3STEMWT	V3LEAFWT
	cm	cm	cm^2	g	g
B300	33.0500 a	7.5750 a	1540.1000 a	1.7550 a	3.6200 b
SF-B300	35.4500 a	7.9000 a	1666.7250 a	2.0700 a	4.3225 ab
QR	34.4500 a	8.3750 a	1675.8000 a	1.9000 a	3.9875 ab
SF-QR	36.5750 a	7.9500 a	1939.3000 a	2.1125 a	4.4450 ab
Mamm	32.6750 a	7.7750 a	1630.1250 a	2.0400 a	4.4225 ab
SF-Mamm	30.9250 a	7.4500 ab	1479.2250 a	2.1250 a	4.9225 a
EM1	34.8750 a	7.4250 ab	1638.5000 a	1.9800 a	3.9675 ab
SF-EM1	34.3750 a	7.2250 ab	1612.9750 a	2.1475 a	4.5850 ab
Seed	32.5250 a	7.4250 ab	1388.1500 a	2.2200 a	4.5300 ab
F-Seed	31.8000 a	6.1250 b	1491.0750 a	2.2075 a	4.3825 ab

Seed treatments B300 = Monsanto proprietary microbial seed treatment, QR = Quick roots Monsanto microbial seed treatment, Mamm = Mammoth P microbial inoculant, EM1 microbial inoculant. Seed = untreated corn seed no fertilizer no biologic compound, F-Seed untreated corn seed with starter fertilizer. Treatments with the abbreviation SF in front designates the addition of starter fertilizer in addition to the microbial treatment. Plant growth characteristics were averaged across the four reps within each treatment. V3LEAF = length of the third leaf from base to tip (cm). V3COLLAR = length from soil level to highest collared leaf (cm), V3LAREA = total leaf area for ten plants (cm^2), V3STEMWT = total stem weight for ten plants (g), V3LEAFWT = total leaf weight for ten plants (g). Means followed by the same letter are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

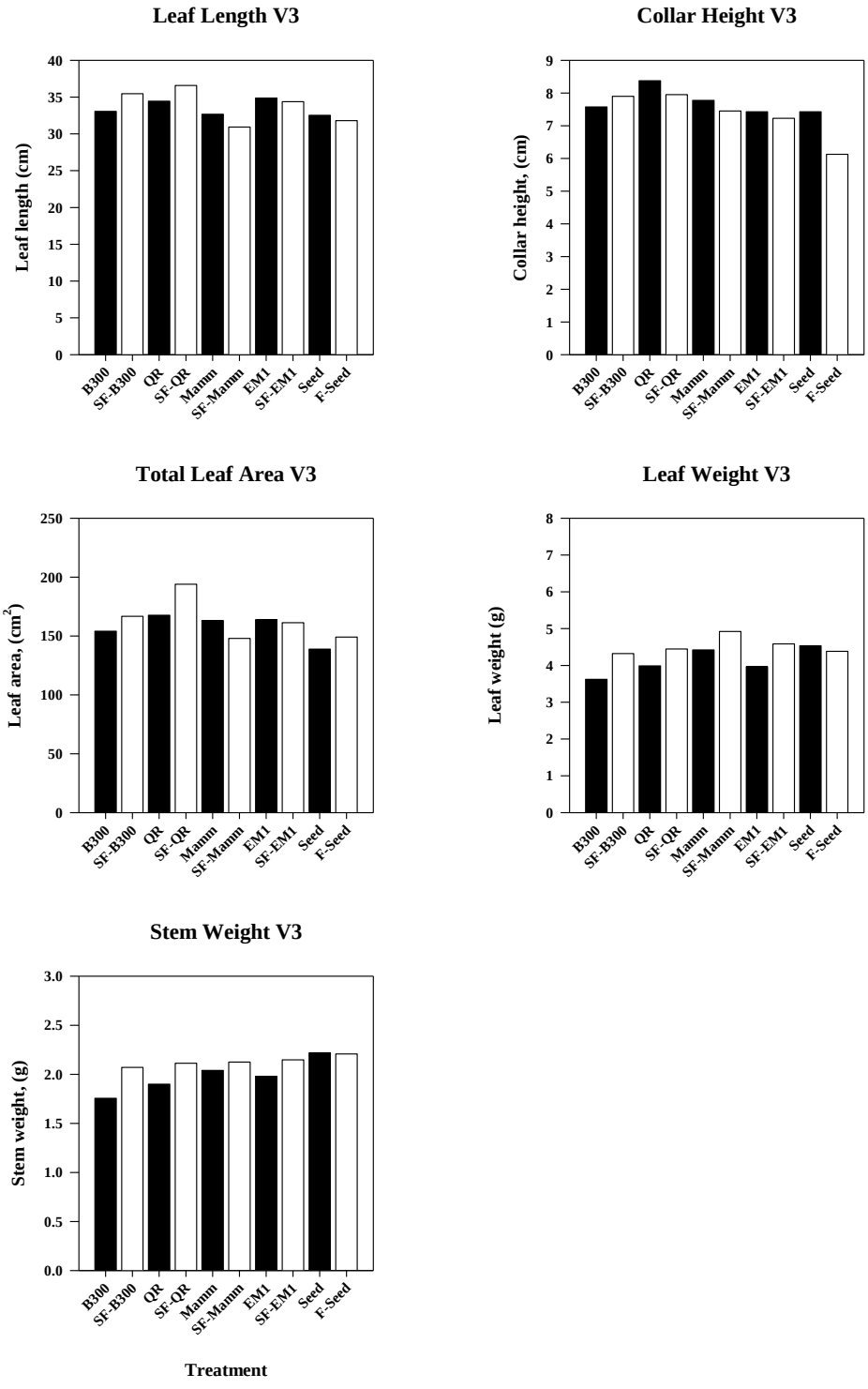

Figure 3.2 Least significant differences for V3 crop growth and development.

Seed treatment starter fertilizer relationship between leaf length, collar heights, leaf area, leaf weight and stem weight at Starkville 2016. ”

Table 3.5 Least significant differences for VT crop growth and development.

Treatment	VTLAREA	VTNUMLF	VTSTEMWT	VTLEAFWT	VTPHEIGHT	VTSPAD	VTPERCTAS
	cm^2	leaf no.	g	g	cm	value	%
B300	5373.65 ab	14.25 a	670.85 abc	331.95 ab	180.97 ab	36.55 a	67.50 ab
SF-B300	5206.98 ab	14.00 a	628.38 abc	287.98 ab	165.73 b	31.55 a	61.25 ab
QR	5702.76 ab	14.75 a	727.78 ab	356.05 ab	183.40 ab	38.55 a	77.50 ab
SF-QR	5785.82 a	13.75 a	775.15 a	357.85 a	186.05 ab	35.55 a	93.75 a
Mamm	5609.61 ab	14.75 a	638.53 abc	326.38 ab	190.5 a	39.38 a	88.75 ab
SF-Mamm	5794.40 a	14.75 a	815.35 a	350.98 ab	180.34 ab	40.75 a	81.25 ab
EM1	5304.67 ab	13.75 a	659.98 abc	328.38 ab	184.78 ab	40.55 a	93.75 a
SF-EM1	4845.90 b	15.00 a	602.15 abc	296.58 ab	193.04 a	38.85 a	92.50 a
Seed	4855.57 b	14.00 a	436.28 c	284.20 b	165.73 b	31.63 a	55.00 b
F-Seed	4988.52 ab	14.25 a	499.20 bc	290.68 ab	172.08 ab	34.15 a	82.50 ab

Seed treatments B300 = Monsanto proprietary microbial seed treatment, QR = Quick roots Monsanto microbial seed treatment, Mamm = Mammoth P microbial inoculant, EM1 microbial inoculant. Seed = untreated corn seed no fertilizer no biologic compound, F-Seed untreated corn seed with starter fertilizer. Treatments with the abbreviation SF in front designates the addition of starter fertilizer in addition to the microbial treatment. Plant growth characteristics were averaged across the four reps within each treatment. VTLAREA = total leaf area for ten plants (cm^2) (LI-COR, Inc.), VTNUMLF = total number of leaves with collars, VTSTEMWT = total stem weight for ten plants (g), VTLEAFWT = total leaf weight for ten plants (g). VTPHEIGHT = height from soil level to top of tassel (cm), VTSPAD = numerical value given from SPAD meter, VTPERCTAS = total percent tassel for experimental plots averaged across reps. Tassel percentages were collected at the VT growth stage from all plots. Means followed by the same letter are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

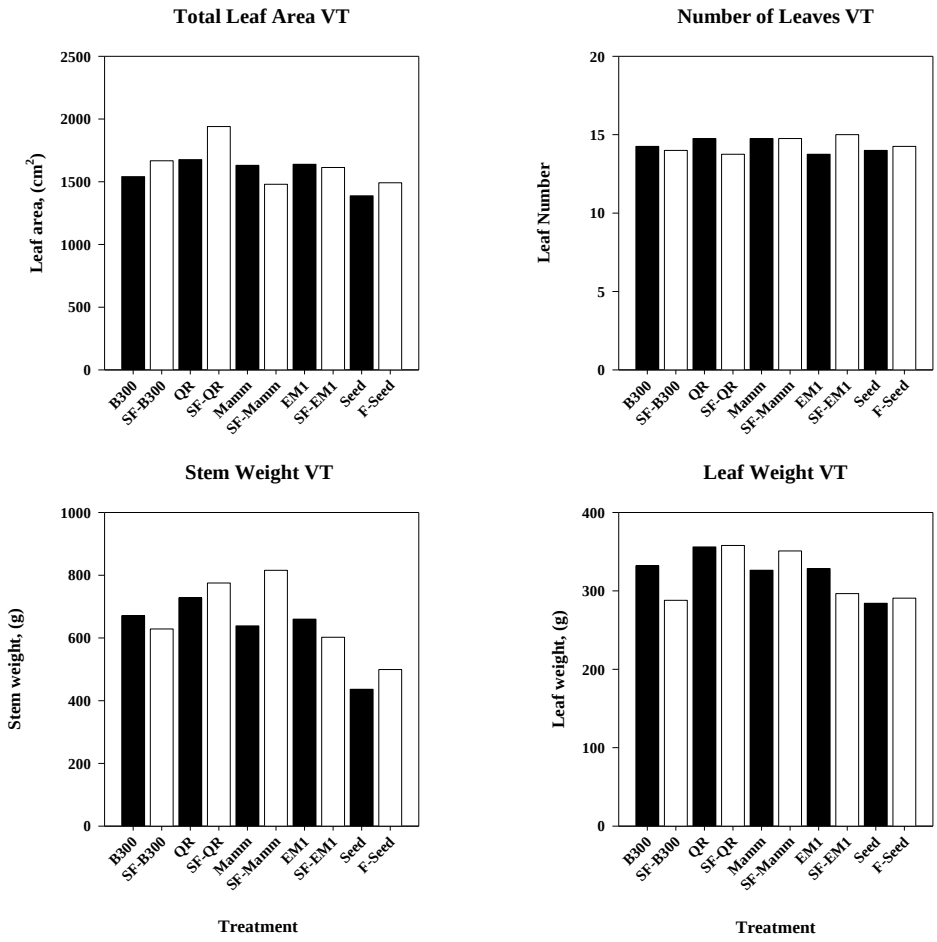

Figure 3.3 Least significant differences for VT crop growth and development.

Seed treatment starter fertilizer relationship between leaf area, number of leaves, stem weight and leaf weight at Starkville 2016.

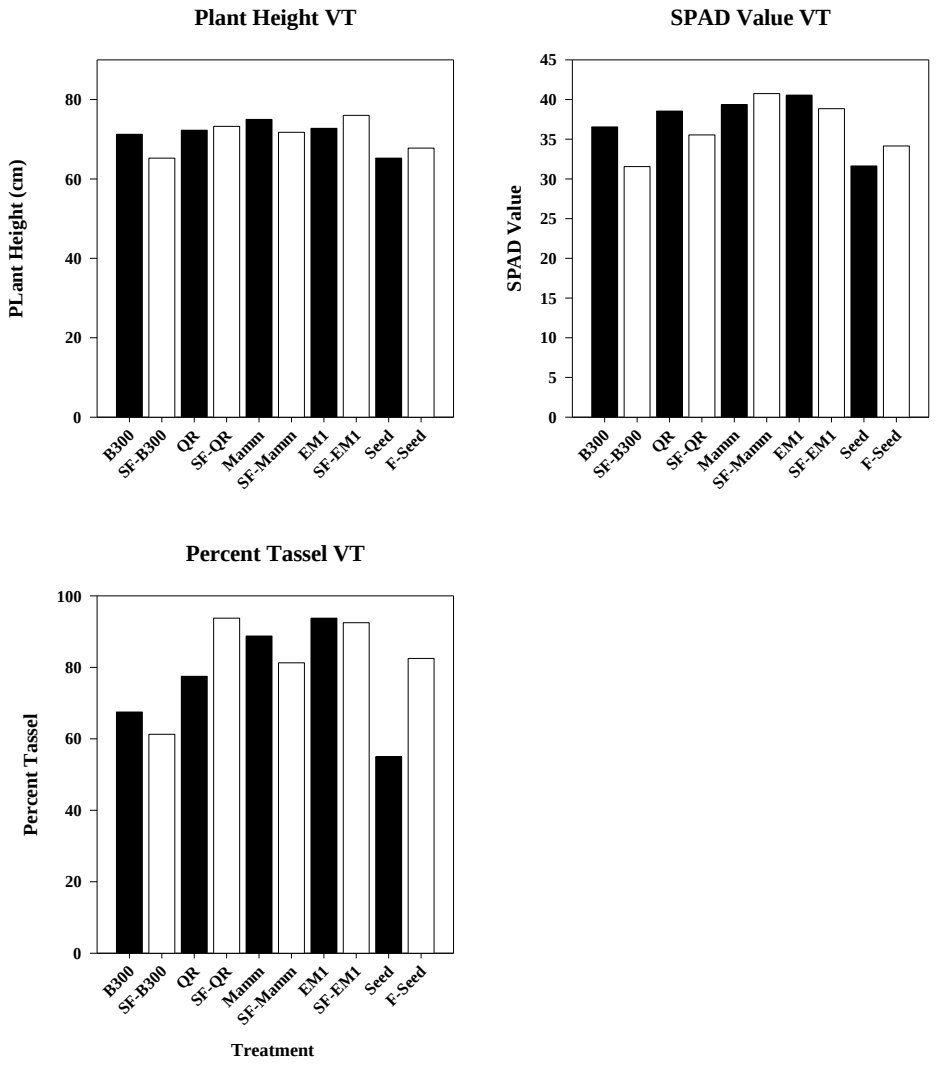

Figure 3.4 Least significant differences for VT crop growth and development

Seed treatment starter fertilizer relationship between plant heights, SPAD value and tassel percentages at Starkville 2016.

Table 3.6 Least significant differences for soil physical and chemical properties.

Treatment	SAND	CLAY	SILT	pH	Ca	K	Mg	Na	P	N	C
	----------%----------				----------mg kg^{-1}----------						
B300	26.73 abc	18.75 a	54.52 a	5.79 a	633.34 a	35.79 ab	28.43 abc	53.20 a	36.67 ab	384 b	2253 a
SF-B300	28.38 abc	20.31 a	51.31 ab	5.77 a	666.75 a	40.23 ab	34.98 ab	46.43 a	26.62 b	402 b	2218 a
QR	30.14 abc	17.81 a	52.05 ab	6.05 a	686.93 a	35.56 ab	28.35 abc	44.66 a	48.00 a	490 ab	2625 a
SF-QR	25.69 c	18.44 a	55.88 a	6.30 a	558.90 a	25.46 b	21.95 c	40.17 a	30.34 ab	583 ab	3498 a
Mamm	30.91 ab	18.13 a	50.97 ab	6.05 a	605.25 a	31.99 ab	26.82 bc	44.16 a	35.29 ab	457 ab	2478 a
SF-Mamm	27.76 abc	18.75 a	53.49 ab	6.23 a	557.45 a	29.30 ab	22.46 c	43.44 a	36.65 ab	456 ab	2531 a
EM1	31.48 a	20.00 a	48.53 b	5.95 a	592.67 a	30.11 ab	25.21 bc	43.56 a	35.19 ab	340 b	2038 a
SF-EM1	26.24 abc	18.75 a	55.01 a	6.43 a	601.30 a	25.80 b	22.95 bc	39.48 a	33.62 ab	444 ab	2621 a
Seed	26.91 abc	20.94 a	52.16 ab	5.96 a	753.00 a	41.13 a	39.10 a	42.76 a	33.84 ab	561 ab	3109 a
F-Seed	27.83 abc	20.94 a	51.24 ab	6.36 a	777.63 a	37.55 ab	32.49 abc	46.81 a	34.97 ab	894 a	2648 a

Seed treatments B300 = Monsanto proprietary microbial seed treatment, QR = Quick roots Monsanto microbial seed treatment, Mamm = Mammoth P microbial inoculant, EM1 microbial inoculant. Seed = untreated corn seed no fertilizer no biologic compound, F-Seed untreated corn seed with starter fertilizer. Treatments with the abbreviation SF in front designates the addition of starter fertilizer in addition to the microbial treatment. Physical and chemical properties were averaged across the four reps for each treatment. Extractable soil nutrients (cmol kg^{-1}) were collected using soil samples at a depth of (0-15cm). Sand = percent sand, Silt = percent silt, Clay = percent clay, pH = soil pH level (degree of acidity or alkalinity), Ca = extractable soil Calcium, K = extractable soil Potassium, Mg = extractable soil Magnesium, Na = extractable soil Sodium, P = extractable soil Phosphorus C = total Carbon N = total Nitrogen. Means followed by the same letter are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 3.7 Least significant differences for plant tissue nutrient properties at V3 growth stage.

	V3 Nutrient Content kg/ha^{-1}										
Treatment	**Ca**	**K**	**Mg**	**Na**	**P**	**B**	**Cu**	**Mo**	**Zn**	**Fe**	**Mn**
	%					ppm					
B300	0.0010 b	0.0027 b	0.0003 a	0.0001 a	0.0002 a	-13.389 a	0.058 abcd	-26.557 ab	-37.6805 a	-256.036 a	-86.027 a
SF-B300	0.0011 ab	0.0032 ab	0.0003 a	0.0001 a	0.0003 a	2.4876 a	0.302 a	1.356 ab	6.4421 a	51.4680 a	16.441 a
QR	0.0011 ab	0.0029 ab	0.0002 a	0.0001 a	0.0003 a	-2.8571 a	0.062 abcd	-16.172 ab	-13.4052 a	-101.916 a	-14.207 a
SF-QR	0.0012 ab	0.0032 ab	0.0003 a	0.0001 a	0.0004 a	6.2032 a	0.144 abcd	10.3889 a	18.0807 a	154.537 a	36.725 a
Mamm	0.0012 ab	0.0031 ab	0.0003 a	0.0001 a	0.0003 a	1.9854 a	-0.021 cd	0.216 ab	4.5581 a	40.955 a	9.974 a
SF-Mamm	0.0014 a	0.0037 ab	0.0003 a	0.0001 a	0.0003 a	2.9921 a	-0.086 d	5.788 ab	9.3364 a	75.619 a	15.970 a
EM1	0.0010 ab	0.0030 ab	0.0003 a	0.0001 a	0.0003 a	-14.352 a	-0.004 cd	-53.846 b	-45.5485 a	-387.928 a	-80.125 a
SF-EM1	0.0012 ab	0.0034 ab	0.0003 a	0.0001 a	0.0003 a	2.5498 a	0.042 bcd	2.805 ab	7.7705 a	26.544 a	17.215 a
Seed	0.0011 ab	0.0038 a	0.0003 a	0.0001 a	0.0003 a	2.4891 a	0.281 ab	1.607 ab	6.3282 a	42.005 a	12.995 a
F-Seed	0.0011 ab	0.0036 ab	0.0003 a	0.0001 a	0.0003 a	2.4295 a	0.179 abc	1.384 ab	5.8655 a	55.687 a	13.912 a

Seed treatments B300 = Monsanto proprietary microbial seed treatment, QR = Quick roots Monsanto microbial seed treatment, Mamm = Mammoth P microbial inoculant, EM1 microbial inoculant. Seed = untreated corn seed no fertilizer no biologic compound, F-Seed untreated corn seed with starter fertilizer. Treatments with the abbreviation SF in front designates the addition of starter fertilizer in addition to the microbial treatment. Tissue analysis were averaged across the four reps for each treatment. Tissue samples were collected at the V3 = third leaf vegetative growth stage. Tissue nutrient concentrations and plant biomass dry weight were used to algebraically derive nutrient content. Nutrient content (kg/ha^{-1}). Ca = Nutrient accumulation Calcium, K = Nutrient accumulation Potassium, Mg = Nutrient accumulation Magnesium, Na = Nutrient accumulation Sodium, P = Nutrient accumulation Phosphorus, B = Nutrient accumulation Boron, Cu = Nutrient accumulation Copper, Mo = Nutrient accumulation Molybdenum, Zn = Nutrient accumulation Zinc, Fe = Nutrient accumulation Iron, Mn = Nutrient accumulation Manganese. Means followed by the same letter are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 3.8 Least significant differences for plant tissue nutrient properties at VT growth stage.

	VT Nutrient Content kg/ha^{-1}				
Treatment	**Ca**	**K**	**Mg**	**Na**	**P**
	%				
B300	0.451 a	0.025 a	0.020 a	0.040 a	0.026 ab
SF-B300	0.447 a	0.026 a	0.023 a	0.031 a	0.017 b
QR	0.491 a	0.026 a	0.021 a	0.035 a	0.038 a
SF-QR	0.440 a	0.020 a	0.017 a	0.032 a	0.025 ab
Mamm	0.406 a	0.022 a	0.018 a	0.031 a	0.025 ab
SF-Mamm	0.491 a	0.026 a	0.020 a	0.037 a	0.034 ab
EM1	0.389 a	0.020 a	0.016 a	0.029 a	0.025 ab
SF-EM1	0.386 a	0.017 a	0.015 a	0.027 a	0.022 ab
Seed	0.388 a	0.021 a	0.020 a	0.022 a	0.018 b
F-Seed	0.448 a	0.021 a	0.018 a	0.026 a	0.021 ab

Seed treatments B300 = Monsanto proprietary microbial seed treatment, QR = Quick roots Monsanto microbial seed treatment, Mamm = Mammoth P microbial inoculant, EM1 microbial inoculant. Seed = untreated corn seed no fertilizer no biologic compound, F-Seed untreated corn seed with starter fertilizer. Treatments with the abbreviation SF in front designates the addition of starter fertilizer in addition to the microbial treatment. Tissue analysis were averaged across the four reps for each treatment. Tissue samples were collected at the VT = Vegetative tassel growth stage. Tissue nutrient concentrations and plant biomass dry weight were used to algebraically derive nutrient content. Nutrient content (kg/ha^{-1}). Ca = Nutrient accumulation Calcium, K = Nutrient accumulation Potassium, Mg = Nutrient accumulation Magnesium, Na = Nutrient accumulation Sodium, P = Nutrient accumulation Phosphorus. Means followed by the same letter are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

CHAPTER IV

CORN PLANT GROWTH AND YIELD AFFECTED BY HYBRID, PLANT POPULATION, AND SOIL CHARACTERISTICS

Abstract

There are multiple factors that affect the yield plant density relationship. This study used grid-sampling techniques and factor analysis to investigate relationships between corn (*Zea mays* L.) yield and several soil and plant developmental variables on four experimental research fields. Variables measured were soil physical properties (percent sand, clay, silt) soil chemical properties (pH, CA, K, MG, NA, P, N, C), and plant developmental (Yield, TW, Plant Height, LAI, KWT, ARD, Long). On average, yields significantly increased 40% as plant population increased from 49,400 to 103,740 plants ha^{-1}. Based on the quadratic model fitted to the least square means data, $r^2 = 0.57$, the optimal plant density for agronomically maximizing yields would be 61,360 plants ha^{-1}. Pooled data correlation analysis between yield and soil physical and chemical properties revealed several significant relationships. There was a significant positive correlation between grain yield and sand ($r^2 = 0.42$), soil K ($r^2 = 0.17$) soil Na ($r^2 = 0.46$), and soil P ($r^2 = 0.49$). There was also significant negative correlations observed between grain yield and clay ($r^2 = -0.52$), silt ($r^2 = -0.27$), soil pH ($r^2 = -0.26$), soil Ca ($r^2 = -0.49$), soil Mg ($r^2 = -0.26$) and soil C ($r^2 = -0.48$). Grain yields and plant growth relationships associated with soil properties were effectively used to create latent variables that could

potentially explain previously unobservable yield variances. Our results indicate that a portion of the yield variability for each location could be explained by the influence of the variables we collected and high variation in some measured variables do not necessarily explain high variability in crop yields. Additionally, the variables involved in significant relationships will likely vary between locations as a result of several factors. Results from this study indicate that the variables that best explain yield variability will likely be different across fields and or locations. For that reason it is important to consider both cropping history and production methods when determining what variables would be most applicable when analyzing the data.

Introduction

Corn production in the Mid-South USA has steadily increased over the past 20 years. Mississippi had over 300,000 hectares of corn harvested in 2016 making corn the second largest crop in the state (USDA-NASS, 2016). Mohsen et al. (2011) attributes the increased corn yields to improved hybrid genetics and agronomic management systems adopted by today's producers. Tollenaar and Lee, (2002) found similar findings in their research, and further accredited yield increases to new hybrids that are better adapted for higher plant populations.

Plant population or the number of plants per unit area is a key component in the grain yield equation along with number of seed per ear (kernel rows "around" and kernels per row "long") and seed weight. Manny of today's cereal crops produce steady yields under a wide range of seeding rates. Physiologically, they have the ability to adjust the number of productive tillers in response to available resources (Darwinkel, 1978; Lafarge et al., 2002).

Corn, unlike other cereal crops does not have the same ability to adjust the number of productive tillers. Corn planted at lower populations and not limited by fertility or moisture has been known to produce additional tillers, however these secondary ears are often late silking and suffer from poor pollination contributing minimally to yield increases (Harris et al. 1976). Modern corn hybrids often only produce one ear per plant even when resources are not limiting (Tokatlidis, 2013). Therefore, finding the optimal plant density is an important management strategy for producers (Harris et al. 1976; Van Roekel and Coulter, 2011; Tokatlidis et al., 2001, 2011).

Compared to similar crops such as sorghum, corn grain yields have responded positively to increased plant populations (Norwood, 2001; Blumenthal et al., 2003; Stanger and Lauer, 2006). Like any crop there are limits to potential yield and the amount of stress a crop will endure. Researchers have conducted numerous experiments with positive yield responses, negative and neutral in relation to increased plant populations (Duncan, 1958; Prior and Russell, 1975; Hashemi et al., 2005; Bruns and Abbas, 2005; Tollenaar, 1992; Ciampitti et al., 2013a, 2013b; Ciampitti and Vyn, 2012, 2013).

There are multiple factors that affect the yield plant density relationship. The main factors include; hybrid genetics (genotype), maturity group, moisture availability (irrigation or rainfall supply), fertility management (soil and fertilizer), and planting date (Keating et al., 1988; Abbas et al., 2012; Sangoi, 2001; Sangakkara et al., 2004; Nik et al., 2011; Tajul et al., 2013; Lindsey and Thomison, 2016). Historically, crop production and yield have greatly improved over time, due in part to better management of plant populations.

Additional improvements in corn genetics have changed the way producers select their optimum plant populations. Producers in the 1950's and 1960's attempted to increase plant populations with limited success. Producers documented an increase in the number barren plants, and reduced grain per ear plant per a function of increasing populations (Bruns and Abbas, 2003). Research evaluating plant populations in Illinois during the same time period found similar results. Barren plant percentages were 1.2, 9.3, 15.7, and 23.6 for populations at 19,760; 29,640; 39,520; and 49,400 plants ha-1. Previous researchers also witnessed an increase in stalk lodging and smaller ear size when plant populations were increased (Rossman and Cook, 1966; Bunting, 1973).

Negative interactions between increased plant population density and hybrids has since been mitigated as a result of better hybrid genetics with greater population stress tolerance. Cox and Crasta (1993) found modern hybrid density recommendations have steadily risen over time. Nielson (2013) estimated in 1998 that 46% of Indiana's corn seeding rates were less than 61,750 plants ha^{-1}. However, by 2012 approximately 50% of Indiana's seeding rates were greater than 74,100 plants ha^{-1}. Statewide seeding rates in 2014 averaged approximately 76,199 plants ha^{-1} (USDA-NASS, 2014). Considering seed germination rates to be 90% to 95% successful, the actual average statewide seeding rate would be between 80,275 and 84,721 plants ha^{-1}. Widdicombe and Thelen (2002) determined grain yield was highest at 90,000 plants ha^{-1}.

There is no questioning that improved hybrid genetics have significantly and positively influenced corn grain yields over the past 30 years. (Duvick, 1984; Castleberry et al., 1984; Eghball and Power, 1995; Assefa et al., 2012; Ciampitti and Vyn, 2012, 2014). Manny researches attribute yield increases to improved competition stress tolerance and the ability to grow more plants per unit area (higher plant populations). Some researchers suggest that yield increases are attributed to hybrids that are more nutrient efficient and respond better to crop inputs. Neilson et al. (2015) attributed the steady increase in plant populations to improved genetics and overall better stress tolerance of current hybrids. Ear size and kernel weight in today's hybrids are less affected by increased plant populations and hybrids are less likely to have late-season stalk health problems.

Research has also shown that increasing corn seeding rates can decrease plant height, reduce stalk diameter, and reduce total leaf area per plant (Boomsma et al., 2009).

Hashemi et al. (2005) suggest that stress caused by density related plant competition during early vegetative growth stages has little effect on final grain yield. However, between V5, anthesis, and early grain fill yield is negatively affected by increased populations if moisture is limiting resulting in a yield decrease. Despite the negative effects caused by increasing corn populations it is important to note that the optimum economic plant density has maximized yields. Seed companies have spent decades breeding and selecting traits to improve hybrids. The end result is a modern hybrid that can produce an ear under moisture and density stress far better that hybrids from 30 years ago.

Modern hybrids have changed the risk/reward equation giving producers an advantage (Butzen, 2013). Any, advantage in grain yield is a major focus for producers. Especially, as global human population estimates predict an increase from 7.1 billion to 9.2 billion in the year 2050 (U.S. Census Bureau, 2014). Mohsen et al. (2011) suggests plant density per unit area is one of the most significant yield determinates of crops. Because, humans and animals both consume corn, and corn products it is realistic to anticipate an increase in the demand for corn. As the population increases Roekel (2011) suggest the amount of available farm land will decrease over time. For that reason alone, it will become even more important for producers to optimize grain yields in a given area and improve their overall cropping efficiency.

Overall, advancements in general crop management practices such as increased fertility management, irrigation, and improved weed and pest control have also significantly influenced grain yield increases and the ability to raise plant populations. (Tokatlidis and Koutroubas, 2004; Duvick, 1997; Carlone and Russell, 1987; Tollenaar

and Wu, 1999; Ciampitti and Vyn, 2012). Yield increases by agronomic management practices such as optimizing planting date and plant populations has been well documented in northern corn production areas. Considerations for determining the optimum planting density include seed corn cost as well as market return on the estimated corn harvest (Roekel and Coulter, 2011). Producers should also take into account the potential reduction in kernel weight and number of kernels associated with increasing population (Hashemi et al., 2005). Ideally, producers will plant corn at high enough populations that the decrease in kernel size and weight caused by the denser stands are offset by the additional plants per unit area, resulting in increased yield.

Early researchers suggest that moisture is often the most restrictive factor in selecting optimal seeding rates and final yields will fluctuate relative to water availability (Averbeke and Marais, 1992). Others believe hybrid selection is the most important factor (Stanger and Lauer, 2006). However, more recent studies suggest soil type or soil productivity should be used to determine optimum seeding rates (Woli et al., 2014). Realistically, all crops species have an optimum plant population, the goal however, is to achieve maximum yield per unit area, and this is determined by a complex relationship between cultivar and environment (Bruns and Abbas, 2005).

Selecting the right cultivar is critical, however if not properly managed the "best" hybrid can still provide poor results. Because of dependence on many environmental factors and regardless of hybrid, crop yields typically vary over time and space. For that reason determining consistent yield patterns that accurately reflect soil properties can be difficult. Luckily, newly introduced precision farming technologies have provided us the opportunity to collect massive amounts across the production landscape. Having more

data could potentially help researchers answer more questions regarding crop production. Producers are now capable of accurately and efficiently collecting crop data in real time at a fine resolution.

Soil chemical and physical properties, climatic data, crop diseases, pests, weeds, and crop yields are some of the most common variables recorded using these technologies. Data can then be georeferenced and organized into multiple layers of useful information for producers. Results are often processed into maps by using different gridding and interpolation techniques. When properly analyzed this data can be useful in understanding the relationships between field variables and crop yields. Crop and soil management zone delineation is an important part of this process (Cox and Gerard, 2012).

There are several benefits for developing management zones. One being producers can more efficiently manage crops and or soil characteristics that share similar yield limitations. Ideally, these areas of the field can be managed separately and crop inputs can be specifically tailored for those areas (site specific). However, identifying soil management zones has been somewhat difficult in previous studies. Spatial and temporal variability in crop growth and yield patterns make identifying yield limiting soil properties extremely tough (Huggins and Alderfer 1995; Lamb et al. 1997; Schepers et al. 2004). As a result, producers have used more of a blanketed approach for managing production fields.

One approach to studying these relationships is to apply various statistical procedures. Simple correlation and multiple regression analyses can be applied to field data and research plots. These relationships can be further studied using conventional and

spatial statistics. Graphical and numerical analytical tools used in geographical information systems (GIS) and spatial statistics are useful tools for analyzing relationships between variables (Mallarino et al., 1999).

Traditional statistics, spatial statistics, and geostatistics are all very useful in studying relationships between variables, however each technique uses a different set of assumptions in the analysis. Traditional correlation analysis emphasizes relationships between variables independently of the spatial distribution. Spatial correlation analysis on the other hand emphasizes the spatial correlation and spatial distribution of variables. For comparing field variables (soil characteristics, plant growth and development) to crop yields, it is very important to select the proper statistical technique.

Using traditional correlated variables in multiple regression analysis to explain crop yields has not always yielded the best results. This is because simple correlations often show many variables are correlated with crop yields and the variables themselves are intercorrelated making it complicated to interpret the regression equation (Bowerman and O'Connell, 1990). Additionally, if several variables are highly correlated the significance of the coefficients can become less reliable. In these types of situations, multivariate analysis techniques using variable grouping, principal component analysis, and factor analysis can produce more meaningful results. Through the years multivariate analysis techniques have been used to study relationships between soil characteristics, microbial populations, plant physiology and crop yields (Norris, 1972; Rosswall and Kvillner, 1978; Dick and Deng, 1991; Kuuluvainen et al., 1993; Gomoryova and Gomory, 1995).

Factor analysis (FA) is often times more successful at identifying groups of correlated variables because it identifies the factors or dimensions that are responsible for the covariation whereas principal component analysis only analyses the variance between variables (Mallarino, et al., 1999; Goldberg, 1997). Factor analysis describes variability among observed, correlated variables in terms of a potentially lower number of unobservable underlying variables called factors. The objective in using FA is to find independent latent variables to explain relationships more accurately.

Unquestionably, there are several complex factors and interactions that affect not only grain yield, but growth and development of the crop from the time it is sown in the ground. That said, producers can only control so many factors of a crops life cycle. Therefore, producers have to concentrate on those factors than can be managed and manipulated to maximize production and profitability. Based on a review of current literature, some of the most significant manageable factors affecting corn yields include seeding rate, hybrid selection, planting date, row width, and overall crop management practices including fertility.

Monneveux et al., (2005) observed increased efficiency in grain yield if plant population and spacing was optimized to capture maximum solar radiation within the canopy. It is important to note that the optimal plant density is differs across hybrids, soil types and geographic regions. Additionally, yield increases accomplished by increasing plant density will at some point yield lower grain and economic return per unit seed increase. Nafziger, (1994) found that newer hybrids produce greater grain yields at higher plant populations compared to older hybrids. Research has also shown that newer hybrids are more tolerant to abiotic stressors at higher plant densities (Tollenaar, 1991). However,

at some point hybrids will decline as plant density is increased past a certain point (Tollenaar et al., 1991).

Ideally, my research would provide some useful insight into plant population stress and yield relationships with multiple affecting factors. Hopefully, this would give producers and agronomists insight into developing more efficient and effective management strategies where production areas and or soil characteristics share similar yield relationships.

Objectives

The objectives of this research study were to investigate seeding rates and yield relationships for hybrids with varied genetic backgrounds under different growing environments and planting dates. Determine the influence of soil characteristics on crop yields, and study the relationships between measurable soil and plant variables and their impact on grain yield.

Materials and Methods

The 2015 field experiments were conducted at Starkville, MS at the R.R. Plant Science Foil Research Center (33.472305°-88.784068°), Verona, MS at the North Mississippi Research and Extension Center (34.165138° -88.740698°) and Brooksville, MS at the Black Belt Experiment Station (33.263536° -88.540222°). Field experiments were repeated at Starkville for the 2016 growing season. The experimental design for each site-year was a split plot arrangement in a randomized complete block design. Starkville and Brooksville 2015 field experiments had four replications. Verona 2015 and Starkville 2016 field experiments had three replications.

Planting dates were determined yearly by field conditions, the earliest point at which soil could maintain the weight of a tractor and planter. Planting dates for the different locations can be found on (Table 4.1). The difference in planting dates between years and locations reflects the variance in geographic location, weather, and planting feasibility in regards to time and weather conditions. Dekalb (DKC Monsanto, St. Louis, MO) '6757', Pioneer (DuPont Pioneer Hi-Bred Int., Johnston, IA) '1498', and Agrisure (Syngenta Crop Protection, Greensboro, NC) 'AGRN-79' hybrids were used for the main plots in 2015. Pioneer (DuPont Pioneer Hi-Bred Int., Johnston, IA) '9329', '0843', and '1637' were used for main plots in 2016. Plots were four 97-cm rows (0.96 m) wide by 9.14 m long.

Relative maturities for the different hybrids are presented in (Table 4.2). Plots were planted in slight excess of the target treatment densities and hand-thinned to the exact desired population of plants ha^{-1} prior to plants reaching the fifth leaf collar stage. Final plant densities were 49,400 plants ha^{-1}, 61,750 plants ha^{-1}, 74,100 plants ha^{-1}, 86,450 plants ha^{-1}, and 98,800 plants ha^{-1} in 2015, and 64,220 plants ha^{-1}, 74,100 plants ha^{-1}, 83,980 plants ha^{-1}, 93,860 plants ha^{-1}, and 103,740 plants ha^{-1} in 2016. Plots consisted of four 97-cm rows (.96 m) wide by 9.14 m long. Standard rainfed corn population recommendations for this region are 69,160 plants ha^{-1}.

The 2015 Starkville planting density experiment was planted in Leeper, silty, clay, loam (Fine, smectitic, nonacid, thermic Vertic Epiaquepts) soil following a previous corn crop. The 2015 Brooksville planting density study was planted in Brooksville, silty, clay, (Fine, smectitic, thermic, Aquic, Hapluderts) also following corn. The 2015 Verona field experiments were planted in Marietta loam (Fine loamy, siliceous, active, thermic

Fluvaquentic) soil following soybeans. The 2016 Starkville planting density experiment was planted in Leeper, silty, clay, loam (Fine, smectitic, nonacid, thermic Vertic Epiaquepts) following cotton (USDA-NRCS Soil Survey Division, 2016).

Pre-plant soil samples were taken for analysis for both years at all locations. Soil analysis indicated that no additional plant nutrients were required for either year or location. Nitrogen (N) was applied with a four row liquid fertilizer applicator equipped with coulter-knives approximately 20-cm from the center row in a split application. Application rates in 2015 consisted of an initial application of 84 Kg/ha^{-1} at V3 leaf stage and 140 Kg/ha^{-1} at the v 6-7 leaf stage using a 32% urea ammonium nitrate (UAN) solution. Field experiments in 2016 consisted of an initial application of 84 Kg/ha^{-1} at V3 leaf stage and 224 Kg/ha^{-1} at the v 6-7 leaf stage.

Weed management for all locations and years was a pre-emergent application of glyphosate (Roundup PowerMax) and Halex GT at recommended, labeled rates. Post-emergent weed control was an additional Roudup PowerMax application as needed at labeled, recommended rates. Field preparation for each location consisted of using a chisel plow to break the soil at a depth of 20-cm in the fall. Fall bed preparation was accomplished by using a packer/roller to flatten the tops of the rows to have a wider surface to plant into in the spring. Corn was planted 6.25-cm deep using a 4-row John Deere 7100 MaxEmerge vacuum planter (Deere and Co., Moline, IL).

Intercepted photosynthetically active radiation and leaf area index (LAI) were measured with an AccuPAR LP-80 (Decagon Devices, Pullman WA) between 10:00 and 3:30 on clear and calm days from all plots at two week intervals throughout the growing season. AccuPar readings were taken using one above-canopy reading, perpendicular to

solar orientation, followed by four below-canopy readings averaged. For the below-canopy readings, the probe was positioned before and after the sampled plant(s) at 45-and 315- degree angles, centered on the row without blocking sunlight.

A SPAD 502 chlorophyll meter (Konica-Minolta, Japan) was used to measure leaf absorbance in the red and near-infrared electromagnetic regions. The Numerical SPAD value is closely related to plant nutritional condition and provides a surrogate to the amount of chlorophyll present in leaf tissue. SPAD is a nondestructive method to monitor the crop N status. SPAD readings have been used to predict the N fertilizer demand for top-dressings in rice (*Oryza sativa* L.) (Cabangon et al., 2011), and maize (*Zea mays* L.) (Varinderpal-Singh et al., 2011).

Three SPAD readings were taken from two plants within the middle two rows of each plot. The values were then averaged. SPAD measurements were taken from the middle portion of the leaf parallel to the mid-vein of the most matured leaf at time of collection. SPAD was taken throughout the growing season at two week intervals to capture treatment differences among hybrids, N status, and planting dates. Because N is the primary mineral nutrient needed for chlorophyll production it plays a key role in a plants life cycle (Muñoz-Huerta et al., 2013). By capturing a plants N status across the season we would have information to potentially explain yield differences among hybrids and planting dates.

Plant height was taken by measuring from the ground to the point of the highest collared leaf. The number of collared leaves was also recorded along with the total number of leaves at time of collection. Growth characteristics were taken throughout the growing season on two week intervals until plants reached tasseling (VT). Measurements

were taken from three random plants within the two inner rows and at least 1-m from the edge of the front of the plot.

Ear samples were collected from five consecutive plants in the center portion of the outer two rows of each plot prior to harvest. The number of kernel rows (around) and number of kernels per row (long) were counted and averaged for comparison. Yield and test weight were collected using a Kincaid 8-XP small plot combine (Kincaid Equipment Manufacturing, Haven, KS). The middle two rows of each plot were harvested. Yield calculations from the plots were adjusted to 155 g kg^{-1} moisture.

A sub-sample of grain was taken from each plot after yield was calculated to collect 100 kernel weights. Test weight and moisture content of the sample was measured with a Dickey-John GAC 2100 grain moisture tester (Dickey-John Corporation, Auburn, Illinois). Kernel weight was then determined by weighing 100 kernels and adjusting moisture content to 155 g kg^{-1}.

Experimental Design and Data Analysis

Main plots consisted of three corn hybrids and five plant densities. The PROC VARCOMP (SAS Institute, 2012) procedure was used to determine yield variation influenced by known factors such as hybrid, plant population, location, year, and interactions as well as other unknown factors influencing yield differences among treatments (Table 4.3). Multilevel regression PROC REG procedures of SAS (SAS Institute, 2012) was used to analyze the effects of planting density on crop yield.

Crop yield and plant density relationships along with other specific factors were also evaluated using the PROC MIXED procedure (SAS Institute, 2012) (Table 4.4). PROC MEANS and PROC GLM procedures of SAS (SAS Institute, 2012) were used to

produce descriptive statistics for data analysis. Minimum, maximum, mean, standard deviation, variance, yield distribution, and factors influencing variation were used to explain and validate the experimental results (Figure 4.11).

PROC GLM procedures of SAS (SAS Institute, 2012) were used to analyze the main effects and interactions of the dependent and independent variables collected in the population precision ag experiment (Table 4.18).Variance influenced by known factor location was also analyzed. Variance percentages were calculated to determine yield variation independent of the previous pooled data set using the PROC NESTED procedure (SAS Institute, 2012) (Tables 4.5 through 4.8)

Correlation analysis for yield, soil physical, chemical, and plant growth and development factors were collected using the PROC CORR procedure (SAS Institute, 2012). Lastly, plant properties representing health, emergence, grain quality, and yield were collected and related to soil fertility and textural properties using factor analysis coupled with stepwise regression and a VARIMAX rotation in PROC FACTOR (SAS Institute, 2012).

Variability Factors Affecting Pooled Data Set

Initial data analysis was evaluated by pooling the entire dataset in order to determine sources of variability. The goal was to determine grain yield variance relationships between hybrid, plant populations, locations and years along with estimating variance percentages for each contributing factor affecting grain yield. This was accomplished by setting yield as the dependent variable while all other factors were considered random. An additional analysis was conducted using the pooled data, however hybrid was separated by its relative maturity group, planting date was included in the

analysis and location and year were categorized by site-year. Yield was again used as the dependent variable while all other factors were considered random. The variance components provide insight on how much each of the random factors contributed to the overall variability in the dependent variable grain yield.

Plant Population Yield Relationship Regression Analysis

The next step involved constructing regression models to explain population specific yield relationships. A hierarchal approach was used to fit the raw data (unadjusted data) and the least square means (adjusted data) to identify the best model (Figures 4.2 & 4.3). Criteria for selecting the best linear, quadratic, exponential, or hyperbolic model was achieved by implementing model selection criteria RSQUARE, ADJRSQ, CP, STEPWISE, F, and B procedures in ROC REG (SAS Institute, 2012).

Corn grain yield least square means (adjusted data) were also evaluated separately by year (Figures 4.4 & 4.5) and location (Figure 4.6). Corn grain yield raw data (unadjusted data) and the least square means (adjusted data) were also plotted to evaluate visual patterns of yield variance for factors including relative maturity (Figure 4.7), hybrid (Figure 4.8), planting date (Figure 4.9) and site year/location (Figure 4.10).

Variability Affecting Grain Yield by Location

Variance influenced by known factor location was analyzed Starkville 2015(Table 4.5), Brooksville 2015 (Table 4.6), Verona 2015 (Table 4.7) and Starkville 2016 (Table 4.8). Variance percentages were calculated to determine yield variation independent of the previous pooled data set using the PROC NESTED procedure (SAS Institute, 2012). The objective was to perform a random effects analysis of variance for yield using a nested

(hierarchical) approach. The random effects model analyzed yield data incorporating factors (hybrid and population).

Descriptive Statistics

Descriptive statistics of the yield distribution for pooled data was calculated and constructed into a histogram (Figure 4.11). The purpose was to create a graphic representation of the distribution of yield data over all site years and locations. This provided a sense of the density of the underlying yield distribution for the pooled data set. Graphs were created using PROC UNIVARIATE procedures of SAS (SAS Institute, 2012).

PROC MEANS and PROC GLM procedures of SAS (SAS Institute, 2012) were used to produce descriptive statistics for corn grain yields by site year/location/population/hybrid (Tables 4.9-4.12), year (Table 4.13), hybrid (Table 4.14), planting date (Table 4.15), relative maturity (Table 4.16) and plant population (Table 4.17). Minimum, maximum, mean, standard deviation, variance, coefficient of variation and corrected sum of squares was calculated.

Main Effects and Interaction Analysis

Main effects and interactions for dependent variables grain yield, grain test weight, plant height, LAI, 100 kernel weight, kernel rows and number of kernels long was analyzed using the PROC GLM procedure (SAS Institute, 2012). This analysis provided detailed results of the single independent variables with respect to the main effects dependent variable. Data were analyzed by pooling the entire data set (Table

4.18), separating hybrid (Table 4.19), plant population (Table 4.20), grain test weight (Table 4.21) and corn grain yield (Table 4.22).

Correlation Analysis

A correlation analysis between yield and continuous variables hybrid, population, location, year, planting date and site-year was conducted to evaluate the strength and direction of the known factors relationship with grain yield. Correlation analysis between yield and soil physical and chemical properties was also evaluated with the goal of developing prediction models. Lastly, analysis between yield and plant growth and developmental factors was analyzed using PROC CORR procedure (SAS Institute, 2012).

Factor Analysis

Lastly, plant properties representing health, emergence, grain quality, and yield were collected and related to soil fertility and textural properties using factor analysis coupled with stepwise regression and a VARIMAX rotation in PROC FACTOR (SAS Institute, 2012). A preliminary correlation analysis was performed for all known measurements collected from each experimental field location. Initially, all variables were included in the data analysis so not to exclude any variable from becoming a possible factor. Determining the number of factors to be included in the later analysis was partially based on the analysis of the eigenvalues. The process for selecting measured variables from each factor from the partial correlation coefficients is sometimes referred to as a loading factor (Johnson and Wichern, 1992; SAS Inc., 1996). In addition to judgmental criteria evaluating differences between successive values, the proportion of the variation represented, and the cumulative proportion of the variation represented

factors were kept by further analysis utilizing the SCREE plot (Figures 4.16-4.19) produced in PROC FACTOR (SAS Institute, 2012). The new variables or latent variables (a term coined by social sciences) denotes an underlying directly unobservable factor.

Groups of correlated variables excluding corn yield were then defined by a factor score. The new factor score replaced the original raw data value by creating a standardized scoring coefficient for each measurement collected from the experimental field locations. To study the relationships between the latent variables and corn yield, a multiple regression hierarchal approach was used and models were fit accordingly. Grain yield was the dependent variable and the latent variables were the independent variables. Example: $Y = b0 + b1L1 + b2L2 + b3L3 + b4L4 + e$, where Y represents estimated corn yields, b0 to b4 are coefficients, L1, to L4 are the latent variables and e represents residual error.

Population Precision Ag Results and Discussion

Variability Factors Affecting Pooled Data Set

Initial analysis of the known factors, hybrid 28%, plant population 8%, location 3%, and year 0.20% accounted for approximately 66% of the total yield variance. The remaining 34% yield variance was attributed to higher level interactions and unknown error factors (Table 4.3). Secondary analysis separating hybrids by relative maturity and evaluating year and location by site year revealed that, relative maturity group 15%, hybrid 13%, plant population 8%, planting date 30%, and site year 2% accounted for approximately 67% of the total yield variance. The remaining 33% yield variance was attributed to higher level interactions and unknown error factors. Separating hybrids into relative maturity groups, adding a planting date component, and using site-year in place

of location and year improved the total yield variance explanation by 1% and provided more detailed insight into known factors influence on yield variation (Table 4.4).

Plant Population Yield Relationship Regression Analysis

Averaged across all variables (hybrid, year and location), yield response to plant population varied significantly as populations increased from 49,400 to 103, 740 ha^{-1}. (Figure 4.1). Average yield significantly increased 40% as plant population increased from 49,400 to 103,740 plants ha^{-1}. A moderate yield increase of 6%, was observed for plant population increased from 49,400 to 61,750 plants ha^{-1}. Comparably, we observed a higher proportional yield increase of 17% after population increased from 49,400 to 64,220 plants ha^{-1}. There was also a higher proportional yield increase of 35% after plant population increased from 49,400 to 83,980 thousand plants ha^{-1} compared to a 14% increase when populations increased from 49,400 to 74,100 thousand plants ha^{-1}. The higher plant populations also advanced grain yields. Population density increased from 86,450 to 93,860 plants ha^{-1}, increased yield by 24%. A similar yield increase of 21%, was observed after plant populations increased from 86,450 to 103,740 plants ha^{-1}.

Based on all statistical model selection criterions considered and compared with the best linear, exponential, and hyperbola models fitted to the data, the quadratic model best explained the yield plant population relationship (Figure 4.2). The quadratic model was fitted to the raw data (unadjusted) the $r^2 = 0.09$. The quadratic model was fitted to the least square means data (adjusted), the $r^2 = 0.57$. Based on the quadratic model, the optimal plant density for agronomically maximizing yields would be 61,360 plants ha^{-1}.

Yield Plant Population Relationship by Year

The average yield plant population relationship observed for the two years of corn field experiments in central Mississippi varied considerably by year. Between the two years there was substantial differences in planting dates (Table 4.1). Grain yields between years followed a similar trend despite abnormal spring rain events in 2015 and a statewide crop planting delay (Figures 4.4 & 4.5). As plant populations increased, the yield response increased positively up to the higher populations of 83,980 and 86,450 plants ha^{-1}. Average yield between the two populations differed by less than 15% (Table 4.17). Averaged across populations there was an 18% yield increase for 2016 (Table 4.13). The quadratic model fitted to the 2015 data resulted in $r^2 = 0.98$. The quadratic model fitted to the 2016 data resulted in $r^2 = 0.82$.

Yield Plant Population Relationship by Location

The average yield plant population relationship for the four locations followed similar trends despite significant differences in actual yield levels (Figure 4.6). As plant populations increased to the highest seeding rate, yields comparably were minimal if not slightly reduced. All four locations did however produce similar yield increases for populations ranging from 74, 100 up to 93,860 plants ha^{-1} (Tables 4.9 – 4.12). Grain yield increases for that population range averaged 0.5% to 6% more grain ha^{-1} compared to the next lowest plant population.

Individually, each location averaged more than 8 Mg ha^{-1} across hybrids. In fact, with exception of Brooksville, yields were 10 Mg ha^{-1} or higher averaged across populations. Yields significantly increased as plant populations increased from 61,750 to 74,100 plants ha^{-1} and continued to increase moderately as plant populations rose from

74,100 to 98,800 plants ha^{-1} at Starkville 2015 (Table 4.20). Averaged across populations, yield was highest at Starkville 2016 followed by Starkville 2015, Verona and Brooksville 2015. Maximum yields of 13.14, 11.49, 10.67, and 8.76 Mg ha^{-1} were observed.

Comparing yields between plant population increases, yield increased 21% by increasing seeding rates from 98, 800 to 103, 740 plant ha^{-1}, 19% after increasing from 93,860 to 98,800, and 14% after increasing from 74,100 to 83,980 plants ha^{-1} (Table 4.17). The quadratic model fitted to Starkville 2015 data the $r^2 = 0.94$, Verona 2015 $r^2 = 0.25$, Brooksville 2015 $r^2 = 0.99$, and $r^2 = 0.82$ after the quadratic model was fitted for Starkville 2016 (Figure 4.6).

Yield Plant Population Relationship by Hybrid

Overall, there was a tendency for yields to increase, at each seeding rate increase as hybrid relative maturity increased within a location. Although, there were fewer earlier maturing hybrids evaluated in the analysis (Figure 4.7). However, there were no significant differences in the yield response between relative maturities of 93,114,115 and 117. Comparatively, there was a significant difference between those same hybrids and hybrids having 108 and 116 relative maturities ranges (Table 4.16). Average yields ranged from 9 to 13 Mg ha^{-1} between the different relative maturity groups. The highest yield of 16.94 Mg ha^{-1} was observed for the hybrid having a relative maturity of 116 days (Table 4.16). The lowest average yield recorded was 8.94 Mg ha^{-1} for the hybrid with the 93 day relative maturity.

In addition, to the generalization that yield was higher with increasing hybrid relative maturity we believe that planting date and geographic location also likely affected yield. It is reasonable to attribute some of the yield differences to the genetic backgrounds of the hybrids as well as the shorter growing season from rain delays and difference longitudinally (amount and quality of solar radiation) between the relative maturity groups for each location. However, overall across populations and when relative maturity was grouped into short season (93-108) mid-season (114-115) and full season (116-117) average yields were highest for the full season 11.77 Mg ha^{-1} , moderately lower for the short season 10.61 Mg ha^{-1} and lowest for the mid- season maturity group 9.78 Mg ha^{-1}.

Variability Affecting Grain Yield by Location

Analysis of the known factors at Starkville 2015, hybrid 1% and plant population 56%, accounted for approximately 57% of the total yield variance. The remaining 43% yield variance was attributed to higher level interactions and unknown error factors (Table 4.5). Analysis of the known factors at Brooksville 2015, hybrid 62% and plant population 35%, accounted for approximately 97% of the total yield variance. The remaining 3% yield variance was attributed to higher level interactions and unknown error factors (Table 4.6). Analysis of the known factors at Verona 2015, hybrid 97% and plant population 3%, accounted for approximately 100% of the total yield variance. Interestingly, there was no remaining yield variance attributed to higher level interactions and unknown error factors (Table 4.7). Analysis of the known factors at Starkville 2016, hybrid 27% and plant population 73%, accounted for approximately 100% of the total

yield variance. Similar to Verona, there was no remaining yield variance attributed to higher level interactions and unknown error factors (Table 4.8).

Taking into consideration the range of soil-test values, planting dates, and soil type differences. We were not surprised to observe differences in the percent of variability attributed to hybrid or population. Corn yields are influenced by so many environmental factors. Naturally, grain yield response to seeding rate would vary over years and locations. Any rational explanation of the grain yield seeding rate response would need to incorporate and account for numerous factors influencing yield. Hybrid, relative maturity group, soil type, soil characteristics, cropping history, management, geographic location and environment all influence crop growth, development and especially yield.

Our experiment and results lacked some consistency among factors and across locations. However, this has been observed before and is not unexpected. The variation in soil properties at Starkville 2015 and management practices/cropping history for Starkville 2016 and planting date window likely affected the hybrid population variance percentages. Realistically, these same variables to a lesser degree explain some of the variance inconsistencies across locations. The variation in the soil type at Brooksville compared to Verona would impact moisture holding capacity which would affect crop growth and yield. The environmental differences such as drought that occurred at Verona during pollination and grain fill would also explain some of the contrasting results. The lack of an overall trend of variance explained by hybrid or population across locations seems reasonable, considering the multi-factor interactions associated with crop growth.

Descriptive Statistics

Descriptive Statistics for Pooled Data & Locations

Overall corn yield ranged from 2.71 to 16.94 Mg ha^{-1} and was normally distributed with a mean of 10.11 Mg ha^{-1} and variance of 5.98 Mg ha^{-1} (Figure 4.11). Corn grain yield at Starkville 2015 ranged from 6.09 to 14.58 Mg ha^{-1}, and averaged 11.28 Mg ha^{-1}, with a variance of 4.18 Mg ha^{-1}. The negative values for the skewness -.275 indicate grain yields were skewed left and the negative kurtosis -0.51 indicate grain yields were light tailed (Figure 4.12). Corn grain yield at Brooksville 2015 ranged from 2.71 to 10.59 Mg ha^{-1}, and averaged 7.85 Mg ha^{-1}, with a variance of 2.41 Mg ha^{-1}. The negative values for the skewness -.980 indicate grain yields were skewed left and the positive kurtosis 1.54 indicate grain yields were right tailed (Figure 4.13). Corn grain yield at Verona 2015 ranged from 7.45 to 12.29 Mg ha^{-1}, and averaged 10.19 Mg ha^{-1}, with a variance of 0.64 Mg ha^{-1}. The negative values for the skewness -.503 indicate grain yields were skewed left and the positive kurtosis 2.63 indicate grain yields were right tailed (Figure 4.14). Corn grain yield at Starkville 2016 ranged from 6.28 to 16.94 Mg ha^{-1}, and averaged 11.50 Mg ha^{-1}, with a variance of 8.14 Mg ha^{-1}. The negative values for the skewness -.281 indicate grain yields were skewed left and the negative kurtosis -0.81 indicate grain yields were light tailed (Figure 4.15).

Descriptive Statistics by Hybrid

Overall, yield varied with respect to hybrid (Table 4.14). Yields for P-9329 ranged from 6.28 to 12.19 Mg ha^{-1} and averaged 11.49 Mg ha^{-1} with a variance of 3.79. Yields for P-1637 ranged from 6.48 to 16.94 Mg ha^{-1} and averaged 13.27 Mg ha^{-1} with a variance of 5.47. Yields for P-0843 ranged from 6.95 to 15.83 Mg ha^{-1} and averaged

12.27 Mg ha^{-1} with a variance of 5.30. Yields for DKC 67-57 ranged from 7.45 to 14.58 Mg ha^{-1} and averaged 10.01 Mg ha^{-1} with a variance of 2.78. Yields for AGRN-79 ranged from 2.7 to 14.5 Mg ha^{-1} and averaged 9.36 Mg ha^{-1} with a variance of 9.11. Yields for P-1498 ranged from 7.17 to 12.90 Mg ha^{-1} and averaged 9.84 Mg ha^{-1} with a variance of 2.37.

Descriptive Statistics by Planting Date

Yield also varied with respect to planting date (Table 4.15). Yields planted on Julian day 82 ranged from 6.28 to 16.94 Mg ha^{-1} and averaged 11.49 Mg ha^{-1} with a variance of 8.13. Yields planted on Julian day 125 ranged from 2.71 to 10.59 Mg ha^{-1} and averaged 7.85 Mg ha^{-1} with a variance of 2.41. Yields planted on Julian day 128 ranged from 6.09 to 14.58 Mg ha^{-1} and averaged 11.27 Mg ha^{-1} with a variance of 4.18. Yields planted on Julian day 141 ranged from 7.45 to 12.29 Mg ha^{-1} and averaged 10.19 Mg ha^{-1} with a variance of 0.65.

Descriptive Statistics by Population

Similarly, yields varied with respect to seeding rate (Table 4.17). Yields planted at 49,400 plants ha^{-1} ranged from 6.13 to 11.53 Mg ha^{-1} and averaged 8.87 Mg ha^{-1} with a variance of 1.52. Yields planted at 61,750 plants ha^{-1} ranged from 5.85 to 12.36 Mg ha^{-1} and averaged 9.36 Mg ha^{-1} with a variance of 2.59. Yields planted at 64,220 plants ha^{-1} ranged from 6.63 to 12.56 Mg ha^{-1} and averaged 10.40 Mg ha^{-1} with a variance of 4.04. Yields planted at 74,100 plants ha^{-1} ranged from 2.71 to 14.48 Mg ha^{-1} and averaged 10.06 Mg ha^{-1} with a variance of 6.24. Yields planted at 83,980 plants ha^{-1} ranged from 6.95 to 15.52 Mg ha^{-1} and averaged 11.89 Mg ha^{-1} with a variance of 11.09.

Yields planted at 86,450 plants ha^{-1} ranged from 4.41 to 14.47 Mg ha^{-1} and averaged 10.20 Mg ha^{-1} with a variance of 5.78. Yields planted at 93,860 plants ha^{-1} ranged from 7.29 to 11.53 Mg ha^{-1} and averaged 15.83 Mg ha^{-1} with a variance of 7.63. Yields planted at 98,800 plants ha^{-1} ranged from 3.95 to 14.58 Mg ha^{-1} and averaged 8.87 Mg ha^{-1} with a variance of 7.10. Yields planted at 103,740 plants ha^{-1} ranged from 6.29 to 16.94 Mg ha^{-1} and averaged 8.87 Mg ha^{-1} with a variance of 8.29.

Main Effects and Interaction Analysis

Hybrid Main Effects

Measured main effects with respect to hybrid varied between locations (Table 4.19). Grain yield, grain test weight, plant height, LAI, 100 kernel weight and kernel rows were affected by hybrid at Starkville 2015. The hybrid AGR-N79 was significantly higher and averaged 10% more grain yield compared to the other hybrids. Interestingly, AGR-N79 statistically also had the lowest grain test weight, LAI, and highest plant height.

Grain yield, plant height, 100 kernel weights, kernel rows and kernels per row were affected by hybrid at Starkville 2016. The hybrid PHB 1637 was significantly higher and averaged 8% more grain yield compared to PHB 0843 and 32% more than PHB 9329. Hybrid PHB 1637 was also significantly larger plaint heights, heavier kernel weights, more kernel rows and more kernels per row compared to the other two hybrids.

Grain yield, LAI, 100 kernel weights, kernel rows and kernels per row were affected by hybrid at Verona 2015. Unlike, Starkville 2015, hybrid AGR-N79 produced significantly less 43% grain yield than hybrid DKC 67-57 and 33% less than hybrid PHB 1498. Hybrid AGR-N79 also produced significantly lower LAI vales comparatively.

Hybrid PHB 1498 averaged significantly more kernel rows compared to other hybrids and more kernels per row compared to hybrid DKC 67-57.

Grain yield at Brooksville 2015 was not affected by hybrid, but we did observe hybrid differences when evaluating plant height, LAI, 100 kernel weight, kernel rows and kernels per row. Hybrid AGR-N79 was once again was significantly higher in plant height compared to other hybrids used in the 2015 field experiments. All hybrids had significantly different 100 kernel weights. Leading the group was DKC 67-57 averaging 32.14 followed by AGR-N79 averaging 30.09, and finally PHB 1498 averaging 27.69.

Population Main Effects

Measured main effects with respect to seeding rate also varied between locations (Table 4.20). Grain yield, grain test weight, LAI and kernels per row were affected by population at Starkville 2015. There was no significant difference between grain yields planted at 74,100 plants ha^{-1} 86,450 plants ha^{-1} or 98,800 plants ha^{-1}. There was also no significant difference between grain yield planted at 49,400 plants ha^{-1} and 61,740 plants ha^{-1}. There was however a significant yield advantage when comparing the two groups. On average there was 26% yield increase for the higher populations compared to the two lowest seeding rates. The highest seeding rate of 98,800 plants ha^{-1} also produced significantly higher LAI vales compared to all other populations, but significantly less kernels per row.

Grain yield, test weight, plant height, LAI, 100 kernel weights and kernels per row were not affected by seeding rate at Starkville 2016. However the number of kernel rows was significantly affected by plant population. There was no significant difference between kernel rows when planted at 64,220 plants ha^{-1}, 74,100 plants ha^{-1}, 83,980

plants ha^{-1} or 93,860 plants ha$^{-1.}$ There was also no significant difference between kernel rows when planted at 83,980 plants ha^{-1}, or 93,860 plants ha^{-1} and 103,740 plants ha^{-1}. There was however a significant difference between the two lowest populations compared to the highest population that resulted in a 13% reduction in the number of kernel rows.

Values for LAI, 100 kernel weights and number of kernels per row were affected by seeding rate at Verona 2015. Interestingly, the lowest seeding rate of 49, 400 plants ha^{-1} had significantly lower LAI values when compared to the other plant populations. The 100 kernel weights were statistically separated by two groups. The lowest two populations 49,400 and 61,750 plants ha^{-1} averaged13% higher seed weights compared the three highest plant populations. The number of kernels per row followed a similar trend with the three highest plant populations 74,100 plants ha^{-1}, 86,450 plants ha^{-1}, and 98,800 ha^{-1} producing 12% fewer kernels per row compared to the lowest two populations.

During the main effects analysis we also observed a significant interaction between hybrid and population with respect to grain test weight (Table 4.21). Based on the small range of test weight values the analysis becomes difficult to make clear distinctions. However, numerically hybrid PHB 1498 at the lowest seeding rate 49,400 plants ha $^{-1}$ produced the highest test weight averaging 58.32. The lowest test weight numerically was also at the lowest seeding rate, but linked to hybrid DKC 67-57.

During the main effects analysis at Brooksville 2015 we observed a significant interaction between hybrid and population with respect to grain yield. Although, there was some yield differences, overall yield ranges were grouped closely between

populations and hybrid combinations. Due to this interaction, interpretation of the statistical analysis was less concise. Summarizing the differences in grain yield for hybrid by seeding rate does reveal a trend. Hybrid AGR-N79 was the only hybrid in which yield continued to increase after seeding rates went from 86,450 to 98,800 plants ha^{-1}. Comparatively, the seeding rate increase provided a 7% yield advantage, whereas PHB 1498 saw a 7% and DKC 67-57 a 1% yield reduction for the same seeding rate increase (Table 4.22).

We did observe seeding rate effects and significant differences when evaluating plant height, LAI, 100 kernel weights and the number of kernels per row (Table 4.20). Although, there was no significant difference in height between populations ranging from 49,400 to 74,100 plants ha^{-1}, there was a plant height advantage for the lowest seeding rate. Much like Starkville 2015, the highest seeding rate of 98,800 plants ha^{-1} once again produced the highest LAI values. There was a significant advantage in the number of kernels per row when seeding rates were at the lowest range as well as a numerical advantage for kernel rows for seeding rates at 49,400 plants ha^{-1}.

Correlation Analysis

Pooled data correlation analysis between yield and continuous variables hybrid, plant population, location, year, planting date and site-year revealed several significant relationships (Table 4.23). There was a significant negative correlation between grain yield and hybrid (r^2 =-0.21) and planting date (r^2 = -0.23). There were also positive correlations between grain yield and plant population (r^2 =0.30), and year (r^2 = 0.30).

Pooled data correlation analysis between yield and soil physical and chemical properties revealed several significant relationships (Table 4.24). There was a significant

positive correlation between grain yield and sand (r^2 = 0.42), soil K (r^2 = 0.17) soil Na (r^2 = 0.46), and soil P (r^2 = 0.49). There was also significant negative correlations observed between grain yield and clay (r^2 = -0.52), silt (r^2 = -0.27), soil pH (r^2 = -0.26), soil Ca (r^2 = -0.49), soil Mg (r^2 = -0.26) and soil C (r^2 = -0.48).

Pooled data correlation analysis between yield and plant growth and developmental factors revealed several significant relationships (Table 4.25). There was a significant positive correlation between grain yield and LAI (r^2 = 0.51) and KWT (r^2 = 0.58). There was also significant negative correlations observed between grain yield and TW (r^2 = -0.17), ARD (r^2 = -0.30), and LONG (r^2 = -0.17).

Factor Analysis

Unfortunately, there are no general rules or guidelines when it comes to interpreting latent variables produced by factor analysis. The unknown common factor represented by the latent variables might include an inherent soil property, a crop production strategy, a climatic variable, or a combination of these variables with numerous others. Initial results often times raises more questions than answers. However, the analysis does provide a basis for speculation. Interpretation requires general agronomic knowledge of plant genetics, plant physiology, meteorology, and soil science as well as subjective judgement.

The latent variable derived from Factor 1 Starkville 2015 was interpreted as a complex variable representing “soil fertility”. Agronomically, however, the negative sign associated with the latent variable “soil fertility” seems unreasonable. Realistically, the highest values of soil P and K in this particular field were nowhere near excessive or

toxic levels and should not decrease corn yields. Statistically, however, the negative coefficient can be explained by a positive correlation (r^2 =.73) between soil P and K and the negative correlations between these two variables and yields (Phosphorus and yield r^2= -.29, Potassium and yield r^2=-.23) (Table 4.26)

Soil fertility levels for P and K are greatly impacted by their availability in the soil and previous crop removal. In corn, K uptake increases rapidly after about the V6 growth stage, approximately four to six weeks after corn planting. Uptake of potassium is completed soon after silking (R1 growth stage). Taking that into consideration and comparing it to the plant development records we collected, K requirements would have been highest starting in June and tapering off in July.

Interestingly, precipitation in June was only 62 mm or approximately 50% less than the 30 year average of 105 mm, and July was also down 23% in terms of average rainfall. Because moisture content greatly impacts P and K transport in soil it is plausible to conclude the proposed latent variable obtained through analysis makes sense even though or initial soil tests indicated fertility levels to be adequate. Similar findings by (Skogley and Haby 1981) found increasing moisture from 10 to 28% increases total K transport by up to 175%.

The latent variable derived from Factor 3 was also interpreted as a complex variable combining “soil texture and environment”. The negative correlation with the latent variable “soil texture and environment” seems more reasonable in this situation. Soil texture in this case was pretty straightforward. There was a statistically significant negative coefficient correlation (r^2 = -.26) between soil sand content and yield (Table 4.26).

Including environment with soil texture to explain the latent variable for factor 3 was based on knowledge of both the production field and growing season. Environment in this latent variable incorporates known physical characteristics as well as growing conditions. We suspect the combination of delayed planting and known physical attributes resulted in less than favorable growing conditions. Abnormal early season rainfall was widespread in 2015. As a result, planting dates were shifted past the normal or optimal planting window 15 March and 20 April (MSU Cares, 2013) resulting in higher temperatures and less precipitation especially during grain fill.

Additionally, we later identified this particular experimental field had irregularities in the form of sand veins running through a large portion of the test site. Aerial imagery was used to detect the sand veins which were none observable from the soil surface. Observing the stress associated with delayed planting and soil textural characteristics in this particular analysis supports the complex latent variables used in this model to explain grain yields.

Stressing the concept that the soil is a dynamic entity with complex interactions among its biological, chemical and physical components the latent variable derived from Factors 4 and 7 were interpreted as "soil quality". The complex relationship between magnesium, carbon and other nutrients are interrelated to both the physical and chemical properties of this experimental field. The components and properties of this field regulate the functionality of the soil and this functioning encompasses the concept of "soil quality".

Agronomically, the positive association of magnesium seems reasonable, however the negative association with Factor 7 carbon making up the latent variable "soil quality" does suggest there are some underlying interactions taking place. Soil organic carbon is the basis of soil fertility and logically would affect grain yields. It releases nutrients for plant growth, promotes soil structure, influences biological and physical health of the soil, and buffers against harmful substances. Soil organic carbon varies greatly according to soil type, climate/region and can vary greatly across fields. Temperature, rainfall, land management, soil nutrition and soil type all influence soil organic carbon levels (Nelson and Sommers, 1996) (Havlin, et al., 1990).

The positive connection with magnesium provides a basis for speculation that it would also be linked to the latent variables categorized as "genetics and environment" for factors 5 kernel weight, 9 plant height and 10 kernels per row (long). Statistically, we observed a positive coefficient correlation between kernel weight (r^2 = .27) kernels per row (long) (r^2 = .28) and yield. Granted, plant height is strongly influenced by environmental conditions and genetics there is also a direct relationship linking it to magnesium. Interestingly, magnesium is a primary constitute of chlorophyll and therefore linked to photosynthesis. Chlorophyll typically accounts for 15 to 20% of the total Mg^{+2} content in plants (Barber, 1984).

The latent variable derived from Factor 4 grain test weight (TW) at Brooksville 2015 was interpreted as a complex underlying variable representing "genetics and environment". We observed a positive coefficient correlation between grain test weight (r^2 = .30) and yield Table 4.27. This was not surprising for the fact that test weight is actually bulk density, measured under specific conditions and it is a general indicator of

grain Quality. We also believe genetic differences between hybrids contributed to grain test weight. While analyzing grain yields at Brooksville we found a significant difference between hybrids and plant heights (Tables 4.18 & 4.19) along with a negative coefficient correlation between plant height (r^2 = -.25) and yield (Table 4.27).

We also realize many factors influenced the measured grain TW. Factors such as physical characteristics of the kernel size, density, shape, and "slickness" of the outer kernel layer. It is also important to note that high-yielding hybrids may not always produce high grain test weight. Other major factors influencing final TW are plant stresses caused by diseases, insects, soil fertility and/or environmental conditions (drought, hail, and early frosts). In other words, anything that impacts the movement of nutrients to the kernel during grain fill or degrades the integrity of the kernel (ear rots and molds) once it is filled can potentially lower grain TW (Hicks, 2004; Nafziger, 2003; Nielsen, 2009; Rankin, 2009).

As expected and similar to results found in Starkville 2015, we observed a positive coefficient correlation between kernel weight (r^2 = .28) and grain yield factor 10 “genetics and environment”. Agronomically, however, the negative correlation relationship with LAI in factor 8 “genetics and environment” was surprising (Table 4.38). Typically, the size and distribution of leaf area determine light interception in a crop canopy and influence overall photosynthesis and yield. Modern maize hybrids selected for optimal plant architecture also tolerate higher plant populations contributing to higher yields. Statistically, however, the negative LAI coefficient could be a result of a complex interaction between factor 10 “genetics and environment” kernel weight (r^2 =-.28) and factor 7 “soil chemical” number of kernels around (r^2 =-.25) (Table 4.27).

The latent variable derived from Factor 2 sand at Verona 2015 was interpreted as a complex variable combining “soil physical and chemical properties”. Unlike, Starkville 2015 we observed a positive sign associated with soil sand content and a strong positive correlation (r^2 = .41) between sand content and kernel weight. To reiterate the complexity and dynamics associated with soil interactions, we also observed negative associations derived from Factor 3 ”soil quality” carbon, Factor 6 calcium ”soil chemical”, Factor 8 “genetics and environment” test weight and a positive association with Factor 7 “soil chemical” sodium. At first glance it is difficult to tease out a simple explanation, however taking into account the range of soil test values and grain yields for this particular location we would expect complex interactions and differences in correlations attributed to soil physical and chemical properties. The statistically significant variables involved in yield correlations at Verona included magnesium (r^2 = .30), LAI (r^2 = .45) and number of kernels per row (r^2 = -.38).

The latent variable derived from Factor 2 at Starkville 2016 was interpreted as a complex variable related to “soil quality”. Considering the history of this field and years of conventional-tillage cotton production. We believe the previous cropping history and lack of organic matter being put back into the soil support the negative association linked to the variables nitrogen and carbon used in Factor 2.

There was a positive link between soil clay content and the latent variable derived from Factor 4 “soil texture”. The advantages of clay content and benefits of higher water holding capacity conceivably minimized some of the environmental stress associated with a less than favorable growing conditions during the 2016 cropping season. There was also a positive link between LAI and the latent variable derived from Factor 6

"environment". Agronomically, the positive sign associated with LAI in factor 6 was to be expected. LAI on average was 20% greater compared to other locations. The size and distribution of leaf area and light interception positively influenced photosynthesis and yield.

Logically, it also makes sense that yield would be affected by a positive relationship with the latent variable "genetics and environment" for Factor 7. The number of kernels per row is a factor directly related to yield. Interestingly, another component involved in corn yields, number of kernels rows (around) has a negative association for Factor 10 latent variable "genetics". From a production standpoint this seems illogical However, determination of kernel rows per ear begins at the sixth leaf stage and is strongly influenced by hybrid genetics (Darby and Lauer, 2004). That being said it is likely there was an unobservable interaction taking place.

All statistically significant variables involved in yield correlations for Starkville 2016 had a positive relationship. Some of the variables were also present at other locations. In addition to Starkville 2016, LAI for example had a positive correlation at Starkville 2015 and Verona 2015. The yield relationship between kernel weight and yield was also present at Starkville 2015 and Brooksville. On the contrary many variables involved in high correlations varied among fields and variables correlated in one field were not always correlated in another.

The range of observed soil-test values, planting date, and soil type differences for example, would warrant differences in corn yields and significant correlations between soil-test values and yields. The lack of a consistent correlations between any two variables across fields has been observed before and should not be unexpected (Pierce et

al., 1994; Mallarino, 1996; Borges and Mallarino, 1997). Variation in soil properties and management practices affect the variables values and cause inherent variation in the soil. For example, different fertility management or different soil types could explain the lack of an overall correlation between two soil tests across locations. Also, it is conceivable that a particular variable was not related to yields in one field because the range of variation within that field was above or below the range in which it influenced grain yield.

It is also possible for correlations between variables to be similar across fields and or locations. For example, in areas with little history of fertility management, significant correlations could be expected between soil physical and chemical properties and or organic matter and between these variables and crop yields. Seemingly, unreasonable correlations for some variables should not be surprising either. For example, the negative correlation at Starkville 2015 between soil phosphorus and yield could be a result of the negative correlation with calcium causing an effect on soil pH potentially reducing corn yields. Another possibility is that the range in calcium values was correlated to a non-measured variable that influenced yields negatively or that it represents random error. The complexity of inter-correlations between variables furthermore, validates the importance of grouping variables when investigating the relationships between growth variables and crop yields.

The fact that several groups of correlated variables were identified for each location does not necessarily mean that yield variability is easily explained. This is evident by our regression models r^2 values ranging from 0.28 to 0.61 across locations (Table 4.38). Additionally, our results suggest that high variation in measured variables

does not necessarily explain highly variable crop yields and the variables correlated to crop yields will often times vary among locations. Our results also advise that interpretation of the signs used with the model coefficients requires careful examination of the factor signs, the bivariate correlations (actual loading value listed for each factor) between each variable and the factor in which the loading is listed.

Conclusion

This research investigated real world variables and complex interactions affecting corn grain yields. The lack of consistent correlations between variables and yield variance explained by each latent variable across locations could be explained by several logical theories. Realistically, corn yields were affected by more than one non-measured variable or different average values or ranges of the measured variables across locations differentiated with respect to optimum levels for corn grain production.

Logically, the models and relationships found in this field experiment might not be applicable across a diverse geographic region or areas having vastly different crop management practices. Therefore we question the predictive effectiveness of the models alone. However, the latent variables identified in this study were significantly related to yield and could be useful in providing further explanations for yield variability. Optimistically, the variables and relationships found in this analysis would provide the opportunity to manage similar fields more efficiently.

Liebig's law of the minimum states that yield potential is determined by the most limiting factor. Sometimes the most limiting factor is a result of an underlying complex interaction. Therefore, determining plant growth relationships associated with soil properties and a technique to separate grain yield by latent variables could give producers and agronomists insight into developing more efficient and effective management strategies. Results from this study indicate that the variables that best explain yield variability will likely be different across fields and or locations. For that reason it is important to consider both cropping history and production methods when determining what variables would be most applicable when analyzing the data.

Technological advancements in crop production (Precision Ag) continuously provide more insight and layers of detailed information. Ideally, analyzing multiple layers of information in production fields would expose more answers for crop producers in the future. Multivariate factor analysis coupled with stepwise regression provided a balanced criterion for including and arranging correlated variables for multiple regression models. Grain yields and plant growth relationships associated with soil properties were effectively used to create latent variables that could potentially explain previously unobservable yield variances. Our results indicate that a portion of the yield variability for each location could be explained by the influence of the variables we collected and high variation in some measured variables do not necessarily explain high variability in crop yields. Additionally, the variables involved in significant relationships will likely vary between locations as a result of several factors.

Table 4.1 Planting dates for Starkville, Verona and Brooksville MS population precision Ag experiment.

		Population Precision Ag Experiment
Location	Year	Planting Date (Julian Day)
Starkville	2015	8-May (128)
	2016	22-March (82)
Verona	2015	21-May (141)
Brooksville	2015	5-May (125)

Table 4.2 Description of hybrids used in the population precision Ag experiment evaluated at Starkville, Brooksville and Verona, MS in 2015 and 2016.

Population Precision Ag Experiment		
Brand	Hybrid	Maturity Days(RM)
DEKALB	DKC67-57	117
Syngenta	AGR-N79	115/116
Pioneer	P-1498	114
Pioneer	P-9329	93
Pioneer	P-0843	108
Pioneer	P-1637	116

RM--Relative maturity

Table 4.3 Yield variation influenced by generalized known and unknown factors.

Known Factors Influencing Grain Yield		
Factors	REML Iteration	VARIANCE %
Var(Hybrid)	2.234162564	28.05170716
Var(Population)	0.619855762	7.782787425
Var(Location)	2.398611356	30.11649396
Var(Year)	0.016530048	0.207548043
Var(Error)	2.695284471	33.84146342
Sum	7.964444201	100%

Table 4.4 Yield variation influenced by isolated known and unknown factors.

Isolated known Factors Influencing Grain Yield		
Factor	REML Iteration	VARIANCE %
Var(RM)	1.202380252	14.7683368
Var(Hybrid)	1.031775543	12.67287008
Var(Population)	0.61985544	7.613426696
Var(Planting date)	2.415188706	29.66475887
Var(SiteYear)	0.177125171	2.175554842
Var(Error)	2.695283981	33.1050527
Sum	8.141609092	100%

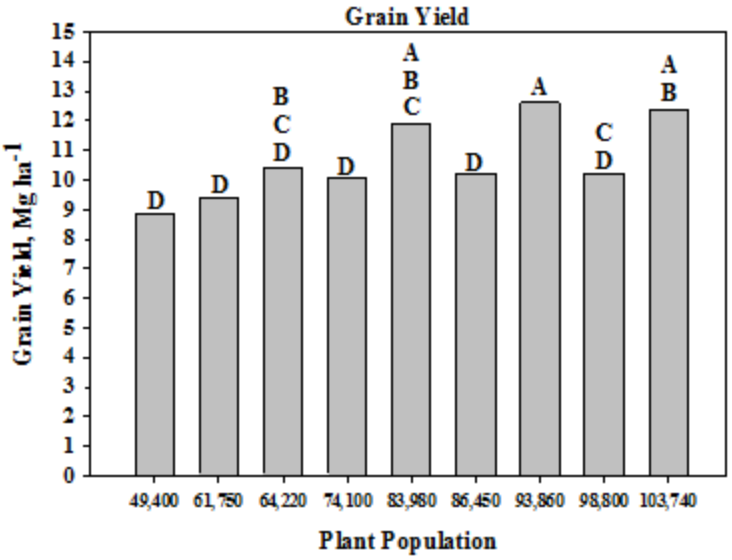

Figure 4.2 Grain yield distribution by plant population.

Grain yield for hybrids DKC67-57, AGR-N79, P-1498, P-9329, P-0843, P-1637, planted at Starkville, Brooksville, and Verona, MS 2015-2016. Plant populations with the same letter are not significantly different (α =0.05).

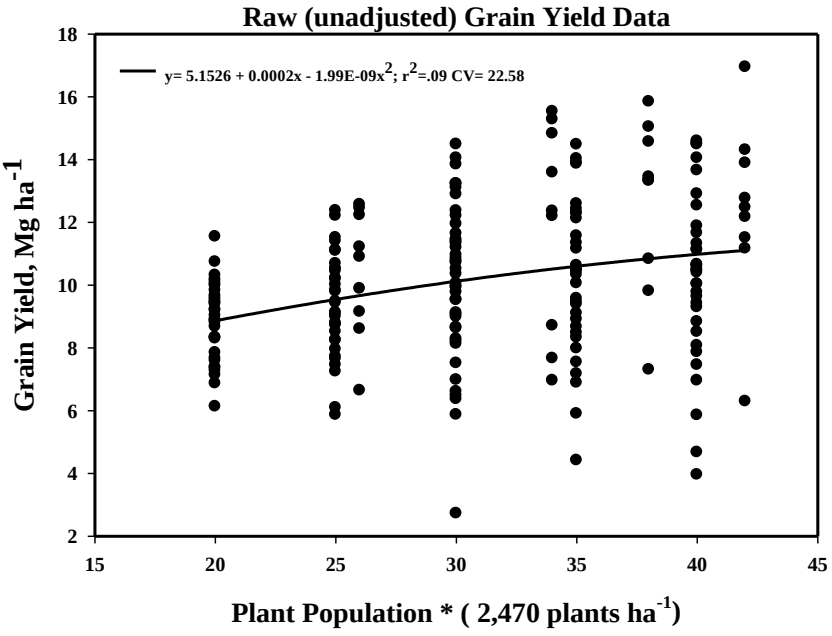

Figure 4.3 Unadjusted plant population yield regression analysis.

Unadjusted grain yield for hybrids DKC67-57, AGR-N79, P-1498, P-9329, P-0843, P-1637, planted at Starkville, Brooksville, and Verona, MS 2015-2016.

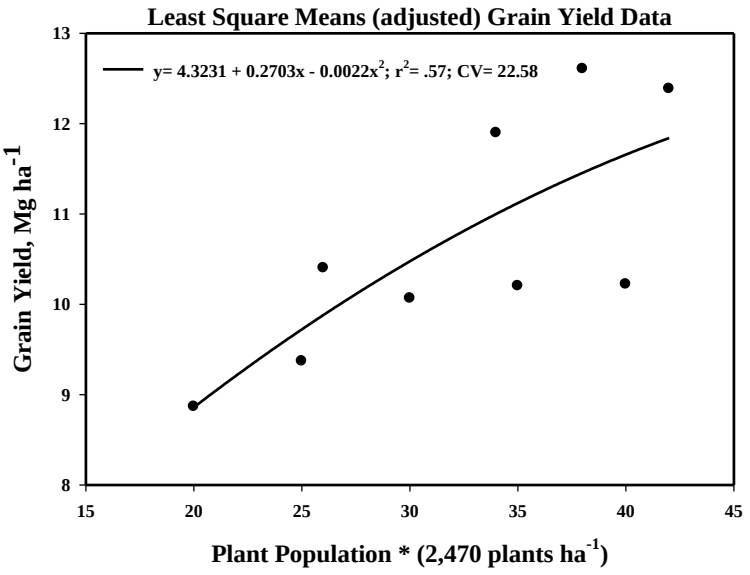

Figure 4.4 Adjusted population yield regression analysis

Adjusted grain yield for hybrids DKC67-57, AGR-N79, P-1498, P-9329, P-0843, P-1637, planted at Starkville, Brooksville, and Verona, MS 2015-2016.

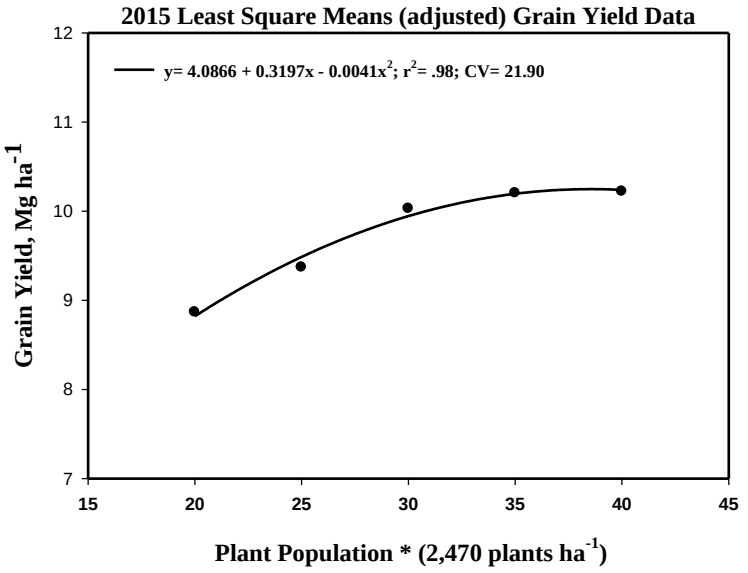

Figure 4.5 Adjusted population yield regression analysis for 2015.

Adjusted grain yield for hybrids DKC67-57, AGR-N79, P-1498, planted at Starkville, Brooksville, and Verona, MS 2015.

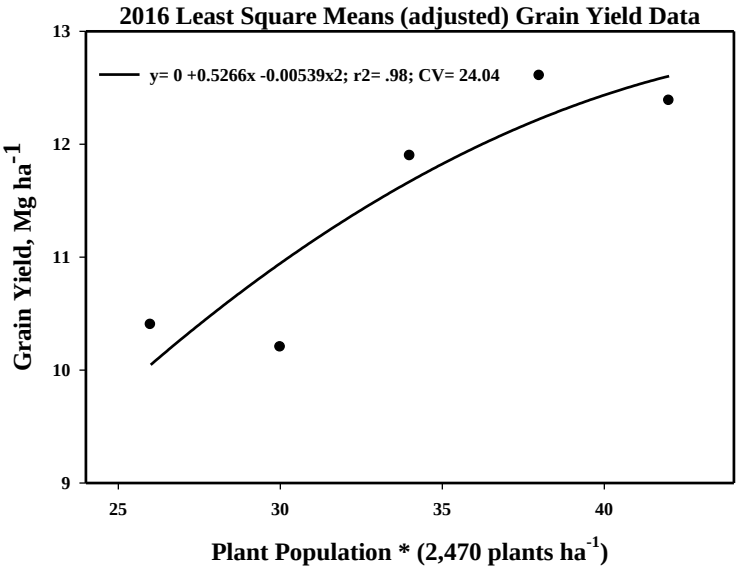

Figure 4.6 Adjusted population yield regression analysis for 2016.

Adjusted grain yield for hybrids P-9329, P-0843, P-1637, planted at Starkville, MS 2016.

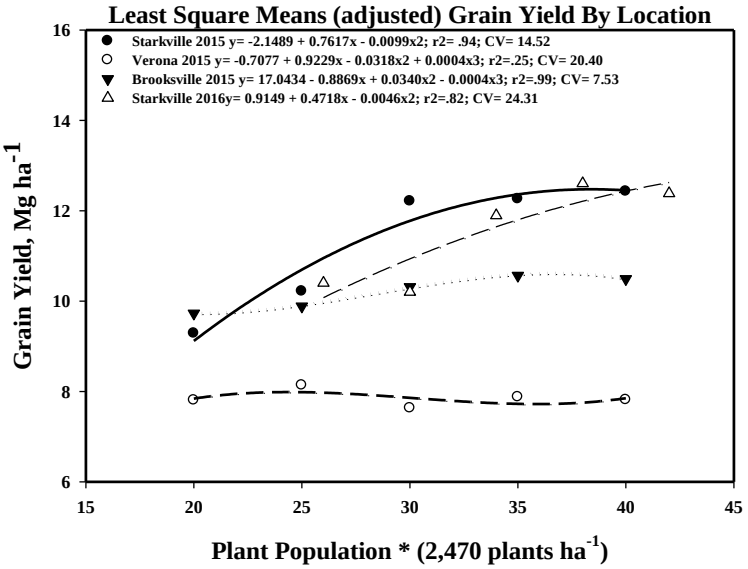

Figure 4.7 Adjusted population yield regression analysis by location.

Adjusted grain yield for hybrids DKC67-57, AGR-N79, P-1498, P-9329, P-0843, and P-1637, planted at Starkville, Brooksville, and Verona, MS 2015-2016.

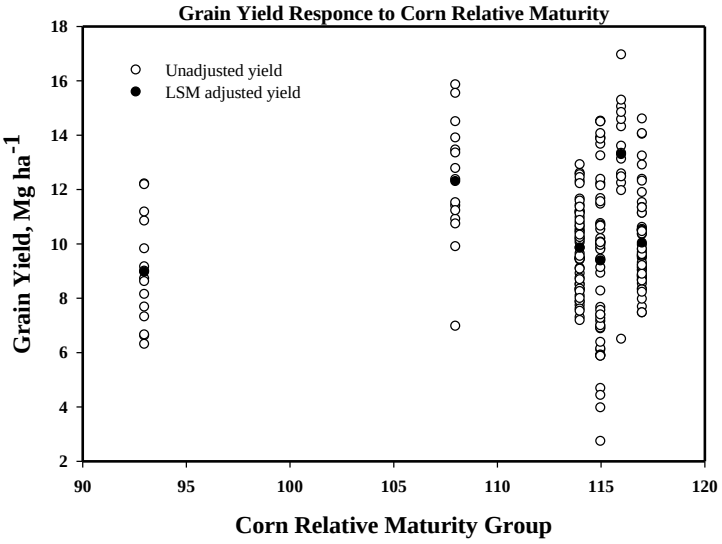

Figure 4.8 Corn yield variance by relative maturity.

Grain yield for hybrids DKC67-57, AGR-N79, P-1498, P-9329, P-0843, P-1637, planted at Starkville, Brooksville, and Verona, MS 2015-2016.

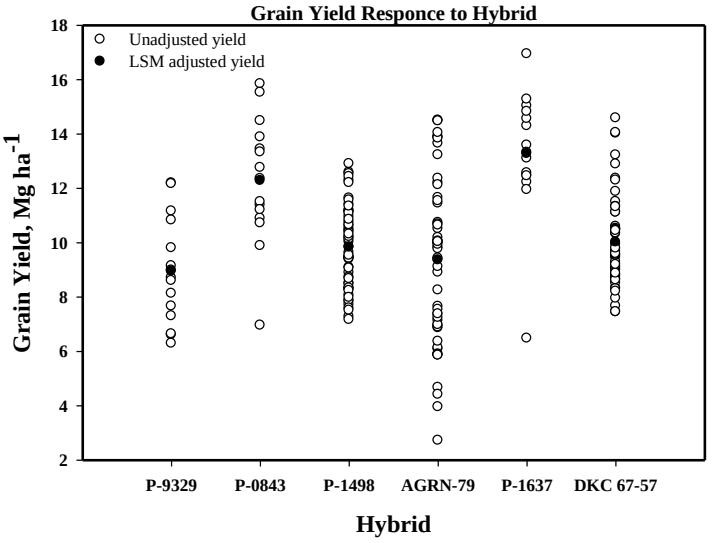

Figure 4.9 Corn yield variance by hybrid.

Grain yield for hybrids planted at 49,400 plants ha^{-1}, 61,750 plants ha^{-1}, 74,100 plants ha^{-1}, 86,450 plants ha^{-1}, and 98,800 plants ha^{-1} at Starkville, Brooksville, and Verona, MS in 2015. Hybrids were planted at 64,220 plants ha^{-1}, 74,100 plants ha^{-1}, 83,980 plants ha^{-1}, 93,860 plants ha^{-1}, and 103,740 plants ha^{-1} in Starkville 2016.

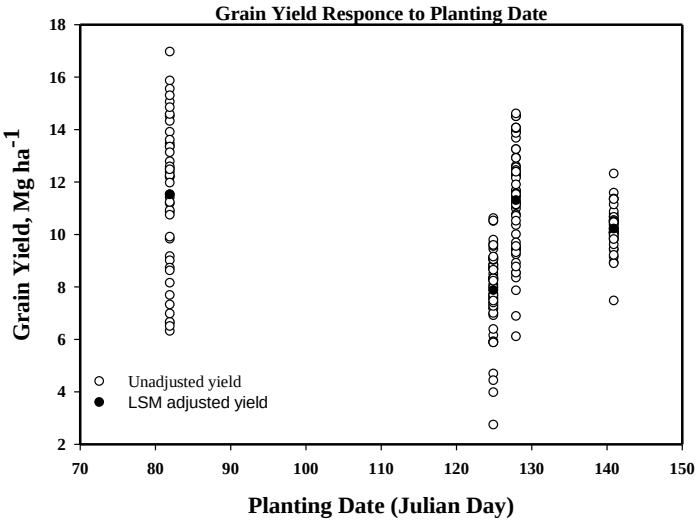

Figure 4.10 Corn yield variance by planting date.

Grain yield averaged across hybrids DKC67-57, AGR-N79, P-1498, P-9329, P-0843, P-1637, and populations 49,400, 61,750, 74,100, 86,450, 98, 64,220, 74,100, 83,980, 93,860, and 103,740 plants ha^{-1} planted at Starkville, Brooksville, and Verona, MS in 2015-2016.

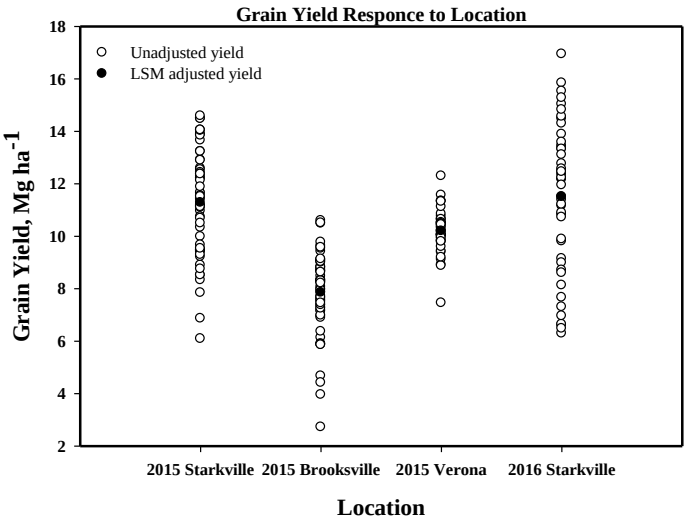

Figure 4.11 Corn yield variance by location.

Grain yield averaged across hybrids DKC67-57, AGR-N79, P-1498, P-9329, P-0843, P-1637, and populations 49,400, 61,750, 74,100, 86,450, 98, 64,220, 74,100, 83,980, 93,860, and 103,740 plants ha^{-1} planted at Starkville, Brooksville, and Verona, MS in 2015-2016.

Table 4.5 Variance statistics for Starkville 2015.

Nested Random Effects Analysis of Variance for Starkville 2015 YIELD					
Variance Source	**DF**	**Sum of Squares**	**Mean Square**	**Variance Component**	**Percent of Total**
Total	59	246.679948	4.181016	4.211365	100.0000
HYBRID	19	78.897555	4.152503	-0.030666	1.0356
POP	39	165.923800	4.254456	2.352773	55.8672
Error	1	1.858592	1.858592	1.858592	43.0972
YIELD Mean 11.27965000					
Standard Error of YIELD Mean 0.26337604					

Table 4.6 Variance statistics for Brooksville 2015.

Nested Random Effects Analysis of Variance for Brooksville 2015 Yield					
Variance Source	**DF**	**Sum of Squares**	**Mean Square**	**Variance Component**	**Percent of Total**
Total	59	142.758208	2.419631	2.503980	100.0000
HYBRID	19	105.342933	5.544365	1.562335	62.3941
POP	39	37.350475	0.957704	0.876845	35.0181
Error	1	0.064800	0.064800	0.064800	2.5879
YIELD Mean 7.85138333					
Standard Error of YIELD Mean 0.35309590					

Table 4.7 Variance statistics for Verona 2015.

Nested Random Effects Analysis of Variance for Verona 2015 Yield					
Variance Source	**DF**	**Sum of Squares**	**Mean Square**	**Variance Component**	**Percent of Total**
Total	44	28.598362	0.649963	0.650598	100.0000
HYBRID	43	28.576730	0.664575	0.628966	96.6751
POP	1	0.021632	0.021632	0.021632	3.3249
Error	0	.	.	0	0.0000
YIELD Mean 7.85138333					
Standard Error of YIELD Mean 0.35309590					

Table 4.8 Variance statistics for Starkville 2016.

Nested Random Effects Analysis of Variance for Starkville 2016 Yield					
Variance Source	**DF**	**Sum of Squares**	**Mean Square**	**Variance Component**	**Percent of Total**
Total	44	358.057582	8.137672	8.172768	100.0000
HYBRID	31	280.041691	9.033603	2.171546	26.5705
POP	13	78.015892	6.001222	6.001222	73.4295
Error	0	.	.	0	0.0000
YIELD Mean 11.27965000					
Standard Error of YIELD Mean 0.26337604					

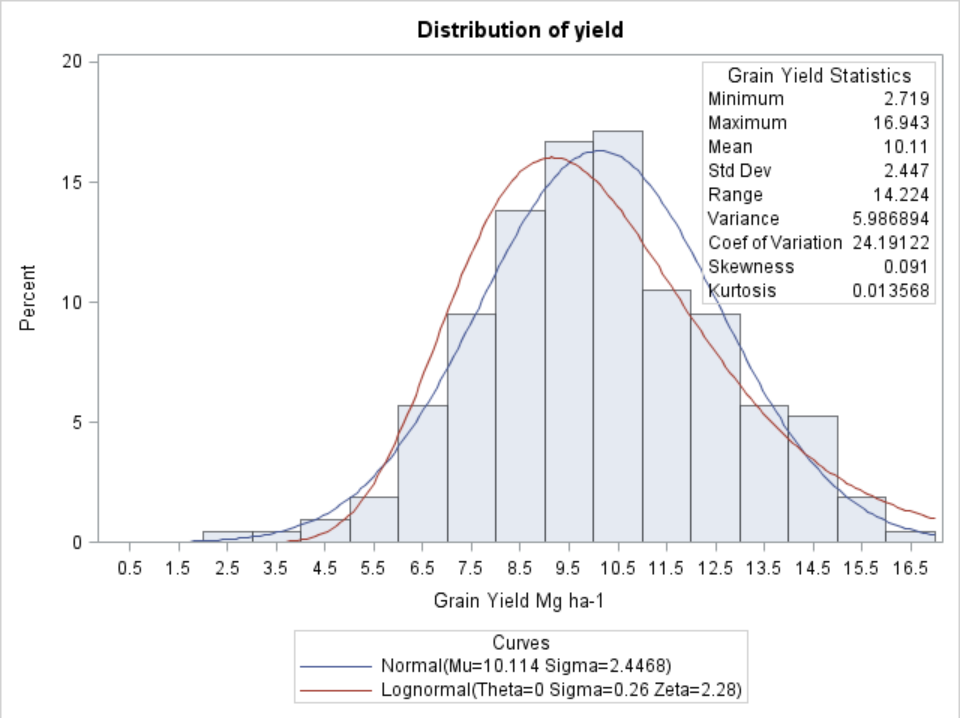

Figure 4.12 Descriptive statistics of grain yield distribution for pooled data set.

Grain yield for hybrids DKC67-57, AGR-N79, P-1498, P-9329, P-0843, P-1637, and populations 49,400, 61,750, 74,100, 86,450, 98, 64,220, 74,100, 83,980, 93,860, and 103,740 plants ha^{-1} planted at Starkville, Brooksville, and Verona, MS in 2015-2016.

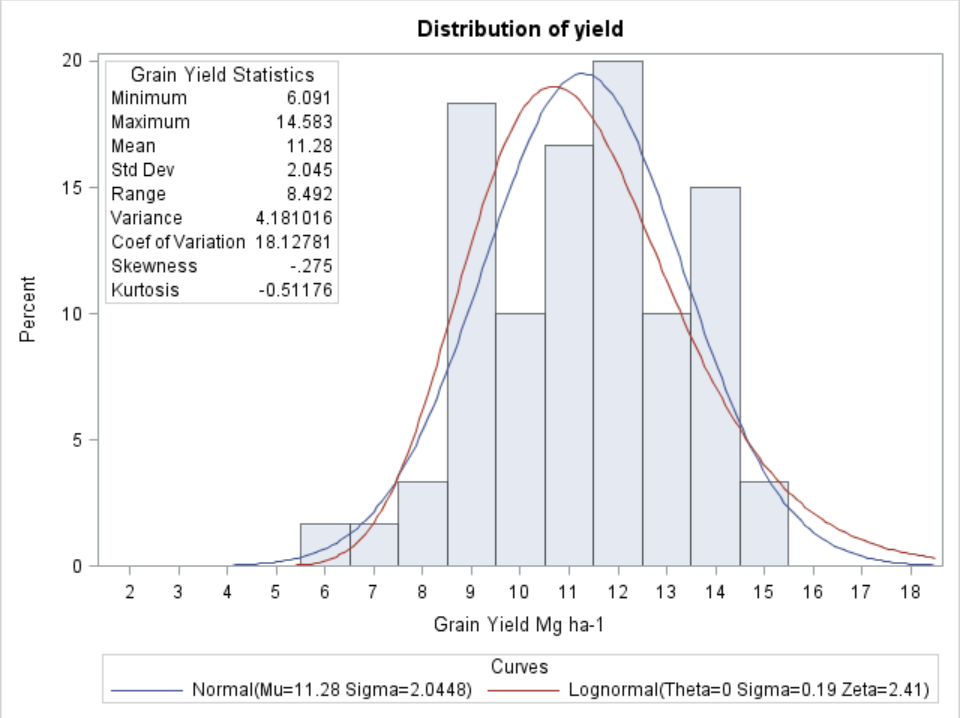

Figure 4.13 Descriptive statistics of grain yield distribution for Starkville 2015.

Grain yield for hybrids DKC67-57, AGR-N79, P-1498, planted at 49,400 plants ha^{-1}, 61,750 plants ha^{-1}, 74,100 plants ha^{-1}, 86,450 plants ha^{-1}, and 98,800 plants ha^{-1} in Starkville, MS 2015.

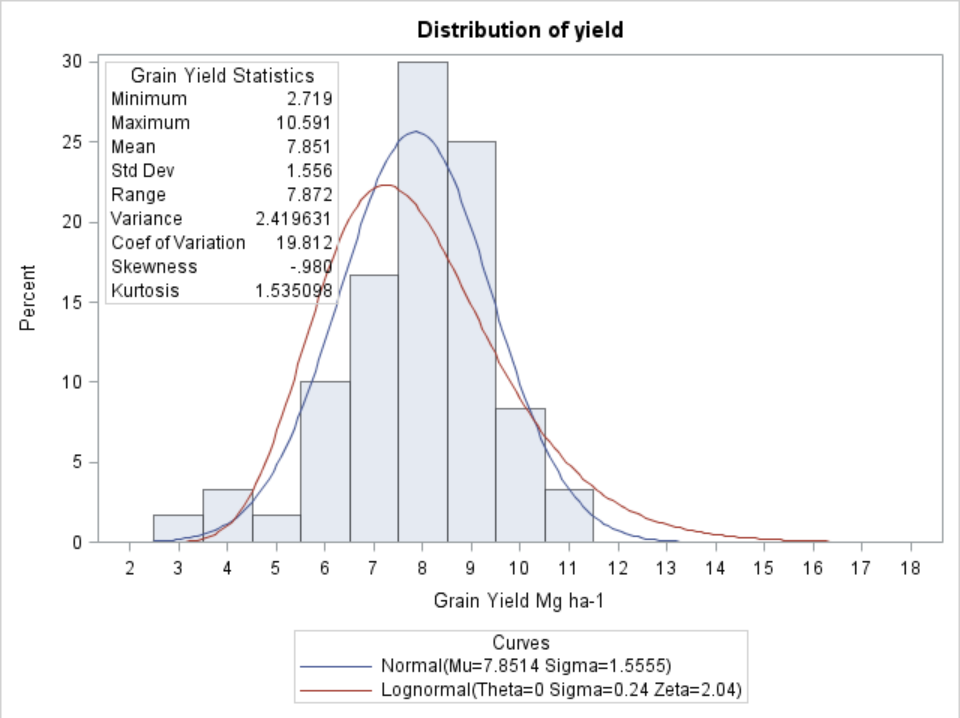

Figure 4.14 Descriptive statistics of grain yield distribution for Brooksville 2015.

Grain yield for hybrids DKC67-57, AGR-N79, P-1498, planted at 49,400 plants ha^{-1}, 61,750 plants ha^{-1}, 74,100 plants ha^{-1}, 86,450 plants ha^{-1}, and 98,800 plants ha^{-1} in Brooksville, MS 2015.

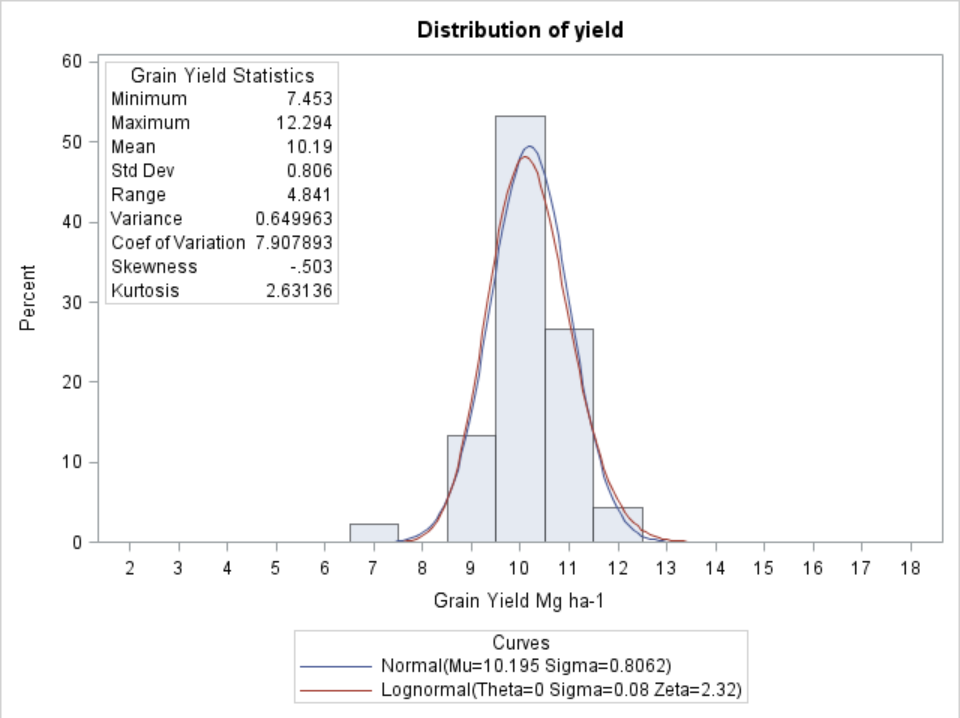

Figure 4.15 Descriptive statistics of grain yield distribution for Verona 2015.

Grain yield for hybrids DKC67-57, AGR-N79, P-1498, planted at 49,400 plants ha^{-1}, 61,750 plants ha^{-1}, 74,100 plants ha^{-1}, 86,450 plants ha^{-1}, and 98,800 plants ha^{-1} in Verona, MS 2015.

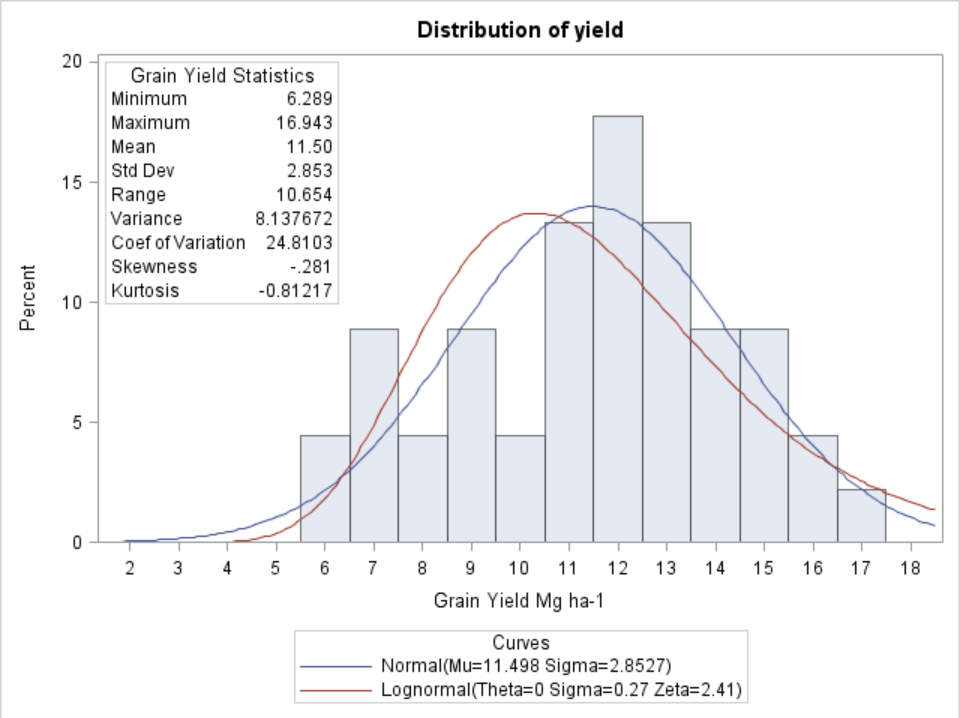

Figure 4.16 Descriptive statistics of grain yield distribution for Starkville 2016.

Grain yield for hybrids P-9329, P-0843, P-1637, and populations 64,220, 74,100, 83,980, 93,860, and 103,740 plants ha^{-1} planted at Starkville, MS in 2016.

Table 4.9 Descriptive statistics for Starkville 2015 populations and hybrids.

Starkville 2015 Grain Yield Mg ha^{-1}								
POP	**HYBRID**	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
20000	**DKC 67-57**	8.3250	9.6620	9.1818	0.6015	0.3618	6.5512	1.0855
	AGRN-79	6.8610	11.5390	9.7788	2.0466	4.1884	20.9286	12.5652
	P-1498	7.8410	9.4480	8.8920	0.7440	0.5536	8.3674	1.6607
25000	**DKC 67-57**	8.5100	11.5060	9.9695	1.5597	2.4325	15.6443	7.2976
	AGRN-79	6.0910	12.3630	10.3338	2.9287	8.5771	28.3409	25.7314
	P-1498	9.4360	11.3990	10.3478	1.0406	1.0829	10.0564	3.2486
30000	**DKC 67-57**	9.5170	13.2190	11.9968	1.6904	2.8575	14.0907	8.5726
	AGRN-79	11.4490	14.0440	13.1393	1.1795	1.3913	8.9770	4.1738
	P-1498	10.9580	12.1990	11.4948	0.5467	0.2989	4.7561	0.8967
35000	**DKC 67-57**	9.4600	14.0220	11.0753	2.0159	4.0640	18.2022	12.1921
	AGRN-79	12.1230	14.4750	13.5900	1.0174	1.0351	7.4864	3.1053
	P-1498	11.1530	12.5840	12.1108	0.6502	0.4228	5.3691	1.2684
40000	**DKC 67-57**	9.2880	14.5830	12.4483	2.4097	5.8068	19.3579	17.4203
	AGRN-79	11.6520	14.5000	13.5713	1.3392	1.7934	9.8678	5.3803
	P-1498	8.5040	12.9010	11.2650	1.9933	3.9731	17.6944	11.9194

Table 4.10 Descriptive statistics for Brooksville 2015 populations and hybrids.

Brooksville 2015 Grain Yield Mg ha^{-1}								
POP	**HYBRID**	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
20000	**DKC 67-57**	7.6650	9.0180	8.4465	0.6030	0.3637	7.1396	1.0910
	AGRN-79	6.1270	7.3740	7.0008	0.5927	0.3513	8.4667	1.0540
	P-1498	7.2720	8.6680	7.9635	0.6439	0.4147	8.0861	1.2440
25000	**DKC 67-57**	7.9480	9.1260	8.7160	0.5300	0.2809	6.0812	0.8428
	AGRN-79	5.8590	8.2520	7.2510	1.0164	1.0330	14.0168	3.0989
	P-1498	7.7150	9.0860	8.4395	0.5968	0.3561	7.0712	1.0684
30000	**DKC 67-57**	8.2040	9.7700	8.8118	0.6707	0.4498	7.6111	1.3494
	AGRN-79	2.7190	6.9750	5.4808	1.8962	3.5956	34.5976	10.7868
	P-1498	7.5080	9.5310	8.5943	0.8891	0.7904	10.3448	2.3713
35000	**DKC 67-57**	8.6640	10.5000	9.4573	0.7867	0.6189	8.3186	1.8567
	AGRN-79	4.4100	7.5390	6.1838	1.3612	1.8528	22.0124	5.5585
	P-1498	7.1700	8.4730	7.9868	0.5827	0.3396	7.2961	1.0187
40000	**DKC 67-57**	7.4490	10.5910	9.3375	1.4960	2.2379	16.0211	6.7138
	AGRN-79	3.9530	6.9580	5.3573	1.3237	1.7523	24.7095	5.2569
	P-1498	7.8610	9.6290	8.7443	0.9084	0.8252	10.3884	2.4755

Table 4.11 Descriptive statistics for Verona 2015 populations and hybrids.

Verona 2015 Grain Yield Mg ha^{-1}								
POP	**HYBRID**	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
20000	**DKC 67-57**	8.8670	9.5920	9.2157	0.3633	0.1320	3.9421	0.2640
	AGRN-79	9.4250	10.0300	9.7597	0.3076	0.0946	3.1516	0.1892
	P-1498	10.1160	10.3090	10.2023	0.0981	0.0096	0.9615	0.0192
25000	**DKC 67-57**	7.4530	10.5170	9.2540	1.6013	2.5641	17.3037	5.1282
	AGRN-79	10.0060	10.5100	10.2320	0.2560	0.0655	2.5019	0.1311
	P-1498	9.8290	10.4420	10.1627	0.3101	0.0962	3.0513	0.1923
30000	**DKC 67-57**	9.9450	11.3250	10.5397	0.7095	0.5034	6.7315	1.0067
	AGRN-79	9.1120	10.0520	9.6977	0.5109	0.2610	5.2685	0.5221
	P-1498	10.5110	10.8460	10.7050	0.1737	0.0302	1.6224	0.0603
35000	**DKC 67-57**	10.4360	12.2940	11.0693	1.0608	1.1253	9.5832	2.2506
	AGRN-79	8.9040	10.0520	9.4470	0.5765	0.3324	6.1025	0.6647
	P-1498	10.6180	11.5630	11.1727	0.4935	0.2435	4.4167	0.4870
40000	**DKC 67-57**	10.4540	11.3140	10.9623	0.4509	0.2033	4.1132	0.4066
	AGRN-79	9.7670	10.6360	10.1443	0.4456	0.1986	4.3930	0.3972
	P-1498	10.0290	10.6520	10.3593	0.3132	0.0981	3.0234	0.1962

Table 4.12 Descriptive statistics for Starkville 2016 populations and hybrids.

Starkville 2016 Grain Yield Mg ha^{-1}								
POP	**HYBRID**	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
26000	**P-9329**	6.6390	9.1410	8.1267	1.3164	1.7330	16.1991	3.4661
	P-1637	12.2240	12.5640	12.4140	0.1735	0.0301	1.3976	0.0602
	P-0843	9.8840	11.2080	10.6617	0.6917	0.4784	6.4873	0.9568
30000	**P-9329**	6.6020	8.9810	7.9030	1.2051	1.4522	15.2483	2.9044
	P-1637	6.4770	13.1020	10.5087	3.5390	12.5243	33.6766	25.0485
	P-0843	10.7180	14.4830	12.1940	2.0099	4.0395	16.4824	8.0791
34000	**P-9329**	7.6630	12.1900	9.5197	2.3706	5.6200	24.9026	11.2399
	P-1637	13.5830	15.2720	14.5580	0.8742	0.7643	6.0051	1.5285
	P-0843	6.9580	15.5260	11.6123	4.3318	18.7641	37.3030	37.5282
38000	**P-9329**	7.2990	10.8260	9.3100	1.8149	3.2937	19.4936	6.5874
	P-1637	13.3160	15.0330	14.3023	0.8866	0.7860	6.1989	1.5721
	P-0843	13.3310	15.8390	14.2040	1.4170	2.0080	9.9763	4.0160
42000	**P-9329**	6.2890	12.1640	9.8700	3.1418	9.8712	31.8323	19.7424
	P-1637	12.4690	16.9430	14.5697	2.2494	5.0599	15.4391	10.1199
	P-0843	11.5000	13.8840	12.7143	1.1926	1.4224	9.3802	2.8447

Table 4.13 Descriptive statistics by year.

Yearly Grain Yield Mg ha^{-1}							
YEAR	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
2015	2.7190	14.5830	9.7372	2.1859	4.7780	22.4486	783.5914
2016	6.2890	16.9430	11.4979	2.8527	8.1377	24.8103	358.0576

Table 4.14 Descriptive statistics by hybrid.

Hybrid Grain Yield Mg ha^{-1}							
HYBRID	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
P-9329	6.2890	12.1900	8.9459	1.9487	3.7974	21.7832	53.1638
P-1637	6.4770	16.9430	13.2705	2.3398	5.4745	17.6314	76.6437
P-0843	6.9580	15.8390	12.2773	2.3039	5.3080	18.7657	74.3124
DKC 67-57	7.4490	14.5830	10.0161	1.6673	2.7800	16.6466	150.1212
AGRN-79	2.7190	14.5000	9.3561	3.0197	9.1188	32.2753	492.4128
P-1498	7.1700	12.9010	9.8393	1.5409	2.3745	15.6610	128.2204

Table 4.15 Descriptive statistics by planting date (Julian day).

Planting Date (Julian Day) Grain Yield Mg ha^{-1}							
Julian Day	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
82	6.2890	16.9430	11.4979	2.8527	8.1377	24.8103	358.0576
125	2.7190	10.5910	7.8514	1.5555	2.4196	19.8120	142.7582
128	6.0910	14.5830	11.2797	2.0448	4.1810	18.1278	246.6799
141	7.4530	12.2940	10.1949	0.8062	0.6500	7.9079	28.5984

Table 4.16 Descriptive statistics by corn relative maturity.

Corn Relative Maturity Grain Yield Mg ha^{-1}							
RM	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
93 b	6.2890	12.1900	8.9459	1.9487	3.7974	21.7832	53.1638
108 a	6.9580	15.8390	12.2773	2.3039	5.3080	18.7657	74.3124
114 b	7.1700	12.9010	9.8393	1.5409	2.3745	15.6610	128.2204
115 b	2.7190	14.5000	9.3561	3.0197	9.1188	32.2753	492.4128
116 a	6.4770	16.9430	13.2705	2.3398	5.4745	17.6314	76.6437
117 b	7.4490	14.5830	10.0161	1.6673	2.7800	16.6466	150.1212

RM with the same letter are not significantly different (α =0.05).

Table 4.17 Descriptive statistics by plant population.

Plant Population Grain Yield Mg ha^{-1}							
POP	**Min**	**Max**	**Mean**	**Std Dev**	**Variance**	**Coeff of Variation**	**Corrected SS**
49,400	6.1270	11.5390	8.8662	1.2362	1.5283	13.9432	48.9053
61,750	5.8590	12.3630	9.3690	1.6106	2.5939	17.1904	83.0055
64,220	6.6390	12.5640	10.4008	2.0113	4.0451	19.3375	32.3612
74,100	2.7190	14.4830	10.0646	2.4997	6.2487	24.8369	256.1961
83,980	6.9580	15.5260	11.8967	3.3305	11.0922	27.9952	88.7377
86,450	4.4100	14.4750	10.2025	2.4055	5.7865	23.5776	185.1666
93,860	7.2990	15.8390	12.6054	2.7627	7.6325	21.9167	61.0598
98,800	3.9530	14.5830	10.2210	2.6661	7.1081	26.0846	227.4587
103,740	6.2890	16.9430	12.3847	2.8794	8.2908	23.2495	66.3263

Table 4.18 Significance of *F*-Values for main effects and interactions for pooled data.

			Main Effects and Interactions Pooled Data Set				
Location (L)	Year	Dependent variable	Hybrid (H)	POPULATION (POP)	H x POP	LOC (L)	YEAR (Y)
Pooled Data	2015-2016	Grain yield	<.0001	<.0001	0.2312	<.0001	<.0001
		Test Weight	0.0775	0.1847	0.9395	0.0143	<.0001
		Plant height	0.0020	0.1374	0.0566	<.0001	<.0001
		LAI††	<.0001	<.0001	0.0250	<.0001	<.0001
		100 Kernel weight†	<.0001	0.0031	0.5617	<.0001	<.0001
		Kernel rows‡	<.0001	0.0006	0.9156	0.0970	<.0001
		Kernels per row§	<.0001	<.0001	0.0549	0.0011	0.0005
Starkville	2015	Grain yield	0.0309	<.0001	0.8032	**	**
		Test Weight	<.0001	0.0346	0.6459	**	**
		Plant height	<.0001	0.5984	0.4229	**	**
		LAI††	0.0001	<.0001	0.6560	**	**
		100 Kernel weight†	0.0003	0.0696	0.9555	**	**
		Kernel rows‡	<.0001	0.1841	0.2301	**	**
		Kernels per row§	0.4277	<.0001	0.7819	**	**
Starkville	2016	Grain yield	<.0001	0.0623	0.7432	**	**
		Test Weight	0.6923	0.4326	0.6254	**	**
		Plant height	<.0001	0.4854	0.4026	**	**
		LAI††	0.0798	0.6020	0.3026	**	**
		100 Kernel weight†	0.0002	0.5376	0.8622	**	**
		Kernel rows‡	0.0160	0.0496	0.9787	**	**
		Kernels per row§	<.0001	0.4696	0.7701	**	**
Verona	2015	Grain yield	<.0001	0.8099	0.0898	**	**
		Test Weight	0.0012	0.8051	0.0169	**	**
		Plant height	0.3990	0.5716	0.5227	**	**
		LAI††	0.0178	<.0001	0.1941	**	**
		100 Kernel weight†	<.0001	0.0013	0.2414	**	**
		Kernel rows‡	<.0001	0.3209	0.9963	**	**
		Kernels per row§	0.0014	<.0001	0.9578	**	**
Brooksville	2015	Grain yield	0.0252	0.0288	0.0255	**	**
		Test Weight	0.5547	0.1551	0.4951	**	**
		Plant height	<.0001	0.0105	0.9713	**	**
		LAI††	0.0050	0.0007	0.3185	**	**
		100 Kernel weight†	<.0001	0.0255	0.6669	**	**
		Kernel rows‡	<.0001	0.1171	0.2243	**	**
		Kernels per row§	<.0001	<.0001	0.2474	**	**

†† Leaf area index (LAI) measurements taken when hybrids reached the silking stage.
† Weight of 100 kernels adjusted to 155 g kg-1 moisture.
‡ Number of kernels around an ear of corn.
§ Number of kernels long from tip to end.
** Insignificant effects.

Table 4.19 Significance of main effects and interactions by hybrid.

				Hybrid Main Effects on Dependent Variables					
Location	Year	Hybrid	Grain Yield	Test Weight	Plant Height	LAI††	100 Kernel Weight†	Kernel Rows‡	Kernels per Row §
Starkville	2015	DKC 67-57	10.934 b	56.00 a	95.53 c	15.07 a	35.002 a	15.07 c	**
		AGR-N79	12.082 a	54.35 b	112.73 a	16.66 b	29.902 b	15.66 b	**
		PHB 1498	10.822 b	56.18 a	108.36 b	16.40 a	30.356 b	16.40 a	**
Starkville	2016	PHB 9329	8.945 b	**	82.04 c	**	40.303 b	14.75 a	32.75 b
		PHB 1637	13.270 a	**	102.80 a	**	51.336 a	14.00 b	38.11 a
		PHB 0843	12.277 a	**	91.47 b	**	43.675 b	15.02 a	33.91 b
Verona	2015	DKC 67-57	8.953 a	**	**	4.31 a	25.625 a	15.26 b	35.25 b
		AGR-N79	6.254 b	**	**	3.98 b	22.592 b	15.83 b	38.47 a
		PHB 1498	8.345 a	**	**	4.25 a	20.408 c	17.14 a	37.48 a
Brooksville	2015	DKC 67-57	**	**	100.24 c	4.00 ab	32.144 a	14.74 c	33.44 b
		AGR-N79	**	**	116.18 a	3.26 b	30.095 b	15.97 b	36.36 a
		PHB 1498	**	**	113.02 b	3.66 ab	27.698 c	17.06 a	36.22 a

†† Leaf area index (LAI) measurements taken when hybrids reached the silking stage.
† Weight of 100 kernels adjusted to 155 g kg-1 moisture.
‡ Number of kernels around an ear of corn.
§ Number of kernels long from tip to end.
Hybrids with the same letter are not significantly different (α =0.05).
** Insignificant effects.

Table 4.20 Significance of main effects and interactions by plant population.

				Plant Population Main Effects on Dependent Variables					
Location	Year	Population	Grain Yield	Test Weight	Plant Height	LAI††	100 Kernel Weight†	Kernel Rows‡	Kernels per Row §
Starkville	2015	49,400	9.284 b	54.89 b	**	4.61 c	**	**	39.93 a
		61,750	10.217 b	54.90 b	**	5.36 b	**	**	38.08 a
		74,100	12.210 a	56.02 a	**	5.70 b	**	**	35.86 b
		86,450	12.258 a	55.72 ab	**	5.93 b	**	**	34.86 b
		98,800	12.428 a	56.02 a	**	6.66 a	**	**	32.73 c
Starkville	2016	64,220	**	**	**	**	**	15.11 a	**
		74,100	**	**	**	**	**	15.03 a	**
		83,980	**	**	**	**	**	14.59 ab	**
		93,860	**	**	**	**	**	14.37 ab	**
		103,740	**	**	**	**	**	13.85 b	**
Verona	2015	49,400	**	**	**	3.42 c	24.97 a	**	39.68 a
		61,750	**	**	**	3.89 b	24.47 a	**	38.78 a
		74,100	**	**	**	4.16 b	22.19 b	**	36.51 b
		86,450	**	**	**	4.63 a	20.92 b	**	35.90 b
		98,800	**	**	**	4.80 a	21.80 b	**	34.45 b
Brooksville	2015	49,400	**	**	112.50 a	3.12 c	31.49 a	**	38.75 a
		61,750	**	**	110.51 ab	3.22 c	29.77 b	**	37.91 a
		74,100	**	**	110.34 ab	3.64 bc	30.28 ab	**	35.11 b
		86,450	**	**	107.64 b	3.93 ab	29.59 b	**	33.22 c
		98,800	**	**	108.07 b	4.28 a	28.74 b	**	31.71 d

†† Leaf area index (LAI) measurements taken when hybrids reached the silking stage.
† Weight of 100 kernels adjusted to 155 g kg-1 moisture.
‡ Number of kernels around an ear of corn.
§ Number of kernels long from tip to end.
Plant populations with the same letter are not significantly different (α =0.05).
** Insignificant effects.

Table 4.21 Significance of main effects and interactions for grain test weight.

				Main Effect Interactions on Grain Test Weight						
Location	Year	Hybrid	Population	Grain Yield	Test Weight	Plant Height	LAI††	100 Kernel Weight†	Kernel Rows‡	Kernels per Row §
Verona	2015	DKC 67-57	49,400	**	55.15 f	**	**	**	**	**
		DKC 67-57	61,750	**	56.97 abcde	**	**	**	**	**
		DKC 67-57	74,100	**	56.70 bcde	**	**	**	**	**
		DKC 67-57	86,450	**	56.67 bcde	**	**	**	**	**
		DKC 67-57	98,800	**	57.52 abc	**	**	**	**	**
		AGR-N79	49,400	**	56.42 bcdef	**	**	**	**	**
		AGR-N79	61,750	**	56.10 cdef	**	**	**	**	**
		AGR-N79	74,100	**	56.32 bcdef	**	**	**	**	**
		AGR-N79	86,450	**	56.05 def	**	**	**	**	**
		AGR-N79	98,800	**	55.60 ef	**	**	**	**	**
		PHB 1498	49,400	**	58.32 a	**	**	**	**	**
		PHB 1498	61,750	**	57.40 abcd	**	**	**	**	**
		PHB 1498	74,100	**	57.72 ab	**	**	**	**	**
		PHB 1498	86,450	**	57.22 abcd	**	**	**	**	**
		PHB 1498	98,800	**	56.17 cdef	**	**	**	**	**

†† Leaf area index (LAI) measurements taken when hybrids reached the silking stage.
† Weight of 100 kernels adjusted to 155 g kg-1 moisture.
‡ Number of kernels around an ear of corn.
§ Number of kernels long from tip to end.
Grain test weight with the same letter are not significantly different (α =0.05).
** Insignificant effects.

Table 4.22 Significance of main effects and interactions for corn grain yield.

				Main Effect Interactions on Grain Yield						
Location	Year	Hybrid	Population	Grain Yield	Test Weight	Plant Height	LAI††	100 Kernel Weight †	Kernel Rows‡	Kernels per Row §
Brooksville	2015	DKC 67-57	49,400	9.21 d	**	**	**	**	**	**
		DKC 67-57	61,750	9.25 d	**	**	**	**	**	**
		DKC 67-57	74,100	10.53 ab	**	**	**	**	**	**
		DKC 67-57	86,450	11.06 a	**	**	**	**	**	**
		DKC 67-57	98,800	10.96 a	**	**	**	**	**	**
		AGR-N79	49,400	9.75 bcd	**	**	**	**	**	**
		AGR-N79	61,750	10.23 abcd	**	**	**	**	**	**
		AGR-N79	74,100	9.69 bcd	**	**	**	**	**	**
		AGR-N79	86,450	9.44 cd	**	**	**	**	**	**
		AGR-N79	98,800	10.14 abcd	**	**	**	**	**	**
		PHB 1498	49,400	10.20 abcd	**	**	**	**	**	**
		PHB 1498	61,750	10.16 abcd	**	**	**	**	**	**
		PHB 1498	74,100	10.70 ab	**	**	**	**	**	**
		PHB 1498	86,450	11.17 a	**	**	**	**	**	**
		PHB 1498	98,800	10.35 abc	**	**	**	**	**	**

†† Leaf area index (LAI) measurements taken when hybrids reached the silking stage.
† Weight of 100 kernels adjusted to 155 g kg-1 moisture.
‡ Number of kernels around an ear of corn.
§ Number of kernels long from tip to end.
Corn grain yield with the same letter are not significantly different (α =0.05).
** Insignificant effects.

Table 4.23 Pooled data correlation analysis between yield and continuous variables hybrid, plant population, location, year, planting date and site-year.

	Pearson Correlation Coefficients					
	Yield	**Hybrid**	**Population**	**Location**	**Year**	**Planting Date**
Hybrid	-0.20948 *					
Population	0.29673 ***	-0.17611 *				
Location	0.10242 0.1391	-0.58016 ***	0.18172 *			
Year	0.29597 ***	-0.74984 ***	0.23486 **	0.77372 ***		
Planting Date	-0.22683 **	0.71949 ***	-0.22536 **	-0.61353 ***	-0.95953 ***	
Site-Year	0.10242 0.1391	-0.58016 ***	0.18172 *	1.00000 ***	0.77372 ***	-0.61353 ***

Correlations differ significantly (α =0.05).
*** Significant at <.0001
** Significant at.001
* Significant at <.05

Table 4.24 Pooled data correlation analysis between yield and soil physical and chemical properties.

	Pearson Correlation Coefficients,										
	Yield	**Sand**	**Clay**	**Silt**	**Soil pH**	**CA**	**K**	**MG**	**NA**	**P**	**N**
Sand	0.42306 ***										
Clay	-0.52418 ***	-0.71859 ***									
Silt	-0.26724 ***	-0.92180 ***	0.39281 ***								
Soil pH	-0.25733 **	-0.60727 ***	0.42742 ***	0.56478 ***							
CA	-0.48893 ***	-0.53288 ***	0.70416 ***	0.31215 ***	0.32377 ***						
K	0.16935 *	0.17495 *	-0.38087 ***	-0.01904 0.7839	0.15675 *	-0.07212 0.2982					
MG	-0.25949 ***	-0.46158 ***	0.41348 ***	0.37989 ***	0.20119 *	0.80177 ***	0.22109 *				
NA	0.45753 ***	0.73749 ***	-0.70377 ***	-0.58292 ***	-0.65403 ***	-0.47465 ***	0.00672 0.9229	-0.26717 ***			
P	0.49274 ***	0.20993 *	-0.61081 ***	0.06288 0.3646	-0.17601 *	-0.46096 ***	0.45473 ***	-0.01321 0.8491	0.52320 ***		
N	-0.06166 0.3740	-0.03893 0.5748	-0.03680 0.5959	0.07200 0.2991	0.01306 0.8507	-0.05125 0.4601	-0.00889 0.8981	0.07596 0.2732	0.15057 *	0.24307 **	
C	-0.47576 ***	-0.36725 ***	0.60849 ***	0.14645 *	0.16706 *	0.53848 ***	-0.31131 ***	0.33854 ***	-0.34797 ***	-0.48297 ***	0.36178 ***

Correlations differ significantly ($\alpha = 0.05$).
*** Significant at <.0001
** Significant at.001
* Significant at <.05

Table 4.25 Pooled data correlation analysis between yield and plant growth and developmental factors.

Pearson Correlation Coefficients						
	Yield	**TW**	**Plant Height**	**LAI**	**KWT**	**ARD**
TW	-0.16789 *					
Plant Height	-0.00549 0.9371	0.13830 *				
LAI	0.50839 ***	-0.14685 *	-0.09107 0.1897			
KWT	0.57558 ***	-0.32141 ***	-0.23624 **	0.39101 ***		
ARD	-0.29924 ***	0.18881 *	0.21486 *	-0.27205 ***	-0.50722 ***	
LONG	-0.16884 *	-0.02458 0.7232	0.18066 *	-0.25640 *	-0.09289 0.1810	0.31230 ***

Correlations differ significantly ($\alpha = 0.05$).
*** Significant at <.0001
** Significant at.001
* Significant at <.05
TW--Grain test weight calculated from combine.
Plant Height--Taken from soil level to top of tassel at VT growth stage.
LAI--Leaf area index (LAI) measurements taken when hybrids reached the silking stage.
KWT--Weight of 100 kernels adjusted to 155 g kg^{-1} moisture.
ARD--Number of kernels around an ear of corn.
LONG--Number of kernels long from tip to end.

Table 4.26 Standardized correlation coefficients evaluating grain yield and other factors for Starkville 2015.

Starkville 2015 Pearson Correlation Coefficients																	
	Yield	**TW**	**SAND**	**CLAY**	**SILT**	**PH**	**CA**	**K**	**MG**	**NA**	**P**	**N**	**C**	**PHEIGHT**	**LAI**	**KWT**	**ARD**
TW	0.00																
SAND	-0.26 *	-0.11															
CLAY	0.18	-0.09	-0.08														
SILT	0.05	0.14	-0.65 ***	-0.71 ***													
PH	-0.23	0.20	0.37 *	0.19	-0.41 *												
CA	-0.33 *	0.16	-0.06	0.30 *	-0.18	0.47 *											
K	-0.23	-0.01	0.03	-0.11	0.06	-0.03	0.38 *										
MG	0.02	0.08	-0.50 ***	0.01	0.35 *	-0.07	0.46 *	0.53 ***									
NA	-0.10	-0.14	0.43 *	-0.16	-0.18	0.05	0.03	0.51 ***	0.04								
P	-0.29 *	-0.09	0.37 *	-0.17	-0.13	-0.15	0.08	0.73 ***	0.08	0.67 ***							
N	-0.05	0.01	-0.14	-0.24	0.28 *	-0.11	0.01	0.24	0.27 *	0.04	0.14						
C	-0.06	-0.06	0.10	-0.06	-0.02	0.16	0.23	0.27 *	0.02	0.10	0.19	0.49 ***					
PHEIGHT	0.06	-0.41 **	0.22	0.00	-0.15	-0.04	0.06	0.18	0.01	0.18	0.18	0.11	0.12				
LAI	0.28 *	0.48 **	-0.02	0.02	0.00	0.19	0.10	-0.01	0.08	0.04	-0.05	-0.11	-0.11	-0.40 *			
KWT	0.27 *	0.09	-0.42 *	-0.01	0.31 *	-0.23	-0.29 **	-0.24	0.18	-0.22	-0.35 *	0.07	-0.19	-0.50 ***	0.03		
ARD	-0.37 *	-0.12	0.19	-0.14	-0.02	-0.10	0.07	0.14	0.04	0.05	0.21	0.23	0.14	0.48 **	-0.28 *	-0.45 *	
LONG	-0.38 *	-0.29 *	-0.09	-0.10	0.14	-0.15	0.08	0.11	0.28 *	0.02	0.01	0.21	-0.10	0.18	-0.48 **	0.26 *	0.32 *

Significance level P < 0.05, *** Significant at <.0001, ** Significant at.001, * Significant at <.05

Table 4.27 Standardized correlation coefficients evaluating grain yield and other factors for Brooksville 2015.

	Brooksville **2015 Pearson Correlation Coefficients**																
	Yield	**TW**	**SAND**	**CLAY**	**SILT**	**PH**	**CA**	**K**	**MG**	**NA**	**P**	**N**	**C**	**PHEIGHT**	**LAI**	**KWT**	**ARD**
TW	0.30 *																
SAND	-0.21	-0.15															
CLAY	-0.08	-0.21	0.05														
SILT	0.12	0.24	-0.26 *	-0.98 ***													
PH	0.16	0.29 *	-0.06	-0.26 *	0.27 *												
CA	-0.09	-0.04	0.35 *	-0.07	0.00	-0.09											
K	-0.05	-0.07	0.20	-0.17	0.13	-0.18	0.94 ***										
MG	-0.04	-0.20	0.23	-0.08	0.03	-0.35 *	0.89 ***	0.93 ***									
NA	-0.10	0.05	0.22	-0.11	0.06	-0.03	0.93 ***	0.90 ***	0.78 ***								
P	0.01	-0.05	0.18	-0.30 *	0.25 *	-0.18	0.82 ***	0.93 ***	0.85 ***	0.77 ***							
N	0.04	-0.02	-0.12	-0.20	0.22	-0.16	0.16	0.31 *	0.32 *	0.20	0.38 *						
C	0.03	0.05	-0.26 *	-0.02	0.08	-0.19	-0.05	0.08	0.07	0.06	0.13	0.84 ***					
PHEIGHT	-0.25 *	0.04	0.16	-0.11	0.07	-0.19	0.17	0.17	0.20	0.16	0.22	0.07	0.00				
LAI	0.11	-0.04	-0.12	-0.12	0.14	-0.03	0.02	0.09	-0.01	0.04	0.15	0.18	0.26 *	0.12			
KWT	0.28 *	0.13	-0.17	-0.11	0.14	0.23	-0.16	-0.20	-0.18	-0.12	-0.17	-0.13	-0.10	-0.07	-0.28 *		
ARD	-0.01	0.18	-0.05	-0.18	0.19	0.27 *	0.03	0.03	-0.05	0.08	0.01	0.04	0.00	-0.08	-0.05	-0.25 *	
LONG	-0.27 *	0.01	0.10	-0.08	0.05	0.19	-0.07	-0.09	-0.08	0.01	-0.14	-0.01	-0.04	-0.01	-0.55 ***	0.06	0.44 *

Significance level P < 0.05, *** Significant at <.0001, ** Significant at.001, * Significant at <.05

Table 4.28 Standardized correlation coefficients evaluating grain yield and other factors for Verona 2015.

	Verona **2015 Pearson Correlation Coefficients**																
	Yield	**TW**	**SAND**	**CLAY**	**SILT**	**PH**	**CA**	**K**	**MG**	**NA**	**P**	**N**	**C**	**PHEIGHT**	**LAI**	**KWT**	**ARD**
TW	-0.27																
SAND	0.22	-0.18															
CLAY	0.08	0.07	-0.35 *														
SILT	-0.28	0.12	-0.67 ***	-0.46 *													
PH	-0.26	0.16	-0.46 *	0.16	0.30 *												
CA	-0.22	0.06	-0.51 *	0.35 *	0.21	0.57 ***											
K	0.07	-0.12	0.37 *	-0.32 *	-0.10	-0.36	-0.06										
MG	0.30 *	-0.09	0.14	-0.21	0.03	-0.58 ***	-0.08	0.71 ***									
NA	-0.13	-0.04	-0.01	-0.12	0.11	0.09	-0.02	0.15	0.00								
P	0.21	-0.34 *	0.36 *	-0.17	-0.20	-0.64 ***	-0.01	0.67 ***	0.67 ***	0.09							
N	0.25	-0.20	-0.18	0.32 *	-0.08	-0.37 *	0.17	0.15	0.40 *	-0.31 *	0.35 *						
C	0.05	0.03	-0.12	0.09	0.04	-0.16	-0.04	0.20	0.32 *	0.05	0.01	0.65 ***					
PHEIGHT	-0.18	0.05	0.03	0.05	-0.07	0.03	-0.06	0.03	-0.08	0.17	-0.06	-0.25	-0.27				
LAI	0.45 *	0.02	-0.19	0.09	0.11	0.08	0.28	0.05	0.09	-0.11	0.18	0.24	0.07	-0.47 **			
KWT	0.06	-0.25	0.41 *	-0.22	-0.21	-0.26	-0.14	0.30 *	0.25	0.10	0.30 *	0.06	0.24	-0.42 *	0.09		
ARD	0.01	0.04	-0.10	0.12	0.00	0.14	-0.02	-0.06	-0.09	0.23	-0.13	-0.26	-0.30 *	0.63 ***	-0.20	-0.50 *	
LONG	-0.38 *	-0.11	0.25	-0.37 *	0.06	0.05	-0.23	0.31 *	0.06	0.30 *	0.05	-0.43 *	-0.19	0.53 *	-0.65 ***	-0.02	0.41 *

Significance level P < 0.05, *** Significant at <.0001, ** Significant at.001, * Significant at <.05

Table 4.29 Standardized correlation coefficients evaluating grain yield and other factors for Starkville 2016.

	Starkville **2016 Pearson Correlation Coefficient**																
	Yield	**TW**	**SAND**	**CLAY**	**SILT**	**PH**	**CA**	**K**	**MG**	**NA**	**P**	**N**	**C**	**PHEIGHT**	**LAI**	**KWT**	**ARD**
TW	0.18																
SAND	0.10	-0.42 *															
CLAY	0.07	0.38 *	-0.58 ***														
SILT	-0.16	0.30 *	-0.89 ***	0.14													
PH	0.15	0.08	-0.08	0.15	0.02												
CA	0.32 *	0.31 *	-0.41 *	0.66 ***	0.13	0.72 ***											
K	-0.08	-0.06	-0.15	0.32 *	0.01	0.35 *	0.36 *										
MG	0.05	0.13	-0.24	0.51 *	0.01	0.78 ***	0.77 ***	0.66 ***									
NA	-0.01	-0.04	0.18	-0.26	-0.07	-0.04	-0.12	-0.19	-0.21								
P	0.30 *	0.07	-0.33 *	0.52 *	0.11	0.45 *	0.73 ***	0.53 *	0.61 ***	-0.15							
N	-0.26	-0.04	0.00	0.19	-0.11	0.17	0.16	0.41 *	0.34 *	0.13	0.25						
C	-0.25	-0.13	-0.07	0.26	-0.06	0.16	0.18	0.49 *	0.37 *	0.03	0.23	0.85 ***					
PHEIGHT	0.73 ***	0.00	0.06	0.06	-0.11	0.34 *	0.38 *	-0.05	0.18	0.08	0.30 *	-0.10	-0.08				
LAI	0.57 ***	0.10	-0.01	0.11	-0.06	0.22	0.47 *	-0.09	0.17	0.09	0.42 *	-0.13	-0.21	0.54 **			
KWT	0.46 *	0.18	0.20	-0.05	-0.22	0.29 *	0.18	-0.19	0.07	0.11	0.05	0.05	-0.06	0.64 ***	0.40 *		
ARD	-0.24	-0.08	-0.29 *	0.06	0.32 *	-0.09	0.03	-0.01	0.05	-0.07	0.15	0.15	0.10	-0.26	-0.13	-0.29 *	
LONG	0.47 **	-0.06	0.39 *	-0.30 *	-0.31 *	-0.01	-0.10	-0.39 *	-0.27	0.30 *	-0.30 *	-0.08	-0.12	0.46 *	0.12	0.29 *	-0.30 *

Significance level P < 0.05, *** Significant at <.0001, ** Significant at.001, * Significant at <.05

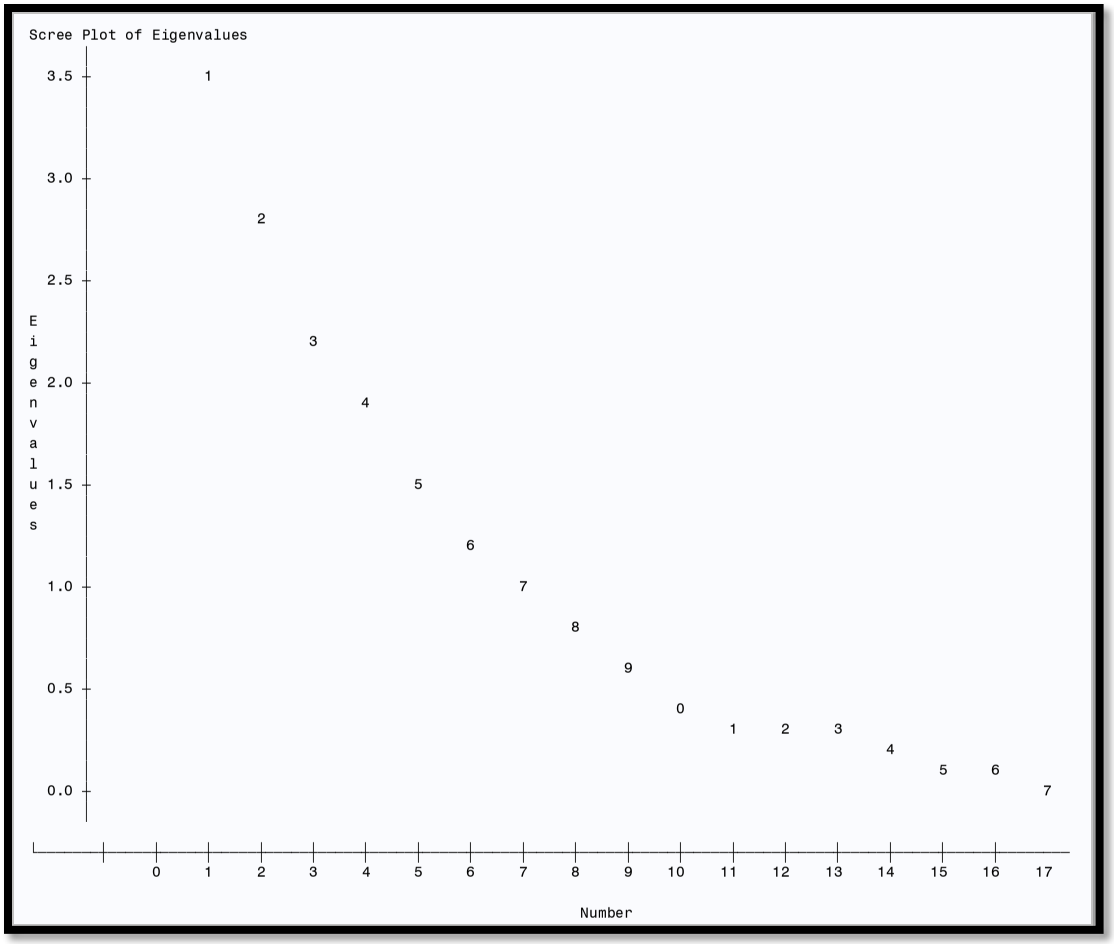

Figure 4.17 Eigenvalues scree plot for Starkville 2015.

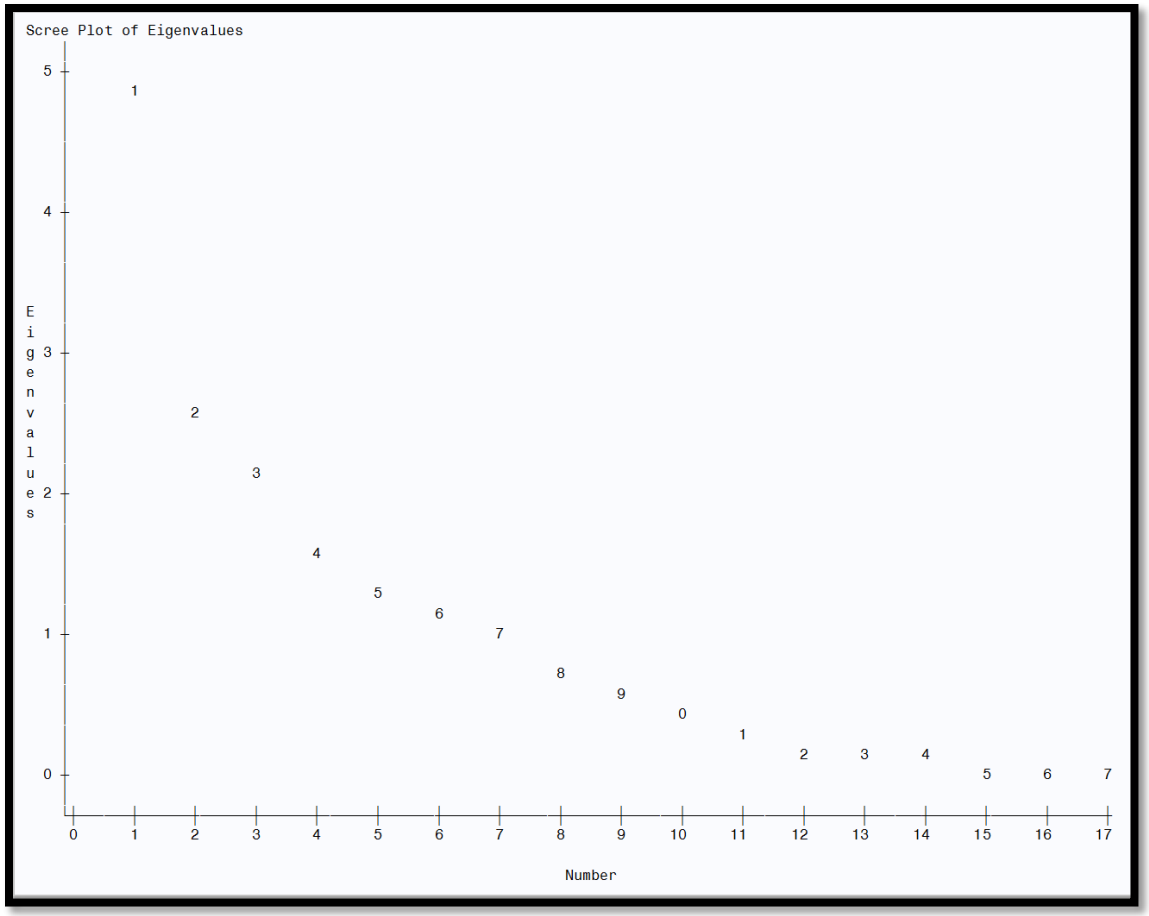

Figure 4.18 Eigenvalues scree plot for Brooksville 2015.

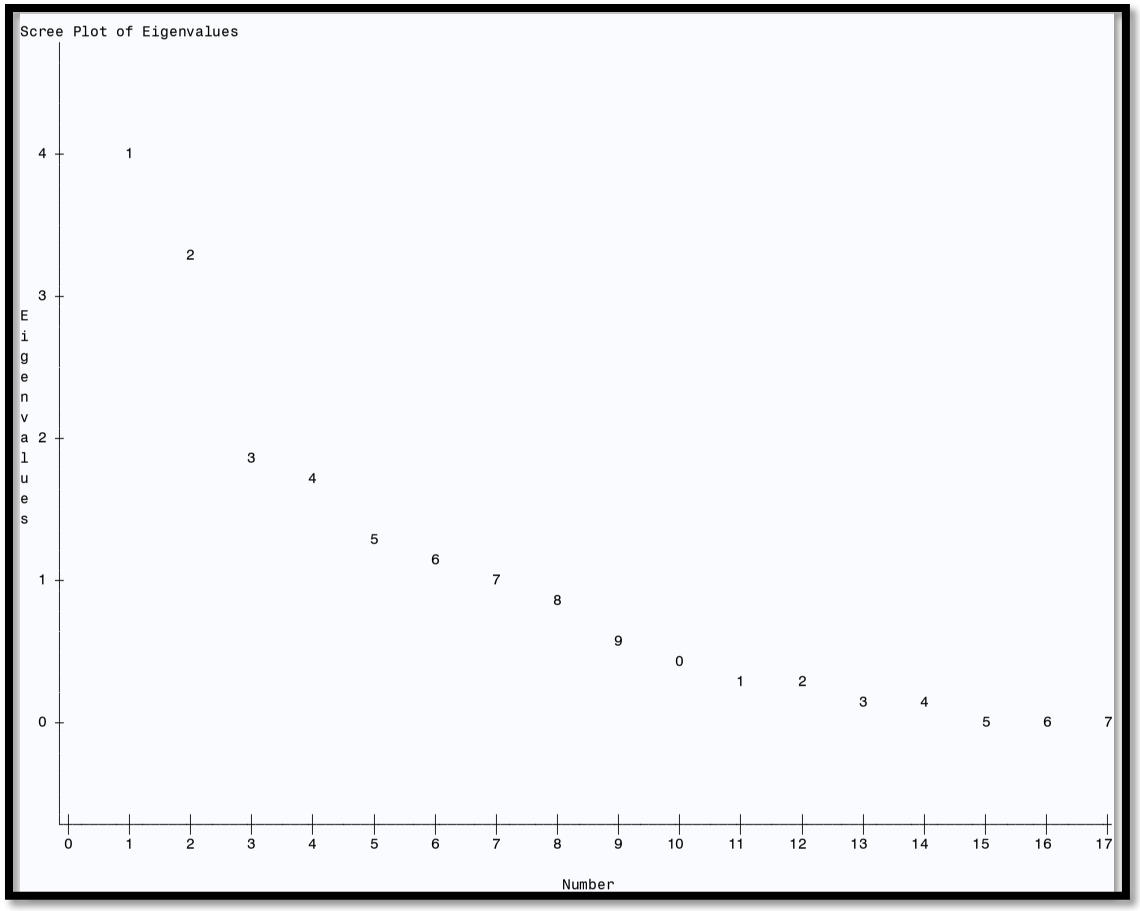

Figure 4.19 Eigenvalues scree plot for Verona 2015.

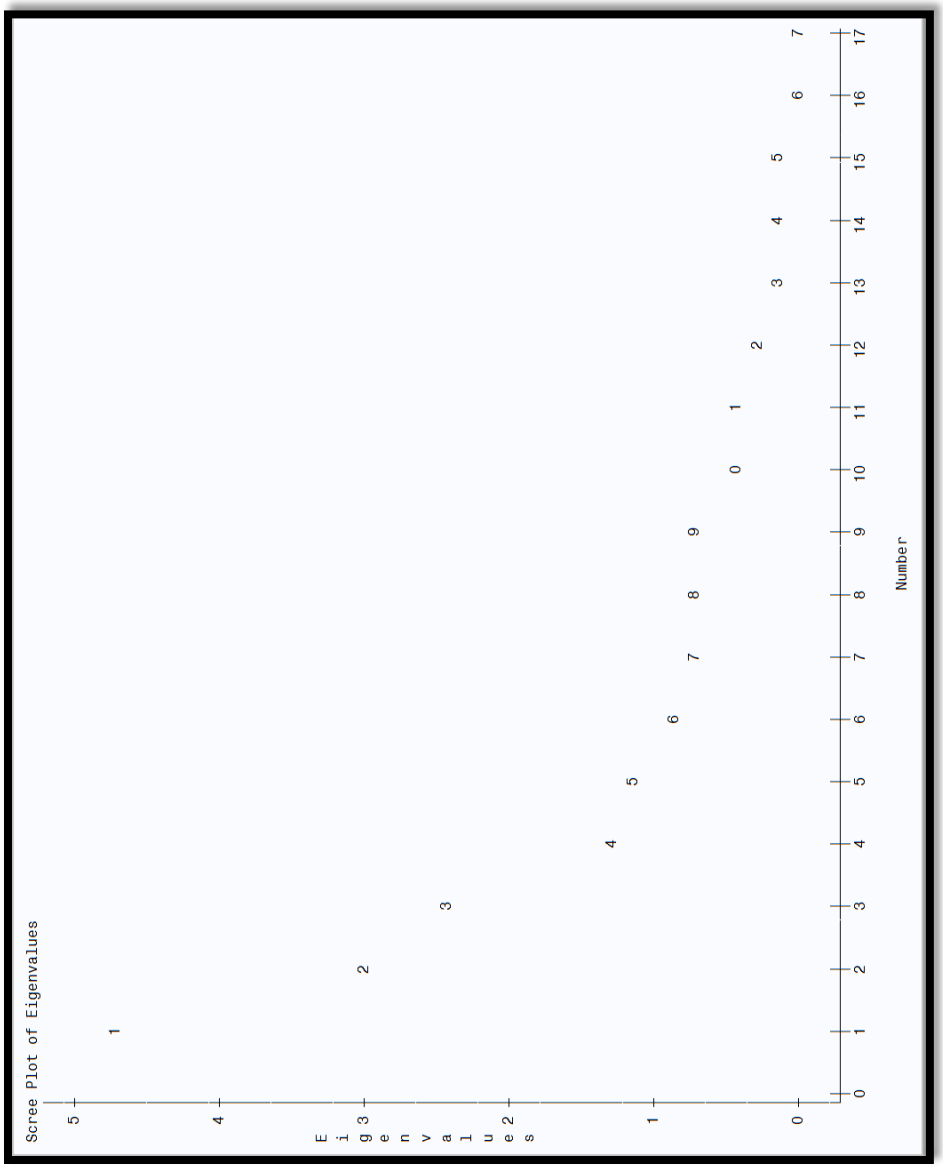

Figure 4.20 Eigenvalues scree plot for Starkville 2016.

Table 4.30 Standardized scoring coefficient factor loadings determined for Starkville 2015 with measured variables selected to create latent variables.

Field	VARIABLE	Factor1	Factor2	Factor3	Factor4	Factor5	Factor6	Factor7	Factor8	Factor9	Factor10
Starkville 2015	**P**	0.8713†	0.0399	-0.1815	-0.2184	0.0163	0.1710	-0.0713	-0.0137	0.0183	0.0090
	K	0.6225†	0.0312	-0.0891	-0.1498	0.0223	0.1070	-0.0639	-0.0162	-0.0046	-0.0067
	CLAY	0.0438	1.0944†	-0.0337	0.0746	0.0267	-0.0930	0.0344	0.1436	-0.0438	0.1032
	SAND	-0.1749	0.1190	1.5321†	0.4932	-0.1297	-0.3552	-0.0118	0.0956	-0.0787	-0.0366
	MG	-0.2428	0.0035	0.4503	1.5196†	-0.0590	-0.0319	0.1009	0.0155	-0.0888	-0.1228
	PH	0.1944	-0.0352	-0.3765	-0.0425	0.0500	1.3053†	-0.1134	-0.0640	0.0432	0.0219
	C	-0.1004	0.0277	-0.0193	0.1243	-0.0183	-0.1160	1.2472†	0.0623	0.0041	0.1895
	TW	-0.0195	0.0949	0.0701	0.0222	-0.1509	-0.0663	0.0635	1.2134†	0.2063	0.1910
	PHEIGHT	0.0096	-0.0214	-0.0753	-0.0963	-0.2155	0.0407	0.0038	0.1794	1.3206†	0.0092
	LONG	0.0065	0.0719	-0.0702	-0.1355	-0.2937	0.0242	0.1735	0.1733	0.0095	1.3962†
	LAI	0.0323	0.0096	-0.0549	-0.1436	0.0207	-0.0340	0.0889	-0.1877	0.1986	0.3212
	N	-0.0694	0.0743	0.0756	-0.1454	-0.1531	0.0244	-0.3703	-0.0353	-0.0375	-0.1039
	CA	-0.1155	-0.1653	0.1314	-0.3774	0.0255	-0.3234	-0.1716	-0.1344	0.0168	-0.1972
	NA	-0.3076	0.0452	-0.2520	-0.0360	0.0610	-0.0468	0.0069	0.0532	-0.0604	-0.0369
	KWT	0.1640	-0.0323	0.0912	-0.2017	0.3339†	0.0538	-0.0019	-0.0816	0.2396	-0.3316
	Eigenvalue	**3.4550**	**2.7843**	**2.2411**	**1.8601**	**1.4701**	**1.1639**	**0.9821**	**0.7602**	**0.5564**	**0.4141**
	Difference	0.6707	0.5432	0.3810	0.3900	0.3061	0.1818	0.2219	0.2039	0.1423	0.0997
	Proportion	0.2032	0.1638	0.1318	0.1094	0.0865	0.0685	0.0578	0.0447	0.0327	0.0244
	Cumulative	0.2032	0.3670	0.4989	0.6083	0.6947	0.7632	0.8210	0.8657	0.8984	0.9228

† Indicates the variables with large factor loadings that were selected from each factor to create latent variables.

Table 4.31 Standardized scoring coefficient factor loadings determined for Brooksville 2015 with measured variables selected to create latent variables.

Field	VARIABLE	Factor1	Factor2	Factor3	Factor4	Factor5	Factor6	Factor7	Factor8	Factor9	Factor10
Brooksville 2015	**P**	0.1345	0.0377	-0.0323	0.0096	0.0259	-0.0425	-0.0085	0.0044	-0.0249	0.0184
	K	0.2731†	0.0252	-0.0283	0.0115	0.0310	-0.0527	-0.0118	0.0116	-0.0241	0.0238
	CLAY	0.0597	1.0748†	0.0601	0.1134	0.1827	-0.0964	0.1017	0.1280	0.0693	0.1152
	SAND	-0.0725	0.0574	0.1044	0.0642	-0.0150	1.102†3	0.0782	0.0577	-0.0645	0.1167
	MG	0.2240	0.0177	-0.0244	0.0188	0.0303	-0.0423	-0.0085	0.0234	-0.0218	0.0189
	ARD	-0.0150	0.0539	0.0131	-0.0899	-0.1285	0.0635	1.2127†	-0.0586	0.0558	0.2177
	PH	0.0421	0.0920	0.0835	-0.1223	1.1783†	-0.0319	-0.1249	-0.0920	0.1100	-0.1325
	C	-0.0242	0.0219	0.585†2	-0.0209	0.0846	0.0909	0.0159	-0.1066	0.0137	0.0256
	TW	0.0166	0.0656	-0.0181	1.0748†	-0.1385	0.0557	-0.1007	0.0796	-0.0604	-0.0406
	PHEIGHT	-0.0422	0.0403	0.0138	-0.0616	0.1269	-0.0773	0.0638	-0.1095	1.0578†	0.0068
	LONG	0.0297	0.0299	-0.0542	0.0733	-0.0890	-0.0756	-0.3061	0.4369	-0.0640	-0.0104
	LAI	0.0110	0.0609	-0.0980	0.0654	-0.0860	0.0432	-0.0507	1.2948†	-0.0890	0.1792
	N	-0.0433	0.0340	0.5333	-0.0083	0.0677	0.0775	0.0098	-0.0814	0.0092	0.0265
	CA	0.2588	0.0156	-0.0192	0.0078	0.0214	-0.0566	-0.0127	0.0131	-0.0252	0.0213
	NA	0.2165	0.0135	-0.0233	-0.0046	0.0051	-0.0467	-0.0097	-0.0029	-0.0224	0.0149
	KWT	0.0343	0.0614	0.0309	-0.0381	-0.1401	0.1039	0.2262	0.1985	0.0064	1.1513†
	Eigenvalue	**4.9102**	**2.5561**	**2.1658**	**1.5525**	**1.2670**	**1.1124**	**0.9622**	**0.7704**	**0.6304**	**0.3884**
	Difference	2.3541	0.3903	0.6133	0.2855	0.1546	0.1502	0.1918	0.1400	0.2420	0.0970
	Proportion	0.2888	0.1504	0.1274	0.0913	0.0745	0.0654	0.0566	0.0453	0.0371	0.0228
	Cumulative	0.2888	0.4392	0.5666	0.6579	0.7324	0.7979	0.8545	0.8998	0.9369	0.9597

† Indicates the variables with large factor loadings that were selected from each factor to create latent variables.

Table 4.32 Standardized scoring coefficient factor loadings determined for Verona 2015 with measured variables selected to create latent variables.

Field	VARIABLE	Factor1	Factor2	Factor3	Factor4	Factor5	Factor6	Factor7	Factor8	Factor9	Factor10
Verona 2015	**P**	0.3974	0.0628	-0.0072	0.0589	-0.0795	-0.0405	-0.0376	0.0500	0.0237	-0.0249
	K	0.1076	0.0976	-0.0986	0.0948	-0.0788	-0.0324	-0.0181	-0.0001	0.0200	-0.0291
	CLAY	0.0813	-0.3065	-0.0960	1.1490†	0.0317	-0.1161	0.0601	0.0149	-0.1289	-0.0173
	SAND	-0.0683	-1.3232†	0.1452	-0.2233	0.1049	0.3271	0.0877	0.0544	0.0024	-0.3122
	MG	0.7187†	0.0181	-0.1059	0.0747	-0.0466	0.0173	0.0045	0.0344	-0.0399	-0.0694
	ARD	-0.0240	-0.0103	0.1096	-0.1123	-0.0633	0.0421	-0.1231	0.0192	1.3878†	0.2956
	PH	0.0000	-0.0682	0.0240	-0.0500	-0.0564	0.0329	-0.0134	0.0006	0.0043	0.0338
	C	-0.1218	-0.1116	1.0061†	-0.1483	0.0343	0.0829	-0.0366	-0.0224	0.1237	-0.0912
	TW	0.0651	-0.0471	-0.0208	-0.0094	-0.0126	-0.0095	0.0083	1.0512†	0.0272	0.1327
	PHEIGHT	-0.0152	0.0325	0.0781	-0.0506	0.2207	-0.0261	-0.0437	-0.0154	-0.3117	0.1983
	LONG	-0.0230	-0.0009	0.0444	0.1360	0.1512	0.0355	-0.0434	0.0337	-0.1606	-0.0713
	LAI	-0.0752	-0.0752	0.0333	-0.0061	1.2277†	-0.1019	0.0273	-0.0103	-0.0857	-0.0365
	N	-0.0665	-0.0518	0.1964	-0.0819	-0.0019	-0.0140	0.0332	0.0317	0.0410	0.0095
	CA	0.0060	-0.2496	0.0746	-0.2496	-0.0990	1.1743†	-0.0067	-0.0082	0.0490	-0.0285
	NA	-0.0092	-0.0703	-0.0343	0.0264	0.0319	-0.0093	1.0745†	0.0079	-0.1623	-0.1488
	KWT	-0.0763	0.1968	-0.0776	0.0975	-0.0305	-0.0242	-0.1090	0.0985	0.2864	1.3514†
	Eigenvalue	**3.9339**	**3.2355**	**1.8662**	**1.7601**	**1.2858**	**1.1414**	**0.9809**	**0.8245**	**0.5436**	**0.3853**
	Difference	0.6983	1.3694	0.1061	0.4743	0.1444	0.1605	0.1563	0.2810	0.1583	0.0549
	Proportion	0.2314	0.1903	0.1098	0.1035	0.0756	0.0671	0.0577	0.0485	0.0320	0.0227
	Cumulative	0.2314	0.4217	0.5315	0.6350	0.7107	0.7778	0.8355	0.8840	0.9160	0.9387

† Indicates the variables with large factor loadings that were selected from each factor to create latent variables.

Table 4.33 Standardized scoring coefficient factor loadings determined for Starkville 2016 with measured variables selected to create latent variables.

Field	VARIABLE	Factor1	Factor2	Factor3	Factor4	Factor5	Factor6	Factor7	Factor8	Factor9	Factor10
Starkville 2016	**P**	-0.1053	-0.0360	-0.0152	-0.1959	0.0472	-0.2254	0.1135	0.0087	0.0346	-0.0888
	K	-0.1668	-0.1569	0.0178	0.0173	0.1730	0.1068	0.2152	0.0567	0.0339	0.1311
	CLAY	-0.0776	-0.1198	-0.4855	1.3277†	0.0336	-0.0466	0.0088	0.1171	-0.1267	0.1107
	SAND	0.0519	-0.0590	-1.3491†	0.1469	-0.2141	-0.0473	-0.2736	0.0007	0.3304	0.2481
	MG	0.3402	-0.0385	-0.0021	-0.0696	-0.0412	-0.0442	0.0122	0.0207	-0.0202	-0.0025
	ARD	0.0055	-0.0795	-0.1337	0.0465	0.1137	0.0321	0.1221	0.0194	0.0903	1.1385†
	PH	0.7488†	-0.0367	-0.0214	-0.0722	-0.1164	-0.0601	-0.0260	0.0166	-0.0248	0.0079
	C	-0.0421	0.5814†	0.0253	-0.1123	-0.0593	0.0983	-0.0254	-0.0675	0.0604	-0.0586
	TW	-0.0335	0.0599	-0.1622	-0.2677	-0.1918	-0.0095	-0.0468	-0.0233	1.1930†	0.0866
	PHEIGHT	-0.0476	0.0601	-0.0416	-0.0597	-0.2410	-0.1307	-0.2748	0.0015	0.1110	0.0450
	LONG	-0.0174	-0.0300	0.1222	0.0925	0.0424	0.0098	1.3240†	-0.1085	-0.0423	0.1036
	LAI	-0.0741	0.1054	0.0246	-0.0375	-0.1574	1.2553†	0.0104	-0.0730	-0.0077	0.0286
	N	-0.0403	0.6158†	0.0338	-0.0977	-0.0863	0.0951	-0.0367	-0.0778	0.0440	-0.0728
	CA	0.2248	-0.0244	-0.0240	0.0498	-0.0304	-0.0253	-0.0097	0.0167	-0.0369	-0.0013
	NA	0.0243	-0.0918	-0.0022	0.1539	-0.0047	-0.0846	-0.1344	1.0774†	-0.0267	0.0203
	KWT	-0.1198	-0.0780	0.0995	0.1026	1.3208†	-0.1564	0.0480	-0.0035	-0.1792	0.1003
	Eigenvalue	**4.6537**	**3.0676**	**2.3689**	**1.3278**	**1.1073**	**0.9012**	**0.7836**	**0.7101**	**0.6722**	**0.4057**
	Difference	1.5861	0.6987	1.0411	0.2205	0.2062	0.1176	0.0735	0.0380	0.2664	0.0127
	Proportion	0.2737	0.1804	0.1393	0.0781	0.0651	0.0530	0.0461	0.0418	0.0395	0.0239
	Cumulative	0.2737	0.4542	0.5935	0.6716	0.7368	0.7898	0.8359	0.8777	0.9172	0.9411

† Indicates the variables with large factor loadings that were selected from each factor to create latent variables.

Table 4.34 Coefficients and statistics of multiple regression models relating grain yield with latent variables identified for each location.

		Factor and latent variable									
Field	Intercept	Factor1	Factor3	Factor4	Factor5	Factor7	Factor9	Factor10	R2	P > F	CV
Starkville 2015	11.35	-0.43	-0.73	0.26	-0.70	-0.67	0.55	0.71	0.61	<.0001	11.96
		P & K	Sand	MG	KWT	C	Pheight	Long			
		soil fertility	soil texture	soil quality	genetics environment	soil quality	genetics environment	genetics environment			
Brooksville 2015	Intercept	Factor4	Factor7	Factor8	Factor10						
	7.85	0.35	0.44	-0.43	0.43				0.28	0.001	17.39
		TW	ARD	LAI	KWT						
		genetics environment	genetics	genetics environment	genetics environment						
Verona 2015	Intercept	Factor2	Factor3	Factor6	Factor7	Factor8					
	10.19	0.42	-0.17	-0.22	0.16	-0.17			0.47	<.0001	6.1
		Sand	C	CA	NA	TW					
			soil quality	soil chemical	soil chemical	genetic environment					
Starkville 2016	Intercept	Factor2	Factor4	Factor6	Factor7	Factor10					
	11.50	-0.60	1.05	1.42	1.12	-0.50			0.61	<.0001	16.4
		N & C	Clay	LAI	Long	Ard					
		soil quality	soil texture	environment	genetics environment	genetics					

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