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Nitrogen Use Efficiency of Pretassel Nitrogen Applications in Corn

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Crop, Soil and Environmental Sciences

by

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University of Arkansas
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ABSTRACT

Corn (*Zea mays* L.) production continues to be a critical component of row-crop production systems within Arkansas and is seeing a resurgence in recent years. Nitrogen (N) is critical for corn growth and is often one of the single largest input costs associated with corn production. Research objectives for this study were to determine the nitrogen use efficiency (NUE) of late season N applications as influenced by sidedress N rate and timing of pretassel application and to quantify the nutrient uptake and partitioning in modern era corn hybrids within a furrow-irrigated production system. Research was conducted at the Milo J. Shult Agriculture Research & Extension Center (SAREC) near Fayetteville, AR and the Pine Tree Research Station (PTRS) near Colt, AR during the 2018 and 2019 growing season. Eight different N treatments were implemented as a combination of sidedress rate and pretassel N application timing. At the sidedress application timing near the V6-V8 growth stage, either 90 or 112 kg N ha^{-1} was surface broadcast as urea. At the pretassel growth stage, treatments received either 0 or 50 kg N ha^{-1} surface broadcast as ^{15}N-labeled urea and were compared across two different application timings; early tassel (VT) or at late reproductive stage 1 (R1). To assess N-fertilizer use, whole plant samples were collected at R2, R4, and R6 and analyzed for total N uptake and atom% ^{15}N to assess Fertilizer Nitrogen Recovery Efficiency (FNRE). Results indicate that N uptake from pretassel N applications were more efficient at the early tassel stage (79% FNRE) compared to late R1 (50% FNRE) applications (*P <.0001*). A significant sidedress rate by growth stage interaction *(P=0.0146)* was identified and indicated that FNRE was maximized at R4 sampling time (79% NUE) when the 112 kg N ha^{-1} sidedress rate was used. This data indicates that earlier applied pretassel N applications near the VT growth stage are preferred and improve NUE in

Arkansas corn production and that optimal rates of sidedress N can result in high NUE of pretassel N applications under furrow-irrigated corn production.

Total aboveground biomass reported in this study was higher than what has been previously reported in the literature and may be attributed to irrigation and enhanced fertilizer management (split applications). Total nutrient accumulation was 326.6 kg N, 62.0 kg P, 437.2 kg K, 30.7 kg Mg, 28.0 kg S, and 686.4 g Zn ha^{-1}, respectively. The average grain yield produced was 15.2 Mg ha^{-1}. The general nutrient uptake patterns could be described as sigmoidal, consisting of a curved shape, a peak accumulation period followed by a transition of nutrient remobilization. These results help to identify the season total nutrient demand for modern era corn hybrids produced in a furrow-irrigated production system and will help guide future soil fertility and nutrient management decisions to ensure maximal corn yield and producer profitability are achieved.

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CHAPTER 1

Introduction and Literature Review

Introduction

Corn (*Zea mays* L.*)* is a vital component not only to the United States, but to the global economy as well. The U.S. has positioned itself as the world's largest producer and exporter of corn, making corn a critical aspect of the agricultural economy. The U.S. dedicates between 10 to 20% of its corn stocks to the world corn trade market (USDA-ERS, 2018). Corn is produced for a wide variety of uses, ranging from livestock feed, ethanol as a biofuel, food products, and alcohol production. In 2019, roughly 37 million hectares of corn was planted in the U.S. Corn is mainly grown in the Corn Belt which consist of the following states: Illinois, Iowa, Indiana, South Dakota, Nebraska, Kentucky, Ohio, and Missouri, but significant hectares can be found in other regions of the country.

The incorporation of corn into crop rotations in Arkansas grew in popularity based on economic competitiveness and management feasibility compared to other commodities that were once grown regularly in the state. In 2019, around 299,500 hectares were planted to corn in Arkansas, accounting for 1% of the U.S. corn hectares (Kelley and Capps, 2018). Arkansas corn production averaged 10,984 kg ha^{-1} compared to the national average of 11,877 kg ha^{-1} in 2017 which was a record high. Arkansas' ability to produce high yields is directly related to irrigation. For Arkansas corn producers, corn production is only recommended where irrigation is available unlike the other regions of the U.S. where irrigation isn't necessary to maximize grain yield most seasons (Tacker et al., 2009). Furrow irrigation is the most common form of irrigation in the Mid-south, accounting roughly for 93% of the irrigated corn in Arkansas.

Within a furrow-irrigated system, corn is planted on a raised bed which allows the water to flow down the furrow between the beds and infiltrate into the soil profile for plant uptake. Another important purpose of planting on raised beds is to ensure the corn has adequate drainage during times of excess precipitation and increased soil temperature in the spring during early planting dates (Ross et al, 2009; Tacker et al., 2009). Raised beds can aid in moisture retention early in the season when seeds need adequate water for germination. Soil and air temperature determine the ideal planting date, and in Arkansas it is around late March to early April. Corn is typically harvested in August and September.

Nitrogen (N) has been identified as the most critical nutrient in corn production to maximize yield; however, unnecessary N inputs can lead to costly economic loss and environmental concerns. Effective management of N can face a variety of obstacles during the growing season; for instance, timing of N application, identifying N deficiency, irrigation timing and determining appropriate season total N rates. To better understand N management and utilization of a given crop, researchers around the globe use a measurement, expressed as a percentage, known as N use efficiency (NUE). Currently, estimates of global NUE for cereal crops, including corn, is roughly 33% with developed countries having a mean reported NUE of 42% (Raun and Johnson, 1999). Average NUE values, even in developed countries, suggest that major improvements need to be made to N management. Evaluation of how N is managed and what management practices work best for the location, soil texture, and financial inputs available should be a focal point of research. Arkansas is unique compared to other regions of the U.S. because of its ability to irrigate and quickly incorporate N following in season application as well as the ability to apply aerial N later in-season which leads to greater potential for N uptake and efficiency. The cultural practices available in Arkansas (i.e., aerial application) provide the potential to increase NUE by applying more N in-season and via later applications when traditional ground application equipment can no longer enter the field.

Managing N loss mechanism is critical for successful economic returns and protecting the environment. Loss pathways can persist in multiple situations throughout a growing season such as volatilization, denitrification, leaching, and soil/water erosion. How producers and researchers mitigate N loss pathways will greatly affect the NUE potential and overall agronomic and economic success of the crop. In areas where irrigation isn't a limiting factor, splitting fertilizer N applications across different growth stages to synchronize with nutrient demand can maximize the NUE. Arkansas corn production implements a two-way split or a three-way split for N fertilizer applications. The two-way split recommends 20 to 25% of the total N at pre-plant with the remaining 75 to 80% applied at side-dress which is between V6 to V8, whereas the three-way split decreases the total N applied at side-dress down to 50-65% followed by an additional application at pre-tassel, between V10 to VT, for the remaining 15-25% (Slaton et al., 2013 a,b). Research studies have shown the three-way split N technique is able to provide higher NUE results and reduce N losses. Research conducted by Muller et al., (2017) found no significant yield response to split N applications, but the timing of the N application did influence fertilizer N recovery efficiency (FNRE) which suggests the potential for economic and environmental advantages.

Years of research have been dedicated to understanding the nutrient accumulation and partitioning in corn. Understanding the total aboveground nutrient accumulation and how it is partitioned within the plant is important to improve agronomic practices as new hybrids are developed to ensure sound economic decisions are made and reduce potential environmental impacts. As modern plant breeding, biotechnology and crop production practices evolve, new discoveries unfold revealing the how the 17 plant essential nutrients are accumulated and partitioned by new hybrids. Noting these changes will allow extension and agronomic guides to navigate producers in the right direction based on their cultural practices, soil test nutrient concentrations and available nutrient sources.

The most investigated nutrients in regard to accumulation and partitioning in corn are: nitrogen (N), phosphorous (P), potassium (K), magnesium (Mg), sulfur (S), zinc (Zn), boron (B), iron (Fe), copper (Cu) and manganese (Mn). The nutrients listed are separated into categories of primary macronutrients (large amounts), secondary micronutrients (moderate amounts) and micronutrients (trace amounts). Categorization is based on the concentration of nutrient required by the plant for it to not be limiting plant growth and reproduction.

Literature Review

Arkansas Corn Production

In recent years, corn continued to be a significant row crop in Arkansas due to its positive impact on crop rotation and economic return for Arkansas producers. Arkansas's top five row crops include: rice (*Oryza sativa* L.), soybean (*Glycine max* L.), corn, cotton (*Gossypium hirsutum*), and forage such as hay (USDA-NASS, 2018a). A key management practice in Arkansas for corn production is irrigation, which is highly recommended for producers to have a successful crop, whereas different regions of the U.S. can maximize corn grain yield under a rain-fed production system. The corn growing season begins with planting in late March carrying over into early April with the crop being harvested by late August into early September. The length of a growing season is dictated by hybrid selection and is directly related to environmental factors such as air and soil temperature along with weather events such as rainfall.

For in-season monitoring, producers will use leaf collar counts and growing degree units (GDUs) to forecast growth stages and crop management decisions such as fertilizer and pesticide application. Growing degree units are calculated based on accumulated temperature or heat units that occur above or below thresholds during the season. Thresholds are set to a specific species of plants, for corn specifically, the minimum threshold is set to 10˚C (50˚F) and the maximum threshold to 30˚C (86 ˚F) (Ross et al., 2009). Thresholds are established based on how the plant will react physiologically to temperature; going above or below the base or maximal temperature will result in the plant halting physiological growth and biomass accumulation at the time. The following is an example of the equations used to determine GDUs:

$$\text{Daily average temperature} = (\text{Max daily temp}\ ^\circ + \text{Min daily temp}\ ^\circ) / 2$$

And

$$\text{Daily GDU} = (\text{Daily average temperature} - 50^\circ\text{F or } (10^\circ\text{C})) / 2$$

At the beginning of the year or even at the end of the previous year producers will determine which hybrid they will grow for the upcoming season. Typically, seeding rates are anywhere between 64,000 to 80,000 plants per hectare depending on the recommendation guideline based on irrigation strategies and management techniques such as row spacing (Ross et al., 2009). Genetic modification has added a significant number of desirable characteristics to corn hybrids to overcome environmental challenges as well as pest pressures that may arise during the season. Hybrid selections are heavily influenced by herbicide and pest tolerance, yield potential, days to maturity, standability, and a few other agronomic properties. Corn hybrids will fall into one of the following classifications; early-, medium-, or full-season based on relative maturity expressed in days-to-maturity. A producer's decision on hybrid selection correlates with the environmental conditions they will face in-season and length of the growing season. Generally, for Arkansas, the highest corn yields are achieved by selection of hybrids with classifications of medium- and full-season which falls in the range of 112- to 120-day maturity (Ross et al., 2009).

Influence of Nitrogen Rate on Yield and Nitrogen Use Efficiency (NUE)

One of the most common yield limiting factors in corn production across the world is nutrient deficiencies, which can thankfully be overcome through proper nutrient management (Mueller et al., 2012). As the population continues to grow, researchers and producers alike must meet the demand to produce more food with similar resources to what they have now (Ruffo et al., 2015). The simplest way to meet this demand is by closing the gap between actual yields produced by farmers and the genetic yield potential of modern corn hybrids. Corn yields increases have fallen behind other popular cereal grains in regard to reaching their genetic yield potential; in all of the regions of corn production not once have the yields exceeded over 70% of the genetic potential. One suggestion to closing this gap is through harmonizing N availability with crop demand which can be obtained through split applications and irrigation management. Previous literature provides evidence that multiple split applications of N aids tremendously to maximizing yield potential of intensively managed corn. Understanding how N rates at different application times affect plant physiological properties will greatly improve efficiency and profitability.

Bender et al., (2012) and Karlen et al., (1988) intensively studied N uptake and partitioning that occurs during the corn growing season. Both found an interesting period between VT and R1 illustrating a reduction in vegetative N accumulation in the plant followed by a steady but slightly decreasing plateau period. An underlying question remains: what is happening to the N in the corn plant during that plateau period? Research does show that with continued N applications, the relationship will cause a reduction in yield at some point, just like it would in other cereal crops. Recent research by Bender et al., (2012) and Roberts, et al., (2016) implies that understanding the relationship between N rate and NUE in corn, relies on studying the three-way spilt application more intensively. The three-way split application suggests that >90% NUE can be achieved under the right conditions at pre-tassel timing of application (Bender et al., 2012). In order to achieve a high NUE at that time, the side-dress N rate might be considered deficient. However, if the side-dress N rate is at optimal, applying pre-tassel N would significantly reduce the NUE to <60%.

Importance of Nitrogen Management

Brady and Weil (2008) said it best: "More money and effort is spent on the management of N than on any other nutrient element". Producers rely on N fertilizer inputs as a security that maximal yields will be achieved at the end of the season. More than anything, producers see an immediate response to N fertilizer application due to plants turning a deeper green color and significant vegetative growth. However, excess N fertilizer use is becoming more prevalent over time especially since some N fertilizer input costs are low. Excess N can be just as problematic as a deficiency or at times worse, causing algal blooms, hypoxia, ozone degradation and economical losses (Brady and Weil, 2008). Undoubtedly, many agricultural soils cannot sustain efficient cereal crop production without inputs of N from various sources (Freney et al., 1995.) Over the years the primary goal for researchers and producers alike has been to increase profit and decrease the potential for negative environmental impacts. These goals are achievable through development of new fertilizer technologies, improved crop management practices, a better understanding of the factors influencing N loss, and timing of N fertilizer applications.

Corn Yield Components

It's essential to understand the components that influence corn grain yield and the growth stages at which they are being determined. In corn production, there are five yield components: plants per hectare, ears per plant, kernel rows per ear, kernels per row, and kernel weight. In relation to N fertilization, four of the five components can be influenced by N availability: ears per plant, kernel rows per ear, kernels per row, and kernel weight. Plants per hectare is set by seeding rate and emergence and is very rarely impacted by fertilization unless overapplications of N fertilizers lead to reduced plant stands. Similarly, the number of ears per hectare is often a function of plant population and the synchrony of corn emergence with most modern hybrids only producing one ear per plant but can be influenced by N fertilization to a limited degree. Kernel rows per ear will be determined between the V6-V8 growth stages, kernels per row is determined from V8-VT, and kernel weight during grain fill from R2-R6. It's important to understand that seeding rate and emergence rate will play a part in each of these components (Iowa State University, 2018). In addition, number of harvestable ears per plant is determined during the reproductive period right before tasseling (Lesoing and Francis, 1999).

Plants per hectare, or plant population, is a critical component and sets the stage for maximal corn grain yield potential. Yields can be maximized when adequate plant spacing is achieved (uniform spacing based on row spacing and seeding rate), leading to accelerated leaf canopy expansion which maximizes leaf area index, thus maximizing interception of solar radiation early in the season (Lobell et al., 2009). Kernel rows per ear, kernels per row and kernel weights were highly influenced by two major factors: irrigation and N availability (Harder et al., 1982; Pandey et al., 2000). More importantly, greater N applications under water stressed conditions will reduce yield further (Pandey et al., 2000). Ultimately as water stress becomes more enhanced, response to N declines. For producers, the biggest take away from this research is that, as irrigation deficits increase, N rates should be adjusted in order to economically optimize yields as maximal yield potential is no longer attainable.

Pre-Tassel Nitrogen Fertilizer

The three-way spilt approach is a new management practice for N in corn. Most farmers will use a two-way split where the bulk of NUE research has been conducted in past literature (Bigeriego et al., 1979; Russelle et al., 1981). Recent research has suggested that a three-way spilt could be more efficient and include an economical gain to farmers (Bender et al, 2012; Walsh et al, 2012 Roberts et al, 2016). However, there is a misleading idea that since N is luxury consumed by most plants more N is always better. Producers are advised to apply N at growth stages that express the highest FNRE values (Roberts et al., 2016). Pre-tassel applications can achieve high FNRE values when suboptimal or optimal side-dress applications exist while low values are obtained following above optimal side-dress rates. Overfertilization with N isn't as noticeable or detrimental to corn as compared to other cereal crops such as rice and wheat (*Triticum aestivum*). As N fertilization increases in corn, yield gains will eventually experience a lag period resulting in a plateau effect between yield and N rate. Although corn has much larger above ground biomass than other cereal crops, it is complimented by brace roots which provide stability to plants that resist lodging events due to excessive N applications. Disease potential is also less of a concern in corn production as N application increases. Overall, genetic makeup, physical attributes and management practices result in corn being less susceptible than other cereal crops to yield loss due to excessive applications of N.

Nitrogen Fertilization Cost

For producers, fertilizer inputs are required to secure a positive net return on crops at the end of the year. Anywhere from 32 to 45% of total operating cost is dedicated to fertilizer applications with N contributing more than any other nutrient source to corn production input costs (University of Arkansas, 2019). In 2021-2022 urea prices hit near record highs as strains on production and natural gas prices soared. As increases in urea price continue, maximizing NUE must be addressed especially when N fertilization alone accounts for 60% of the fertilizer expense cost for corn production (University of Arkansas, 2019). The best way to improve profitability is by maximizing NUE through proper rates, sources, placement, and timings of application. Roberts et al., (2016) found that higher FNRE values can be obtained by adjusting N rates based on environmental and management practices. Corn has an advantage when it comes to application fees since most of the N fertilizer can be applied via ground application equipment. According to the University of Arkansas (2019), it cost \$18.51 ha^{-1} to apply fertilizer by ground application at a straight rate regardless of the amount applied. In reference to N application at the pre-tassel stage, there are limited options to apply fertilizer via ground application equipment, but aerial application is often available to Arkansas producers due to the high concentration of rice production in the region. Aerial application can increase expenses compare to a ground application; \$19.75 ha^{-1} for aerial use plus an additional fee of \$ 0.18 kg^{-1} if more than the 45 kg product ha^{-1} is applied. The required minimum application rate for aerial application raises critical evaluation of whether applying pre-tassel N fertilizer is economically feasible.

Importance of Nutrient Accumulation and Partitioning

An important component of understanding nutrient accumulation and partitioning within plants relies heavily on the understanding of how the plants use the nutrients for metabolic processes. For instance, N is used for amino acid production which leads to protein and enzyme synthesis (Brady and Weil., 2008). It is estimated roughly 50% of increased corn grain yield is traceable to genetic improvement (Duvick, 1977, 1992) while the remainder can be attributed to improved management of fertilizer nutrient inputs. Often N is the focus of nutrient use efficiency improvement, although other essential macronutrient and micronutrient fertilizer inputs contribute to high-yielding modern corn hybrids. With improved grain yields in crops over the last 50 yrs comes decreased soil macronutrient and micronutrient levels (Bender et al, 2012). Due to the demand of nutrients from high yielding crops, some soils in North America have dropped to below critical nutrient levels in the last decade (Fixen, 2010). Evaluating accumulation of nutrients such as Phosphorus (P), Potassium (K), Sulfur (S), Calcium (Ca), Magnesium (Mg), Iron (Fe) and Zinc (Zn) in modern corn hybrids can help address corn yield gaps.

Fertilizer recommendations in many states is based on data collected from previous decades which may provide inadequate rate recommendations for modern corn hybrids. In-season fertilizer applications are known to improve nutrient use efficiencies when timing and rate is associated with crop demand of the nutrient. Plants use various pathways to obtain and utilize nutrients. Partitioning pathway behaviors are dictated by the chemical properties of the nutrient. As agriculture research provides new technology that improves crop grain yield and biomass production, there should be a focus on improvements to nutrient uptake ability to accommodate the increase in biomass production too (Bender et al., 2012). More importantly, there is a need for a deeper understanding of nutrient accumulation and partitioning patterns in row crops to establish better management practices and avoid nutrient loss along with economic losses.

Nutrient Loss Mechanisms Associated with Irrigated Corn

The most difficult nutrient to manage in most crop production systems is N. The bulk of N management difficulties result from the complexity of the N cycle. An atom of N may appear in many different chemical forms, each with its own unique properties, behaviors, and consequences for the ecosystem due to its ability to exist in several different oxidation states (Brady and Weil., 2008). The potential for N loss will vary across associated factors situated through ecosystems, soil characteristics, cropping procedures, fertilizer application techniques and weather conditions in-season (Freney et al., 1995). The four possible soil loss mechanisms when N is in the form of ammonium (NH_4^+) are: immobilization, plant uptake, ammonium fixation in 2:1 clay soils, and volatilization. Nitrogen loss while in the form of nitrate (NO_3^-) can be caused by immobilization, plant uptake, leaching (especially associated with sandy soil textures), and loss due to denitrification (Brady and Weil, 2008). For Arkansas irrigated corn production, the main sources of N loss will be denitrification, ammonia volatilization and leaching.

Denitrification. Denitrification is an anaerobic process by heterotrophic and autotrophic bacteria that reduces NO_3^- to a gaseous form like nitric oxide (NO), dinitrogen monoxide (N_2O), and dinitrogen gas (N_2) (Brady and Weil, 2008). Denitrification potential is much greater under wet conditions which have received large N fertilizer applications or high organic carbon (C) inputs (Nieder et al. 1989; von Rheinbaben, 1990). Research conducted by Linn and Doran (1984), found that denitrification will only be present when soil water content is >60% of the air-filled pore space. In Arkansas, untimely rainfall or reflooding events caused by furrow irrigation will increase the potential for denitrification after N fertilization.

Ammonia Volatilization. The process of losing NH_4^+ to gaseous ammonia (NH_3) and can result in significant N loss from some ammonium-based fertilizers. Ammonia losses are greatest where the cation exchange capacity of the soil is low or where the NH_4^+ isn't in close contact with the soil (Brady and Weil., 2008). Soil incorporation of ammonium-forming N fertilizers is critical to avoiding volatilization losses. When monitoring NH_3 loss, it's crucial that temperature, soil pH solution and/or irrigation water is closely regulated. Soil pH affects the equilibrium between NH_4^+ and NH_3. As the relative percentage of NH_3 increases from 0.1 to 1, 10 and 50%, soil pH gradually increases 6 to 7, 8 and 9, respectively (Freney et al. 1993). Another major environmental factor is wind speed. When high winds are present, transport of NH_3 away from air-water or air-soil interface via evaporation can increase the volatility (Freney et al. 1981; Denmead et al. 1982; Fillery et al. 1984).

Leaching. When NH_4^+ and NO_3^- are not adsorbed to soil colloids, leaching can occur. Since most soils carry a net negative charge, NO_3^- is the form of N which is most prone to leaching in soils when there is a net downward movement of water through the soil profile. The majority of all soils have some leaching capacity, but this will vary greatly depending on soil texture and structure (Brady and Weil, 2008). Nitrate ions can move freely down the soil profile into the drainage water, causing major environmental concerns along with a loss in profitability as this reduces the NUE of applied fertilizers. Sandy soils most likely will suffer from this form of N loss. Heavy rainfall events favor leaching of NO_3^- past root zones, which decreases fertilizer recovery efficiency. Smaller portions of rainfall/irrigation over multiple events can help reduce the leaching potential of many soils.

<u>Delayed-Nitrogen Fertilization</u>

Nitrogen application timing is critical to sustain high yields and is pivotal to reducing potential N losses. Delayed-N fertilization research over the years has proven time and time again that the best practice in managing N applications in corn is to apply N at the time when both the need for N and N uptake are maximized. By doing so, corn will be able to achieve higher NUE by reduction of loss mechanisms (Walsh et al, 2012). Delayed-N fertilization can cause significant yield loss if not managed correctly. The key to delaying N application starts with providing enough N early in the season to stimulate rapid root development for better crop establishment. Walsh et al., (2012) describes this as an early on ‘catch up’ strategy. If the crop cannot catch up, it will fail to maximize yields. Research conducted by Bigeriego et al. (1979) found evidence that delayed N fertilization resulted in greater efficiency in utilization of N for grain production and that the corn plant remained physiologically active longer in the translocation of N from other plant parts to grain. The research further explained that application of smaller rates of N at side-dress encouraged the roots to have more active absorption which contributed to more efficient translocation of N to grain.

A major consequence of delaying N for too long is reducing yields and NUE (Binder et al., 2000). One way to determine how long to delay N application relies on how much native soil N is available to the plant. When plants are grown on a soil with low soil N in the beginning of a season, the maximized N uptake rate will be significantly reduced. Therefore, response to side-dress N rates later in the season are related to insufficient N uptake earlier. Determining how long to delay N applications is not clear for irrigated corn production and needs to be further evaluated.

Irrigation and Nitrogen Management in Corn

The ability to use irrigation in the Mid-south region allows diverse N management strategies. Without irrigation in the Mid-south, corn production would most likely not be profitable. The Arkansas Corn Production Handbook recommends that corn should only be grown if and only if it can be irrigated. Even though reasonable yields can be achieved without irrigation in wet years, any drought stress can lead to charcoal rot and aflatoxin which can lead to total crop failure (Tacker et al., 2009). Irrigation systems influence N management by making it more efficient in N uptake by allowing producers to supply multiple applications of fertilizer-N to crops via conventional techniques and fine-tuning N supply (Muirhead et al., 1985). When N fertilizer is incorporated by means of irrigation, N becomes dissolved into solution and incorporated into the root zone making it readily available for plant uptake. The biggest advantages to fertilizer being supplied by irrigation are simplicity, convenience, and low cost (Freney et al., 1995.) The most common source of N fertilizer in Arkansas is urea, which has proven to be an efficient N source for corn production when managed properly (Muirhead et al., 1985). However, urea is often applied broadcast as a dry granular fertilizer and fertigation is restricted to areas with overhead irrigation such as center or lateral pivots

Irrigation allows for better distribution of mineral-N throughout the soil profile as well. Mineral-N, such as NO_3^- and NH_4-N is the readily plant available N that the plants can take up from the soil (Brady and Weil, 2008). Accumulation of mineral-N in the upper soil profile along with an active root system will create more absorption of N from the side-dress application thus resulting in less leaching and denitrification. Russelle et al. (1981), found that at-planting fertilizer did not have the same significant benefit to mineral-N or residual-N compared to side-dress N. Evidence from Walsh et al. (2012), supports this conclusion as well. Pre-plant or at-planting fertilizer should be applied to help establish the corn crop, not to secure maximal grain yield. At-planting, N has more potential to leach beneath the rooting zone of the crop which in return will prevent the crop from being able to take up the mineral-N from the soil. High occurrence of N leaching at planting is entirely related to the fact that corn roots have not penetrated the soil profile far enough nor had the time to develop enough root length to capture N before it moves below the root zone. As the corn plant develops, its roots can penetrate deeper into the soil profile leading to reduced leaching potential.

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Chapter Two:

Uptake Efficiency of Pretassel Nitrogen Applications in Arkansas Corn Production

Abstract

Corn (*Zea mays* L.) grain yield within highly intensive fertilizer management and irrigation systems can be influenced by late-season N applications. Research was conducted at the Milo J. Shult Agriculture Research & Extension Center (SAREC) near Fayetteville, AR and the Pine Tree Research Station (PTRS) near Colt, AR during the 2018 and 2019 growing seasons. Eight different N treatments were implemented as a combination of side-dress rate and pretassel N application timing. At the side-dress application timing near the V6-V8 growth stage, either 90 or 112 kg N ha^{-1} was surface broadcast as urea. At the pretassel growth stage, treatments received either 0 or 50 kg N ha^{-1} surface broadcast as ^{15}N-labeled urea and were compared across two different application timings; early tassel (VT) or at late reproductive stage 1 (R1) to determine the effect on (fertilizer-nitrogen recovery efficiency) FNRE. Grain yields, total-N uptake and FNRE were influenced by the interaction of N treatments. Corn grain yields were maximized at two of the four sites with the optimal sidedress N rate ($p = 0.0201$) or a combination of sidedress and pretassel N rates ($p = 0.0143$). The lowest FNRE was 12% and occurred when 50 kg ha^{-1} was applied at late R1. The highest FNRE was 85% when 50 kg ha^{-1} was applied at early tassel. The results provided in this paper highlight that although higher FNRE can achieved, that does not necessarily correlate to a grain yield increase.

Introduction

The increasing number of furrow-irrigated corn (*Zea mays* L.) hectares across the Mid-south region continues to enhance the overall productivity of the crop rotation and provide significant economic returns for producers. The ability to irrigate and advancements in nutrient management have allowed Arkansas average corn yields of near 12,105 kg ha^{-1} in 2018 (Kelley and Capps, 2018) to be competitive with national average yields. Nitrogen (N) fertilization contributes 32-45% of the total operating cost for corn production in Arkansas (University of Arkansas, 2019). In order to be more profitable and environmentally sound there is a need to investigate N fertilization methods that are applicable to furrow-irrigated corn systems. Two different N management strategies are used in furrow-irrigated corn production: two-way split and three-way split. These spilt-N methods strategically time N applications around important corn growth stages allowing for maximal utilization of the fertilizer-N being applied which in return leads to reduced loss potential of fertilizer-N (Robert et al., 2016 and Scharf, et al., 2002). The split strategies break down as follows: two-way split begins with preplant application of 1/4 to 1/3 of the recommended N for the season incorporated before or during planting with the remaining N applied from V4 to V6; three-way split being the same amount of N applied at preplant with a reduction in the sidedress to 50% of the total recommendation but including an additional application time later in the season around 1-2 weeks prior to tasseling. Research conducted by Raun and Johnson, 1999 illustrate that N use efficiency (NUE) can be improved when splitting the N applications. The season total N requirement depends on the soil texture classification, yield goal, and native soil-N content.

It is emphasized repeatedly that N-application timing and rates must coincide with peak demands across the growing season for the sake of improving NUE. Current global NUE values are estimated at around 35% with the United States average of 41% for cereal grains suggesting that there is still room for improvement in how N is managed within a production system (Omara et al., 2019). Late-season N applications provided at the right rate and time can help improve the

NUE in crop production systems. Research conducted by Walsh et al., (2012) emphasizes the importance of determining appropriate fertilizer rates, timing and the ability to incorporate into the soil when considering late-season N applications. Research suggests that when fertilizer-N is applied at optimal rates and time, total-N uptake values can be maximized (Roberts et al., 2016). Total-N uptake values are influenced by the native and residual-N values at site locations (Bigeriego et al., 1979). Previous research in furrow irrigated production systems provide indication that not only is incorporation of N important but placement within the furrow as well (Greub et al., 2017). As mentioned by Roberts et al., (2016) NUE values include various environmental, cultural and production systems that may can reduce the overall NUE. Previous research provides evidence that increased NUE can be achieved under certain circumstances such as rainfed production (Bender et al., 2012) in contrast to furrow irrigation systems (Roberts et al., 2016). In-season management tools have potential to further increase the NUE. Research conducted by Greub et al., 2018 provided valuable insight to using the corn stalk nitrate test during post-harvest tissue analysis and can adequately determine the N status of corn produced within furrow irrigated production systems. The continued development of in-season and post-season N analysis coupled with a better understanding of the N dynamics of late-season N applications will help to improve overall NUE while not sacrificing yield or profitability. The objectives of this research were to investigate the influence of side-dress N rate and late-season N application timing on corn total N uptake, FNRE and grain yield using ^{15}N.

Materials and Methods

In 2018, one experimental trial was established at the Milo J Shult Agricultural Research and Extension Center (SAREC) in Fayetteville, AR, (36.09 N, 94.17 W). In 2019, three trials were established: one at the SAREC and two at the Pine Tree Research Station (PTRS) near Colt, AR, (35.12 N, 90.92 W). Table 2-1 provides the site characteristics and soil series for each site year in the study. Each trial followed soybean (*Glycine max* L.) in rotation, which represents the most common rotation used for furrow-irrigated corn in the Mid-south. The experiments were conducted to determine the influence of N rate and N application strategy on total N uptake, corn grain yield, and fertilizer N recovery efficiency (FNRE) in furrow-irrigated corn production.

The experiment contains eight fertilizer-N treatments generated by a factorial arrangement with combinations of the following: sidedress N rate of either 90 or 112 kg N ha^{-1} applied between the V6 - V8 growth stage and a pretassel N application of either 0 or 50 kg N ha^{-1} applied at early tassel or R1. All treatments received 34 kg N ha^{-1} applied as urea (460 g N kg^{-1}) at preplant which was incorporated into the bed immediately prior to planting. Table 2-2 provides a breakdown of the eight N treatments that were implemented at each location. All fertilizer-N treatments for these trials were hand-applied as granular urea 460 g N kg^{-1} treated at a rate of 0.89 g N-(n-butyl) thiophosphoric triamide (NBT) kg $^{-1}$ urea as Agrotain Ultra (285 g NBT L^{-1}, Koch Fertilizer LLC., Witchita, KS). To determine the FNRE of different N rates and application strategies among the specific treatment combinations, 2.5 atom % ^{15}N-labeled urea (Isotec, Miamisburg, OH) was applied at the designated pretassel application timing. All post-emergence N applications were incorporated with rainfall or irrigation within two days of hand-broadcast application to the soil surface.

At the beginning of the growing season, one composite soil sample composed of four, 3 cm diameter cores were taken from the field experiment area at a depth of 0-15 cm. The soil samples were oven-dried at 60 C, ground to pass through a 2 mm sieve, and submitted to the

University of Arkansas, Division of Agriculture Agricultural Diagnostic Lab (Fayetteville, AR) for soil pH and routine soil analysis. The soil analysis was used to ensure that soil pH and other nutrients were not limiting corn growth and productivity (Espinoza, L., and J. Ross. 2009) Corn GDUs were tracked using the Pioneer GDU calculator (Corteva, Indianapolis, IN) and number of leaf collars were monitored in the field throughout the season to support growth stage determination and time fertilizer applications.

For experimental purposes, fields were arranged into four blocks with plots that were four rows wide. Preplant fertilizer applications were made and raised beds were established on 76 cm row spacing at the PTRS location and on 91 cm spacing at the SAREC location. The blocks were parallel with the furrow direction and separated by a 1.52 m planted buffer. The fertilized area in each plot was four rows wide by 3.05 m long. Irrigation and pest management was implemented following recommendations for furrow-irrigated corn provided by the University of Arkansas Cooperative Extension Service (Espinoza and Ross, 2009). In 2018 at the SAREC location, the corn hybrid used was Pioneer 1197YHR (Corteva, Indianapolis, IN) a 111-day relative maturity hybrid and was planted atop the raised beds at a seeding rate of 84,000 seeds ha^{-1}. In 2019 at all locations, the corn hybrid used was Pioneer 1464VYHR (Corteva, Indianapolis, IN) a 114-day relative maturity hybrid planted atop the raised beds at a seeding rate of 84,000 seeds ha^{-1}. Important agronomic dates are provided in Table 2-1.

Biomass samplings were taken at three different growth stages; R2 (reproductive blister), R4 (reproductive dough), and R6 (physiological maturity) to capture the uptake of the ^{15}N-labeled pretassel application timings (Richie, et al. 1996). Timings of tissue and aboveground biomass samplings are presented in Table 2-3. Once plants reached at least 50% of the designated growth stage, sampling was initiated. Whole aboveground plant samples were collected from a 1 m section within the middle two rows in each plot at the soil surface. Based on the row spacing and plant populations a total of six whole plants were collected. The 1 m sections of corn taken from the middle two rows were used to ensure that no border row effect influenced N uptake and that the plants were collected were within the ^{15}N-labeled fertilizer application area. Samples were separated into three different components for individual analysis: leaves and stalks, husks and cobs, and grain.

Plant samples taken from the field were immediately brought back to the lab and all individual parts were dried with a forced air oven at 60 C until a constant weight was reached. Dry biomass weights were collected for each component and recorded. After dry weights were obtained the individual parts (i.e. leaves and stalks) were processed using a Craftsman 77615 wood chipper (Stanley Black & Decker, New Britain, CT) to collect a representative subsample before being ground to pass through a 1 mm sieve using a Thomas-Wiley Laboratory Mill, Model 4 plant grinder (Thomas Scientific, Swedesboro, NJ). The husks and cobs were not preprocessed in the woodchipper; instead, they were placed directly in the Wiley Mill and ground to pass through a 1 mm sieve. Grain preparation started with shelling kernels off all six cobs collected from individual plots in the field. The best way to shell whole cobs is using specialized equipment created by Almaco®, a Mazier (Almaco, Nevada, IA). The specialized equipment allows for each batch of cobs to be shelled fast, efficiently, and provides less kernel carry-over from treatment to treatment. Once grain is collected off the cobs, grain moisture was determined using a Dickey-John GAC® 2500-UGMA Grain Analysis Computer, (Precision Scale & Controls, INC., St. Louis, MO). Grain is further processed through a kitchen Aid Blade Coffee Grinder model BCG111 (Whirlpool Corporation, Benton Harber, MI), until grain is considered fine-textured powder for ^{15}N analysis. Subsamples of each plant part were submitted to the University of California - Davis Stable Isotope Facility (Davis, CA) to determine total nitrogen (TN) concentration and atom % ^{15}N, using an elemental analyzer interfaced to continuous flow isotope ratio mass spectrometer (Europa, Sercon, Ltd., Cheshire, UK). Fertilizer enrichment within the plant was calculated from % ^{15}N change according to the equation:

$$F = TN\ (x-y) / (z-y)$$

where *F* is the weight of ^{15}N labeled fertilizer N taken up by plant material (i.e., grain) (kg N ha^{-1}), *TN* is total nitrogen uptake in aboveground biomass of a specific plant component (kg N ha^{-1}), *x* is the atom % ^{15}N measured in the plant component, *y* is the average atom % ^{15}N measured in the untreated control, and z is the atom % ^{15}N of enriched urea fertilizer applied. The next step will be calculating the percent FNRE. To do this, the mass of ^{15}N labeled fertilizer-N recovered from each specific plant component was summed to determine the total mass of ^{15}N labeled fertilizer-N contained in the aboveground biomass of each treatment. The calculation was based on the following equation:

$$FNRE = (F/R) \times 100$$

where *F* is the total mass of ^{15}N recovered in the aboveground plant tissue (kg N ha^{-1}) and *R* is the ^{15}N labeled fertilizer-N application rate (kg N ha^{-1}).

The experiment was a three-by-three factorial randomized complete block design. The factorial consisted of two sidedress N rates, two N application timings, and three growth stage sampling times. In total there were eight different fertilizer-N treatments, but several of the 0 kg N ha^{-1} rates were included for N^{15} analysis and not included in all of the analyses. Corn grain yield was adjusted to 15% moisture prior to statistical analysis. Corn TN uptake and FNRE comparison represent only the N -treatments with ^{15}N-labeled urea. Grain yield was analyzed focusing on comparing N-treatment combinations (sidedress by pretassel rate) and the timing of pretassel application. Due to the complex nature of N^{15} analysis and the variations in native N availability and yield potential at each site, locations were analyzed separately. An Analysis of variance (ANOVA) was used to determine how response variables changed throughout the reproductive growth stages. All statistical analyses were analyzed using the PROC GLIMMIX function and ANOVA statistics in SAS v 9.4 (SAS Institute, Cary, NC). Separation of means was conducted using Fisher's protected LSD at an α=0.05 where appropriate.

Results and Discussion

Total Nitrogen Uptake

Total N uptake varied across locations and was influenced by a variety of factors included in the trial. Overall, the total N uptake in the aboveground biomass ranged from a low of 122 kg N ha^{-1} at the PTRS-West location to a high of 360 kg N ha^{-1} at the SAREC-18 location. The ANOVA for total N uptake indicated that there were no significant three-way interactions but growth stage at the time of sampling was influential as a main effect and as part of several two-way interactions (Table 2-4).

At the SAREC-18 location, total N uptake was influenced by the two-way interaction of sidedress rate x pretassel application time and the main effect of growth stage sample time (Table 2-4). Comparison of growth stage sampling times at the SAREC-18 location indicated that total N uptake increased from the R2 to R4 growth stage and then slightly decreased at the R6 growth stage (Figure 2-1). The highest total N uptake at the SAREC-18 location occurred at the R4 growth stage (360 kg N ha^{-1}) followed by 349 kg N ha^{-1} at the R6 growth stage. Statistically, there was no difference between the R4 and R6 total N uptake at the SAREC-18 location. At the R2 growth stage, total N uptake was at 315 kg N ha^{-1} and was statistically lower than either of the two later growth stage sample times. It is not surprising that the R2 growth stage represents the lowest accumulation of N of the three sample times, N demand increases more between the start of R2 and R4 growth stages as more N is required for grain fill (Bender et al, 2012). The significant two-way interaction of sidedress N rate and pretassel application time is presented in Figure 2-1. For the SAREC-18 location, when combining the 90 N kg ha^{-1} side dress rate with the late pretassel application timing the total N uptake was 246 kg N ha^{-1} and was statistically higher than the combinations of a low sidedress N rate (90 N kg ha^{-1}) and an early pretassel application timing and the high sidedress rate (112 N kg ha^{-1}) and the late pretassel application timing.

For the SAREC-19 location, the main effect of growth stage at time of sampling and the two-way interaction of growth stage and pretassel application timing were significant (Figure 2-2). Since the two-way interaction also includes the main effect of growth stage the two-way interaction is all that will be discussed in regard to the total N uptake at the SAREC-19 location. Similar to results from the SAREC-18 location, pretassel application time in combination with the 90 N kg ha^{-1} sidedress rate and the late pretassel application timing, a total N uptake of 248 kg N ha^{-1} was observed (Figure 2-3).

Total N uptake at the PTRS-East location includes the same pattern statistically with the highest total N accumulation at R6 (220 kg N ha^{-1}), next being R4 (196 kg N ha^{-1}) and finally R2 (157 kg N ha^{-1}) with the lowest accumulation (Figure 2-4). Note the difference in the amount of N kg ha^{-1} recovered from the locations in Fayetteville compared to the location at Pine Tree. The same pattern of events is noticed at the PTRS-West location. The highest total N was accumulated at R6 (204 kg N ha^{-1}), followed by R4 at 170 kg N ha^{-1} and lastly 122 kg N ha^{-1} at R2. In contrast to the PTRS-East location, total N uptake was influenced by a combination of pretassel time and sidedress rate. The highest total N uptake was achieved when the pretassel was applied at late R1 in combination with 112 kg N ha^{-1} applied at sidedress. It is important to note the only statistical differences were between early pretassel and late R1 pretassel within the lower sidedress N rate (90 kg ha^{-1}).

There was a two-way interaction between the pretassel application timing and side dress N rate. This interaction was significant at the SAREC-18, SAREC-19, and PTRS 96-West locations. At the SAREC-18 location, when combining the early tassel application with 112 N kg ha^{-1} side dress rate, the total N accumulation reached up to 386 kg N ha^{-1} (Figure 2-7). The other combinations whether an early or late R1 tassel application regardless of the side dress rate of either 112 kg N ha^{-1} or 90 kg N ha^{-1} resulted in no significant difference. It is worth mentioning that the combination of late R1 with a side dress rate at 112 kg N ha^{-1} resulted in the next highest total N uptake of 339 kg N ha^{-1} (Figure 2-5).

The total N uptake as the SAREC-19 location was influenced by a different interaction. The lowest total N uptake (195 kg N ha^{-1}) occurred with a late R1 tassel application rate with 112 kg N ha^{-1} sidedress rate. In contrast, the highest total N (248 kg N ha^{-1}) was observed with a late R1 tassel application in combination with a 90 kg N ha^{-1} side dress rate (Figure 2-6). There were no statistical differences between any of the other timing applications and side dress rates.

The only significant difference for the Pine Tree location occurred at the PTRS-West site. Statistically, when the side dress rate of 112 kg N ha^{-1} was applied we observed the highest total N uptake. Though there was no statistical differences between early tassel vs late R1 timings, total N uptake at late R1 was 193 kg N ha^{-1} while the early tassel application time resulted in a total N uptake of 169 kg N ha^{-1}. The 90 kg N ha^{-1} side dress rate resulted in the lowest observed total N accumulation at this site. Comparatively, total N uptake increased when the pretassel application occurred at early tassel (156 kg N ha^{-1}) while the late R1 application only resulted in 134 kg N ha^{-1}total N uptake. Though the side dress rate is important to the total N uptake at this location, the timing of pretassel application was more influential on total N uptake (Figure 2-6).

<u>Fertilizer Nitrogen Recovery Efficiency</u>

Like total N uptake, FNRE was variable across locations and was highly influenced by the growth stage at the time of sampling as a main effect and a component of several two-way interactions. For FNRE there were no three-way interactions at any of the locations, but two, two-way interactions of sidedress rate and growth stage at the time of sampling for the SAREC-18 location and pretassel application time and growth stage at the PTRS-West location. Values reported for FNRE ranged from a low of 18% to a high of near 80% across the growth stages that were sampled in this study. The timing of growth stage sampling in relation to when the N^{15} labeled fertilizer was applied was expected to have a profound impact on the rate of fertilizer recovery.

At the SAREC-18 site, N treatment recovery efficiencies were influenced by the main effect of pretassel application time and the two-way interaction of sidedress N rate and growth stage at time of sampling. When describing the two-way interaction at the SAREC-18 location, the FNRE peaked at 79% for the R4 sample time and a sidedress N rate of 112 kg N ha^{-1} was applied (Figure 2-7). That combination was higher than all 90 kg N ha^{-1} sidedress rates and growth stages as well as the R2 and 112 kg N ha^{-1} sidedress N rate combination. The influence of sidedress N rate at the SAREC-18 location seems to suggest that increased sidedress N rates led to an increase in the uptake of the pretassel N application, but all combinations of sidedress N rates and growth stages had FNRE values above 58%. The main effect of pretassel application time is presented in Figure 2-8. When the pretassel N application was made earlier in the season the FNRE was higher than if the application was delayed. Earlier application of the pretasel N at the SAREC-18 location resulted in 79% FNRE which was significantly higher than an application made at the late R1 growth stage. However, the application made at the late R1 growth stage resulted in an FNRE of 50% which suggests that even very late applications of N can be taken up effectively by the corn plant.

There were two significant main effects and no interactions for the FNRE at the SAREC-19 location. Like the SAREC-18 location, FNRE was impacted by the timing of the pretassel N application where early applications led to higher FNRE values (Figure 2-9). The FNRE results as influenced by pretassel application time were much lower than those reported for SAREC-18 even though the fields were situated on similar soils. The highest FNRE reported for pretassel application time at SAREC-19 was 41% which was almost half what was reported for SAREC-18 highlighting how changes in environment or other factors can lead to large reductions in FNRE even when soils and management practices are assumed to be similar. The main effect of growth stage and sample time on FNRE values for the SAREC-19 location are presented in Figure 2-10 and suggest a linear increase in FNRE as the growth stage at sample time increased. The highest FNRE value for the main effect of growth stage at SAREC-19 was 43% and occurred at the R6 growth stage, which was only statistically higher than the R2 growth stage. The main effect of growth stage at time of sampling provides an overview of how the N^{15} fertilizer was taken up by the plant following application and the fact that there was not an interaction with pretassel application time indicates that the fertilizer was taken up similarly regardless of whether it was applied earlier or later in the season.

Similar to the SAREC-19 location, the main effects of pretassel N application time and the growth stage at the time of sampling impacted the FNRE at the PTRS-East location but in different ways. The effect of pretassel application timing at the PTRS-East location indicated that the later application time resulted in a significantly higher FNRE of 48% (Figure 2-11), which was an opposite trend to what was noticed for SAREC-19 where the higher FNRE was observed when the pretassel N was applied earlier. The main effect of growth stage at the time of sampling at the PTRS-East location was similar to that of SAREC-19 in the sense that as the sampling time was delayed the FNRE increased, but it was not to the same degree. Both the R4 and R6 locations resulted in statistically similar FNRE values and were 54 and 55%, respectively. The two later sample times (R4 and R6) were both significantly higher than the earliest sample time at R2 which resulted in an FNRE of 21% (Figure 2-12). The results for FNRE across the various growth stage sampling times indicates the rapidity at which late-season N applications can be accumulated by the corn plant with the FNRE more than doubling in the eight-day time frame between the R2 and R4 growth stage samplings.

At the PTRS-West location the two main effects of pretassel application time and growth stage at the time of sampling were significant which led to a two-way interaction of these two main effects. The FNRE describing the interaction of pretassel application time and growth stage at the time of sampling is presented in Figure 2-13 and the FNRE is higher at the R4 and R6 growth stages when the pretassel timing was applied at late R1 rather than early tassel. There were no differences in FNRE between the pretassel N application timings at the R2 growth stage which most likely led to the significant interaction that was observed. Similar to other locations the effects of growth stage at the time of sampling were apparent as FNRE tended to increase with later sampling times and the highest overall FNRE (38%) at the PTRS-West location occurred when the corn was sampled at the R6 growth stage and the pretassel application was made at the late R1 growth stage. These results are somewhat counterintuitive and in contrast to some of the results at other locations. Generally, it would be expected for FNRE to be higher at later growth stages, as it often was, but that it would be higher for earlier pretassel N application times. These results suggest that environment and cultural management practices may impact late-season FNRE in ways that are not easily predictable.

Grain Yield

The impact of fertilizer management (sidedress N rate, time of pretassel N application and pretassel N application rate) only significantly influenced yield at the SAREC-18 and SAREC-19 locations (Table 2-5). There were no yield differences amongst treatments for either of the locations at the PTRS. At SAREC-18 the main effect of sidedress N rate was the only main effect that was statistically significant and there were no significant interactions. Grain yield at SAREC-18 was higher when the higher sidedress N rate (112 kg N ha^{-1}) was applied and suggests that yield potential was determined by this N application and was not impacted by the late-season N application. The largest grain yield advantage was achieved when the side dress rate of 112 kg N ha^{-1} was applied (1,5820 g m^2). Comparatively, the 112 kg N ha^{-1} rate yielded 146.0 g m^{-2} more than the 90 kg N ha^{-1}. These results are important as they highlight the fact that regardless of how well late-season N applications are taken up by the corn crop they are wasteful if they do not impact yield. At the SAREC-18 and two PTRS locations the data indicates that there was no benefit from late-season N applications and suggests that more work should focus on identifying when and where late-season N applications are needed to increase corn grain yield.

The SAREC-19 grain yields were influenced by the interaction of pretassel N rate and sidedress N rate (Table 2-5). The response of corn grain yield for this location follows more of an anticipated response where yields were increased by a pretassel N application when the lower sidedress N rate was applied. When 90 kg N ha^{-1} was applied at sidedress (which was most likely suboptimal) corn grain yield was significantly increased by the late-season N application, whereas there was no yield benefit from late-season N applications when 112 kg N ha^{-1} was applied at sidedress (Figure 2-14). The highest yield at the SAREC-19 location (1,546 g m^{-2}) was achieved when 90 kg N ha^{-1} was applied at sidedress and 50 kg N ha^{-1} was applied late-season, which was significantly higher than when 112 kg N ha^{-1} was applied at sidedress and 50 kg N ha^{-1} was applied late-season. The results for the SAREC-19 location suggest that late-season N application may increase corn grain yield when sidedress N rates are insufficient, but also raises questions as to why higher season total N rate combinations did not lead to higher overall corn grain yields. More work is needed to tease out the complex interactions between N rate, N application timing and environmental conditions to help predict when and where a response to late-season N may be expected.

Conclusions

Our results indicate that environmental and cultural factors alone cannot predict increasing grain yield simply by increasing the FNRE. Previous research has shown that it is not uncommon for results to indicate high FNRE values with no increase in grain yield (Mueller et al., 2017). Although, splitting fertilizer-N applications across different stages of development results in higher FNRE, there needs to be a significant increase in yield or economic returns to justify the practice. Within the four field trials included in this study there were a wide range of environmental conditions, but similar management approaches and considerations. However, there were no clear trends in the impacts of sidedress N rate and pretassel N timing on total N uptake, FNRE or corn grain yield. These results suggest that the intertwined complexity of these management factors require more research to fully understand. The development of remote sensing tools which can correctly identify potential N deficiencies and projected yield potential of the corn crop may help to predict when and where late-season N applications are warranted. Nutrient management tools such as in-season leaf tissue tests can play a vital role in indicating whether additional fertilizer applications are necessary to increase corn grain yields while maximizing net returns. Overall, high FNRE values can be obtained in furrow-irrigated corn production systems (>50%). However, there is a wide range in values that can be achieved, and the application timing of late season N applications needed to maximize FNRE at a particular location is currently not easy to predict. Future research should focus on the development of tools or methods to better predict when and where late-season N applications are needed to not only improve FNRE but increase corn grain yield or overall producer profitability.

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Table 2-1. Site characteristics for the four trial locations used in this study during 2018-2019.

Location	**Year**	**Planting Date**	**Emergence Date**	**Sidedress N application**	**Early R1 N application**	**Late R1 N application**	**Soil Texture**
SAREC-18	2018	4/24/2018	5/1/2018	5/29/2018	6/15/2018	6/28/2018	Captina Silt Loam
SAREC-19	2019	4/11/2019	4/24/2019	5/28/2019	6/28/2019	7/5/2019	Captina Silt Loam
PTRS-East	2019	5/1/2019	5/7/2019	5/29/2019	7/4/2019	7/9/2019	Calloway Silt Loam
PTRS-West	2019	5/1/2019	5/7/2019	5/29/2019	7/4/2019	7/9/2019	Calhoun Silt Loam

Table 2-2. Description of the nitrogen (N) treatment combinations included in the trial.

Treatment	Preplant Rate	Sidedress Rate	Pretassel Rate	Late-Season Timing
	---------------------(kg N ha^{-1})---------------------			
Trt 1	34	90	0	Early Tassel
Trt 2	34	90	0	Late R1
Trt 3	34	90	50*	Early Tassel
Trt 4	34	90	50*	Late R1
Trt 5	34	112	0	Early Tassel
Trt 6	34	112	0	Late R1
Trt 7	34	112	50*	Early Tassel
Trt 8	34	112	50*	Late R1

*Denotes ^{15}N-labeled urea fertilizer application.

Table 2-3. Tissue sampling dates for each site.

Location	Year	R2 Whole Plant	R4 Whole Plant	R6 Whole Plant
SAREC-18	2018	7/12/2018	7/27/2018	8/20/2018
SAREC-19	2019	7/11/2019	7/23/2019	8/26/2019
PTRS-East	2019	7/16/2019	7/24/2019	8/21/2019
PTRS-West	2019	7/17/2019	7/24/2019	8/21/2019

Table 2-4. Analysis of variance for total nitrogen (TN) uptake, and fertilizer N recovery efficiency (FNRE) at all locations in 2018 and 2019.

	SAREC-18		SAREC-19		PTRS-East		PTRS-West	
Effects	**Total N Uptake**	**FNRE**	**Total N Uptake**	**FNRE**	**Total N Uptake**	**FNRE**	**Total N Uptake**	**FNRE**
Sidedress Rate (SR)	0.0143	0.0017	0.0802	0.2029	0.0823	0.3101	0.0008	0.6318
Pretassel Timing (T)	0.3352	< 0.0001	0.8737	0.0064	0.7852	0.0139	0.8222	0.0037
Growth Stage (GS)	0.0099	0.0691	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
SR x T	0.0508	0.1413	0.0200	0.2553	0.9993	0.5504	0.0115	0.3267
SR x GS	0.9615	0.0146	0.2003	0.7527	0.1610	0.6614	0.6175	0.9624
T x GS	0.7745	0.0506	0.3568	0.1952	0.8303	0.6326	0.0693	0.0294
SR x T x GS	0.3891	0.1648	0.1267	0.9514	0.7822	0.7032	0.7049	0.5826

Table 2-5. Analysis of variance for grain yield at all locations.				
	SAREC-18	**SAREC-19**	**PTRS-East**	**PTRS-West**
Effects	**Grain Yield**			
Sidedress Rate (SR)	0.0201	0.0108	0.5171	0.2384
Pretassel Timing (T)	0.9057	0.2641	0.7818	0.9686
Pretassel Application (PT)	0.0540	0.0253	0.0659	0.0565
SR x PT	0.3670	0.0143	0.8407	0.5374
PT x T	0.1432	0.7886	0.3043	0.7235
SR x T	0.1808	0.4576	0.9999	0.4213
SR x T x PT	0.1861	0.6584	0.5643	0.2111

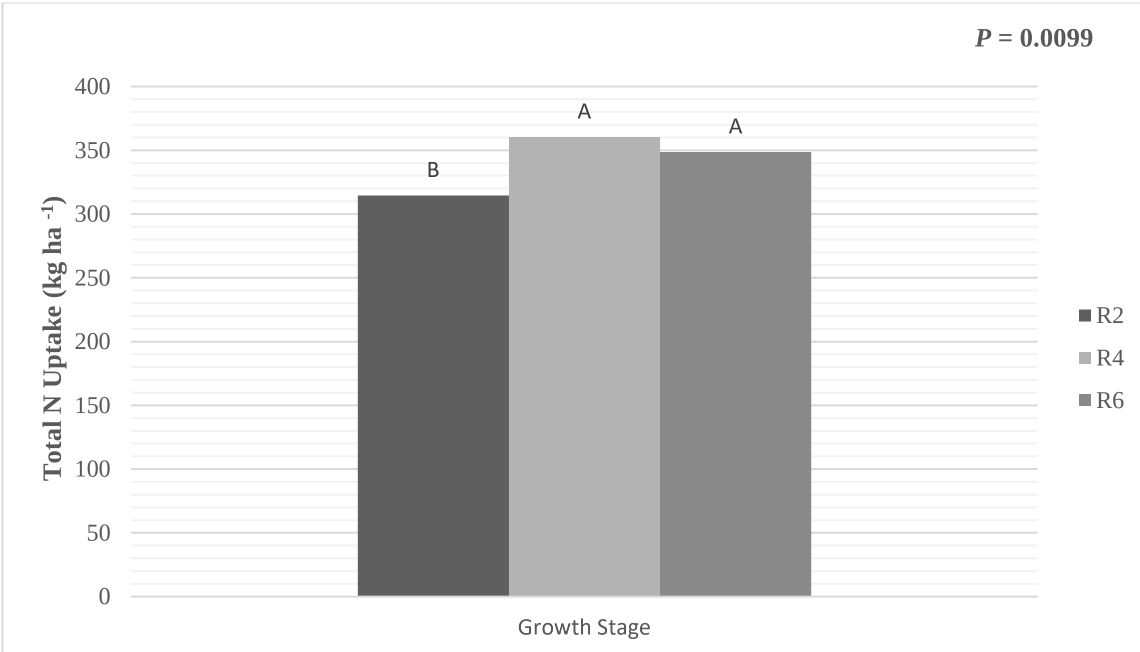

Figure 2-1. Total N Uptake as influenced by growth stage at the SAREC-18 location. Means not sharing the same letter are significantly different (Fisher’s, P < 0.05).

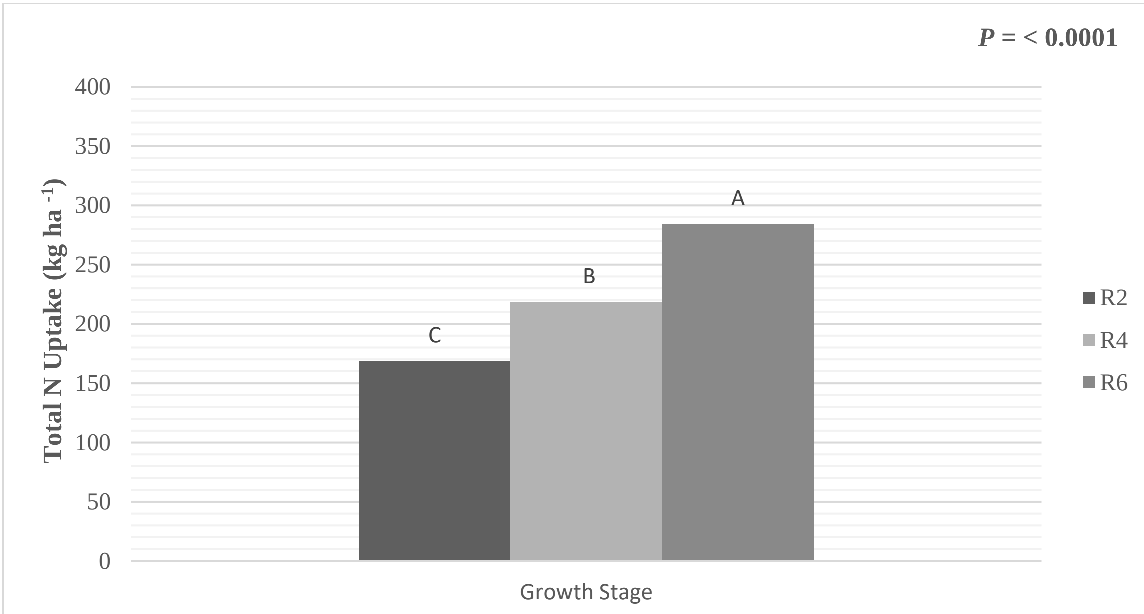

Figure 2-2. Total N Uptake as influenced by growth stage at the SAREC-19 location. Means not sharing the same letter are significantly different (Fisher's, P < 0.05).

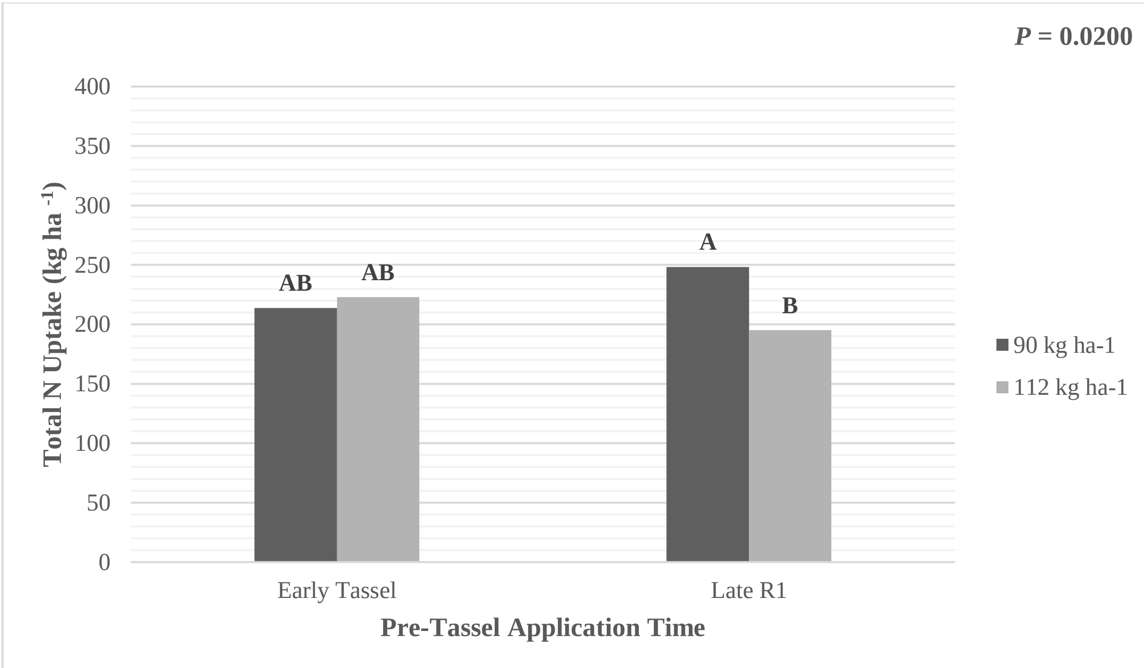

Figure 2-3. Total N Uptake as influenced by growth stage at the SAREC-19 location. Means not sharing the same letter are significantly different (Fisher's, P < 0.05).

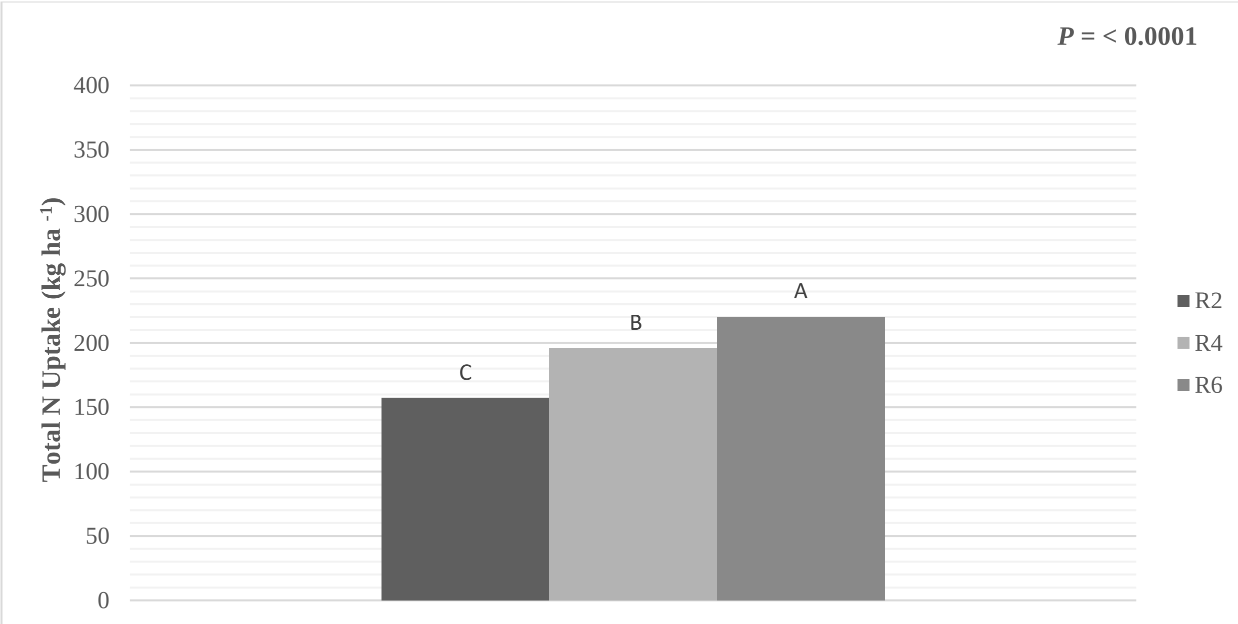

Figure 2-4. Total N Uptake as influenced by growth stage at the PTRS-East location. Means not sharing the same letter are significantly different (Fisher’s, $P < 0.05$).

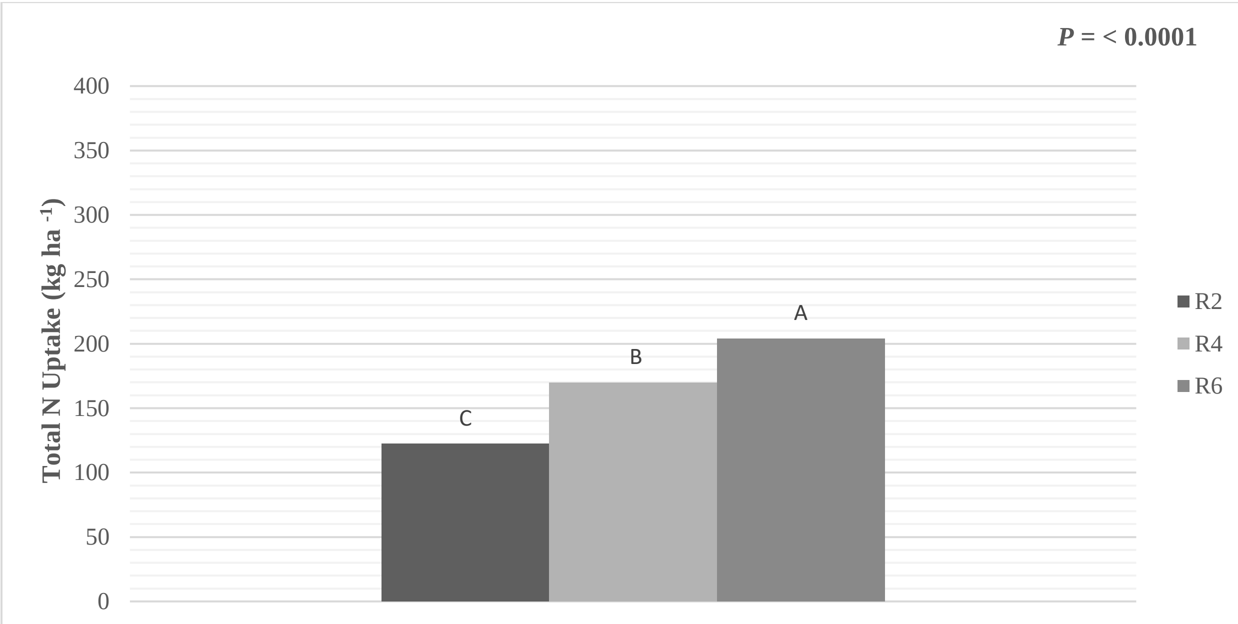

Figure 2-5. Total N Uptake as influenced by growth stage at the PTRS-West location. Means not sharing the same letter are significantly different (Fisher's, P < 0.05).

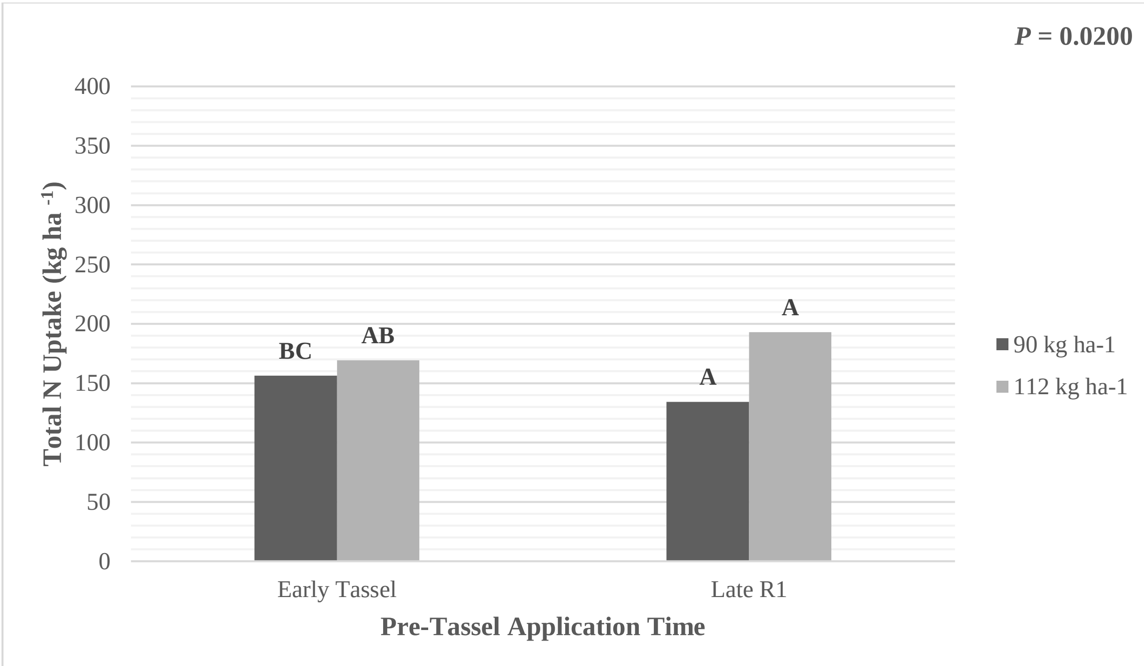

Figure 2-6. Total N Uptake as influenced by pretassel timing x side dress rate at the PTRS-West location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

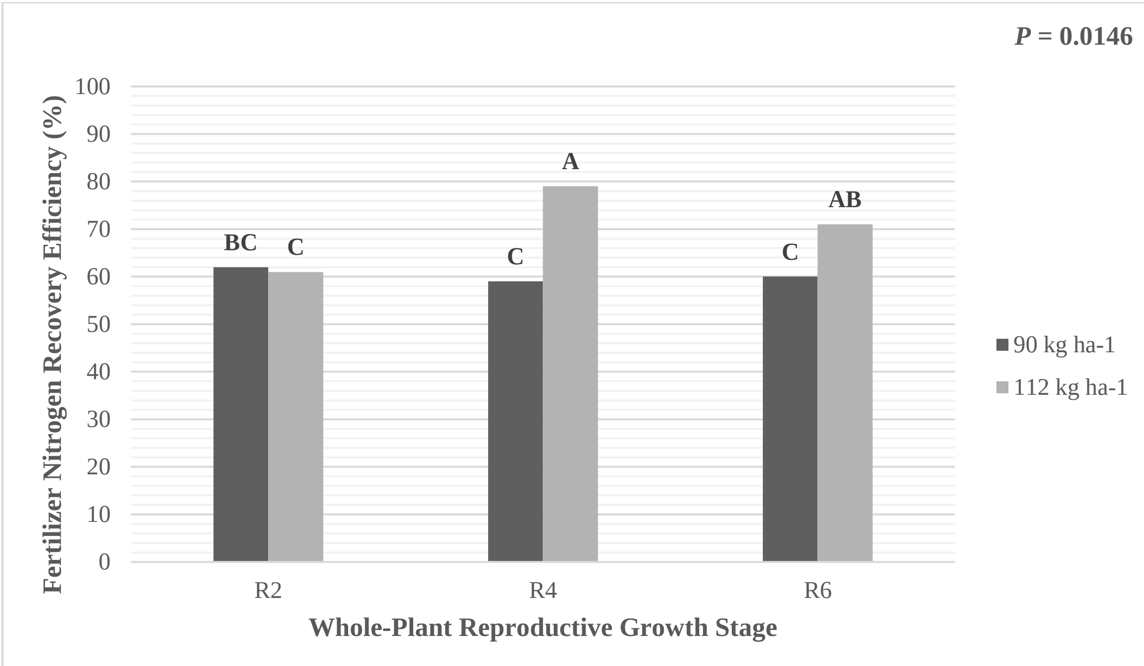

Figure 2-7. Fertilizer nitrogen recovery efficiency (FNRE) as influenced by sidedress rate x growth stage at the SAREC-18 location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

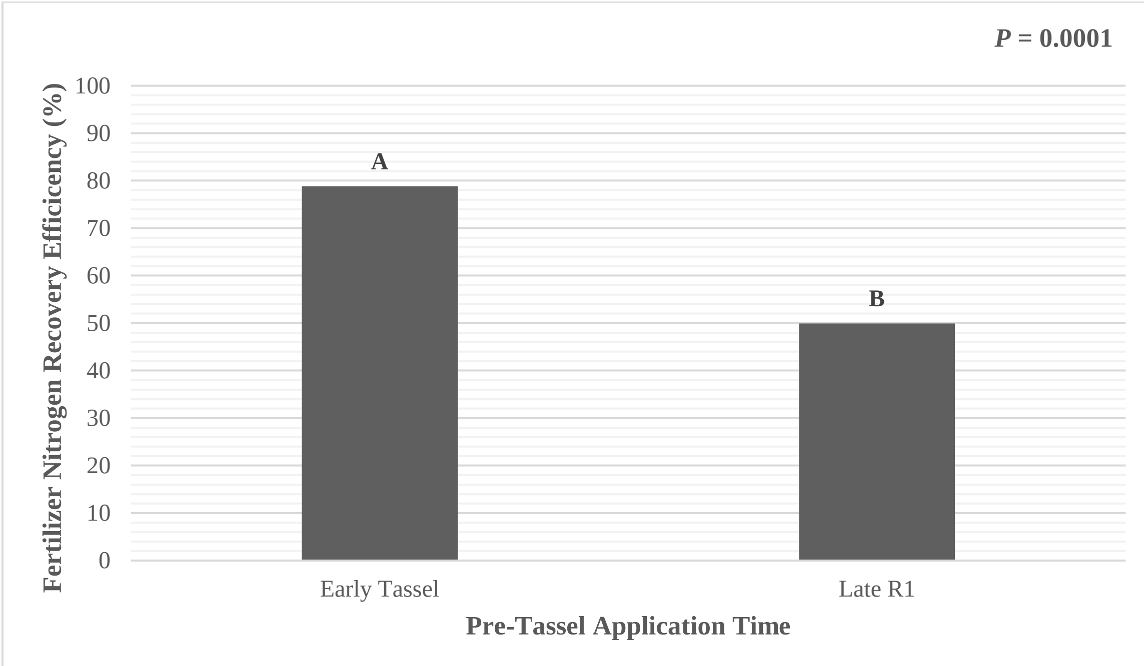

Figure 2-8. Fertilizer nitrogen recovery efficiency (FNRE) as influenced by pretassel timing at the SAREC-18 location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

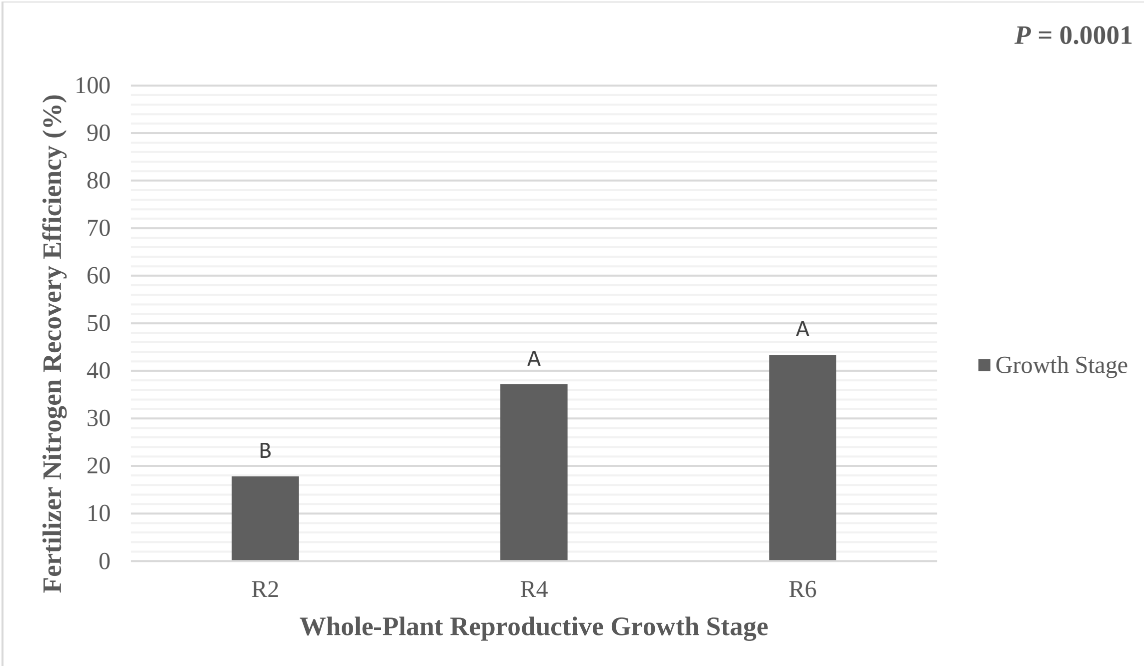

Figure 2-9. Fertilizer nitrogen recovery efficiency (FNRE) as influenced by growth stage at the SAREC-19 location. Means not sharing the same letter are significantly different (Fisher's, $P <$ 0.05).

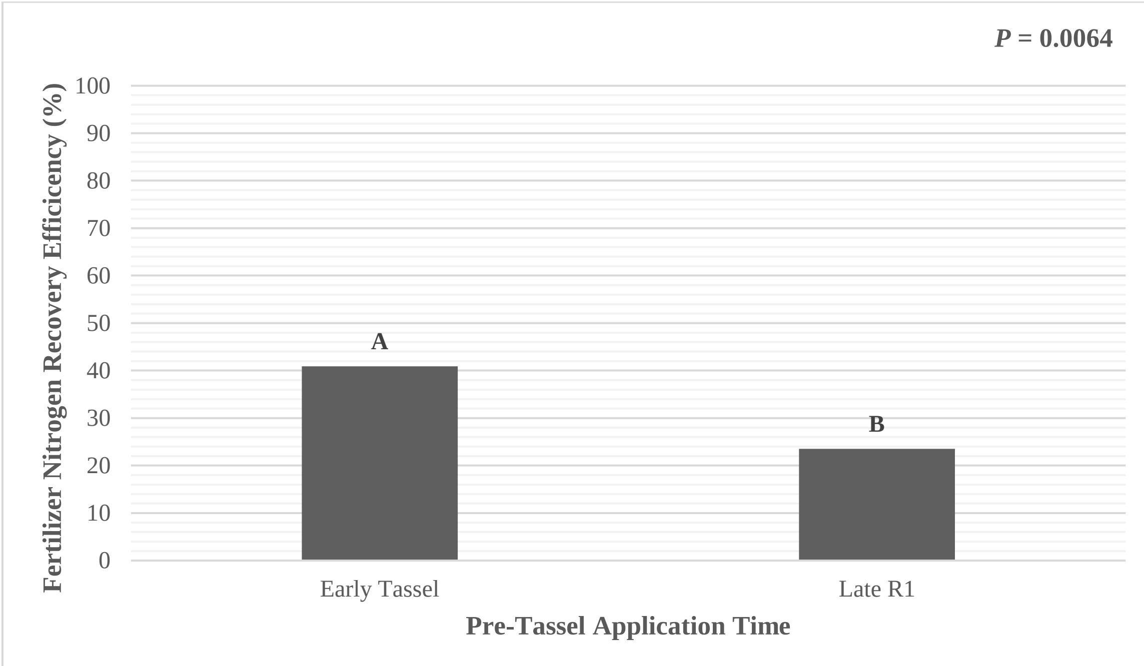

Figure 2-10. Fertilizer nitrogen recovery efficiency (FNRE) as influenced by pretassel timing at the SAREC-19 location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

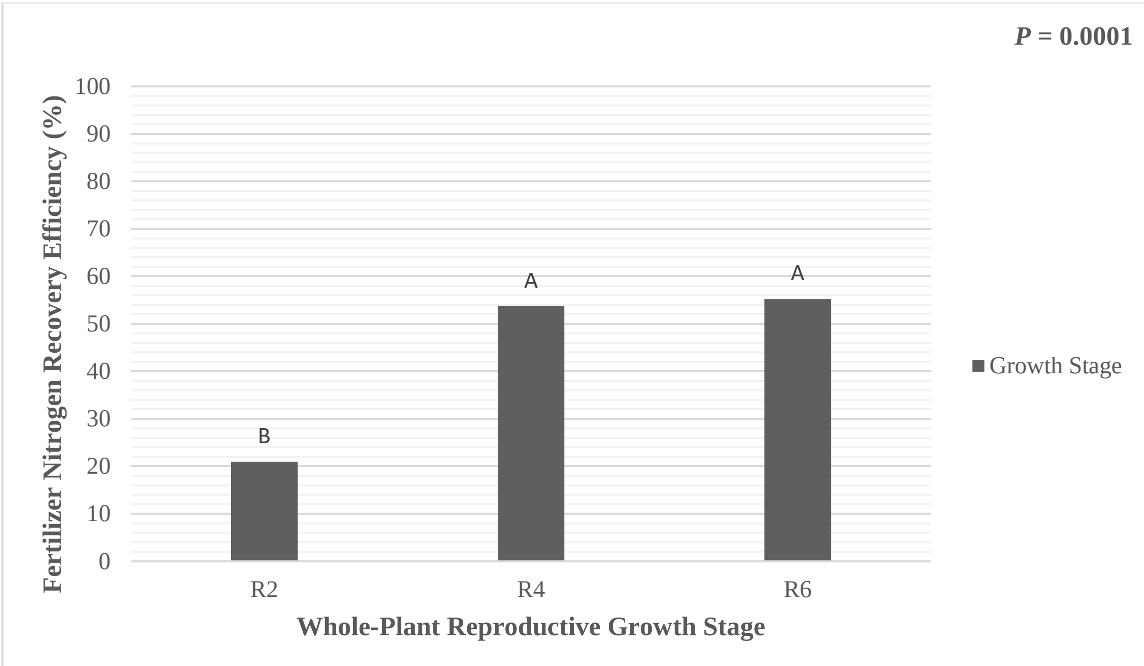

Figure 2-11. Fertilizer nitrogen recovery efficiency (FNRE) as influenced by growth stage at the PTRS-East location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

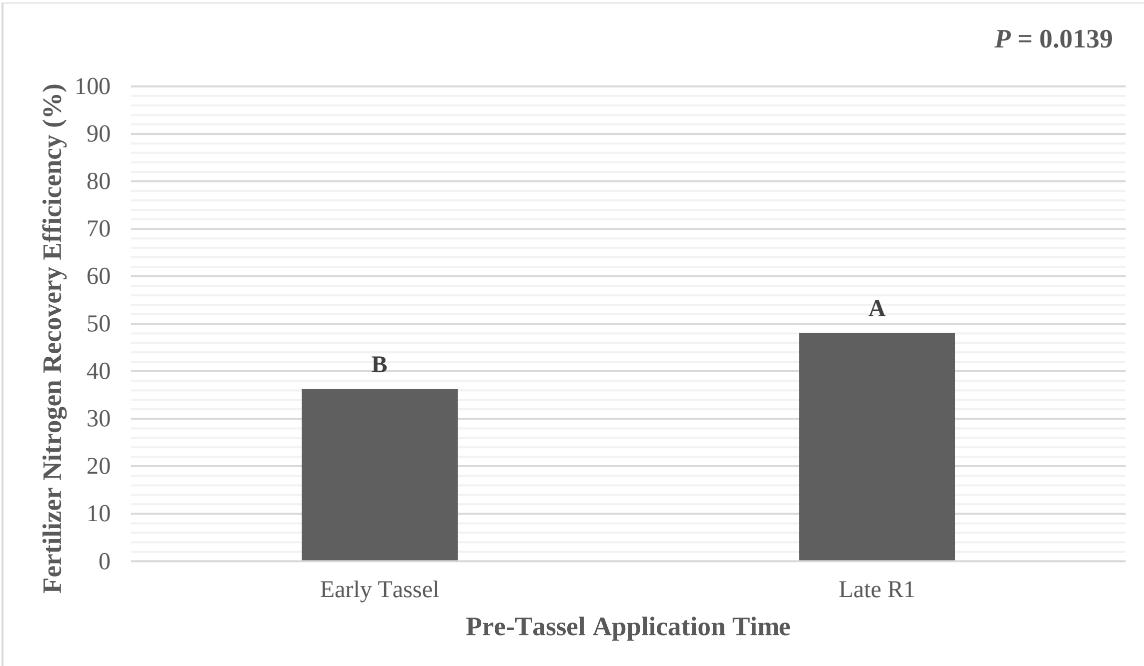

Figure 2-12. Fertilizer nitrogen recovery efficiency (FNRE) as influenced by pretassel timing at the PTRS East location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

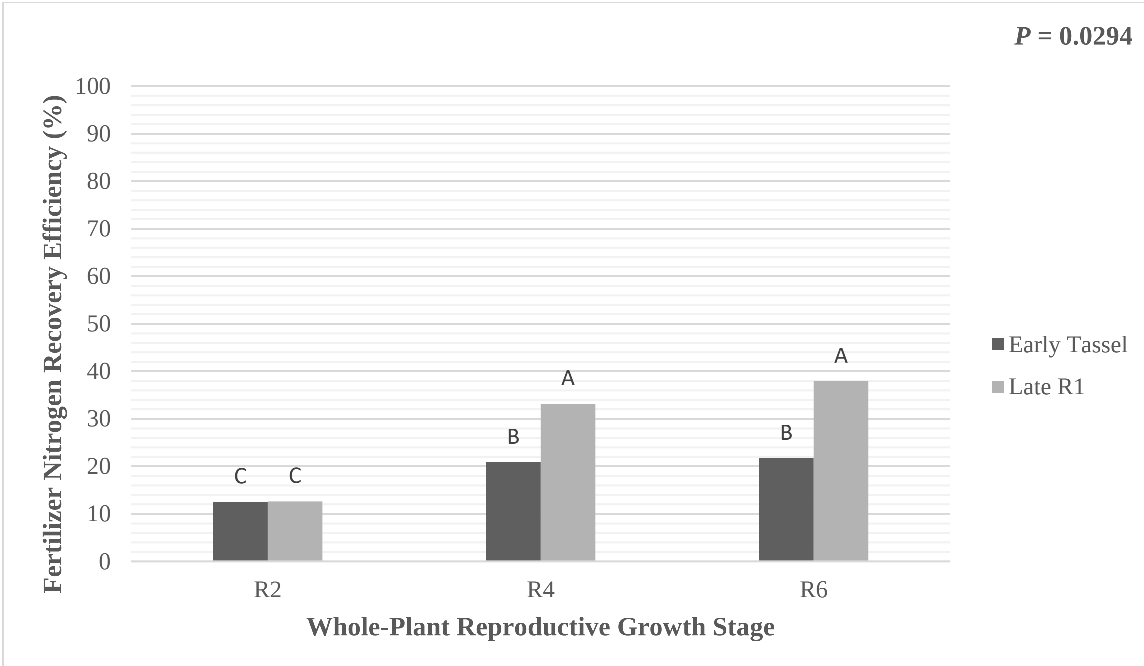

Figure 2-13. Fertilizer nitrogen recovery efficiency (FNRE) as influenced by pretassel x growth stage interaction at the PTRS-West location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

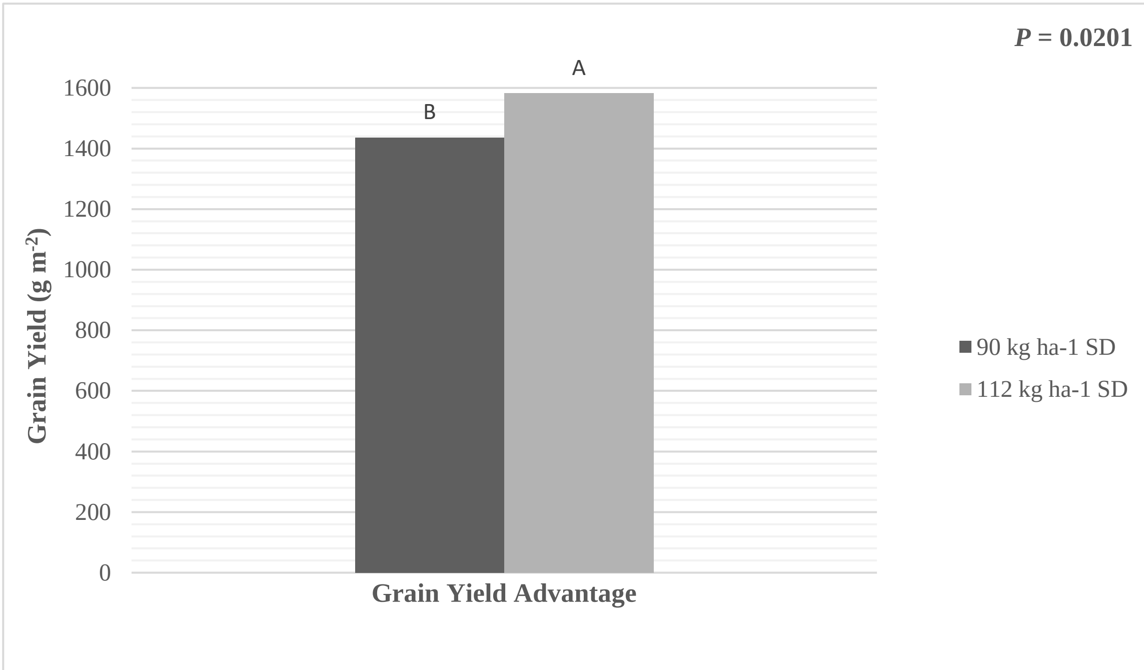

Figure 2-14. Corn grain yield as influenced by sidedress rate at the SAREC-18 location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

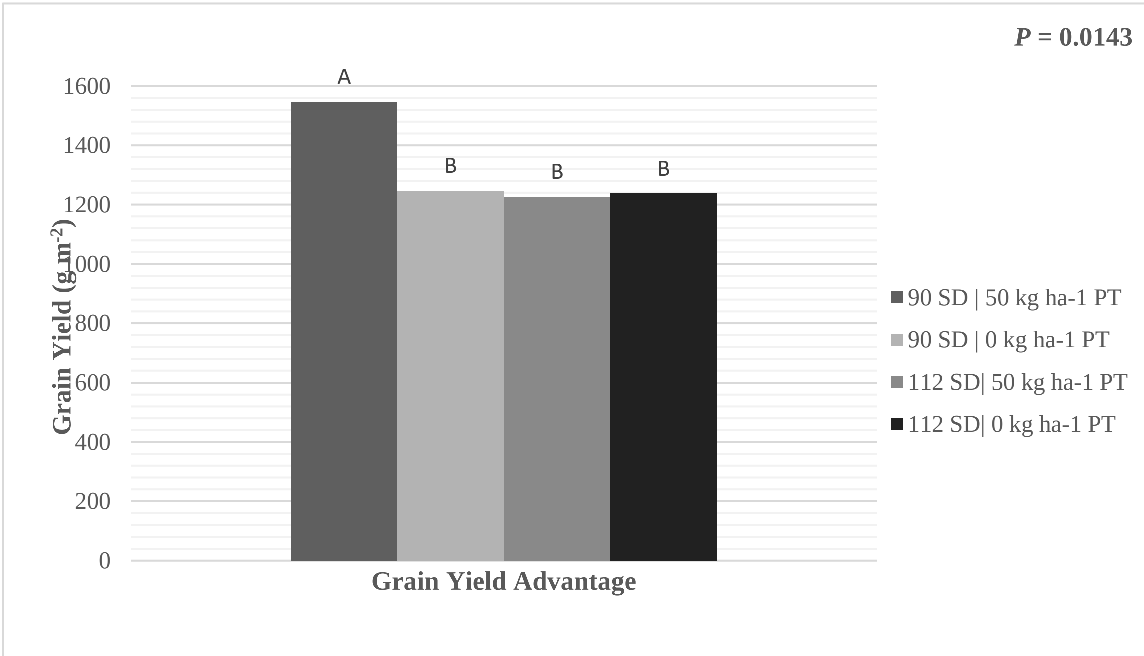

Figure 2-14. Corn grain yields as influenced by sidedress x pretassel application at the SAREC-19 location. Means not sharing the same letter are significantly different (Fisher's, $P < 0.05$).

Chapter Three:

Late-Season Nutrient Accumulation Dynamics in Furrow Irrigated Corn

Abstract

Maize (*Zea mays* L.) grain yields over the last century have significantly increased due to genetic selection and improved agronomic practices. Late-season fertilizer applications are widely known to enhance the uptake efficiency of fertilizer inputs when timing and quantity is associated with crop demand. It is necessary to investigate the nutrient accumulation and partitioning dynamics of these high-yielding modern hybrids to increase understand season long nutrient demand and help improve nutrient use efficiencies. The objective of this study was to examine nutrient accumulation and partitioning of two different maize hybrids (Pioneer 1197YHR and Pioneer 1464VYHR) under furrow-irrigated conditions under a standard fertilizer program. The season total N rate applied was 196 kg N ha^{-1} which was spilt in three applications: 34 kg N ha^{-1} preplant, 112 kg N ha^{-1} sidedress, and 50 kg N ha^{-1} pretassel. To determine nutrient partitioning dynamics and total nutrient accumulation, plant samples were collected at R2 (reproductive growth stage blister), R4 (reproductive dough), and R6 (physiological maturity). Plant samples were separated into leaves & stalks (LS), husks & cobs (HC), and grain (G). Total aboveground biomass accumulation was 36.8 Mg ha^{-1}. Total nutrient accumulation was 326.6 kg N, 62.0 kg P, 437.2 kg K, 30.7 kg Mg, 28.0 kg S, and 686.4 g Zn ha^{-1}, respectively. The average grain yield produced was 15.2 Mg ha^{-1}. The general nutrient uptake patterns could be described as sigmoidal, consisting of a curved shape, a peak accumulation period followed by a transition of nutrient remobilization. Overall, these results are similar to slightly higher than previous literature reports indicating that longer growing seasons and increased aboveground biomass accumulation may require greater nutrient applications to achieve maximal yield potential.

Introduction

Maize (*Zea mays* L.) hybrid yields have increased significantly over the years with advanced breeding and agronomic management practices. There is a need to investigate nutrient accumulation and partitioning in new era hybrids to better understand metabolic processes that ensure continued hybrid success. Aligning fertilizer management strategies to nutrient accumulation behaviors ultimately improves environmental and economic impacts. Exploration of nutrient uptake pathways enhances the understanding of nutrient accumulation behaviors. Plants use various pathways to obtain and utilize nutrients, often these pathways are dictated by the chemical properties of the nutrient and the physical, chemical, and biological properties of the soil. Decades of research have been dedicated to studying accumulation of nutrients in plant parts over growing periods providing valuable nutrient demand information at key developmental stages in different crops.

Nutrient partitioning in corn is very specific and depends on the timing, rate, and duration of nutrient uptake including tissues that nutrients are partitioned to (Bender et al., 2012). Most of the previous research focuses on nutrient uptake and accumulation of nitrogen (N) behavior as this is most often the most yield limiting nutrient for corn across all production systems. However, it is just as critical to explore macro- and micro- nutrient patterns as well as these are becoming more limited in soils and could cause significant yield loss if not managed properly. New era hybrids are high yield producing plants which require advance understanding of essential macronutrients and micronutrients uptake and partitioning. Nutrients are either mobile or immobile in the plant or the soil and this mobility or lack thereof needs to be understood to manage the nutrients properly and avoid associated yield loss (Brady and Weil, 2008). Nitrogen is mobile in the plant meaning, if there is a deficiency, the plant will show chlorotic characteristics on the older, lower vegetative growth. In the soil, N is described as mobile so long as the nutrient stays in the form of nitrate (NO_3^-) but can be considered relatively immobile if present as ammonium (NH_4^+). As GDD units accumulate throughout the season, different nutrients in plants are required in varying amounts to accommodate plant metabolic needs (Bender et al., 2012). As the corn plant develops over the growing season, N partitioning or mobility in the plant allow N to be moved from lower leaves where sunlight interception is low to upper leaves where the N can be better utilized. Current and previous literature highlights the N partitioning in corn for both old and newly released hybrids. In the early stages of development (from emergence to V4), N partitioning starts with the leaves, stalks, and sheaths (Karlen et al., 1988; Bender et al., 2012). Rapid N uptake increases as demand by leaves, sheaths and stalks begins at V5 with a peak of accumulation at R2. Nitrogen uptake in leaves, sheaths, and stalks eventually drops as N begins to remobilize to grain late in the season. Between the V14 and R2 stage, partitioning of N becomes shifted to tassels, cobs, and husks. Later in the season, the demand for N is shifted to accommodate for grain fill and N partitioning begins from R2 until the end of physiological maturity (R6). Research shows optimizing grain production in corn requires N uptake to be available at a high rate during the vegetative growth stages when biomass accumulation is the highest (Bender et al., 2012). Phosphorous (P) and Magnesium (Mg) uptake over the season has shown to be steady and consistent from V6-R6 (Karlen et al., 1988; Bender et al., 2012). While recent studies have suggested that the highest P uptake occurred around silking (V15-R3) (Ciampitti et al., 2013). Potassium (K) uptake patterns observed in previous studies suggest a slow start to accumulation in early vegetative stage (V10) with maximum uptake around R3, followed by a decline to maturity (Ciampitti et al., 2013). Sulfur (S) follows a similar pattern with the highest uptake occurring around silking (Ciampitti et al., 2013). Zinc (Zn) uptake is described as rapid accumulation in early vegetative stage into early reproductive stage while leveling off into maturity. The pattern of Zn accumulation has been described by Ciampitti et al., 2013; Bender et al., 2012; and Karlen et al., 1988.

Nitrogen accumulation studies show two very significant drops in N uptake during reproductive stages which suggest a net loss of N from the plant between VT and R1 (Karlen et al., 1988). The transition for N uptake from vegetative to reproductive stages via translocation provides some explanation but this is not a definitive answer. Two possible causes could be the following: volatilization could be occurring via emissions given off by plant parts or a mechanism of inhibition that might stop N uptake by the plant. Until these possibilities are explored, there can be no definite answer which provides some direction for future research objectives.

Fertilizer rate recommendations are developed to correlate with the plant's nutrient needs and an understanding of what plant parts require nutrients at a given growth stage will help define the best nutrient management practices for corn producers. Timing of fertilizer application strongly dictates what plant parts ultimately house the nutrients that are accumulated following an application (Walsh et al., 2012). At-planting nutrient applications tend to stay immobilized by the vegetative plant parts, suggesting that N applied at planting will contribute to the growth of leaves, sheaths, and stalks in corn with less N going towards the ears (Bigeriego et al., 1979). Meanwhile, side-dress N applications play a different role in the development of the plant. Research found that side-dress N was held more in the crown and ear than the foliage and roots. Results confirmed that side-dress N provides a direct channeling of N fertilizer to grain with less of it being immobilized in vegetative plant part.

Nutrient uptake and accumulation in furrow-irrigated, modern era corn hybrids has not been investigated in the Mid-south. Understanding the season total nutrient uptake and how the nutrients are partitioned and removed in the harvested grain will be essential to maintain high yields and optimize profitability. Therefore, the objectives of this study were to quantify the season total nutrient accumulation and late season partitioning of nutrients in two modern era corn hybrids grown in a furrow-irrigated production system.

Materials and Methods

In 2018 and 2019, two experimental trials were established at the Milo J Shult Agricultural Research and Extension Center (SAREC) in Fayetteville, AR, (36.09 N, 94.17 W). Each trial followed soybean (*Glycine max* L.) in rotation, instituting a close representation of the most common rotation used for furrow-irrigated corn in the Mid-south. The experiments were conducted to observe season total nutrient uptake and nutrient remobilization/partitioning patterns.

The observation experiment selected one fertilizer-N treatment to focus on maximizing nutrient uptake with the following N application strategy: pre-plant rate of 34 kg N ha^{-1} incorporated into the bed immediately prior to planting, broadcast side-dress application of 112 kg N ha^{-1} applied between the V6 - V8 growth stage and a pre-tassel application of 50 kg N ha^{-1} applied at early tassel (VT). The total N rate applied was 196 kg N ha^{-1}. The fertilizer-N treatment for these trials were hand-applied as granular urea 460 g N kg^{-1} treated at a rate of 0.89 g N-(n-butyl) thiophosphoric triamide (NBT) kg^{-1} urea (Agrotain Ultra [285 g NBT L^{-1}], Koch Fertilizer LLC., Witchita, KS). All post-emergence N applications were incorporated with rainfall or irrigation within 2 days of hand-broadcast application to the soil surface.

At the beginning of the growing season, one composite soil sample composed of four, 3 cm diameter cores were taken from the field experiment area at a depth of 0-15 cm. The soil samples were oven-dried at 60 C, ground to pass through a 2mm sieve, and submitted to the University of Arkansas, Division of Agriculture Agricultural Diagnostic Lab (Fayetteville, AR) for soil pH and routine soil analysis. Corn GDDs were tracked using Pioneer GDD calculator (Corteva, Indianapolis, IN) and number of leaf collars were monitored in the field throughout the season to support growth stage determination and time fertilizer applications.

For experimental purposes, fields were arranged into four blocks with plots that were four rows wide. Pre-plant fertilizer applications were made and raised beds were established on 91 cm spacing at the SAREC location. The blocks were parallel with the furrow direction and separated by a 1.52 m planted buffer. The fertilized area in each plot was four rows wide by 3.05 m long. Irrigation and pest management was implemented following recommendations for furrow-irrigated corn provided by the University of Arkansas Cooperative Extension Service (Espinoza and Ross, 2009). In 2018, the corn hybrid used was Pioneer 1197YHR (Corteva, Indianapolis, IN) a 111-day relative maturity hybrid and was planted atop the raised beds at a seeding rate of 84,000 seeds ha^{-1}. In 2019, the corn hybrid used was Pioneer 1464VYHR (Corteva, Indianapolis, IN) a 114-day relative maturity hybrid planted atop the raised beds at a seeding rate of 84,000 seeds ha^{-1}. Irrigation was scheduled throughout the season and initiated when fields reached a 5-cm soil profile water deficit.

Aboveground biomass samples were collected at three different growth stages and separated into the following: LS, HC, and G. The growth stages for collection were R2, R4, and R6. Once 50% of the plants in each plot reached the respective growth stage, samples were collected from at the soil surface and separated accordingly. Plant samples taken from the field were immediately placed in a forced air oven at 60 C until a constant weight was reached. Dry weights are obtained for each plant component after removal from the ovens and the samples were allowed to cool to room temperature. Leaves and stalks were processed by a Craftsman 77615 woodchipper (Stanley Black & Decker, New Britain, CT) to collect a representative subsample before being ground to pass through a 1 mm sieve using a Thomas-Wiley Laboratory Mill, Model 4 plant grinder (Thomas Scientific, Swedesboro, New Jersey). The husks and cobs were not preprocessed in the woodchipper; instead, they were ground to pass through a 1 mm sieve. Preparation for grain starts with shelling kernels off all cobs collected from individual plots in the field. Whole cobs were shelled using specialized equipment created by Almaco®, a Mazier (Almaco, Nevada, Iowa). The specialized equipment allows for each batch of cobs to be shelled fast, efficiently, and provides no kernel carry-over from treatment to treatment. Once grain is collected off the cobs, moisture percentages are recovered with a DICKEY-John GAC® 2500-UGMA Grain Analysis Computer, (Precision Scale & Controls, INC., St. Louis, MO). Grain is further processed through subsampling grain to be ground using a kitchen Aid Blade Coffee Grinder model BCG111 (Whirlpool Corporation, Benton Harber, MI), until grain is considered fine-textured powder. Processed plant components were submitted to the Arkansas Agricultural Diagnostics Lab for analysis of N, P, K, Mg, S and Zn.

SigmaPlot (SigmaPlot v14.5; Systat Software Inc., San Jose, CA), was used to illustrate nutrient uptake and partitioning figures. All figures were generated with the simple spline curve option with smoothed data points. Nutrient uptake totals were combined and averaged together from both site years. Statistical analysis was not necessary for the purpose of this study. The main objective for this study was to illustrate of accumulation and partitioning patterns graphically.

Results and Discussion

Aboveground Biomass Accumulation

Total aboveground biomass accumulation was an average of 36.8 Mg $ha^{-1}$with a grain yield of 15.2 Mg ha^{-1} at physiological maturity. Past literature (Karlen et al, 1988, and Bender et al, 2012) focused on the biomass accumulation from the early reproductive stage to physiological maturity. The aforementioned research studies paved the way to increasing fertilizer efficiency improvements and answer questions related to the accumulation relationships between individual essential elements and maize cultivars. To further investigate those relationships, nutrient uptake and accumulation rates of N, P, K, Mg, S, and Zn were observed during this same time period to capture a screenshot of the nutrient partition and uptake dynamics. To generate 36.8 Mg ha^{-1} of biomass, season total nutrient accumulation was 326.6 kg N, 62.0 kg P, 437.2 kg K, 30.7 kg Mg, 28.0 kg S, and 686.4 g Zn ha^{-1}, respectively. Previous research supports as biomass accumulation increases, the rate of total nutrient uptake and grain yield increases (Bender et al, 2012, Hay 1995, Lorenz et al., 2010). Biomass accumulation increased by (+13.6) Mg ha^{-1} when compared to Bender et al., 2012, and may be attributed in the present study using a more intensive fertilizer management (multiple N splits) and irrigation. Compared to the results presented by Karlen et al. (1988), total biomass accumulation increased by only (+5.0) Mg ha^{-1} which suggests similar agronomic management practices produce similar results (However, Karlen et al. 1988 planting population was 111,111 seeds per ha^{-1}; the present study was 84,000 seeds per ha^{-1}). Aboveground biomass partitioning observed at the end of the season shows 15% towards HC, 15-50% for LS and 50-100% within the grain (Figure 3-1). Biomass accumulation in the HC increases beginning at the R2 growth stage but plateaus from then until R6. The LS accumulate rapidly from R2 until R4 with a plateau from then on to R6. The grain begins to slowly increase in accumulation from R2 until maturity is reached at a relatively steady pace. The modern hybrids used in this study can efficiently produce more above ground biomass compared to older hybrids. Additionally, when modern corn hybrids are coupled with intensive fertility management and irrigation, aboveground biomass accumulation can be up to 58% greater when compared to the findings of Bender et al., 2012. As a result, the data presented here supports the conclusion of Bender et al., 2012 suggesting that fertility requirements alone cannot be determined by the genetic potential for biomass accumulation (Figure 3-1).

Total Aboveground Nutrient Uptake

Different from previous literature, total nutrient uptake dynamics were captured between R2-R6 to provide a magnification of fertility recommendations during late-season practices and provide researchers with the season total nutrient accumulation and partitioning at harvest. In regions like the Mid-south that have means for intensive fertility management and irrigation, more emphasis can be placed on the nutrient use efficiency and a justification for late-season fertilizer applications may be warranted. When considering a highly intensive management system with corn, economic inputs can begin to add up rapidly. Agronomic practices need to be more efficient now more than ever. As total biomass accumulation increased through modern hybrid development (Bender et al., 2012; Ciampitti et al., 2013) grain yield increased as a result. The question becomes, do nutrient accumulation patterns yield similar results?

Each plant essential element partitioning is specific and influenced by the reproductive growth stage. In the case of N, P, K, and Mg which exhibit mobile characteristics within the plants, post-flowering translocation from other plant fractions is often observed when nutrient availability is adequate (Karlen 1988). Previous research from Bender, Karlen and Ciampitti, all supported that most of the total accumulation for N, K, and Mg occurred before flowering. While accumulation of P, S, and Zn uptake continued occurring during reproductive growth. Comparable to the Bender et al., 2012 findings, increased nutrient accumulation post-flowering can be influenced by the increased rates of dry matter in modern day hybrids. For the purposes of this study, we focused on season total nutrient uptake and partitioning of N, P, K, Mg, S, and Zn as these are the nutrients that are most often limiting Mid-south corn production and are essential for maximal yield.

Total Aboveground Nitrogen Uptake

At physiological maturity (R6), total aboveground accumulation of N was 326.6 kg N ha^{-1}, which was partitioned at 94.0, 30.3, and 202.30 kg N ha^{-1} in LS, HC, and G, respectively (Fig. 3-2). Focusing on the late-season N partitioning, HC plant section represented the smallest percent of the total N uptake at 9.3%. The N accumulation pattern in the HC can be described as peaking around R3 and plateaus through R6. The LS plant component accounts for 28% of the total N uptake during reproductive growth. Rapid accumulation occurred from R3-R4 as the corn matures and then the N is remobilized towards the grain as the season progresses. By the time the corn is at the R4 growth stage, the N content in the LS starts to decline significantly until R6. We found that 74.3 kg N ha^{-1} translocated from the LS with an addition 6.0 kg N ha^{-1} from the HC to the grain from their peak level of accumulation. The grain accounts for 61.9% of the N uptake at R6 or physiological maturity. The results presented here represent a 40 kg N ha^{-1} increase over the total N uptake reported by Bender et al., 2012. Due to the nature of elements such as N and K which are luxury consumed by plants, nutrient accumulation should continue if these elements are plant available in the soil. Accumulation of N and K tend to continue into R6 which has previously been described in literature by (Bender and Ciampitti). In contrast to Karlen et al 1988, there was not a decline in N at any point of accumulation during grain fill. The lack of decline would indicate that N availability was adequate all the way to harvest, but not excessive.

The accumulation pattern of N in the grain is similar to the patterns for P, Mg, and S (Figure 3-2, 3-3, 3-5 and 3-7).

Total Aboveground Phosphorus Uptake

The total aboveground P accumulation was approximately 61.9 kg P ha^{-1} and exhibited similar uptake, accumulation, and partitioning dynamics as N, but at a much lower magnitude of accumulation. Our P accumulation and partitioning results are comparable to what was observed by Bender et al., 2012. For the plant fractions, accumulation amounts were 15.1, 3.6, and 43.21 kg P ha^{-1} for LS, HC, and G respectively (Fig 3-3). Translocation of P from the LS fraction accounts for 8.37 kg P ha^{-1} while HC only accounted for 0.5 kg P ha^{-1}. For the HC plant component, the peak accumulation was at R3 with a small but steady decline from R4 to maturity as the P was remobilized to filling grains. The LS plant component has a peak P accumulation at R2-R3 followed by a decline in accumulation from R4-R6. Accumulation of P in the G fraction continues to increase all the way to physiological maturity. The P accumulation pattern is very similar to results presented by Bender et al, 2012 although the total P accumulation presented here is slightly higher (12.2 kg P kg ha^{-1}) which can be attributed to the increase of total biomass accumulation.

Total Aboveground Potassium Uptake

Potassium was the only nutrient investigated in this study where the total accumulation peaked at the R4 growth stage and then declined as the corn crop matured (Fig. 3-4). Other studies have observed and reported this same pattern in accumulation and decline during the reproductive growth stages (Oltmans and Mallarino, 2014 and Karlen et al., 1988). The peak accumulation of K was 437.2 kg ha^{-1}and occurred at the R4 growth stage. At physiological maturity, aboveground K accumulation totaled to 275.8, 29.7, and 63.5 kg ha^{-1} for LS, HC, and G fractions respectively. At least 16.1 kg K ha^{-1} was translocated from LS and HC to the maturing grain but there was a total net loss of 67.9 kg K ha^{-1} from the peak accumulation of K at R4 to physiological maturity. Compared to Bender et al., 2012, our observations resulted in 202.3 kg K ha^{-1} more than what was reported in their research. A similar trend in declining K accumulation was present in both our study and Bender et al., 2012. Unlike N, P, Mg, S, and Zn, total K accumulation tends to decline as maize matures. Research in Iowa (Oltmans and Mallarino, 2014) reported significant drops in corn tissue-K concentration near maturity and following harvest as K can easily leach from plant tissues, especially when K is luxury consumed. Evidence in our study agrees with previous research that luxury consumption of K tends to remain in the vegetative plant parts and rather than the grain.

Total Aboveground Magnesium Uptake

Total aboveground accumulation of Mg was approximately 30.6 kg ha^{-1} at R6. Distribution within plant fractions at R6 was 13.7, 2.2, and 14.6 kg ha^{-1} in LS, HC, and G respectively (Fig 3-5) . A total of 3.5 kg Mg ha^{-1} was translocated from the LS and HC to the G fraction during the reproductive growth stages. In contrast to Bender et al., 2012, our study had a smaller accumulation of total Mg (28.4 kg ha^{-1} less) and could be attributed to differences in soil test Mg. At R6, the proportions of total Mg kg ha^{-1} were split almost evenly between LS (44.6%) and G (47.8%). Based on these results it appears that soil test Mg and Mg fertilization in Arkansas irrigated corn production should be investigated to ensure that Mg is not limited corn growth, development, and grain yield. Magnesium is an essential component of chlorophyll and other enzymes responsible for seed germination and phosphate energy transfer (Havlin et al., 2014)

Total Aboveground Sulfur Uptake

Total aboveground accumulation of S was approximately 27.9 kg ha^{-1}. Distribution of S within the various plant fractions were 11.8, 2.2, and 13.9 kg ha^{-1} for the LS, HC, and G, respectively (Fig 3-6). Approximately 2.5 kg ha^{-1} of S was translocated from the LS and HC to the G fraction during the reproductive growth stages. Like Mg, at physiological maturity the proportions of S were 42.3, 7.7, and 49.8 % for LS, HC, and G respectively. The partitioning of S almost evenly between the biomass and grain is similar to other reports on S accumulation and also highlights the importance of S in the plant. Sulfur is most often used in protein and enzyme folding as it is a key component of several essential amino acids. Sulfur is also considered relatively immobile in the plant which is why very little S appeared to be remobilized from the LS and HC to the G (<10%). The total S accumulation reported here was almost exactly the same amount of S (kg ha^{-1}) that Bender et al., 2012 reported.

Total Aboveground Zinc Uptake

Aboveground Zn accumulation totaled 686.3 g ha^{-1} at R6 (Fig. 3-7). Since Zn is a micronutrient, the amounts needed by the plant for optimal growth and reproduction are significantly less than other primary and secondary macronutrients (Havlin et al., 2014). The fraction of Zn within the various plant components were 270.8, 143.4, and 272.1 g Zn ha^{-1} distributed into LS, HC, and G, respectively. The vast amount of translocation of Zn was from the LS fraction, accounting for approximately 110.2 g ha^{-1} while the HC fraction only provided approximately 17.35 g ha^{-1} to the developing G. Proportions of Zn uptake at R6 were the following: 39.4, 20.8 and 39.6 % for LS, HC, and G respectively and was more evenly distributed across the three components measured than the other nutrients investigated. Accumulation patterns for the three plant components considered were similar to those observed by Bender et al., 2012. Our total aboveground Zn uptake was 188.3 g Zn ha^{-1} more than Bender et al., 2012. The increase in total Zn accumulation can be attributed to increase biomass accumulation over what was reported by Bender et al., 2012 and the likelihood that soil test Zn was higher at our locations. For optimal corn yields, adequate amounts of Zn need to be available throughout the growing season which is supported by results from Bender et al., 2012 and Karlen et al., 1988.

Corn Grain Yield and Nutrient Removal

The mean grain yield observed in this trial was 15.2 Mg ha^{-1} which is substantially greater than the state average in Arkansas for 2021 which was 11.5 Mg ha^{-1} (Kelley and Capps, 2022). Our yield results can be attributable to precise small-scale plot management, planting date and adequate fertility management. Grain yield was slightly higher (3.2 Mg ha^{-1}) than what was reported by Bender et al., 2012. Nutrient removal in the G is an important consideration for long-term nutrient management and essential for soil test philosophies such as the Build and Maintain approach. The amount of each nutrient removed by the grain in this trial was 202.3, 43.2, 63.5, 14.6, 13.9 kg ha^{-1}, and 272.1 g ha^{-1} for N, P, K, Mg, S and Zn, respectively. In comparison to Bender et al., 2012, our total grain removal for N, P, and K was greater and may be attributed to higher yields. For N, our trial resulted in 36.3 kg N ha^{-1} more removal than the previous comparable study. When considering P removal, our results indicated that 3.9 kg P ha^{-1} more P was removed than the data presented by Bender et al., 2012. Lastly, we removed 9 kg K ha^{-1} more than Bender which is most likely negligible considering the larger grain yield observed in the present study. For Mg, S, and Zn, our results for grain removal all decreased in comparison to results provided by Bender et al., 2012. The removal decreased by 2.4 and 1.1 kg ha^{-1}, and 36 g ha^{-1} for Mg, S and Zn, respectively.

Conclusions

Although Bender et al., 2012 and the present study have similar nutrient accumulation totals, there is a difference in total aboveground biomass accumulation. Grain yield in this trial was higher which supports the previous observations that as biomass increases, it may result in an increase in grain yield, but not always. When comparing to Bender et al., 2012 there was a grain yield advantage (+3.2 Mg ha^{-1}) and a concurrent increase in the aboveground biomass accumulation (+5.0 Mg ha^{-1}). The increase in biomass accumulation in this trial can be attributed to the fertility management program and the use of irrigation in this study. The differences in aboveground biomass accumulation, grain yield, total nutrient uptake and grain removal reported here highlight the need for regional research in areas with similar soils and production practices. Regional data on these parameters will allow soil fertility professionals to better understand corn nutrient needs and nutrient removal in the harvested grain to adapt and tailor fertilizer rate recommendations. In areas of the country that implement Build and Maintain soil test philosophies, the crop removal component of the fertilizer rate calculation is very important and can strongly impact the likelihood of building soil test values over time. The patterns of nutrient accumulation and total nutrient uptake reported in this paper are a novel addition to the literature and support the need for research on these parameters as corn hybrids evolve and production systems change. Future research should focus on trends in soil test values for P, K, Mg, S and Zn, the effects of fertilizer timing on nutrient uptake and partitioning and overall nutrient use efficiency in these high yielding irrigated corn production systems.

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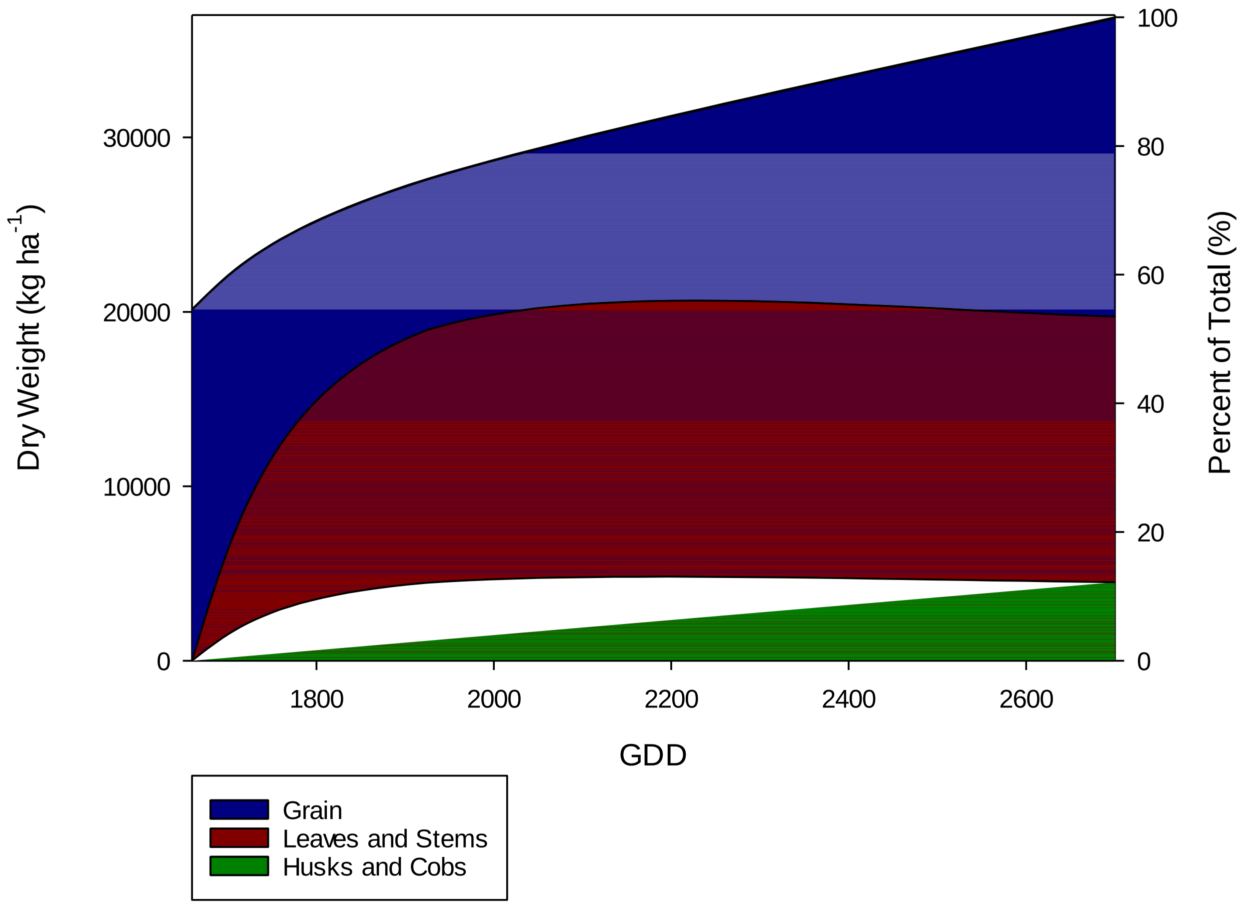

Figure 3-1. Biomass accumulation and partitioning for SAREC. Values are averaged across two hybrids and two years.

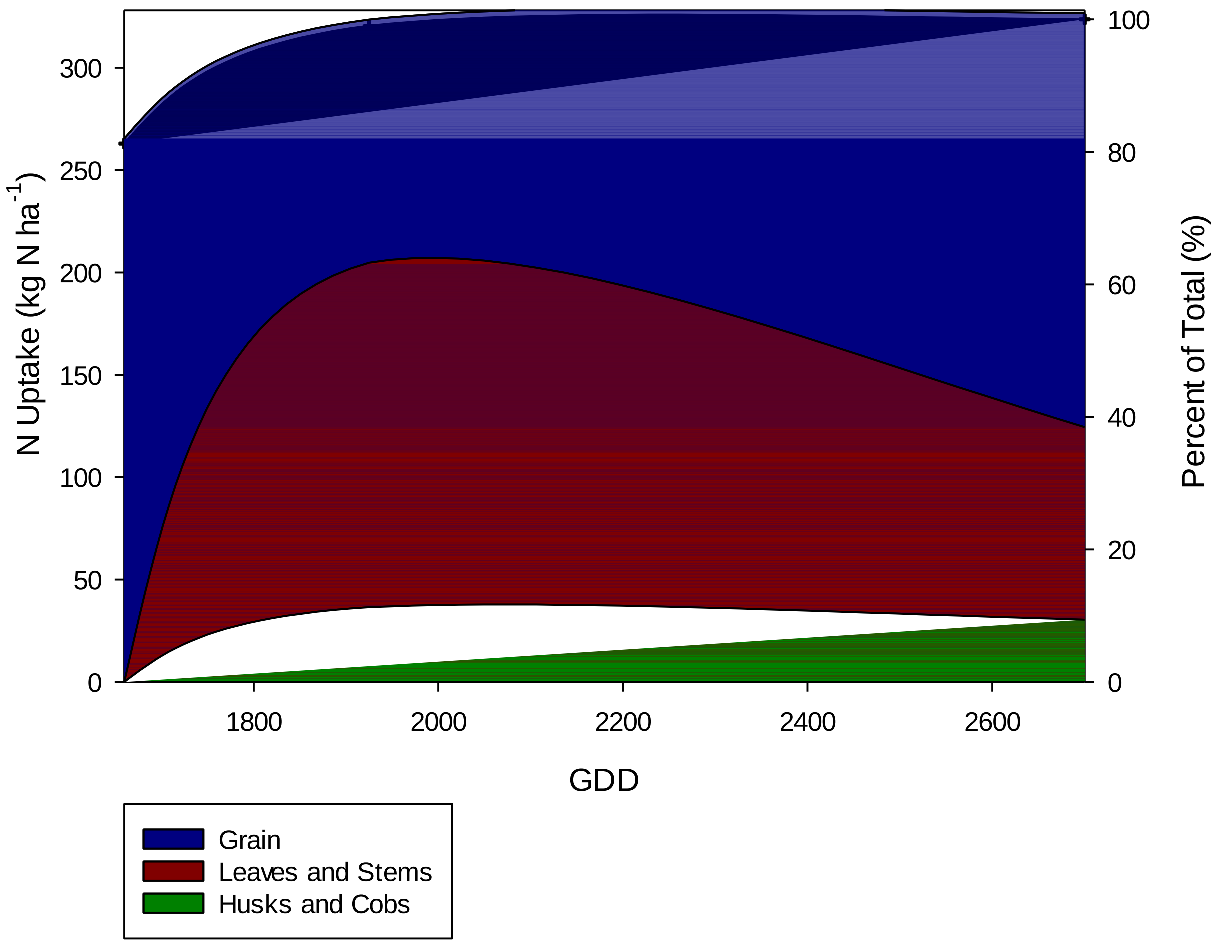

Figure 3-2. Late-season accumulation and partitioning for N averaged across two hybrids and two years. The average grain yield of the two hybrids was approximately 15.2 Mg ha^{-1}.

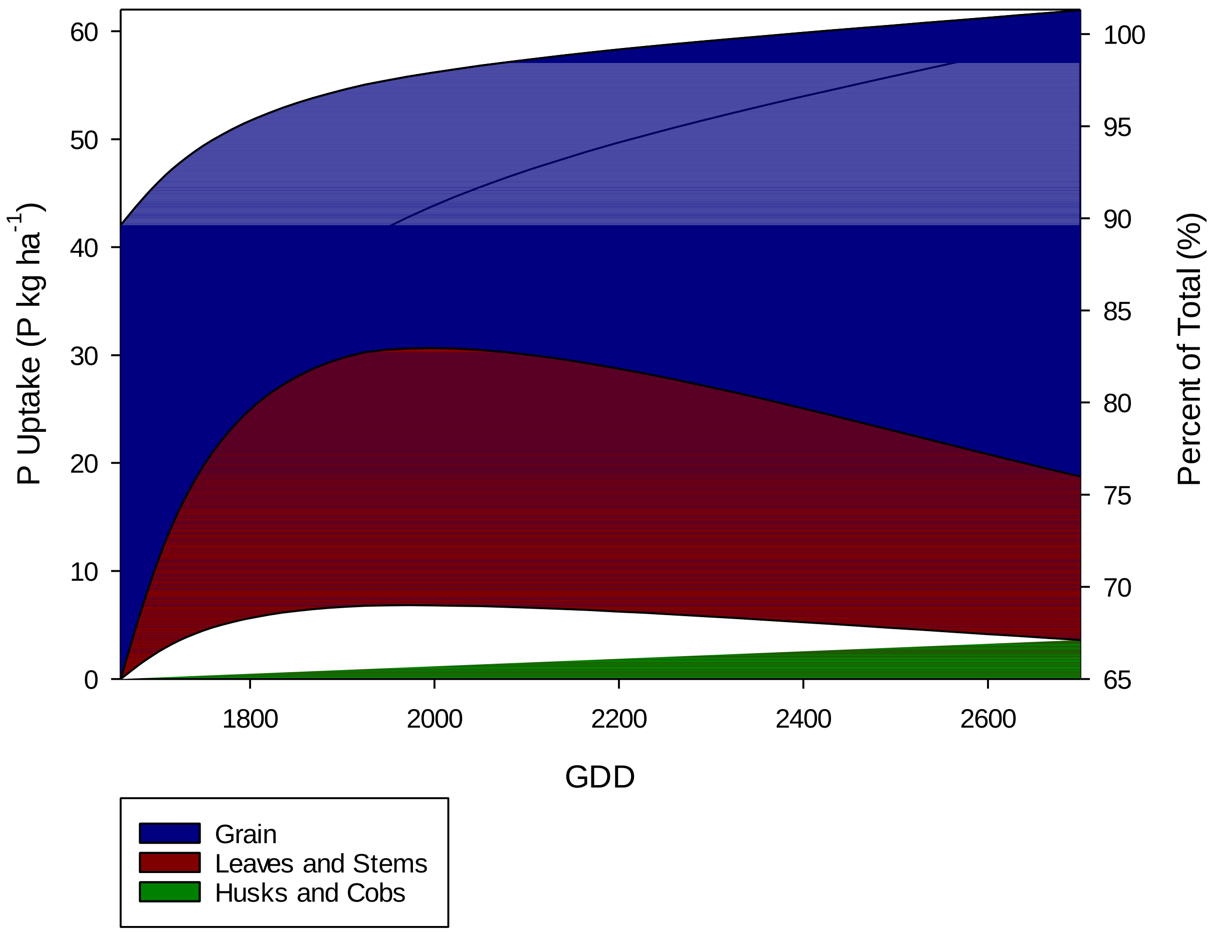

Figure 3-3. Late-season accumulation and partitioning for P averaged across two hybrids and two years.

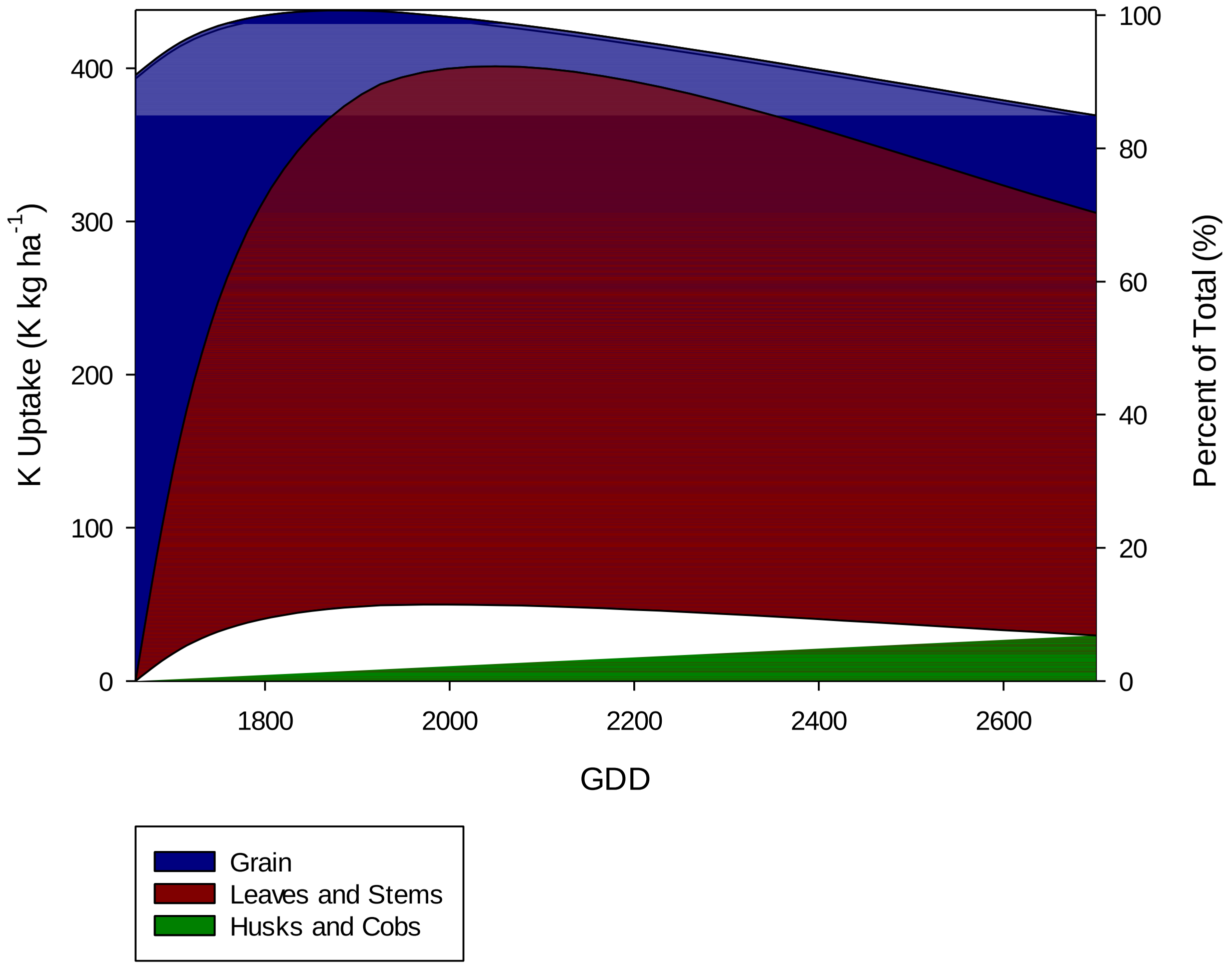

Figure 3-4. Late-season accumulation and partitioning for K averaged across two hybrids and two years.

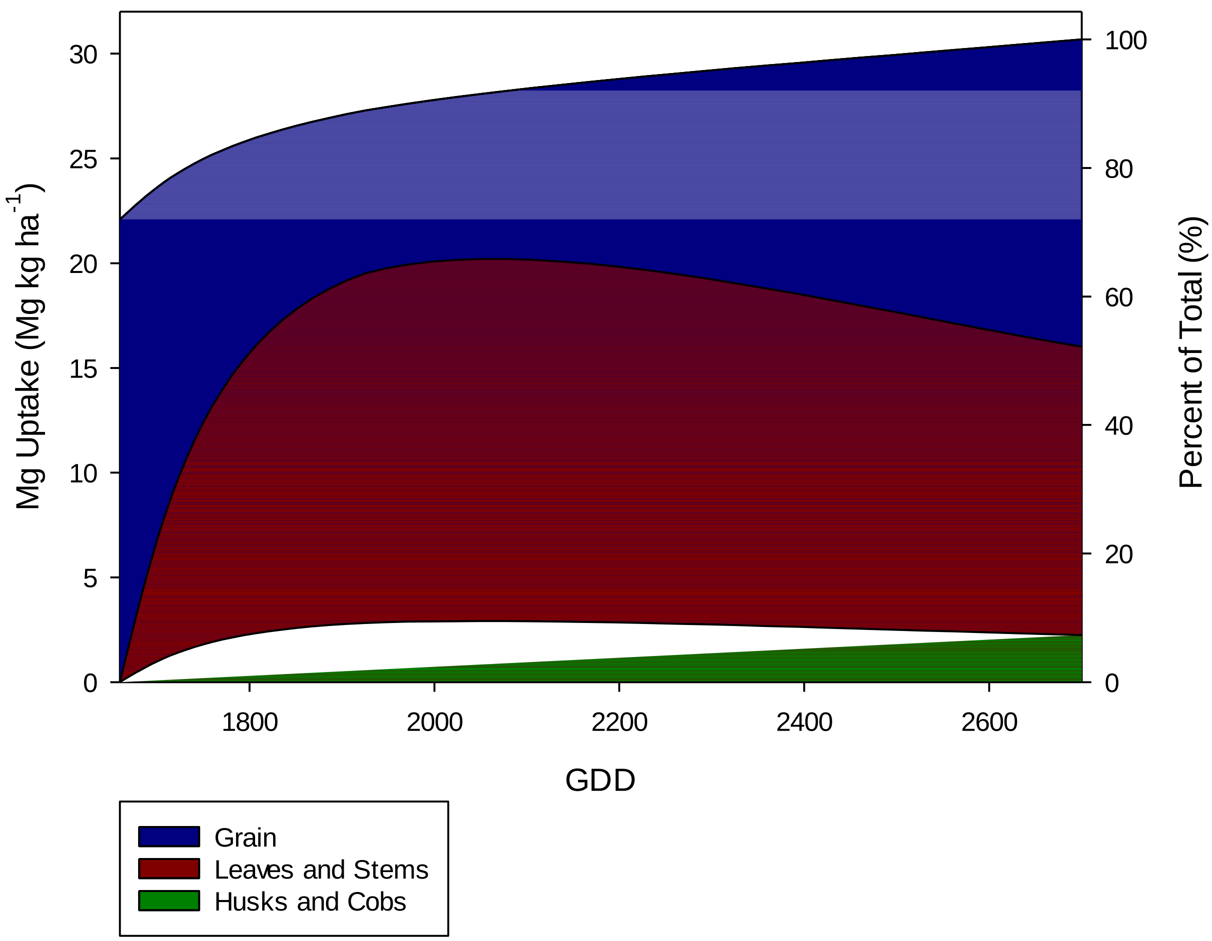

Figure 3-5. Late-season accumulation and partitioning for Mg averaged across two hybrids and two years.

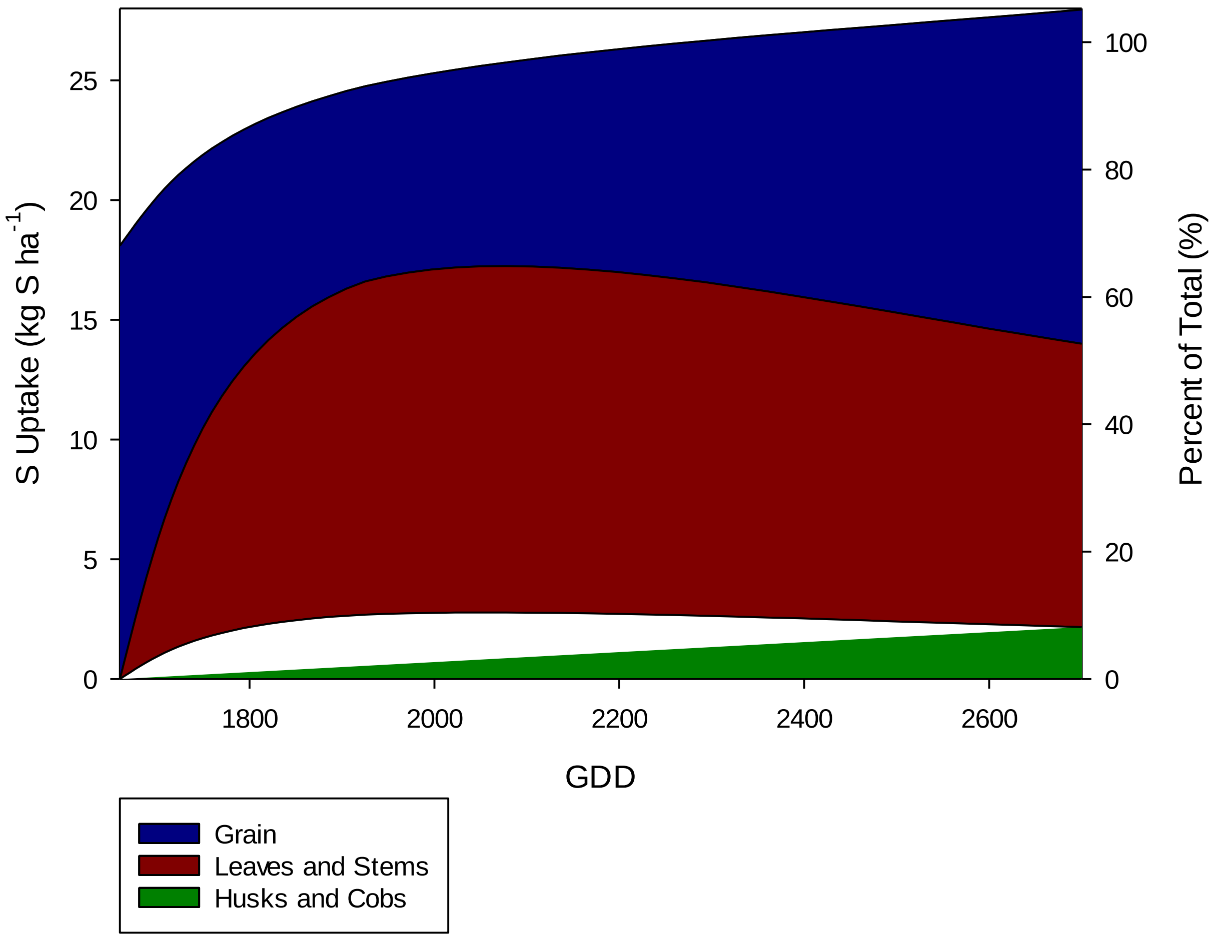

Figure 3-6. Late-season accumulation and partitioning for S averaged across two hybrids and two years.

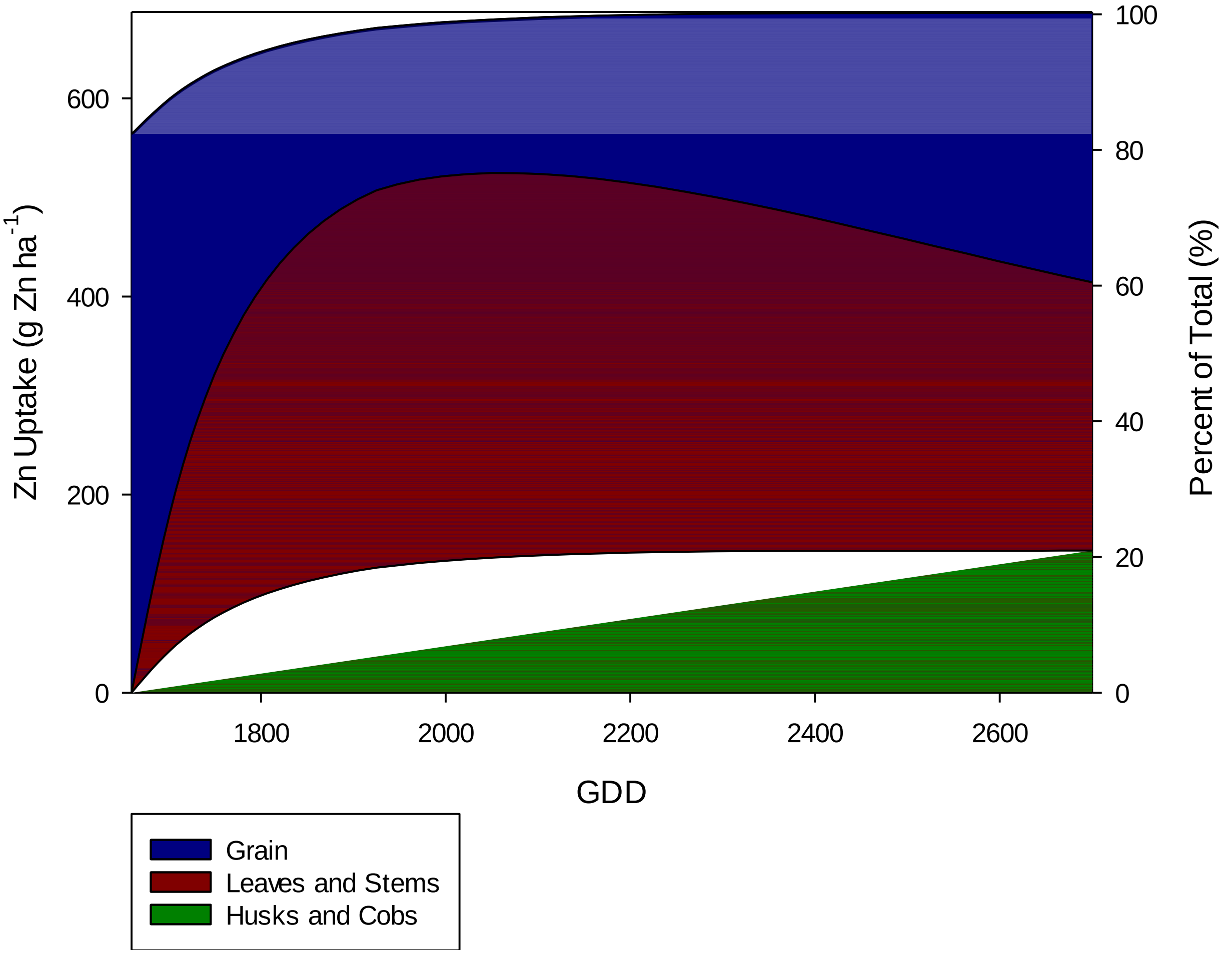

Figure 3-7. Late-season accumulation and partitioning for Zn averaged across two hybrids and two years. The average grain yield of the two hybrids was approximately 15.2 Mg ha^{-1}.

Chapter Four:

Conclusions

The purposes of these studies were to evaluate the fertilizer nitrogen recovery efficiency (FNRE) values within furrow irrigated corn production systems. Recommendations based on methodology and environmental factors that increase FNRE values cannot assume an increase in grain yield. The four trials were evaluated under similar management approaches and recommendations but did not provide clear patterns of the impact on sidedress and late-season N rates. Certainly, splitting fertilizer-N applications will increase the FNRE but impactful economical cost is associated with multiple applications across producer fields. The impact of grain yield response to the multiple applications will provide justification for producers. The complex relationship between FNRE values and grain yield causes difficulty when providing clear recommendations for producers that will maximize returns on economic inputs. As a result, we suggest further investigation into N management tools for predicting the need of late season N applications. Within furrow irrigated corn production, high FNRE values can be achieved but that does not indicate an increase in corn grain yield. Predicting the correct timing of late-season N application for maximizing FNRE will need further evaluation. More importantly, focusing on developing tools and recommendations to not only improve FNRE but also increase the producer profitability.

Late season nutrient dynamics observed in our results yield similar accumulation and partitioning patterns from previous research. However, total overall biomass accumulation was higher and resulted in grain yield increases at the SAREC locations. It is worth mentioning that increased biomass values will not always increase grain yield. In comparison to Bender et al., 2012 we were able to increase grain yield (+3.2 Mg ha^{-1}) and aboveground biomass (+5.0 Mg ha^{-1}). The differences in our increases compared to Bender et al., 2012 can be attributed to our fertility management and furrow irrigated production system. Our highlighted results of biomass accumulation, grain yield, total nutrient uptake and grain removal indicate further investigation within regions under similar soils and management practice. Our observation highlights the demand for soil fertility professionals to develop regional data inputs to begin the process of tailoring management programs under specific field environmental circumstances. As biomass accumulation increases with hybrid development, as does the increase of nutrient removal from grain. The crop removal component of fertilizer rate calculation will need to further be assessed to evaluate the impact of soil test values.