EVALUATING CORN NITROGEN RECOMMENDATION METHODS AND OPTIMIZING SEEDING DENSITIES IN GEORGIA

by

JOHN AUSTIN WINKLER

(Under the Direction of HENRY SINTIM)

ABSTRACT

Optimizing corn production in Georgia necessitates precise management of nitrogen (N) fertilizer rates, irrigation practices, and seeding densities to enhance yields and minimize environmental impacts. This study evaluated three N recommendation methods—Crop Yield Goal (CYG), Agronomic Optimum N Rate (AONR), and Economic Optimum N Rate (EONR). Results indicated that CYG often overestimated optimal rates, underscoring the importance of site-specific adjustments. Irrigation scheduling methods, including the checkbook system, half-checkbook system, and Smart Irrigation CropFit app, were assessed for their effects on yield and N use efficiency, revealing that precise irrigation enhances nitrogen utilization. Additionally, field trials investigated the influence of seeding density on yield and growth, highlighting its role in maximizing efficiency. Collectively, these findings support tailored management practices that integrate N, water, and planting strategies. This research provides actionable insights to improve corn productivity and sustainability under Georgia's diverse environmental and agronomic conditions.

INDEX WORDS: Nitrogen Management; Corn Production; Irrigation Scheduling; Nitrogen Use Efficiency; AONR; EONR; Crop Yield Goal

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DEDICATION

I would like to dedicate this thesis to my parents, Jay and Margaret Winkler. Thank you for always pushing me to chase my dreams, shaping me into the man I am today, and being great examples of followers of Christ. I believe that my successes are because of the constant love and support that you both have given me. Dad, thank you for instilling in me the love of agriculture, as I will always remember the fun I had scouting peanuts with you from a young age. Mom, thank you for always taking a phone call when needed, it has helped me push through the hard and stressful moments. I could not have asked for better parents, I love you both, thank you for everything!

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CHAPTER 1. LITERATURE REVIEW

1.1 History and Production of Corn

Corn, as we know it today, stands as a testament to human agricultural innovation, having evolved from its wild ancestor, teosinte. This remarkable journey of transformation, believed to have spanned over 8,000 years (Galinat, 1988), highlights the crop's evolution into a form that bears little resemblance to its original state. Over recent decades, corn has firmly established itself as a cornerstone of American agriculture. In 2023 alone, the dedication to this crop was evident, with a staggering 94.1 million acres across the United States being planted (NASS 2023), highlighting its significance as a staple in the nation's agricultural landscape.

There are a several varieties of corn grown in the United States including dent corn, flint corn, sweet corn, flour corn, and popcorn. Dependent upon variety uses may include livestock feed, alcohol, ethanol, starches, sweeteners, oil, and decoration.

- **Dent Corn:** Dent corn makes up the majority of corn production in the United States. Dent corn, which is derived from the hybridization of Southern Dent and Northern Flint, comprises most of the corn grown in the United States and is primarily used for animal feed; however, small portions are also used for industrial products and human consumption (Doebley et al., 2008).
- **Flint Corn:** Flint corn has a tougher outer layer with smoother – soft kernels. Flint corn is not grown a lot in the United States today, as it was primarily grown through colonial times. Now, flint corn can be seen more as decoration, than used for consumption.
- **Sweet Corn:** Sweet corn is the only type of corn that is used primarily for human consumption. Sweet corn is primarily grown in the northern parts of the country. Sweet corn has a genetic inability to convert the sugar into starch, leaving the sweet taste.

- **Flour Corn:** Flour corn is one of the oldest types of corn grown, it is primarily grown to make corn flour. The soft starch from the corn makes it able to grind into corn meal.
- **Popcorn:** Popcorn, distinguished by its hard endosperm and small kernels, is considered a relatively minor crop compared to other varieties like dent corn and sweet corn. It is primarily cultivated for human consumption. (Brown et al., 1986; Shultz, S. 2008; Grubinger, V. 2008).

Corn has always been a staple crop in the state of Georgia, dating all the way back past colonial days. Colonial founder James Oglethorpe used the colonist to grow corn and other commodities to export back to England. In 2023 farmers in Georgia planted 490,000 acres (USDA NASS 2023).

In 2023, Georgia planted approximately 500,000 acres of corn, yielding an estimated 79.7 million bushels (USDA NASS, 2023). This production pales in comparison to major corn-producing states such as Iowa and Illinois, where outputs exceed 2 billion bushels annually. Historical data reveal that corn cultivation in Georgia reached its peak in 1935 with about 4.5 million acres planted. This prompts an investigation into the factors contributing to the subsequent decline in corn acreage within the state.

One significant factor is the advancement in agricultural technologies, which has enabled higher yields from smaller acreages. In contrast to the average yield of 10.5 bushels per acre in 1935, modern farming techniques now achieve approximately 200 bushels per acre (Lee, D., 2013). Consequently, less land is required to produce comparable quantities of corn.

The decrease in corn acreage in Georgia can be partly attributed to several key historical events that emphasize the complex relationship of environmental challenges and agricultural policy. One significant factor was the southern corn leaf blight epidemic in the 1970s, which ravaged about 15% of the state’s total corn crop, leading to economic losses estimated at $1 million (Burns, H., 2017). Following this, the 1980s saw the implementation of the boll weevil eradication program, which directly affected crop cultivation preferences within the state. This initiative successfully reduced the pest's impact, subsequently encouraging farmers to expand cotton cultivation, often at the cost of corn acreage. These shifts demonstrate how technological advancements and environmental incidents, intertwined with economic considerations, have historically influenced and shaped agricultural trends in Georgia.

Methods of corn production in the United States, and specifically Georgia, have undergone substantial transformations the colonial era. One of the most significant changes has been in the variety of tillage practices adopted by farmers to prepare their fields for planting. These practices are generally divided into three principal categories: conventional tillage, reduced tillage, and conservation tillage. The evolution of corn production in the United States, especially in states like Georgia, has been profoundly influenced by advancements in agricultural technology. Precision agriculture, characterized through the use of GPS navigation, sensors, and data analytics, has revolutionized the way corn is cultivated. This technology allows for precise mapping of field variability, enabling farmers to apply the exact amount of inputs (such as fertilizers, pesticides, and water) needed at different locations within a field, thereby optimizing growth conditions and conserving resources (Zhang, N. et al., 2002). Additionally, modern machinery such as high-precision planters and variable-rate applicators has been integral in implementing these sophisticated strategies. These machines provide unparalleled accuracy in seed placement and input application, further enhancing crop yields and reducing environmental impacts. The integration of these technologies into traditional farming practices marks a pivotal shift towards more sustainable and efficient agricultural systems (Vellidis, G. et al., 2016).

Conventional tillage, which leaves less than 15% of crop residue on the field, typically employs methods such as the use of a moldboard plow, disk harrow, and chisel plow. In contrast, reduced tillage systems, which preserve 15 to 30% of the residue, might include the field cultivator, spike tooth harrow, and sweep plow. Conservation tillage, maintaining more than 30% residue, integrates techniques such as strip till, no-till, and ridge till. These practices are documented extensively in agricultural literature (Strudley, M., 2008; Kainiemi, V. et al., 2013; Boyhan, G. and Dawson, E., 2022). In Georgia convention tillage is still a common practice, however over a ten-year period, from 2012 to 2022, conventional tillage acreage has decreased by 28% from 2,692,870 acres to 1,933,310 acres. While the number of acres conservation till acreage has increased by 48%, in the same time period, from 1,810,294 acres to 2,647,626 acres. (USDA NASS)

Extensive studies have provided insights into the environmental benefits of conservation tillage, noting its efficacy in reducing surface crusting, enhancing water infiltration, and decreasing runoff, thus contributing to more sustainable farming practices (Cassel, D.K. et al., 1995; Thierfelder et al., 2012). However, it has also been noted that while conservation tillage is beneficial for soil health, it may lead to slower crop development and potentially lower yields when compared to conventional tillage methods (Raimbault, B.A. and Vyn, T.J., 1991; Vetsch, J. and Randall, G., 2004). This contrast underscores the critical trade-offs that farmers must consider when selecting tillage methods, balancing between immediate agricultural productivity and long-term sustainability goals (Omonode et al. 2015).

Crop row spacing is another major change that has taken place over time. Originally, row spacing was determined by the width of the horse, but with technological advancements and as growers began to shift from animals to tractor, corn row spacing narrow to approximately 100 to 112 centimeters, which was determined optimal for growth and weed control by cross cultivation (Olson, R.A. and Sander, D.H., 1988). However, recent studies have decreased row spacing to 75 centimeters or narrower. With narrowed row spacing, the number of seeds planted per acre increases leading to higher population and higher yield (Sharratt & Mcwilliams, 2005). Georgia farmers on a cotton / corn / peanut rotation (popular in Georgia) typically use a row spacing of 90 cm (recommended row spacing for cotton and peanut production) for corn production despite the potential for increased yield with narrower row spacing (Lambert and Lowenberg-DeBoer 2001). However, in modern practices, growers that practice a cotton / corn / peanut rotation typically will keep their row spacing for corn due to peanuts and cotton being planted on 90 cm. The change in row spacing would be a big economic decision, as it would require the farmers to buy new equipment for this specific row spacing.

Irrigation plays a pivotal role in the cultivation of corn, representing both a significant investment and a critical component of agricultural success. As recent inter-state disputes over water resources intensify, effective water management becomes increasingly more essential. One of the key strategies in optimizing water use is precise irrigation scheduling, which ensures that water application is timed appropriately and in the correct amounts according to the developmental stage of the corn (Vellidis, G. et al., 2016; Moursy, M., 2017).

Numerous tools and resources are available to assist growers in managing their irrigation practices effectively. For instance, the checkbook method, recommended by the University of Georgia Extension, offers a systematic approach to monitor water usage, allowing farmers to track both the volume of water already applied and the quantity still required based on growth stage. Additionally, various software solutions are designed to facilitate irrigation scheduling, enhancing the precision of water application.

Moreover, technological advancements such as soil moisture sensors and weather stations provide real-time data, further aiding growers in making informed decisions about irrigation.

These tools collectively support sustainable agriculture by optimizing water use and reducing waste. ("A Guide to Corn Production in Georgia," University of Georgia, 2021).

In Georgia a common crop rotation on a three-year period of cotton, corn, and peanuts. Prior to crop rotations being a common practice, farmers would allow fields to lay fallow for a growing season to rebuild soil nutrients. A good crop rotation can have numerous benefits, such as preventing nematode damage, helping with, soil fertility, weed, and disease management (Kirkpatrick, T.L. and Sasser, J.N., 1984; Hague, S.S. and Overstreet, C. 2002). Planting similar species in the soil in continuous years can result in decrease in soil quality (Delang, C. 2018). A crop rotation that includes corn behind peanuts is beneficial to take advantage of any leftover Nitrogen (N) that is in the soil. Incorporating corn into crop rotation systems can effectively reduce pest pressures on peanuts, especially in regions like Georgia. This is largely due to corn serving as a non-host for many pathogens and insects that typically affect peanuts. By interrupting the lifecycle of these host-specific pests and pathogens when corn is rotated with peanuts, there is a significant decrease in their populations. As pests like the lesser cornstalk borer and thrips, which severely impact peanuts, find corn an unsuitable host. Additionally, certain corn varieties are either resistant to or not preferred by root-knot nematodes, which are detrimental to peanut crops (Ouda, S. et al., 2017). This strategic use of corn in crop rotation not only controls pest populations but also contributes to healthier, more productive peanut crops.

Incorporating cover crops between growing seasons is another strategy that growers employ to enhance soil fertility. These crops are generally categorized into three types: grasses, legumes, and brassicas. The literature presents mixed effects of cover crops on subsequent crops, attributing variability to interactions between N and water availability in the soil (Dabney, S. et al., 2010). Cover crops can potentially increase the yield of the following crop by enhancing soil

N levels. A study by Miguez and Bollero (2005) reported that a legume-based cover crop boosted corn yields by 37% in the absence of applied N. Conversely, there is evidence suggesting that cover crops may also compete with cash crops for nutrients, potentially impeding their growth (Munawar et al., 1990). Therefore, while cover crops are considered a beneficial investment in soil health, their impact on subsequent crops can vary significantly based on their management and the specific environmental conditions. According to the USDA census of agriculture over a 10-year period cover crop acreage increased by 34% from 370,137 to 494,450.

1.2 Threats to Corn Production

The agricultural landscape in Georgia is continually challenged by various diseases and pests that threaten corn production. One prominent disease has been southern corn leaf blight, which damages the plant by killing green tissue on the leaves, thus reducing the photosynthetic area available to the plant (Burns, H. 2017). Additionally, aflatoxin, a mycotoxin produced by the fungus Aspergillus flavus, frequently occurs in nature and poses a significant risk to corn, as well as other agricultural commodities. Aflatoxin is harmful to mammals, and its presence in corn can diminish the feed value and marketability of the crop. Outbreaks of aflatoxin are typically triggered by conditions of heat stress and moisture, which are common in Georgia (Sumner & Dewey 2017). Preventing aflatoxin outbreaks in corn requires a multifaceted approach focused on cultural practices, pest control, and diligent post-harvest handling. Key cultural strategies include maintaining adequate soil moisture through irrigation, especially during drought conditions, and rotating crops to disrupt the life cycle of Aspergillus spores. Planting corn early in the season and managing soil nutrients effectively can also reduce the crop's susceptibility to aflatoxin contamination. Additionally, implementing robust pest management strategies to control insects that damage corn kernels and using resistant corn varieties can further mitigate the risk of aflatoxin. After harvest, it is crucial to dry corn promptly to a moisture content of 15% or less and store it in cool, dry conditions to prevent fungal growth, while regular inspections and testing for aflatoxin levels in stored corn are essential for ensuring the safety and quality of the crop (Shotwell, O 1977).

Another serious fungal threat is tar spot, caused by Phyllachora maydis. First confirmed in Indiana in 2015, tar spot forms distinctive circular-black lesions on corn plants, potentially degrading the quality of grain, stover, husks, and silage (Valle-Torres et al. 2020). Southern rust in corn is caused by the fungus Puccinia polysora, which primarily affects the leaves of the corn plant, manifesting as small, circular, orange to light brown pustules. First confirmed in the United States in 1969, this disease thrives in warm, humid conditions and can spread rapidly, potentially causing significant yield losses if not managed promptly. The rust spores are airborne and can travel long distances, making vigilant monitoring and timely fungicide applications critical for managing outbreaks (Debnath et al., 2019).

Entomological challenges such as stink bugs including the green, brown, one-spotted, and red-shouldered varieties also pose a significant threat in Georgia (Ni, X. et al., 2010). These pests damage corn by feeding on the base of the plant during its vegetative state and penetrating the husks to feed on developing kernels during the reproductive stage (Tillman, P. 2010). Effective strategies include regular scouting to detect early signs of stink bug presence and employing pheromone traps or visual inspections to monitor their activity levels. Cultural practices such as crop rotation with non-attractive crops, timely planting to avoid peak stink bug activity, and maintaining field cleanliness can significantly disrupt stink bug life cycles and habitat. Additionally, chemical controls should be applied judiciously when populations exceed economic thresholds, using insecticides like bifenthrin or lambda-cyhalothrin, while promoting natural predators through biological control methods can enhance overall stink bug management.

These integrated pest management strategies help maintain crop health and optimize yields by effectively managing stink bug populations (Hunt, T. et al. 2015).

In addition to biological threats, regulatory challenges also affect corn growers. Legislation such as the Endangered Species Act (1973), the Federal Insecticide, Fungicide, and Rodenticide Act, and the Federal Food, Drug, and Cosmetic Act impose stringent regulations on the use of agricultural chemicals. These laws require pesticides to be registered with the Environmental Protection Agency and establish tolerances for pesticide residues on crops intended for consumption. Furthermore, the Food Quality Protection Act of 1996 mandates rigorous safety assessments for pesticides, ensuring they pose no harm before registration and necessitating reviews every fifteen years (McDonald, Jr., E. et al., 2001). While these regulations are designed to protect environmental and human health, they can also restrict the use of certain chemical treatments, impacting agricultural practices and productivity.

1.3 New Technologies in Corn

Advancements in modern technology have significantly enhanced corn cultivation, enabling growers to achieve greater productivity. This progress owes much to the development of new genetic traits and breeding techniques. Notably, hybrids have revolutionized corn farming by facilitating yields that were once considered unattainable (Troyer, A. et al., 1999). The introduction of various genetic traits has provided growers with powerful tools to combat diseases and pests effectively.

Among these genetic advancements, insecticide-resistant hybrids represent a notable contribution. One prominent example is Bt (Bacillus thuringiensis) corn, which builds resistance to insect pests by producing insecticidal toxins, such as the European corn borer, corn rootworm, corn earworm, fall armyworm, southwestern corn borer, and the western corn rootworm (Peairs, F.B., 2014). By deploying such hybrids, growers can reduce their reliance on pesticides while achieving higher yields. However, concerns regarding the development of resistance to the Bt trait have prompted the implementation of refuge corn strategies, wherein a small percentage of non-Bt corn is planted alongside Bt corn to mitigate the risk of insect resistance (Bessin, R., 2019; DeVries, T. & Wright, R. 2012).

Another valuable trait found in modern corn varieties is herbicide resistance, which addresses the challenge posed by weeds. Weeds compete with corn plants for essential resources, thereby reducing yields. Herbicide-resistant crops enable growers to effectively manage weeds without harming the corn plants. While the benefits of herbicide resistance are evident in increased yields, there are concerns that excessive use could lead to weed resistance, undermining its long-term efficacy (Owen, M. & Zelaya, I. 2005). Various types of herbicide-resistant corn, such as IMI corn, LibertyLink Corn, Roundup Ready Corn, and Poast Protected Corn, offer growers diverse options for weed management (Pacific Northwest Pest Management Handbook).

Weather variability remains an unpredictable factor in farming, particularly for dryland corn fields reliant on rainfall for growth. The introduction of drought-tolerant corn varieties in 2011 has become increasingly valuable in regions with limited rainfall. Field trials have demonstrated the superiority of drought-tolerant corn over conventional varieties under water-limited conditions, as a 2016 study by McFadden, J. et al., 2019, showed a 5% increase in DT corn over non-DT corn in non-irrigated fields.

Seed treatment represents another biotechnological innovation embraced by growers for its numerous benefits. These treatments, which often include fungicides, insecticides, and additives, help preemptively address various issues upon planting. While seed treatments offer potential advantages, some studies have failed to establish a clear correlation between seed treatment and increased yields (Wilde, G. et al., 2007; Taylor, A.G. & Harman, G.E. 1990).

1.4 History of synthetic Nitrogen fertilizers

Before the discovery of the Haber-Bosch process, the approach to N management in agriculture was largely dependent on natural N sources like manure, compost, the reliance on good crop rotations, and plants capable of N fixation. The decomposition of organic material and the growing of leguminous plants, which have the unique ability to convert atmospheric N into a usable form through a symbiotic relationship with bacteria in their root nodules, played an essential role in preserving soil health (Peoples, M. B. et al 1995). However, the introduction of the Haber-Bosch process in the early 20th century marked a pivotal shift in agricultural practices. This groundbreaking method enabled the mass production of ammonia by synthesizing it from N in the air and hydrogen gas, facilitating the creation of synthetic N fertilizers and significantly enhancing their accessibility for agricultural use (Smil, V. 2001).

The application of N fertilizer is pivotal for achieving profitable yields in corn cultivation, as evidenced by the direct correlation between fertilizer usage and yield enhancement (Binford, G.D. et al., 1990; Mulvaney, R.L. et al., 2005). This correlation highlights the transformative impact of synthetic N on modern agriculture, a development largely attributed to the seminal work of Fritz Haber and Carl Bosch. Haber innovated the chemical process that binds atmospheric N to hydrogen molecules, while Bosch, an engineer at BASF, refined this method to facilitate the commercial production of ammonia. Together, they developed what is now known as the Haber-Bosch process (Milton, R. et al., 2017).

This process, a cornerstone of industrial chemistry, is regarded as one of the most significant scientific achievements of the 20th century. It revolutionized agriculture by enabling the mass production of synthetic fertilizers, thereby significantly boosting global food production capacity. For their contributions, both Haber and Bosch were awarded the Nobel Prize. Reflecting on its enduring impact, the global production of ammonia reached approximately 150 million metric tons in 2022, with an estimated 80% dedicated to agricultural applications (Kissel, D.E., 2014; Apodaca, L., Mineral Commodity Summaries 2023, pp. 126-127). This massive scale underscores the critical role of the Haber-Bosch process in sustaining modern agricultural systems and food security worldwide.

1.5 Nitrogen Behavior

Once N is applied to the soil, its behavior is complex and achieving 100% N use efficiency is not feasible. Various processes influence how N interacts within the soil environment, including immobilization, denitrification, leaching, volatilization, and plant uptake, each affecting its availability to crops.

- **Immobilization:** Microorganisms in the soil compete for available nutrients, rendering some of the N inaccessible to the plants.
- **Denitrification:** Conversion of soil nitrate into N gases, prevalent in waterlogged soils.
- **Leaching:** Leaching occurs when N is transported by water past the root zone, making it unavailable to plants. This is facilitated by the negative charge of both soil particles and N ions, which prevents soil from retaining N. The process is concerning for its potential impacts on water quality.
- **Volatilization:** Transformation of N into ammonia gas and released into the atmosphere, exacerbated by higher soil pH levels. Losses are significant especially when manure or urea is not adequately incorporated into the soil through rain or tilling.
- **Plant Uptake:** Optimal outcome where N is absorbed by the plant. The efficiency of plant uptake is greatly influenced by proper management of N application.

In Georgia, N loss through various mechanisms significantly impacts agricultural efficiency and environmental health, with each loss pathway contributing differently based on soil and climatic conditions. Immobilization, where microorganisms make N temporarily inaccessible to plants, is influenced by soil organic matter but is not often quantified as a percentage of total N loss. Denitrification, prevalent in waterlogged soils, can result in 10-20% of applied N being lost as gases like N2 and N2O. Leaching, particularly in sandy soils or during heavy rainfall, can account for substantial losses, with studies indicating 30-50% of N can be lost this way, posing a significant threat to water quality. Volatilization, which transforms N into ammonia gas, can lead to losses of 10-20%, especially with surface-applied urea or manure and is exacerbated by high temperatures and windy conditions. Plant uptake, ideally, captures 40-60% of applied N, influenced heavily by management practices such as the timing and type of N application. Research in Georgia underscores the importance of managing volatilization and leaching, recommending strategies like urease inhibitors and split-application techniques to enhance N use efficiency and minimize environmental impacts. Overall, these N loss mechanisms vary in their significance, with their impact largely dependent on local environmental conditions and agricultural management practices (Anas et al., 2020; Mahmud et al., 2021).

These various behaviors highlight the challenges in managing N in agricultural settings and stress the need for precise and informed application strategies to maximize efficiency and minimize environmental impacts (Cornell Agronomy Fact Sheet, Nitrogen Basics; Baker, J. 2001).

1.6 Different Soils in Georgia

Georgia's diverse geography can be segmented into three major regions and six soil provinces, each influencing a variety of agricultural management decisions, including planting dates and crop variety. The Limestone Valley, situated in the northwest corner of the state, is characterized by high soil erosion and receives an average of 52 inches of rain annually. The soils here are generally thinner and more acidic. The Blue Ridge region features a soil composition that includes loam, clay, silt, and sand, with typically acidic soils that may restrict the availability of essential nutrients. The Southern Piedmont, encompassing the middle portion of the state, presents thinner soils prone to erosion due to its topography, though more optimal farming land is found towards its southern end. To the southeast, the Atlantic Coast Flatwoods stretch into Florida, North Carolina, South Carolina, and Virginia, with soils that are generally poorly drained. The Sand Hills region, running across the state near the fall line (a geologic boundary that stretches from Columbus to Augusta in a northeast direction, representing the ancient shoreline of the Atlantic Ocean), serves as a transitional zone between the Piedmont and the Coastal Plain and is known for its drought susceptibility and less productive soils (Schmidt, J., 2013). The largest soil province, the Southern Coastal Plain, covers most of the southern part of the state and is dominated by the Tifton soil series, which comprises 75% of the region (Soil and Fertilizer Management Considerations for Forage Systems in Georgia).

Soil organic matter plays a crucial role in nutrient delivery to plants and is particularly beneficial for legumes that fix their own N. The preservation of organic matter is significantly influenced by tillage practices; reduced tillage helps retain organic matter in the soil, which is advantageous for holding and mobilizing N. However, Georgia's soils generally exhibit low levels of organic matter, ranging from 1.4% organic matter in conventional tilled fields, and 2.7% in conservation tillage fields (Dean, J. et al., 2003). Low organic matter can impair the ability to retain water and plant nutrients, posing a challenge for local growers. This overview underscores the need for region-specific management strategies that consider both the geological and soil characteristics of each area to optimize agricultural productivity and sustainability.

1.7 Effects of Different Tillage with Nitrogen

Tillage practices have a significant influence on N dynamics within agricultural soils, directly impacting both the efficacy of N fertilizer use and the broader environmental effects of farming. These practices affect a multitude of factors, including soil aeration, temperature, moisture content, and microbial activity, which are crucial in controlling N transformations and its availability to crops (Borin, M. et al., 1997).

Conventional Tillage often involves turning over the soil, enhancing soil aeration and increasing soil temperature more rapidly in the spring. This escalation in temperature and aeration can boost microbial activity, leading to a faster mineralization of organic matter. Although this results in a swift release of N in a form accessible to plants, it may also hasten the depletion of organic N stores in the soil (Mulvaney, R.L. et al., 2009). However, the use of convention tillage can result in nitrate leaching losses up to 35% greater than no tillage (Mkhabela et al., 2008; Patni et al. 1998; Thiagarajan 2005). Moreover, conventional tillage heightens the risk of soil erosion, which can transport topsoil and its inherent nutrients, including N, away from fields, diminishing soil fertility and exacerbating water quality issues in adjacent waterways (Imani, R. 2022).

Reduced Tillage practices, such as chisel plowing or minimum tillage, involve lesser soil disturbance than conventional methods, helping preserve soil structure and organic matter. This preservation is beneficial for the soil's N retention capabilities. Additionally, with reduced soil disturbance, the rate of organic matter decomposition and N mineralization is slower, resulting in a more sustained release of N throughout the growing season. The enhanced soil structure and organic matter content also contribute to reduced erosion and a slower rate of N leaching, thereby making N more available to crops over extended periods (Carter, M.R. et al., 1992).

No-Till farming leaves crop residues on the soil surface, which over time increases the soil's organic matter content. This accumulated organic matter acts as an N reservoir, gradually releasing nutrients as it decomposes. Moreover, the presence of crop residues and the undisturbed soil structure in no-till systems can enhance water infiltration and retention capabilities of the soil, which could improv N utilization by crops. In addition, no till has the potential to reduce nitrate leaching by up to 35% compared to conventional tillage. However, no till has been shown to increase gaseous N losses via volatilization, by up to 4.2 times and N_2O emissions by up to 10 times (Mkhabela et al., 2008; Patni et al. 1998; Thiagarajan 2005). Additionally, the initial high residue cover and cooler, wetter soil conditions under no-till can temporarily immobilize N as microbes consume available N to decompose residues. This necessitates specific adjustments in N management strategies, particularly in the timing and placement of N applications (Derpsch, R. et al., 2010).

Conservation Tillage combines the benefits of conventional and no-till systems by allowing precise nutrient placement near the seed row, significantly enhancing N use efficiency. By disturbing only specific portions of the field, these methods help maintain soil structure and reduce N losses through erosion and volatilization (Abdollahi, L. et al., 2014).

Each tillage practice necessitates tailored N management strategies to accommodate the unique soil and crop dynamics. Effective N management in these varied tillage systems typically involves a combination of adjusting N application rates, timing, and methods, such as side-dressing or utilizing slow-release fertilizers, to optimize nutrient availability and meet the specific requirements of the crop.

1.8 Nitrogen Use Efficiency

Nitrogen Use Efficiency (NUE) measures the ratio of N absorbed by the crop to the total N input, with a higher ratio reflecting better efficiency. The formula commonly used to calculate NUE is: NUE = ΔYield / ΔN applied, where "Δ" (Delta) represents the change in a variable. Specifically, ΔYield refers to the change in crop yield resulting from a change in applied N, denoted as ΔN applied. This formula helps quantify how effectively a crop utilizes the added N. Research estimates that about half of all synthetic N applied to crops is either lost to the atmosphere or leached into water bodies, highlighting the importance of optimizing N use (Follett, R.F. and Hatfield, J.L., 2001).

Nitrogen Use Efficiency (NUE) is a crucial metric in agricultural science that measures how effectively a crop utilizes N. It can be calculated using various formulas, each focusing on different aspects of N dynamics and plant response. The basic NUE formula, NUE=$\frac{Y}{N}$, represents the ratio of crop yield (Y) to the nitrogen input (N), highlighting the efficiency of N conversion into yield. Agronomic Efficiency (AE) is defined as AE = $\frac{G_f - G_u}{N_a}$, where G_f and G_u are the grain yields of fertilized and unfertilized plots, respectively, and $NaNa$ is the rate of N applied, emphasizing the yield gain per unit of N applied. Physiological Efficiency (PE), PE = $\frac{Y_f - Y_u}{N_f - N_u}$, measures the increase in biomass per unit of N absorbed, considering the total aboveground biomass (Y) and nitrogen content (N) differences between fertilized and unfertilized plots. Agrophysiological Efficiency (APE) focuses on the efficiency of converting absorbed N into grain yield, APE = $\frac{G_f - G_u}{N_f - N_u}$. Apparent Recovery Efficiency (ARE), ARE = $\frac{N_f - N}{N_a}$, assesses how much of the applied N is found in the aboveground biomass of the crop compared to unfertilized controls. Utilization Efficiency (UE), UE = $\frac{Y_f - Y_u}{N_a}$, considers the total aboveground biomass gain per unit of N applied, while the Biologically Meaningful NUE, NUE $= \frac{A_n}{L_n}$, introduces a concept where A_n is the N productivity and L_n is the mean residence time of N in the plant, offering insight into the productivity and turnover of N within the crop system. Each of these formulas provides a unique lens through which to view and optimize N use, aiming to enhance both environmental sustainability and crop productivity (Govindasamy, P. et al., 2023).

One method of alleviating N losses and enhancing availability to plants, is for growers to employ N stabilizers. These compounds are designed to retain N in the soil, making it accessible to plants when needed. Urease inhibitors prevent the hydrolysis of urea into ammonia, while nitrification inhibitors delay the conversion of ammonium into nitrate. Additionally, products that combine both urease and nitrification inhibitors, known as double inhibitors, are effective in reducing emissions of NH^3, NO^3, and N_2O (Li, T. et al., 2017). Research has demonstrated that the application of urease inhibitors, nitrification inhibitors, and double inhibitors can increase N uptake by crops by 24.1%, 1.5%, and 47.6% respectively (Sha, Z. et al., 2020). This approach highlights the critical role of targeted interventions in improving N use efficiency, thereby supporting sustainable agricultural practices and reducing environmental impacts.

Seeding density significantly impacts NUE in maize, according to research that investigates the interplay between plant populations and N management strategies tailored to specific sites. A 2012 study showed that increased plant density resulted in a NUE of 56 kg of grain per kg of N, which was slightly higher but not significantly different than the 54 kg of grain per kg of N observed at normal plant densities. This suggests that under certain conditions, higher seeding densities may enhance NUE. Moreover, integrating site-specific management strategies, particularly variable-rate (VR) N applications in conjunction with high plant densities, has shown further improvements in NUE (Ciampitti and Vyn, 2012). In cases where VR management strategies were implemented, NUE increased by about 3 to 4 kg of grain per kg of N compared to standard uniform management, due to more efficient N use that avoids excess and does not compromise yield (Ping et al., 2008). Economically, the interaction of higher seeding densities and VR N management has proven beneficial, enhancing the gross return above fertilizer and seed costs (GRC) by $15 to $26 per hectare compared to standard density and uniform N management (Ping et al., 2008). This economic advantage corroborates findings from earlier studies that suggest a potential increase in NUE from higher seeding densities, primarily due to better N uptake and utilization by a denser plant population (Ciampitti and Vyn, 2011). Consequently, increasing seeding density in maize cultivation, especially when combined with VR N management strategies, not only optimizes N application, and reduces waste but also offers modest economic returns, thereby supporting sustainable agricultural practices.

1.9 The 4 Rs of Nutrient Management

Another method of mitigating environmental N losses is by observing the 4 Rs of nutrient management, which are guidelines to enhance crop production through precise fertilization. This strategy includes using the right source, right placement, right timing, and right rate of nutrient application, each critical for maximizing both economic and environmental benefits. As outlined by Mattson, N. and van Iersel, M. (2011), the core principle of this approach is that the appropriate nutrient source should be applied in the correct amount, at the optimal time, and placed precisely where the crop can best utilize it. This holistic approach to fertilization, where all elements of the 4 Rs are interconnected, aims to optimize nutrient efficiency and minimize wastage, thereby supporting sustainable agricultural practices.

Right source is fundamental to the 4 Rs, ensuring that the type of fertilizer used is specifically tailored to meet the crop's nutrient demands. This involves not only choosing the correct fertilizer type but also determining if a combination of sources might be more effective than a single source. Various options such as manure, liquid, and granular applications are considered, each with distinct impacts on soil health and nutrient availability. For instance, the use of organic N, including manure, compost, and other organic fertilizers can significantly influence soil microbial activity, which in turn affects N cycling and potential losses (Abalos, D. et al., 2013).

In Georgia, the predominant N sources for corn include various commercial fertilizers such as ammonium nitrate, ammonium sulfate, UAN solution, and urea, each tailored for specific agricultural practices and environmental considerations. Ammonium nitrate and ammonium sulfate are favored for their high N content; however, they significantly acidify the soil, necessitating careful soil pH management to prevent adverse effects on forage growth. UAN solution, a liquid N form, is advantageous as it is less vulnerable to volatilization losses compared to urea, making it suitable for scenarios where soil incorporation is not immediate. Urea, offering the highest N concentration, is prone to volatilization under warm, humid conditions; therefore, it is often treated with urease inhibitors or timed before rainfall to enhance soil integration. The selection of an appropriate N source is influenced by factors like tillage practices, erosion risks, and the timing of applications concerning rainfall events. For example, in regions with high soil erosion or where no-till practices prevail, less soluble or slow-release N forms such as ammonium nitrate are preferred to minimize runoff and leaching. Moreover, splitting N applications is advised in erodible or sandy soils to align with crop uptake and reduce environmental losses. Effective N management is vital not only for maximizing forage yield but also for reducing the ecological footprint of N use in agriculture (Hancock, D. et al., 2008).

The concept of "right place" in fertilization refers to strategically positioning fertilizer to maximize its uptake by crops. Fertilizer application techniques are categorized into three primary types: broadcast, surface banded, and injected, each designed to meet specific agricultural requirements and conditions. Broadcast application involves dispersing fertilizer uniformly across the soil surface, either before planting or after. This method is especially effective for covering large areas and allows for flexibility in top-dressing, which supplements nutrients during the crop's growth phase. Surface banded application targets fertilizer placement more precisely, either beside or on the crop rows. This placement strategy concentrates nutrients where they are readily accessible to roots, thereby enhancing nutrient use efficiency (Kelley and Sweeney, 2007). In contrast, injected applications deposit fertilizer beneath the soil surface. Methods like the 2x2, where fertilizer is placed two inches to the side and two inches below the seed, and deep injection, which targets deeper soil layers, are types of injected applications. Techniques such as fertigation integrate fertilizer with irrigation systems, delivering nutrients to the crop canopy, while deep injection targets deeper soil layers. These methods aim to minimize nutrient loss and facilitate better nutrient absorption, optimizing plant growth. Each fertilization method is designed to align nutrient placement with the most beneficial points of access for plant uptake, thereby supporting effective and sustainable agricultural practices.

The right timing for N application is essential to match the crop’s nutrient demands, particularly during periods of rapid growth. Research indicates that corn has the highest demand for N in the six weeks following emergence (Lory et al., 2003). Applying N either too early or too late can significantly impact crop yields and lead to adverse environmental effects. A study by Vetsch and Randall (2004) stresses that the timing of N application is critical, with yields being highly sensitive to the precise days of application, impacting outcomes positively or negatively.

Determining the right rate of N application is equally vital for maximizing agronomic efficiency and environmental stewardship. Over-application can lead to not only reduced yields but also detrimental environmental consequences such as increased soil erosion, decreased soil health, and even profitability. Conversely, under-application might result in lower yields and profitability. Kumar, M. et al. (2021) highlight that accurate nutrient rates enhance soil health by fostering microbial activity and minimizing erosion. Several methods are available for setting N rates, including the crop yield goal (CYG) method, the Agronomic Optimum Nitrogen Rate (AONR), and the Economic Optimum Nitrogen Rate (EONR).

1.10 Crop Yield Goal Method

In 1973, George Stanford, a prominent soil scientist, undertook a significant study to establish the optimal N application rates for corn using what became known as the CYG method. Stanford's method calculates fertilization rates by multiplying the targeted corn yield per acre by a factor of 1.2 $Y_{bu/a}$, a formula that has since been widely adopted by growers across the United States, significantly enhancing corn production (Stanford, G., 1973).

The CYG method is acclaimed for its broad acceptance and implementation among U.S. corn producers. Its simplicity and general effectiveness have made it a staple in agricultural practice. However, the method's universal approach does not account for regional differences in soil composition and environmental conditions. For instance, farmers in diverse agricultural zones such as the Midwest would apply the same fertilization rates as a state such as Georgia, despite their distinct local conditions. This oversight raises questions about the method's adaptability and relevance in varied regional contexts.

Despite these critiques, recent findings from Morris et al. (2018) reveal that 34 Land Grant Universities continue to support the use of Stanford's CYG method. This sustained endorsement from significant academic institutions highlights the method's entrenched role in agricultural education and practice. Nonetheless, it also emphasizes the ongoing debate regarding its applicability in the face of changing agricultural landscapes and advancements in agronomic science. This scenario calls for a need of regional agricultural specificity and evolving research to ensure the method's continued efficacy and relevance.

1.11 Alternative Nitrogen Rate Recommendations Methods

The EONR and AONR are two approaches for determining the ideal N fertilizer rate for crop production. EONR is the N rate that provides the highest economic net return to the grower, while AONR is the N rate that provides the maximum yield per unit of applied N. A study in Mississippi found that using AONR method resulted in higher corn yield compared to the traditional recommended N rate and the EONR method, which aims to have the highest economic return (Oglesby et al., 2022). However, fertilizing according to the AONR could lead to overfertilization and lead to N losses via leaching and greenhouse gas emissions, which can lead to negative impacts on water quality and ecosystem health. Additionally, AONR may not always result in the highest economic return. In contrast, utilizing the EONR method can help to minimize over-fertilization and reduce N losses to the environment, but it may not always result in the highest crop yield. A study found that using the EONR reduced nitrate leaching compared to the AONR method, but also resulted in a lower corn yield (Al-Kaisi et al. 2006). Thus, using the EONR is designed to provide a balance between achieving optimum yield (within 1% of maximum yield) and optimizing economic returns to N application. Likewise, AONR focuses solely on crop response, which can be considered constant for a specific site and year, whereas EONR considers both crop response and the more volatile factors of input costs and crop prices.

One disadvantage of both the AONR and EONR methods is that they do not account for factors such as weather, soil type, fertilizer source, timing or placement, hybrid, tillage, and cover crop use. Furthermore, a limitation to these approaches is the copious amount of data needed to produce accurate models to derive AONR and EONR. Additionally, to ensure an up-to-date model, new data needs to be added on an annual basis to account for factors such as different weather years, changes in genetics, and the myriad combinations of management practices that exist. However, it is unlikely that field trials alone could generate enough data to encompass all combinations of genetics, environment, and management across geographic regions. One potential solution to address these problems is to use data collected from field trials to train crop production models which can then simulate thousands of different genetics by environment by management combinations to estimate the distribution of optimum nitrogen rates to fit different regions.

Currently, models for calculating AONR and EONR exist in the Midwest, yet they are limited to its region, primarily accounting for only N and grain prices, without considering regional specifics. For Georgia, a tailored model would require the aggregation of extensive research data collected from various regions across the state over several years. This model would need to incorporate diverse local factors such as weather variations, soil types, seed prices, crop prices, fertilizer costs, and irrigation practices to accurately meet the unique agricultural needs of Georgia's growers (Oglesby et al. 2022). Thus, the overarching objectives of my thesis are to:

1. Compare corn N rate recommendation methods and their impact on corn growth, development, and yield across Georgia
2. Assess irrigation scheduling methods and their impact on optimal N rates for corn and corn growth, development, and yield.

3. Evaluate corn seeding densities and their impact on corn growth, development, and yield.

1.12 Objectives

To address the goals set forth in this thesis, the following hypotheses were formed with specific objectives designed to address these hypotheses:

Study 1: Corn Nitrogen Rate Recommendation Methods and Their Effects on Corn Growth, Development, and Yield in Georgia

Objectives:

1. Evaluate the CYG N rate recommendation method across Georgia.
2. Compare the CYG N rates to calculated AONR and EONR.
3. Evaluate the effect of nitrogen rate on measures of corn growth, grain yield components, and NUE.

Hypotheses:

1. The CYG Method will result in over-application of N compared to the AONR and EONR methods, as the CYG utilizes the same N rate regardless of location in the state of Georgia.
2. Measures of corn growth, grain yield components, and N use efficiency will increase with increasing N application rate.

Study 2: Evaluating Irrigation Scheduling Methods and Their Influence on Optimal N Rates and Corn Productivity.

Objectives:

1. Evaluate the CYG N rate recommendation method under different irrigation scheduling methods.
2. Assess the effect of irrigation scheduling method on AONR and EONR.

3. Evaluate the effect of irrigation scheduling method on measures of corn growth, grain yield components, and NUE.

Hypotheses:

1. The SI CropFit app will yield greater and have a lower AONR and EONR than the checkbook and half-checkbook irrigation scheduling methods but perform similarly to the full checkbook irrigation scheduling method due to the real time data leading to more timely irrigation.
2. The SI CropFit app and checkbook method will out perform the half-checkbook irrigation scheduling methods in terms of measures of corn growth, grain yield components, and NUE, due to the water stress from having less water applied than both the SI CopFit app and checkbook methods.

Study 3: Assessing the effects of corn seeding densities on growth, development, and yield in the state of Georgia

Objectives:

1. Evaluate the effect of seeding density on corn yield.
2. Assess the impact of seeding density on corn yield, yield components, NUE parameters, and end-of-season stalk nitrate results.

Hypotheses:

1. Corn grain yield will increase with increasing seeding density.
2. Corn biomass production and N uptake will increase with increasing seeding density.
3. Metrics of N use efficiency will increase with increased seeding density.

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CHAPTER 2. CORN NITROGEN RATE RECOMMENDATION METHODS AND THEIR EFFECTS ON CORN GROWTH, DEVELOPMENT, AND YIELD IN GEORGIA[1]

[1] Winkler et al., 2024. To be submitted to a peer-reviewed journal.

Highlights

1. Comparison of crop yield goal, agronomic optimum nitrogen rate, and economic optimum nitrogen rate across diverse locations in Georgia.
2. EONR was 21.3 kg N ha^{-1} (8%) less than AONR, but YEONR was just 0.8% (0.103 Mg ha^{-1}) less than YAONR, on average.
3. NUE metrics, including NRE and NAE, decrease with increased nitrogen rates, reinforcing diminishing returns.

Abstract

Optimizing nitrogen (N) fertilizer rates is critical for maximizing corn yield, nitrogen use efficiency, and farm profitability while minimizing environmental impacts. This study compared the traditional Crop yield goal (CYG) approach with two site-specific methods, the Agronomic Optimum Nitrogen Rate (AONR) and Economic Optimum Nitrogen Rate (EONR), across six diverse locations in Georgia, using N rates from 0 to 470 kg N ha^{-1} in 67 kg N ha^{-1} increments. Results demonstrated that AONR values varied by site, ranging from 189 to 313 kg N ha^{-1}, achieving maximum yields of 11.3 to 15.8 Mg ha^{-1}. The EONR values, slightly lower at 179 to 289 kg N ha^{-1}, delivered comparable yields (just 0.8% below AONR) with an average profitability improvement of \$3.14 ha^{-1} due to reduced fertilizer input costs. Applying N rates above EONR did not produce significant yield gains, instead raising costs and the potential for N leaching and emissions, especially in Georgia's sandy soils. Additionally, the effect of increasing nitrogen rate on measures of crop growth and NUE such as grain yield, stover, grain, and whole plant biomass and N uptake, stover and grain N concentration, thousand kernel weight (TKW), kernels per ear (KPE), nitrogen fertilizer recovery efficiency (NRE), nitrogen physiological efficiency (NPE), nitrogen agronomic efficiency (NAE), and nitrogen internal efficiency (NIE)

were evaluated. Generally, the crop yield, biomass production, TKW, KPE, and nitrogen uptake increased with increasing N rate; however, the efficiency with which the crop utilized applied N fertilizer and converted absorbed N into crop yield tended to decrease with increasing N fertilizer application rates. Overall, the findings support using site-specific recommendations via AONR and EONR over CYG to balance high productivity with economic and environmental sustainability. However, to do this, continuous data collection across multiple locations on an annual basis would be needed to generate accurate models. This research suggests a shift toward precision N management in Georgia's corn systems, emphasizing the need for further studies on intra-field variability and in-season adjustments to optimize N applications.

2.1 Introduction

Corn (*Zea mays* L.), a staple crop in American agriculture, plays a critical role in both food production and the agricultural economy (Doebley et al., 2004). Its versatility and high yield potential have made it a key component of farming systems, especially in regions like Georgia. However, optimizing corn production in the diverse regions of Georgia requires precise management practices, particularly concerning nitrogen (N) fertilizer application. Nitrogen is a vital nutrient for corn growth, significantly influencing crop development, yield, and overall productivity (Binford, G.D. et al., 1990; Mulvaney, R.L. et al., 2005). Yet, its management presents numerous challenges due to the complex dynamics of N in soil and its susceptibility to environmental losses.

The efficiency with which N is used by crops, referred to as nitrogen use efficiency (NUE), is a critical aspect of sustainable agriculture. The most commonly used measures of NUE are functions of yield thus, achieving high NUE is essential not only for maximizing crop yields but also for minimizing the environmental impacts associated with N losses, such as leaching into groundwater and the emission of greenhouse gases. Therefore, determining the optimal N rate for corn is a fundamental task for agronomists and farmers alike (Follett, R.F. and Hatfield, J.L., 2001).

Various methods exist for recommending N rates, each with its strengths and limitations. The traditional CYG method has been widely used because of its simplicity and practicality. This method involves applying N based on a predetermined yield target, assuming a direct relationship between N input and yield. While straightforward, this approach does not account for the variability in soil types, weather conditions, and management practices, which can lead to either under or over-application of N. In contrast, more advanced methods such as the AONR and the EONR offer more refined approaches. AONR is determined by identifying the N rate that maximizes crop yield, while EONR considers both yield maximization and economic returns (Oglesby et al., 2022). These methods provide a more tailored recommendation by factoring in the diminishing returns of N application and the cost-benefit analysis of fertilizer use (Al-Kaisi et al. 2006).

Georgia’s diverse soil types, ranging from the sandy soils of the Coastal Plain to the clay-rich soils of the Piedmont, present additional challenges for N management. Georgia's soils are naturally acidic and low in fertility (Harris et al., 2024). Moreover, these soils differ in their capacity to retain and supply N to crops, affecting the optimal N rate for corn production. Sandy soils, for instance, tend to have lower water and nutrient retention, making leaching a significant concern, while clay soils may lead to waterlogging, with soils in Georgia having a 1:1 type clay with low CEC, which can reduce N availability (Schmidt, J., 2013). As a result, farmers must adopt site-specific management practices to ensure efficient N use and minimize environmental impacts.

This study aims to address these challenges by evaluating different N rate recommendation methods across various regions in Georgia. The study is designed to compare the traditional CYG method against the AONR and EONR approaches, assessing their impact on yield. By conducting field trials at multiple University of Georgia research farms, the research seeks to provide region-specific insights into the effectiveness of these N management strategies. Through this research, the aim is to identify the most effective N management strategies for maximizing corn yield and NUE in Georgia. The findings of the study are expected to contribute to the development of more precise and sustainable N recommendations, enhancing the productivity and environmental stewardship for corn growers in Georgia. This study lays the groundwork for developing a more ideal, regionally specific N management approach for the state of Georgia.

The overarching goal of this study was to compare corn N rate recommendation methods and their impact on corn growth, development, and yield across Georgia. To achieve the intended goal of this study, the following specific objectives were developed:

1. Compare the CYG N rates to calculated AONR and EONR.
2. Gauge the efficacy of the different methods based on yield, NUE parameters, and end-of-season stalk nitrate results.

2.2 Materials and Methods

2.2.1 Site Description and Experimental Design

The study consisted of ten N rate trials conducted at five University of Georgia (UGA) Research Farms throughout Georgia in 2023, each chosen to represent different agricultural regions within the state. The locations included Camilla (Stripling Irrigation Park), Midville (Southeast Georgia Research and Education Center), Tifton (encompassing Plant Science Farm and Ponder Farm), and Watkinsville (Iron Horse Farm) (Table 2.1).

2.2.1.1 Experimental Design:

The experiment followed a randomized complete block design consisting of eight N rate treatments (described below) with a minimum of six replications, except the Gibbs Farm which originally had 11 replications but Harvest was effected by a hurricane resulting in data only being available from four replications of the trial. Detailed site descriptions for each location including farm name, field coordinates, number of trials, and number of replications, are provided in Table 2.1.

2.2.2 Cultural Practices

2.2.2.1 Tillage:

Tillage practices varied amongst the research farms based on their standard practice, reflecting the diverse agricultural practices across Georgia. Conventional full-width tillage was predominantly practiced, with the exception of two locations where strip tillage trials were conducted. Conventional tillage consisted of disking to a depth of 15 – 20cm followed by a pass with a field cultivator with rolling baskets to prepare the seedbed. Strip tillage was perform using a two-row ripper stripper. All tillage was done within a week prior to planting. Table 2.2 has information tillage and soil type for each location.

2.2.2.2 Fertility, Pest, and Irrigation Management:

Soil samples were collected from each field by the respective farm managers for initial nutrient analyses. Phosphorus and potassium applications were then tailored based on the results of these samples, following the UGA fertility guidelines. The primary phosphorus source used at most locations was diammonium phosphate (18-46-0) and the primary potassium source was muriate potash (0-0-60). When possible zero N was included with preplant fertilizer; however, given the need for phosphorus fertilizer based on soil tests and the lack of availability of triple superphosphate fertilizer, many of the experimental locations received a small amount of N via preplant fertilizers that were applied uniformly across the field and was not included in our total N applications described below. Notably, at the Ponder Farm, phosphorus levels were deemed sufficient. Consequently, no N was included in the preplant application at Ponder Farm. Meanwhile, Midville and Iron Horse Farms were able to procure triple superphosphate (0-46-0), eliminating the need for N in their preplant applications.

Weed management practices included preemergence and post-emergence herbicide applications tailored to each location's needs according to UGA guidelines in the 2023 Georgia Pest Management Handbook. At most locations, preemergence applications consisted of 1.16 L ha^{-1} of Dual II Magnum (S-Metolachlor) and 2.35 L ha^{-1} of atrazine 4L. Post-emergence applications typically included 1.16 L ha^{-1} of Dual II Magnum, 3.51 L ha^{-1} of atrazine 4L, and 2.35 L ha^{-1} of Roundup PowerMAX II (Glyphosate). However, at the Tifton farms, the post-emergence application also included 2.35 L ha^{-1} of Reckon 280SL (Glufosinate). Insecticide and fungicide applications were limited to necessity and followed UGA guidelines outlined in the 2023 Georgia Pest Management Handbook.

All locations were irrigated using center pivot systems, except for Stripling Irrigation Research Park (SIRP) and Iron Horse Farm where lateral irrigation systems were utilized. The primary method of scheduling irrigation across all locations, except for Stripling (described in Chapter 3), was based on the University of Georgia (UGA) checkbook recommendations (Roth et al., 2023). The checkbook method involves determining irrigation needs based on crop water requirements at different growth stages. This approach considers factors such as crop evapotranspiration to schedule irrigation and optimize water use efficiency.

2.2.2.3 Nitrogen Management

We utilized 8 total N rates ranging from 0 to 470 kilograms per hectare in 67 kg ha^{-1} increments (Table 2.3). Each 67 kg ha^{-} increment in N rate corresponds to a projected increase of 3.14 Mg ha^{-1} in yield based on the current yield goal recommendation of 21.4 kg N Mg $grain^{-1}$. At planting, 67 kg N ha^{-1} was applied using the Precision Planting Conceal 2x0x2 starter N application system, positioning the N 5 cm to the side of the furrow at seed depth on both sides of the furrow. The remaining N was applied at the V3-V5 corn growth stage using a custom sidedress applicator, which employed opening discs to create a shallow furrow approximately 5 centimeters from the row on both sides. Liquid UAN was then dribbled into this furrow. The N source utilized as both starter and sidedress in this study was a liquid 24-0-0-3S fertilizer, which was a blend of urea ammonium nitrate (28-0-0), BASF's 19E fertilizer (19-0-0), and ammonium thiosulfate (12-0-0-26S). The author acknowledges that the use of 24-0-0-3S fertilizer could results in confounding effects due to different rates of sulfur applied across plots. This was done for two reasons: 1) this was the only N sources readily available within a reasonable distance of the UGA Tifton Campus, and 2) there is mounting evidence that excessive N application can induce sulfur deficiency and is especially prevalent in higher rates within N rate trials; thus, the use of 24-0-0-3S which kept sulfur in a constant ratio relative to the N application was utilized to help avoid artificially induced sulfur deficiencies. Application rates at both timings were controlled using a Precision Planting vApplyHD system.

2.2.2.4 Planting and Harvest:

Planting operations were conducted using a 4-row Harvest International planter outfitted with precision planting equipment to ensure accuracy and uniformity across all sites (Table 2.4). The planter was equipped with the following precision planting components: DeltaForce automated downforce control, vSet seed meters, vDrive electronic seed meter drive, BullsEye seed tubes, Conceal banded N placement, and vApplyHD liquid control system. These state-of-the-art technologies were chosen to optimize planting precision and facilitate consistent seed placement and N application.

A consistent corn seeding rate of 79,000 seeds per hectare was utilized across all trial sites to maintain consistency in plant density. Row spacing was set at 91 cm for all trials, with an average inter-plant spacing of approximately 12 cm. This spacing aligns with common practices among farmers in Georgia and was selected to represent real-world agricultural conditions in the state.

Plot dimensions were consistent across most locations, measuring 3.7 m by 9.1 m. However, slight variations were observed at Stripling Irrigation Research Park (SIRP) and Iron Horse Farm (Table 2.5). These adjustments were made to accommodate specific requirements at each site. The hybrid utilized for the majority of the study was Pioneer 1622VYHR, chosen for its suitability to the region's conditions and farming practices. At Iron Horse Farm, Pioneer 1289YHR was selected due to its earlier relative maturity, better aligning with the farm's northern location within the state (Table 2.5).

All plots were harvested using a plot combine equipped with a calibrated HarvestMaster GrainGage, allowing for the measurement of yield, test weight, and harvest moisture with precision. The use of this equipment ensured accurate and reliable data collection during harvesting. For each plot, the middle two rows were designated for yield data collection to minimize edge effects and ensure representative sampling. The lone exception to this is the Gibbs Farm where a hurricane caused total loss of the crop prior to harvest; thus, yields from the Gibbs Farm are calculated from physiological maturity crop samples that were collected prior to the hurricane. Harvest dates were recorded for each site and can be seen in Table 2.4, with operations conducted promptly upon reaching physiological maturity to capture yield potential accurately.

2.2.3 Sampling and Data Collection

2.2.3.1 Plant Sampling and Analysis

At the R6 growth stage, plant samples were collected from four replications at each experimental location. Specifically, two plants were randomly selected from three separate locations within each plot to ensure representative sampling. Stand counts for each plot were also conducted at each of the three sampling locations to assess plant density and uniformity.

The collected plant samples were separated into three fractions: stalk nitrate samples, remaining stover, and grain. Stalk nitrate samples were collected by excising a 20-cm segment from the stalk, specifically from 15 to 35 cm above the base of the plant. Grain was separated from cobs using an ALMACO Maizer SES. Prior to further processing the grain, yield components were evaluated, including kernels per ear and weight per kernel. Subsequently, all plant fractions were dried at 60°C to a constant weight to remove moisture content. Once dried, the samples were weighed to determine biomass. Following biomass determination, the samples were ground to pass through a 1-mm sieve for further analysis.

Nitrogen concentration in the ground samples was analyzed via dry combustion analysis. This analysis provides precise measurements of N concentration in each plant fraction. The N concentration was multiplied by the biomass of each fraction to determine the total N content. To determine the total plant N uptake, we added the total N content from each plant fraction (grain N + Stover N + Stalk Sample N). The results from these analyses were used to calculate various measures of NUE. Additionally, stalk nitrate samples were subjected to standard stalk nitrate testing procedures. Specifically, 0.5 g of the ground stalk material were extracted with 50 ml of distilled water. The resulting solution was analyzed colorimetrically for nitrate content using an autoanalyzer with the cadmium reduction method.

2.2.3.2 Nitrogen Use Efficiency Calculations

The inclusion of a zero N treatment in this study allowed us to utilize Nitrogen fertilizer recovery efficiency, Nitrogen physiological efficiency, and agronomic efficiency as our measures of NUE, which were calculated using the following equations.

Fertilizer-N Recovery Efficiency

$$RE_{fert} = \frac{Plant\ N_f - Plant\ N_0}{Fertilizer\ N} \times 100$$

where RE_{fert} is fertilizer-N recovery efficiency, Plant N_f is whole plant N uptake in the fertilized plot, Plant N_0 is whole plant N uptake in the zero N plot, and Fertilizer N is the total amount of N fertilizer applied to the fertilized plot.

Physiological Efficiency

$$PE = \frac{Yield_f - Yield_0}{Plant\ N_f - Plant\ N_0}$$

where PE is physiological efficiency, $Yield_f$ is grain yield in the fertilized plot, and $Yield_0$ is grain yield in the zero N plot.

Agronomic Efficiency

$$AE = RE_{fert} \times PE$$

where AE is agronomic efficiency.

Nitrogen Internal Efficiency

$$NIE = \frac{Yield}{Plant\ N}$$

where NIE is nitrogen internal efficiency.

2.2.4 Statistical Analysis

For the determination of AONR and EONR, we employed the model averaging method described by Miguez and Poffenbarger (2022). Briefly, this method involves fitting linear plateau and quadratic plateau N response models to the yield data and then using weighted averages of fit to derive an average model. In this study, there were no study locations where a linear plateau and quadratic plateau could not be successfully fitted to the data. AONR and EONR are then computed from this average model. AONR is defined as the breakpoint of the model and EONR is defined as the point at which the slope of the response curve falls below the chosen fertilizer to grain price ratio. Using this method of model averaging helps mitigate negative bias in prediction that can occur with linear plateau models and positive bias in prediction that can occur with quadratic plateau models. For this study a fertilizer to grain price ratio of 5.6, which is common in the literature was utilized, considering a fertilizer price of $1.10 per kg and a grain price of $0.197 per kg.

For the analysis of grain yield, stover, grain, and whole plant biomass and N uptake, stover and grain N concentration, thousand kernel weight (TKW), kernels per ear (KPE), nitrogen fertilizer recovery efficiency (NRE), nitrogen physiological efficiency (NPE), nitrogen agronomic efficiency (NAE), and nitrogen internal efficiency (NIE), we conducted Analysis of Variance (ANOVA) using the Agricolae package in the R statistical environment. In this study, all locations were analyzed independently, with N rate being treated as a fixed effect and block being treated as a random effect. When the ANOVA model yielded significant results, a least significant difference (LSD) test was employed for the separation of means. This allowed for the identification of statistically significant differences between treatment means. An alpha level of 0.05 was used for all means comparisons.

2.3 Results and Discussion

2.3.1 Corn Yield Response to Nitrogen Application Rate

Corn grain yield showed a significant response to increasing N rate at all six locations (Table 2.6). The findings reveal significant trends in yield response to N, that varied based on the location being analyzed which emphasizes the importance of site-specific N recommendations. This variability aligns with findings from previous research, such as the study by Oglesby et al. (2022), which demonstrated that a generalized approach to N recommendations, like the CYG method, often fails to account for the specific environmental and soil conditions that influence N efficiency and crop yield.

At the Iron Horse location, the 403 kg N ha^{-1} treatment was similar to the 134, 201, 268, 336, and 470 treatments, while being significantly greater than the 0 and 67 kg N ha^{-1} treatments, while the 67 kg N ha^{-1} treatment was similar to all treatments. At the Midville location, the 0 kg N ha^{-1} treatment was significantly less than the 67 kg N ha^{-1} treatment, which was significantly less than the remaining treatments. At Ponder, similar to Midville, the 0 and 67 kg N ha^{-1} treatments, were significantly less than the 134 – 470 kg N ha^{-1} treatments. At RDC Con, the 134 kg N ha^{-1} treatment is significantly greater than the 0 kg N ha^{-1} treatment and significantly less than the rest of the treatments. 470 kg N ha^{-1} treatment, while being similar to the rest of the treatments. At the RDC Strip the 0 kg N ha^{-1} treatment was significantly less than the 67 kg N ha^{-1} treatment, which was significantly less than 134 kg N ha^{-1} treatment, which was significantly less than the remaining treatments, as they were all similar, except the 268 and 470 kg N ha^{-1} treatments. Stripling was similar to RDC Strip, as the 0 kg N ha^{-1} treatment was significantly less than the 67 kg N ha^{-1} treatment, which was significantly less than 134 kg N ha^{-1} treatment, which was significantly less than the remaining treatments, as they were all similar, except for the 201 kg N ha^{-1} treatment with the 403 and 470 kg N ha^{-1} treatments (Table 2.6).

The various yield differences in response to increasing N rate by location are consistent with previous studies in the literature that observed location-specific responses within N rates trial studies (Oglesby et al., 2022; Raza and Farmaha, 2022; Rajkovich et al., 2015) suggests that site-specific characteristics, such as soil type, organic matter, weather conditions, etc., play a critical role in determining the N needs of the plant. The lack of statistical increases in yield past a certain N rate aligns with previous literature. For instance, Tamang et al. (2024) reported yields that plateaued or declined after rates of 180 kg N ha^{-1} and suggested that excessive N application may not always lead to proportional increases in yield. The results in the current study agree with Tamang et al. (2024) which confirms that NUE may decrease with increasing N rates beyond the optimum (Kitchen et al., 2022; Martinez-Feria et al., 2018; Woli et al., 2016). Decreasing NUE means that additional N fertilizer above the optimum is likely not economically beneficial (Sawyer et al., 2006) and could result in excess soil nitrate which is susceptible to loss via leaching (Bosch et al., 2015; Hubbard and Sheridan, 1983) or denitrification (Mosier et al., 1998; Van Groenigen et al., 2010) especially in the sandy soils of the southeastern Coastal Plain. The variability in N response across different locations observed in this study highlights the need to explore alternative N rate recommendation strategies, moving beyond the current one-size-fits-all CYG approach used in Georgia.

In general, the Ponder location had the lowest overall yields, while the RDC Strip location had the highest. These two locations are only 12 kilometers apart and share the same soil type. They also received similar rainfall between planting and harvest (664.75 mm vs 639.83 mm), peanuts were the previous crop, the same hybrid was planted, and fertility was maintained according to University of Georgia guidelines. The main differences were in tillage practices, fallow period groundcover, and crop rotation. At Ponder, the field was in a 2-year corn-peanut rotation with no winter ground cover and tillage involved disking followed by field cultivation, while the RDC Strip location was in a 4-year corn-soybean-cotton-peanut rotation with a cereal rye cover crop and strip tillage. This highlights the fact that crop management practices can lead to differences in yield amongst similar geographic locations.

2.3.2 Agronomic and Economic Optimum Nitrogen Rates

The agronomic optimal nitrogen rate (AONR) refers to the N rate required to achieve maximum corn grain yield. In this experiment, estimated AONR ranged from 189 kg N ha^{-1} to 313 kg N ha^{-1} and estimated yield at AONR (YAONR) ranged from 11.28 Mg ha^{-1} to 15.81 Mg ha^{-1}. This equates to 124 kg N ha^{-1} spread in AONR amongst the locations in this study. It is common within the literature to observe a large spread in AONR amongst experimental sites within the same state or region (Table 2.7). For example, Oglesby et al. (2022) observed a range in AONR of 108 kg N ha^{-1} in Mississippi, while Kaur et al. (2024) observed AONRs ranging from 179 to 291 kg N ha^{-1} across Nebraska, Missouri, and Illinois. The AONR only considers maximizing grain yield, but farmers are generally interested in maximizing profit, thus it is necessary to explore N recommendation tools that consider economics as well.

The EONR optimizes profitability while considering both crop market price and N input costs to determine a suggested N rate. EONR represents the N rate at which the revenue gained from an additional unit of yield no longer outweighs the cost of the additional N fertilizer required to produce that yield. In this study, EONR ranged 179 kg N ha^{-1} to 289 kg N ha^{-1} while Yield at EONR ranged from 11.15 Mg ha^{-1} to 15.67 Mg ha^{-1}. In this study, EONR was 21.3 kg N ha^{-1} (8%) less than AONR, but YEONR was just 0.8% (0.103 Mg ha^{-1}) less than YAONR, on average. By definition, EONR is the profit maximizing N rate for a given operation. In the context of this study, where a fertilizer price of \$1.10 kg^{-1} N and a grain price of \$0.197 kg^{-1}

grain was utilized when calculating EONR, this equates to an average reduction in fertilizer price of \$23.43 ha^{-1} and a reduction in grain revenue of just \$20.29 ha^{-1}. So, in this study, utilizing EONR rather than AONR could have resulted in realizing \$3.14 ha^{-1} greater profit, while utilizing lower N rates which could also result in less losses on N to the environment (Table 2.7).

In this study, the CYG method overestimated and underestimated both AONR and EONR 67% and 33% of the time, respectively. These findings align quite well with previous literature finding that the CYG method commonly results in over-application or under-application of N for corn production (Niemeyer et al., 2021). In fact, in a study across eight Midwest U.S. states, Ransom et al. (2020) found that only 20-41% of sites were estimated within ±30 kg N ha^{-1} of the EONR when using various CYG methods. Furthermore, in a Mississippi study, Oglesby et al. (2022) observed that the CYG method overestimated and underestimated AONR and EONR 86 and 14% of the time, respectively.

In addition to the inter-field variability observed between locations in this study, it is possible that intra-field variation in optimal N rate also exists, which would further necessitate the move away from the CYG approach in Georgia. In a Missouri study, Scharf et al. (2005) found median EONR values ranging from 63 to 208 kg N ha^{-1} within a given field, which suggests that applying a uniform N rate across a field could lead to significant over- or under-fertilization in many areas. To help account for intra-field variability it may be necessary to explore in-season sensor based variable rate N recommendation tools, which are capable of helping to make real-time decisions regarding N management as the crop is actively growing.

2.3.3 Nitrogen Rate Effects on Yield Components

Thousand kernel weight (TKW) and kernels per ear (KPE), along with plants per hectare (PPH) and ears per plant (EPP) are the primary components that determine corn grain yield. In this study, there were no significant differences in PPH between N rates in a given location and, though not directly recorded, it was observed that the hybrid utilized generally had just one EPP on average, thus any differences in yield were most likely driven by differences in TKW, KPE, or a combination of these two components. Previous studies have shown that increasing N application rates can increase yield components such as KPE and TKW (Abera et al., 2017; Imran et al., 2015; Cambouris et al., 2016). More generally, the positive effect of N fertilizer on corn yield components can lead to increased corn grain yields (Bao et al., 2024; Imran et al., 2015; Cambouris et al., 2016).

In general, TKW showed a positive response to increasing N rate up to a point; however, this response varied by location. At Iron Horse, the TKW in the 470 kg N ha^{-1} treatment was significantly greater than the 67 kg N ha^{-1} and 134 kg N ha^{-1} but similar to all other treatments. Thousand kernel weight at Midville in the 269 kg N ha^{-1} treatment was significantly less than the 336, and 470 kg N ha^{-1} treatments, similar to the 134, 201, and 401 kg N ha^{-1} treatments, and significantly greater than the 67 kg N ha^{-1} treatment which was significantly greater than the 0 kg N ha^{-1} treatment. At Ponder, TKW in the 0 kg N ha^{-1} treatment was significantly less than the 269, 336, 403, and 470 kg N ha^{-1} treatments but similar to the remaining treatments. At RDC Con, the 134 kg N ha^{-1} treatment was significantly less than the 269 through 470 kg N ha^{-1} treatments, similar to the 67 and 201 kg N ha^{-1} treatments, and significantly greater than the 0 kg N ha^{-1} treatment. At the RDC Strip location, the TKW in the 0 and 67 kg N ha^{-1} treatment was significantly less than the 134 – 470 kg N ha^{-1} treatments. At Stripling, TKW was significantly less in the 0 and 67 kg N ha^{-1} treatments compared to all other treatments, the 134 kg N ha^{-1} treatment was significantly less than all treatments except 0 and 67 kg N ha-^{1}, and TKW in the 201and 269 kg N ha^{-1} treatments was significantly less than the 336 kg N ha^{-1} treatments but neither were significantly different from the 403 and 470 kg N ha^{-1} treatments (Table 2.8). Our results are similar to findings in previous studies in terms of general increases in corn TKW with increasing N fertilizer rate (Moser et al., 2006; Abbasi et al., 2012; Pico et al., 2023). For instance, Cambouris et al. (2016) observed a 5 - 7% increase in TKW with each 50 kg N ha^{-1} increase in N fertilizer rate between 0 and 150 kg N ha^{-1}. Similarly, Imran et al. (2015) found that TKW increased by approximately 3 to 5% as N rate increased from 0 to 180 kg N ha^{-1}. In contrast to these previous studies and the findings of the current study, Krnjaja et al. (2021) found no consistent response in TKW to increasing N fertilizer rate beyond their 0 kg N ha^{-1} control. TKW is dependent not only on N fertilizer rate but also on soil properties, weather conditions, and water availability (Moser et al., 2006; He et al., 2013; Cambouris et al., 2016; Ruiz et al., 2022), which could explain the varied response in TKW observed across locations in the current study.

For KPE, the response to increasing N rate again varied by location. However, unlike TKW, there was no trend for increased KPE with increasing N rate except at ponder and Stripling. At Iron Horse, the 0 kg N ha^{-1} treatment was significantly less than the 336 and 470 kg N ha^{-1} treatments, while all three were similar to the remaining treatments. At both Midville and RDC Con, KPE was significantly less in the 0 kg N ha^{-1} treatment relative to all other treatments with no other significant differences observed. At Ponder, KPE in the 403 kg N ha^{-1} treatment was significantly less than the 269, 336, and 470 kg N ha^{-1} treatments, similar to the 134 and 201 kg N ha^{-1} treatments, and significantly greater than the 67 kg N ha^{-1} treatment which was significantly greater than the 0 kg N ha^{-1} treatment. Kernels per ear at the RDC Strip till location in the 67 kg N ha^{-1} treatment was significantly greater than the 0 kg N ha^{-1} treatment and significantly less than the 134 kg N ha^{-1} treatment, but the 67 and 134 kg N ha^{-1} treatments were similar to the 201, 269, 403, and 470 kg N ha^{-1} treatments. At Stripling, KPE was significantly less in the 0 kg N ha^{-1} treatments relative to the 67 kg N ha^{-1} treatment which was significantly less than the 134 kg N ha^{-1} treatments which was significantly less than the 269, 403, and 470 kg N ha^{-1} treatments; however, the 134 kg N ha^{-1} treatment was similar to the 201 and 336 kg N ha^{-1} treatments and the 201 kg N ha^{-1} treatment was also similar to the 269 through 470 kg N ha^{-1} treatments (Table 2.9).

Unlike the findings in this study, previous literature has consistently reported increased KPE with increasing N fertilizer rates, up to an optimal level (Amoruwa et al., 1987; Woldesenbet and Haileyesus, 2016;). For instance, Amoruwa et al. (1987) observed a consistent and positive response in KPE with increasing N rate up to 100 N kg ha^{-1}, suggesting that any additional changes in grain yield beyond this point would have been due to yield components other than KPE. Similarly, Woldesenbet and Haileyesus, (2016) found that KPE increased from 498 with no N application to 587 with 69 kg N ha^{-1}, with no further increases with additional N fertilizer, which suggests that a N rate exists at which KPE is optimized. However, similar to the finding in the current study, Hokmalipour et al. (2010) reported no consistent significant effect of N fertilizer rate on KPE. Likewise, Costa et al. (2002) observed no consistent significant effect of N fertilizer rate on kernel row number per ear or kernel number per row, which are the components that comprise KPE. The results from the current study suggest that any observed differences in yield are not a result of N rate influencing KPE but more likely a result of the changes observed in TKW.

2.3.4 Nitrogen Rate Effects on Measures of Crop Growth and Nitrogen Use Efficiency

2.3.4.1 Impact of nitrogen rate on biomass production

One objective of this study was to observe the effect of N rate on corn stover and grain biomass production, N concentration, and N uptake. The results obtained in this study demonstrate that increasing N rate has the potential to significantly influence corn biomass production, N concentration, and N uptake. However, the magnitude in which these measures of corn growth respond to N rate varies based on experimental location. In general, there was a positive response in corn biomass production, N concentration, and N uptake to increasing N rate in this study. The positive response to increasing N rate observed in this study aligns with previous literature that has found that in general increasing N rate tends to result in increased corn growth, including corn biomass production, N concentration, and N uptake (Irmak et al., 2023; Asibi et al., 2022; Chen et al., 2020; Biswas and Ma, 2016; Halvorson and Bartolo, 2014). This suggests that high N rates results in improved yields and N uptake; however, this is not always the case and we must be wary of making excessively high N recommendations which could lead to environmental issues such as nitrate leaching. Thus, improved N rate recommendations, rather than the CYG which assumes a linear relationship between N rate and crop growth which does not necessarily exist, are needed to maintain the delicate balance between optimizing crop growth and production and minimizing environmental impacts (Andraski et al., 2000; Morris et al., 2018; Sawyer et al., 2006).

In this study, corn stover, grain, and whole plant biomass was evaluated at the R6 (physiological maturity) growth stage. The R6 biomass response to N rate varied by location. At Iron Horse, there was no significant difference in R6 biomass among N rate treatments. R6 biomass at Midville was significantly less in the 0 kg N ha^{-1} treatment, compared to the 134, 269, 336, and 470 kg N ha^{-1} treatments but all treatments were similar to the 67, 201, and 403 kg N ha^{-1} treatments. At Ponder, the 0 kg N ha^{-1} treatment was significantly less than the 67 kg N ha^{-1} treatment which was similar to the 134, 201, and 403 kg N ha^{-1} treatments, and the 269 kg N ha^{-1} treatment was significantly greater than the 0, 67, and 403 kg N ha^{-1} treatments, but similar to all other treatments. R6 biomass at RDC Con was significantly less in the 0 kg N ha^{-1} treatment, compared to the 269, 336, 403 and 470 kg N ha^{-1} treatments but all treatments were similar to the 67, 134, and 201 kg N ha^{-1} treatments. At the RDC Strip the 201 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments, but similar to all other treatments. Finally, at Stripling R6 biomass significantly increased up to the 134 kg N ha^{-1} treatment after which there was no significant differences (Table 2.10).

Grain biomass again had a varied response to increasing N rate, but in general was less sensitive to changes in N rate than the stover biomass. At Iron Horse, R6 grain biomass was significantly greater in the 470 kg N ha^{-1} treatment compared to the 0 kg N ha^{-1} treatment but both treatments were similar to all remaining treatments. The R6 grain biomass at Midville was significantly less at the 0 kg N ha^{-1} treatment, compared to the rest of the treatments. At the Ponder location, the 269, 336, and 403 kg N ha^{-1} treatments were significantly greater than the 0 and 67 kg N ha^{-1} treatments, but similar to the 134, 201, and 403 kg N ha^{-1} treatments. At RDC Con the 201 through 470 kg N ha^{-1} treatments were significantly greater than the 0 kg N ha^{-1} treatment, however the 67 and 134 kg N ha^{-1} treatments were similar to all treatments. Similarly, at RDC Strip the 134 through 470 kg N ha^{-1} treatments were significantly greater than the 0 kg N ha^{-1} treatment, but the 67 kg N ha^{-1} treatment was similar to all treatments. Finally, at Stripling R6 grain biomass significantly increased up to the 201 kg N ha^{-1} treatment after which there was no significant differences, except for the 403 kg N ha^{-1} treatment being significantly greater than the 0 through 201 kg N ha^{-1} treatments (Table 2.10).

Whole plant biomass at R6 followed very similar trends to the R6 grain biomass, which suggests that changes in whole plant biomass are driven by changes in grain biomass. In fact, the response of whole plant biomass at Iron Horse and Midville to increasing N rate followed the exact same pattern as R6 grain biomass. At the Ponder location, the 269, 336, and 403 kg N ha^{-1} treatments were significantly greater than the 0 and 67 kg N ha^{-1} treatments, but similar to the 134, 201, and 403 kg N ha^{-1} treatments. Additionally, the 67 kg N ha^{-1} treatment was significantly greater than the 0 kg N ha^{-1} treatment, but similar to the 134, 201, and 403 kg N ha^{-1} treatments. At the RDC Con location the 134 through 470 kg N ha^{-1} treatments were significantly greater than the 0 kg N ha^{-1} treatment, but the 67 kg N ha^{-1} treatment was similar to all treatments. At the RDC Strip the 269 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments, but similar to all other treatments. Finally, at Stripling R6 whole plant biomass significantly increased up to the 269 kg N ha^{-1} treatment after which there was no significant differences, except that the 201 kg N ha^{-1} treatment was similar to both the 134 and 269 kg N ha^{-1} treatments (Table 2.10).

Our findings align with previous studies that have found varying degrees of corn biomass response to increasing N fertilizer rate (Pantoja, 2013; Davies et al., 2020; Biswas and Ma, 2016). For example, Sawyer et al. (2017) found that stover biomass significantly increased with increasing N rate from 0 kg N ha^{-1} to 168 kg N ha^{-1} and again when further increasing to 280 kg N ha^{-1}. Similarly, Shapiro and Wortmann (2006) also found that corn biomass production increased with increasing N fertilizer rates. However, unlike Sawyer et al., Shapiro and Wortmann identified that corn biomass increased in a quadratic manner relative to applied N fertilizer. Liu et al. (2022) saw similar results to Shapiro and Wortmann on a loam soil in southern China where yields initially increased with increasing N rates up to a point in which yields began to decrease. Quadratic responses in corn stover biomass production to increasing N fertilizer rates were also found in a Colorado study on a silty clay soil (Halvorson and Bartolo, 2014). Given that the quadratic response in corn stover biomass to N fertilizer rates has been observed across soil types and regions of the world, this suggests that there is a N rate that can optimize corn biomass production and that it does not follow a linear response as assumed with the CYG N rate recommendation method. While the CYG was originally developed with yield in mind rather than biomass, the results of this study and previous studies show that there is a strong correlation between corn biomass and corn grain yield. Thus, we must explore N rate recommendation methods beyond the CYG.

2.3.4.2 Impact of nitrogen rate on nitrogen concentration

Nitrogen fertilization can have a significant impact on the N concentration in corn. For instance, Wang et al. (2006) found that higher N treatments generally result in higher N concentrations in the plants. Increased N supply leading to changes in plant tissue N concentration has the potential to improve corn agronomic performance. Interestingly, Amoruwa et al. (1987) found that increasing N supply tends to increase not only N but also K and Mg concentrations in plant tissues and that grain yield is closely associated with ear leaf N concentration. They reported a 177 kg ha^{-1} increase in grain yield per 0.1% increase in ear leaf N concentration in their study. Similarly, Sawyer et al. (2017) reported decreasing stover and grain C:N ratios with increasing N rate which suggests that the N concentration in those plant parts increased with increased N supply. There was also a corresponding grain yield increase with decreasing C:N ratio and increasing N supply in their study. These studies demonstrate the critical role of N in corn productivity.

In this study, stover and grain N concentration were determined in plant samples taken at the R6 growth stage. For both the Iron Horse and RDC Strip locations, the 403 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments, but all three treatments were similar to the remaining treatments. At Midville, the 0, 67, and 134 kg N ha^{-1} treatments were significantly less than the 336, 403, and 470, but were similar to the 201 and 269 kg N ha^{-1} treatments. There was no significant effect of N rate on stover N concentration at the Ponder location. At RDC Con, the 0 and 67 kg N ha^{-1} treatments were significantly less than the 403 and 470 kg N ha^{-1} treatments and were similar to the 134, 201, 269, and 336 kg N ha^{-1} treatments. Additionally, the 470 kg N ha^{-1} treatment was similar to the 201, 269, 336, and 403 kg N ha^{-1} treatments. Finally at Stripling, the 0, 67 and 134 kg N ha^{-1} treatments were significantly less than the 336, 403, and 470 kg N ha^{-1} treatments, but all three were similar to the 201 kg N ha^{-1} treatment and 0 kg N ha^{-1} treatment was also similar to the 269 kg N ha^{-1} treatment (Table 2.11).

In general, grain N concentration was less responsive to increasing N rate relative to the stover N concentration. At Iron Horse, the 201, 336, 403, and 470 kg N ha^{-1} treatments were significantly greater than the 67 kg N ha^{-1} treatment, but all were similar to the 0, 134, and 269 kg N ha^{-1} treatments. At Midville, the 269, 336, 403, and 470 kg N ha^{-1} treatments were significantly greater than the 0 and 67 kg N ha^{-1} treatments but were similar to the 134 and 201 kg N ha^{-1} treatments. For the Ponder location, the 0 kg N ha^{-1} treatment was significantly greater than the 67, 134, and 201 kg N ha^{-1} treatments, while the 269, 336, 403, and 470 kg N ha^{-1} treatments were similar to all treatments. For the grain N concentration at RDC Con, the 0 and

67 kg N ha^{-1} treatments were significantly less than the 336 kg N ha^{-1} treatment and all three were similar to the rest of the treatments. Similarly, at the RDC Strip location, the 0 kg N ha^{-1} treatment was significantly less than the 403 kg N ha^{-1} treatment, while both were similar to the rest of the treatments. At Stripling, the 201 through 470 kg N ha^{-1} treatments were significantly greater than the 0 through 134 kg N ha^{-1} treatments (Table 2.11).

2.3.4.3 Impact of nitrogen rate on nitrogen uptake

Corn N uptake is a function of biomass and N concentration, thus N uptake values often follow trends similar to one of these components (Sawyer et al., 2017; Zhou et al., 1997; Bennett et al., 1989; Sistami et al., 2017). The results of this study are no different in that the stover, grain, and whole plant N uptake values followed relatively similar patterns as observed in the biomass data. In this study, stover N uptake significantly responded to increasing N rate at all locations except Iron Horse where no significant differences were observed, which is the same pattern as observed in biomass. These results are not surprising as N uptake is a result of biomass multiplied by N concentration, and these findings are common within the literature (Sawyer et al., 2017; Killorn and Zourarakis, 1992; Ciampitti and Vyn, 2011). At Midville, the 0 kg N ha^{-1} treatment was similar to the 67, 134, and the 201 kg N ha^{-1} treatments, but significantly less than the rest of the treatments and the 403 and 470 kg N ha^{-1} treatments were significantly greater than the 201 and 269 kg N ha^{-1} treatments but similar to the 336 kg N ha^{-1} treatment. At Ponder, the 269 and 470 kg N ha^{-1} treatments were similar with 134, 201, 336, and 403 kg N ha^{-1} treatments, but were significantly greater than the 0 and 67 kg N ha^{-1} treatments. At RDC Con, the 0 kg N ha^{-1} treatment was similar to the 67, 134, 201, and 269 kg N ha^{-1} treatments and significantly less than the rest of the treatments, and the 470 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments but similar to all other treatments. At

RDC Strip, the 403 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments but similar to all other treatments. At Stripling the 201 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments, similar to the 134, 269, and 336 kg N ha^{-1} treatments, and significantly less than the 403 and 470 kg N ha^{-1} treatments (Table 2.12).

For the R6 grain, there was a general trend increasing N uptake with increasing N fertilizer rate at all locations. Again, these results are unsurprising and tend to follow similar patterns to grain biomass and N concentration. At Iron Horse, the 470 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments, and all three were similar to the rest of the treatments. At Midville, the 67 kg N ha^{-1} treatment was significantly greater than the 0 kg N ha^{-1} treatment, significantly less than the 269, 336, 403, and 470 kg N ha^{-1} treatments, and similar to the 134 and 201 kg N ha^{-1} treatments. At Ponder, the 0 kg N ha^{-1} treatment is significantly less than all treatments except for the 67 kg N ha^{-1} treatment, and the 269 and 336 kg N ha^{-1} treatments were significantly greater than the 201 kg N ha^{-1} treatment but similar to 134, 403 and 470 kg N ha^{-1} treatments. For the grain N uptake at RDC Con, the 0 kg N ha^{-1} treatment was significantly less than the 269, 336, 403, 470 kg N ha^{-1} treatments and all were similar to the rest of the treatments. A similar pattern was observed at the RDC Strip location, where the 0 kg N ha^{-1} treatment was significantly less than the 134 - 470 kg N ha^{-1} treatments, but all treatments were similar to the 67 kg N ha^{-1} treatment. At Stripling, the 201 through 470 kg N ha^{-1} treatments were significantly greater than the 0 through 134 kg N ha^{-1} treatments and the 134 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments (Table 2.12).

In a similar trend to the stover and grain N uptake, whole plant N uptake generally increased with increasing N fertilizer rate. In fact, the response of whole plant N uptake at the

Iron Horse and RDC Con locations was the same as that observed for grain N uptake, which indicates that grain represents a greater proportion of whole plant N uptake than stover. This finding has been confirmed in precious literature which has found that grain N content can account for up to 55% - 73% of whole plant N content (Sawyer et al., 2017; Sindelar et al., 2015). At Midville, the 134 kg N ha^{-1} treatment is significantly greater than the 0 kg N ha^{-1} treatment and significantly less than the 470 kg N ha^{-1} treatment, while being similar to the rest of the treatments. At the Ponder location, the 269, 336, and 470 kg N ha^{-1} treatments are significantly greater than the 0 and 67 kg N ha^{-1} treatments, but similar to the 134, 201, and 403 kg N ha^{-1} treatments. At RDC Strip, the 403 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments, but the 67 kg N ha^{-1} treatment was similar to all remaining treatments. For Stripling, the 403 kg N ha^{-1} treatment was similar to the 269, 336, and 470 kg N ha^{-1} treatments but significantly greater than the 201 kg N ha^{-1} treatment which was significantly greater than the 134 kg N ha^{-1} treatment which was significantly greater than the 0 and 67 kg N ha^{-1} treatment (Table 2.12).

In general, the findings for N uptake in the current study agree with those of previous literature in that there was a trend for greater N uptake with increasing N rate. Specifically, Sawyer et al. (2017) observed a significant increase in stover, grain, and whole plant N uptake when increasing fertilizer rates from 0 kg N ha^{-1} to 168 kg N ha^{-1}, and again when further increasing to 280 kg N ha^{-1}. Similarly, Stevens et al., (2005) reported that corn N uptake increased with increasing N fertilizer rate in a study that utilized fertilizer rates from 0 to 269 kg N ha^{-1} in 67 kg N ha^{-1} increments, which is the same approach used in the current study. In a Minnesota study, Davies et al (2020) reported a general trend for greater plant N uptake as N fertilizer rate increased across all three of their study locations. Likewise in Colorado, Halvorson and Bartolo (2014) found a positive linear response in both grain and stover N uptake to increasing N fertilizer rate in all five site years of their study. While each of these studies demonstrated increased N uptake with increasing N rate, it is also commonly reported that N use efficiency decreases as N fertilizer rate increases. Thus, it is not enough to simply observe how N rate influences N uptake, but the efficiency with which the crop utilizes additional N fertilizer must be considered.

2.3.4.4 Impact of nitrogen rate on measures of nitrogen use efficiency

In the most general of terms, NUE is an effective tool to examine how effectively a crop utilized the applied N fertilizer. There are numerous formulas, each considering different variables, utilized to derive NUE and these NUE formulas are typically categorized as fertilizer-based, plant-based, soil based, isotope-based, ecology-based, or system-based (Congreves et al., 2021; Dobermann et al., 2007). Though the concept of NUE may seem simple, it is in fact quite complex given the various N sources that can contribute to crop production and the fact that factors such as genetics, crop management, and weather can all influence NUE. While it could be argued that having multiple methods of calculating NUE could be beneficial for understanding NUE within different experimental designs, the counterpoint is that having multiple formulas dilutes the authority of any single definition for NUE. In this study we used a combination of fertilizer and plant-based measures of NUE, including Nitrogen fertilizer recovery efficiency, nitrogen agronomic efficiency nitrogen physiological efficiency, and nitrogen internal efficiency to evaluate how well the corn utilized applied nitrogen fertilizer.

2.3.4.4.1 Nitrogen Fertilizer Recovery Efficiency

Nitrogen fertilizer recovery efficiency (NRE) is defined as the increase in N uptake per unit of N fertilizer applied. In general, NRE is dictated by N availability at the time of highest crop demand. Additionally, NRE can be affected by the 4R's of nitrogen management and other factors that control crop N demand such as genetics, climate, plant density, and other stresses (Dobermann, 2007). In this study, there was little response in NRE to increasing N rates. In fact, no significant differences in NRE were observed at Iron Horse, Midville, RDC Strip, or Stripling. However, at Ponder, NRE in the 134 kg N ha^{-1} treatment was significantly greater than the 403 and 470 kg N ha^{-1} treatments, but similar to all remanding treatments. At RDC Con the 336, 403, and 470 kg N ha^{-1} treatments were significantly less than the 67 kg N ha^{-1} treatment, but all were similar to the 134, 201, and 269 kg N ha^{-1} treatments (Table 2.13). The values observed in this study align with those from previous literature, such as Roberts et al. (2016) who observed corn NRE ranging from 61 to 91%, Sindelar et al. (2016) who reported NRE ranging from 38 to 113%, and Wortmann et al. (2011) that found NRE ranging from 40 to 85%. Similar to the results in this study, previous literature has reported a trend for decreasing NRE with N rates (Walsh et al., 2012; Wortmann et al., 2011; Sindelar et al., 2016). Unlike the findings in this study, Bindhani et al. (2001) found NRE to be greatest at their highest N fertilizer rate; however, they also reported that agronomic efficiency and physiological efficiency decreased with increasing N rate which was similar to what was observed in the current study. Our findings, confirmed by findings in the literature, suggests that corn is less efficient at taking up N as fertilizer rates increase.

2.3.4.4.2 Nitrogen Physiological Efficiency

Nitrogen physiological efficiency (NPE) is defined as the increase in grain yield per unit increase in N uptake from fertilizer. A plants NPE is indicative of its ability to transform N acquired from fertilizer into grain and is dependent on factors such as genotype, environment, and crop management (Dobermann, 2007). In general, NPE ranges from 40 to 60 kg of grain per kg increase in N uptake in fertilizer and values greater than 50 kg kg^{-1} are typically observed in soils with low N supplying power which is representative of the soils in this study. In this study, there was little significant response in NPE to increasing N rates. In fact, no significant differences in NPE were observed at Iron Horse, Midville, Ponder, RDC Con, or RDC Strip. However, there was a general trend for increasing NPE up to a point before decreasing at higher N rates at all locations. Stripling was the only location where a significant response in NPE to N rate was observed. Specifically, at Stripling, the 67 and 134 kg N ha^{-1} treatments were significantly greater than the 403 kg N ha^{-1} treatment, but all were similar to the 201, 269, 336, and 470 kg N ha^{-1} treatments. In this study, NPE followed a very similar pattern to NRE with decreasing values as N fertilizer rate increased (Table 2.13). These findings are common withing the literature (Bindhani et al., 2001; Biswas and Ma, 2016; Wortmann et al., 2011) Specifically, Biswas and Ma (2016) reported NPE of 126.9 kg kg^{-1} at 30 kg N ha^{-1}, 73.0 kg kg^{-1} at 150 kg N ha^{-1}, and 62.8 kg kg^{-1} at 210 kg N ha^{-1}. Likewise, Sindelar et al. (2015) observed a negative linear relationship between NPE and N fertilizer rate, reporting a 21% reduction in NPE and fertilizer rate increased from 45 to 224 kg N ha^{-1}. The results from this study, and those from previous literature, indicate that corn is less efficient at converting N fertilizer into grain yield as fertilizer rates increased.

2.3.4.4.3 Nitrogen Agronomic Efficiency

Nitrogen agronomic efficiency (NAE) is defined by Dobermann (2007) as the change in crop yield (typically grain) between fertilized and unfertilized treatments per unit change in N fertilizer applied between fertilized and unfertilized treatments and can be calculated as the product of NRE and NPE. Nitrogen agronomic efficiency is a critical measure for understanding the overall effectiveness of N management, including the timing, rate, and placement of fertilizer. Nitrogen agronomic efficiency typically ranges from 10 to 30 kg of yield per kg of nutrient applied (Dobermann 2007). Generally, NAE values greater than 25 kg of yield per kg of nutrient applied are indicative of low N use or soils with low N supplying power. Previous studies have shown that NAE generally decreases with increasing N application rates but can be improved through optimized management practices (Ma et al., 2020; Zhang et al., 2020; Sindelar et al., 2015; Sawyer et al., 2017). At Iron Horse, the 269, 336, 403, and 470 kg N ha^{-1} treatments were significantly less than the 67 and 134 kg N ha^{-1} treatments, but similar to the 201 N ha^{-1} treatment, while the 134 kg N ha^{-1} treatment was similar to both the 0 and 201 kg N ha^{-1} treatments. At Midville, the 336, 403, and 470 kg N ha^{-1} treatments were significantly less than the 67 kg N ha^{-1} treatment, but all were similar to the 134, 201, and 269 kg N ha^{-1} treatments. At Ponder, the 269 kg N ha^{-1} treatment is significantly greater than the 134 kg N ha^{-1} treatment and significantly less than the 403 and 470 kg N ha^{-1} treatments, while being similar to the 67, 201, and 336 kg N ha^{-1} treatments. At RDC Con there was no significant difference in NAE among any of the treatments. At RDC Strip, the 403 and 470 kg N ha^{-1} treatments were significantly less than the 67 kg N ha^{-1} treatment, however all were similar to the remaining treatments. Finally, at Stripling NAE decreased with N rate, as the 67 and 134 kg N ha^{-1} treatments were significantly greater than the 269 through 470 kg N ha^{-1} treatments. The 269 kg N ha^{-1} treatment was similar to the 201, 336, and 403 kg N ha^{-1} treatments and the 470 kg N ha^{-1} treatment was similar to the 336 and 403 kg N ha^{-1} treatments (Table 2.13). The findings for NAE in this study confirm those of previous literature, in that NAE tends to decrease with increasing N rate which, like NPE, indicates corn becomes less efficient at transforming N fertilizer into grain yield as fertilizer rate increases.

2.3.4.4.4 Nitrogen Internal Efficiency

Nitrogen Internal Efficiency (NIE) is defined by Dobermann (2007), as the plant's ability to convert absorbed N, from both soil and fertilizer sources, into economic yield. Similarly to NPE, it is influenced by factors such as genotype, environmental conditions, and crop management practices. Higher NIE values may indicate N deficiency, while lower NIE values often signal suboptimal nutrient conversion due to environmental stresses or biotic pressures. The typical range for NIE in cereal crops is between 30 and 90 kg kg^{-1}, with 55 to 65 kg kg^{-1} being considered the optimal range for balanced nutrition (Dobermann, 2007). Similar to NPE, there was little significant response in NIE to increasing N rates in this study. In fact, no significant differences were observed at the Iron Horse and RDC Con locations. At Midville, the 470 kg N ha^{-1} treatment was significantly less than the 134 kg N ha^{-1} treatment, and both were similar to the remaining treatments. At Ponder, the 0 kg N ha^{-1} treatment was significantly less than all other treatments. At RDC Strip the 134 kg N ha^{-1} treatment was significantly greater than the 0 kg N ha^{-1} treatment, and both treatments were similar to the remaining treatments. Finally at Stripling, the 201 kg N ha^{-1} treatment was significantly greater than the 0 and 67 kg N ha^{-1} treatments, but was similar to the 134, 269, 336, 403, and 470 kg N ha^{-1} treatments (Table 2.13). Unlike the results for NRE, NPE, and NAE in this study, there was no observable trend in NIE values as N rate increased. In contrast to our study, Ciampitti and Vyn (2011) observed the greatest values for NIE at their greatest N application fertilizer rate. Unlike Ciampitti and Vyn (2011), Sindelar et al. (2015) observed decreasing NIE as N fertilizer rate increased, which suggests that the corn was less efficiently converting N taken into grain yield as fertilizer rate increased. The lack of consensus amongst the literature regarding corn NIE response to increasing N fertilizer rate suggests that further research is needed to better understand the conversion of corn N uptake into grain yield.

2.3.5 Study Limitations

This study was limited by the fact that it was conducted over only one growing season, which restricts the ability to capture the variability in environmental factors such as weather, pest pressure, and disease occurrence that could influence crop performance by year. Multi-year research would provide more robust and generalizable results across varying conditions. Additionally, irrigation and pest management decisions were left to the discretion of each site's farm manager, introducing variability that was not controlled across study locations. This variability in management could affect the yield outcomes. Another major limitation is the potential confounding effects of other nutrients based on different fertilizers and rates used across locations; however, within a given location P and K were equal across all plots while S varied with N application rates. Future research should address these limitations by incorporating multiple years of data and standardized management practices.

2.4 Conclusion

The findings of this study highlight the need for N rate recommendation methods that take consider specific environmental and management factors to optimize corn yield and NUE across diverse agricultural landscapes. Traditional one-size-fits-all N rate recommendation methods, like the CYG, involve N fertilizer application based on an expected target yield which can lead to over- or under-application as they do not consider site-specific factors like soil type and seasonal weather variations. This study's comparisons across multiple locations in Georgia highlighted significant variability in N response amongst locations, indicating that a "one-size-fits-all" approach is insufficient for optimal N management. These results reinforce the notion that site-specific should be incorporated into N rate recommendations to further improve productivity and environmental sustainability.

AONR and EONR provided more accurate recommendations compared to the CYG method. Both AONR, which aims to maximize crop yield, and EONR, which balances yield maximization with economic feasibility, offered insights into how N rates could be optimized to align with specific site conditions. The results from this study showed N applications above EONR offered limited yield benefits with increased input costs, while also potentially increasing environmental risk through possible N leaching and nitrous oxide emissions. By selecting EONR over AONR or CYG (or even just AONR over CYG), it is possible that farmers could improve profitability through reduced input costs with no sacrifice in corn grain yield. This was supported by the findings of this study, where a modest profit increase was seen with the use of EONR over AONR or CYG.

Other trends within the measured growth and NUE parameters also support the hypothesis of diminishing return with higher N fertilizer application rates. Generally, the crop yield, biomass production, TKW, KPE, and N uptake increased with increasing N rate; however, the efficiency with which the crop utilized applied N fertilizer and converted absorbed N into crop yield tended to decrease with increasing N fertilizer application rates. Specifically, NRE, which is the percentage of applied fertilizer absorbed by the crop, and NAE, which is a measure of how well the crop converts applied N fertilizer to yield, both decreased with increasing N fertilizer application rate. The findings of this study agree with previous research that indicated over-application of N not only decreases NUE but also increases the potential for N loss to the environment, especially in Georgia's sandy soils which are prone to leaching.

The results of this study suggest that adopting more intricate N recommendation methods like AONR and EONR is critical for sustainable and profitable corn production in Georgia. By transitioning from a generalized CYG approach to site-specific N management, farmers could maximize both yield and economic returns while minimizing environmental impact. Future research should place greater focus on intra-field variability of optimum N rates and further potential of precision agriculture tools, like in-season sensor-based applications, to perform micro-scale optimizations of N management. A multi-year study that covers a broader range of environmental conditions could provide a better understanding N recommendation methods utilized in this study, while at the same time enhancing their applicability and robustness within different agricultural landscapes.

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2.6 Tables and Figures

Table 2.1 Location, name, and field coordinates for each of the six experimental site.

Location	Farm Name	Field Coordinates
Camilla	Stripling Irrigation Park	31.279307, -84.295330
Midville	Southeast Georgia Research and Education Center	32.874510, -82.209646
	Rural Development Center (RDC)- Strip-till	31.485293, -83. 522102
Tifton	RDC- Conventional Till	31.485060, -83.522815
	Ponder Farm	31.508354, -83.645705
Watkinsville	Iron Horse Farm	33.723607, -83.302671

Table 2.2 Tillage practice and soil type for each of the six experimental location.

Farm	Tillage	Soil Type
Stripling Irrigation Park	Strip Till	Lucy Loamy Sand
Southeast Georgia Research and Education Center	Conventional Till	Tifton Loamy Sand
Plant Science Farm	Strip Till	Tifton Loamy Sand
	Conventional Till	Tifton Loamy Sand
Gibbs Farm	Conventional Till	Tifton Loamy Sand
Ponder Farm	Conventional Till	Tifton Loamy Sand
Iron Horse Farm	Conventional Till	Wickham Sandy Loam

Table 2.3 Rate, timing, and placement of the eight nitrogen fertilizer treatments used across all six experimental locations.

	Nitrogen Fertilizer Application Rate							
	Kg N ha^{-1}							
Total N Rate	0	67	134	201	269	336	403	470
2x0x2 at Plant	0	67	67	67	67	67	67	67
Sidedress Injected	0	0	67	134	202	269	336	403

Table 2.4 Planting, sidedress, and harvest dates for each of the six experimental location.

Farm	**Planting Date**	**Sidedress Date**	**Harvest Date**
Stripling Irrigation Park	April 10, 2023	May 4, 2023	August 29, 2023
Southeast Georgia Research and Education Center	April 12, 2023	May 9, 2023	September 12, 2023
Plant Science Farm	April 17, 2023	May 17, 2023	September 14, 2023
Gibbs Farm	April 20, 2023	May 15, 2023	September 10, 2023
Ponder Farm	April 15, 2023	May 12, 2023	September 10, 2023
Iron Horse Farm	April 26, 2023	May 30, 2023	September 19, 2023

Table 2.5 Plot size and hybrid for each of the six experimental locations.

Farm	Plot Size	Hybrid
Stripling Irrigation Park	3.7m x 7.6m	Pioneer 1622VYHR
Southeast Georgia Research and Education Center	3.7m x 9.1m	Pioneer 1622VYHR
Plant Science Farm	3.7m x 9.1m	Pioneer 1622VYHR
Gibbs Farm	3.7m x 9.1m	Pioneer 1622VYHR
Ponder Farm	3.7m x 9.1m	Pioneer 1622VYHR
Iron Horse Farm	3.7m x 12.2m	Pioneer 1289YHR

Table 2.6 Corn grain yield by nitrogen rate for each of the six experimental locations. Different capital letters within a column indicate significant difference in grain yield between nitrogen rates within a given location at an alpha level of 0.05.

N Rate	**Corn Grain Yield**					
	Iron Horse	**Midville**	**Ponder**	**RDC Con**	**RDC Strip**	**Stripling**
kg N ha^{-1}	Mg ha^{-1}					
0	7.04 A	7.29 A	3.03 A	2.92 A	6.85 A	4.13 A
67	9.87 AB	11.65 B	5.09 A	5.87 AB	10.11 B	7.74 B
134	11.28 BC	14.54 C	9.40 B	9.12 BC	12.70 C	11.20 C
201	11.34 BC	15.38 C	10.68 B	11.72 CD	15.60 DE	13.48 D
268	11.62 BC	14.40 C	11.25 B	12.55 CD	14.72 D	14.30 DE
336	11.65 BC	16.03 C	11.41 B	12.41 CD	15.26 DE	14.41 DE
403	13.54 C	15.87 C	11.36 B	13.27 D	16.21 DE	14.99 E
470	12.42 BC	15.43 C	11.33 B	13.98 D	16.54 E	14.91 E

Table 2.7 Crop yield goal, agronomic optimum, and economic optimum N rates, yield at AONR and EONR, and current, agronomic optimum, and economic optimum yield goal N rates by location.

Site	**CYG Rate**†	**AONR**	**EONR** ‡	**YAONR**	**YEONR**	**CYG**	**AOYG**	**EOYG**
	Kg N ha^{-1}			Mg ha^{-1}		Kg N Mg^{-1} Grain		
Iron Horse	262	245	218	12.24	12.16	21.4	20.0	17.9
Midville	329	189	179	15.35	15.29		12.3	11.7
Ponder	242	265	244	11.28	11.15		23.5	21.9
RDC Con	279	298	280	13.01	12.90		22.9	21.7
RDC Strip	339	308	280	15.81	15.67		19.5	17.9
Stripling	316	313	289	14.75	14.65		21.2	19.7

†Calculated as AONR yield multiplied by current CYG N rate recommendation of 21.4 kg N Mg^{-1} grain.

‡Calculated with fertilizer to grain price ratio of 5.6. Fertilizer price was \$1.10 kg^{-1} and grain price was \$0.197 kg^{-1}.

Table 2.8 Thousand kernel weight by nitrogen rate for each of the six experimental locations. Different capital letters within a column indicate significant difference in thousand kernel weight between nitrogen rates within a given location at an alpha level of 0.05.

N Rate	Thousand Kernel Weight					
	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
	g 1000 seeds^{-1}					
0	286.7 (11.0) BCD	242.6 (15.7) A	184.3 (23.7) A	154.2 (7.3) A	212.8 (7.1) A	242.3 (3.7) A
67	257.9 (12.1) A	272.1 (3.4) B	201.4 (9.1) AB	191.7 (8.7) B	241.4 (15.6) A	245.9 (4.2) A
134	279.5 (4.6) AB	307.4 (8.0) CD	217.8 (12.0) ABCD	214.6 (10.9) BC	277.5 (7.2) B	275.8 (3.8) B
201	305.1 (6.2) CD	301.5 (13.4) CD	213.9 (7.7) ABC	241.1 (31.5) CD	284.5 (9.6) B	300.1 (3.0) C
269	309.7 (4.8) CD	294.1 (6.3) C	253.6 (9.1) E	255.3 (12.5) D	295.1 (8.7) B	306.4 (3.3) C
336	309.2 (4.1) CD	316.9 (9.9) D	248.4 (4.3) CDE	252.4 (9.5) D	311.9 (12.6) B	321.0 (4.1) D
403	302.5 (12.6) BCD	308.1 (8.3) CD	222.9 (26.3) BCDE	254.5 (1.6) D	303.7 (5.4) B	311.4 (7.2) CD
470	323.2 (7.8) D	319.2 (6.1) D	251.6 (8.3) DE	275.5 (9.0) D	286.6 (13.3) B	309.9 (5. 6) CD

Table 2.9 Kernels per ear by nitrogen rate for each of the six experimental locations. Different capital letters within a column indicate significant difference in kernels per ear between nitrogen rates within a given location at an alpha level of 0.05.

	Kernels ear^{-1}					
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	423.17 (33.62) A	327.63 (74.86) A	94.29 (36.06) A	271.25 (37.06) A	457.62 (56.84) A	307.81 (15.04) A
67	557.17 (52.74) AB	565.29 (15.36) B	263.96 (31.9) B	553.71 (36.87) B	604.33 (54.03) B	407.9 (24.3) B
134	559.04 (46.79) AB	606.17 (18.39) B	461.54 (56.73) CD	566.79 (82.65) B	732.71 (26.98) C	562.35 (15.85) C
201	544.37 (64.51) AB	618.22 (39.33) B	449.38 (44.66) CD	571.94 (83.83) B	679.11 (15.35) BC	599.21 (20.91) CDE
269	538.04 (86.12) AB	654.12 (5.46) B	554.04 (93.61) D	636.46 (28.11) B	706.08 (36.41) BC	619.02 (24.33) DE
336	621.88 (47.49) B	618.25 (41.89) B	569.71 (12.12) D	534.62 (109.17) B	612.33 (65.83) BC	594.99 (11.27) CD
403	595.75 (116.62) AB	623.89 (6.37) B	410.83 (74.84) C	649.29 (73.5) B	693.58 (17.18) BC	645.96 (13.11) E
470	626.17 (59.67) B	601.08 (14.69) B	534.5 (22.1) D	695.28 (39.13) B	688.25 (31.32) BC	621.76 (12.61) DE

Table 2.10 Corn R6 stover, grain, and whole plant biomass by nitrogen rate for each of the six experimental locations. Different capital letters within a column within a biomass component indicate significant difference in biomass production between nitrogen rates within a given location at an alpha level of 0.05.

R6 Stover Biomass kg Biomass ha^{-1}						
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	7.65 (1.10)	8.91 (1.05) A	3.07 (0.19) A	5.95 (0.32) A	8.83 (0.57) A	6.55 (0.53) A
67	8.84 (0.90)	11.04 (0.42) AB	6.03 (0.38) B	8.95 (0.92) AB	10.49 (0.31) AB	8.45 (0.38) B
134	9.52 (1.49)	12.69 (0.96) B	7.43 (0.46) BCD	8.99 (0.45) AB	12.28 (0.43) BC	10.54 (0.35) C
201	9.25 (1.48)	11.33 (0.24) AB	7.25 (0.37) BCD	8.77 (0.78) AB	13.04 (0.84) C	11.50 (0.40) C
269	12.36 (1.32)	12.53 (0.49) B	8.40 (0.45) D	9.49 (1.06) B	12.52 (0.53) BC	11.53 (0.31) C
336	11.23 (1.72)	12.60 (0.67) B	8.10 (0.32) CD	9.45 (0.69) B	11.74 (0.61) BC	11.53 (0.25) C
403	10.17 (2.31)	11.93 (0.88) AB	6.94 (0.56) BC	9.23 (0.66) B	12.01 (0.47) BC	11.73 (0.69) C
470	11.99 (0.53)	13.35 (0.74) B	8.01 (0.35) CD	10.15 (0.55) B	11.92 (0.73) BC	11.66 (0.28) C
R6 Grain Biomass kg Biomass ha^{-1}						
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	6.99 (0.83) A	7.00 (1.65) A	1.47 (0.61) A	3.35 (0.54) A	7.43 (0.90) A	5.84 (0.32) A
67	9.05 (6.18) AB	12.57 (0.38) B	4.25 (0.66) AB	8.65 (0.83) AB	11.30 (1.56) AB	8.08 (0.45) B
134	10.27 (1.77) AB	15.23 (0.68) B	7.97 (1.28) BC	10.30 (1.94) AB	15.73 (0.89) B	12.28 (0.34) C
201	9.18 (0.98) AB	14.79 (0.50) B	7.62 (1.12) BC	10.96 (2.61) B	15.16 (0.84) B	14.61 (0.52) D
269	11.37 (2.00) AB	15.36 (0.67) B	11.21 (1.97) C	12.52 (1.09) B	15.92 (0.60) B	14.98 (0.54) DE
336	11.39 (2.09) AB	15.94 (0.90) B	11.43 (0.44) C	10.72 (2.40) B	15.12 (1.11) B	15.20 (0.28) DE
403	9.53 (2.49) AB	15.57 (0.27) B	7.72 (2.18) BC	13.23 (1.45) B	15.74 (0.56) B	16.50 (0.25) E
470	13.79 (12.59) B	15.87 (0.62) B	10.79 (0.66) C	14.48 (1.62) B	15.62 (1.07) B	15.25 (0.39) DE
R6 Whole Plant Biomass kg Biomass ha^{-1}						
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	14.64 (1.84) A	15.91 (2.62) A	4.54 (0.68) A	9.30 (0.80) A	16.26 (1.28) A	12.38 (0.71) A
67	17.89 (1.38) AB	23.61 (0.77) B	10.89 (0.68) B	17.60 (1.66) AB	21.79 (1.83) AB	16.52 (0.78) B
134	19.79 (3.26) AB	27.92 (1.53) B	15.40 (1.66) BC	19.29 (2.34) B	28.01 (1.14) BC	22.82 (0.60) C
201	18.42 (2.38) AB	25.99 (0.38) B	14.88 (1.49) BC	19.62 (3.61) B	26.81 (1.61) BC	26.11 (0.81) CD
269	23.73 (2.31) AB	27.89 (1.04) B	19.61 (2.41) C	22.01 (2.15) B	28.44 (0.82) C	26.55 (0.79) D
336	22.62 (3.27) AB	28.54 (1.19) B	19.53 (0.69) C	20.18 (2.54) B	27.69 (1.59) BC	26.73 (0.44) D
403	19.70 (4.54) AB	27.43 (1.30) B	14.66 (2.70) BC	22.47 (2.08) B	27.75 (0.86) BC	28.23 (0.77) D
470	25.78 (1.32) B	29.23 (1.33) B	18.80 (0.81) C	24.52 (2.29) B	27.54 (1.79) BC	26.03 (1.31) CD

Table 2.11 Corn R6 stover and grain nitrogen concentration by nitrogen rate for each of the six experimental locations. Different capital letters within a column within a nitrogen concentration component indicate significant difference in nitrogen concentration between nitrogen rates within a given location at an alpha level of 0.05.

	R6 Stover Nitrogen Concentration % N					
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	0.86 (0.12) A	0.54 (0.06) A	0.70 (0.05)	0.37 (0.02) A	0.55 (0.03) A	0.73 (0.03) AC
67	0.83 (0.07) A	0.54 (0.03) A	0.48 (0.04)	0.39 (0.01) A	0.6 (0.09) A	0.63 (0.02) A
134	0.9 (0.13) AB	0.62 (0.04) A	0.59 (0.07)	0.45 (0.04) AB	0.67 (0.08) AB	0.63 (0.03) A
201	1.13 (0.14) AB	0.84 (0.05) ABC	0.59 (0.04)	0.49 (0.07) ABC	0.77 (0.08) AB	0.74 (0.04) ABC
269	1.11 (0.09) AB	0.76 (0.1) AB	0.66 (0.01)	0.51 (0.08) ABC	0.82 (0.08) AB	0.85 (0.04) BCD
336	1.17 (0.07) AB	1.05 (0.09) BCD	0.59 (0.02)	0.56 (0.03) ABC	0.86 (0.07) AB	0.89 (0.05) BD
403	1.35 (0.09) B	1.2 (0.07) D	0.64 (0.07)	0.6 (0.05) BC	1.03 (0.06) B	0.99 (0.05) DE
470	1.23 (0.11) AB	1.11 (0.06) CD	0.71 (0.03)	0.66 (0.07) C	0.91 (0.15) AB	1.07 (0.03) E
	R6 Grain Nitrogen Concentration % N					
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	1.17 (0.07) AB	1.05 (0.05) A	1.28 (0.08) A	0.99 (0.02) A	0.95 (0.04) A	0.96 (0.03) A
67	0.98 (0.1) A	1.1 (0.03) AB	1.08 (0.03) B	0.99 (0.02) A	1.05 (0.07) AB	0.97 (0.04) A
134	1.2 (0.06) AB	1.26 (0.04) BC	1.07 (0.04) B	1.09 (0.04) AB	1.12 (0.07) AB	1.05 (0.02) A
201	1.4 (0.05) B	1.28 (0.03) BC	1.05 (0.03) B	1.05 (0.08) AB	1.22 (0.06) AB	1.19 (0.02) B
269	1.3 (0.06) AB	1.29 (0.04) C	1.2 (0.02) AB	1.13 (0.03) AB	1.23 (0.04) AB	1.21 (0.03) B
336	1.36 (0.03) B	1.28 (0.02) C	1.21 (0.04) AB	1.21 (0.05) B	1.2 (0.04) AB	1.2 (0.04) B
403	1.49 (0.1) B	1.29 (0.02) C	1.15 (0.04) AB	1.14 (0.03) AB	1.3 (0.04) B	1.22 (0.04) B
470	1.41 (0.05) B	1.29 (0.04) C	1.19 (0.03) AB	1.2 (0.1) AB	1.21 (0.11) AB	1.26 (0.04) B

Table 2.12 Corn R6 stover, grain, and whole plant nitrogen uptake by nitrogen rate for each of the six experimental locations. Different capital letters within a column within a nitrogen uptake component indicate significant difference in nitrogen uptake between nitrogen rates within a given location at an alpha level of 0.05.

	R6 Stover Nitrogen Uptake					
	mg N ha^{-1}					
N_Rate	Iron_Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	67.5 (19.0)	46.4 (6.1) A	21.3 (1.9) A	22.1 (2.1) A	48.1 (2.8) A	45.9 (3.2) A
67	70.4 (5.7)	57.5 (5.1) AB	28.0 (2.2) AB	34.9 (4.4) AB	63.4 (11.1) AB	52.6 (3.9) A
134	80.9 (10.8)	75.6 (6.6) AB	42.0 (3.7) BC	39.9 (3.0) ABC	70.9 (3.5) ABC	64.4 (4.1) AB
201	108.3 (27.4)	91.1 (5.4) ABC	41.7 (3.3) BC	42.2 (6.5) ABC	89.1 (11.1) ABC	82.0 (5.1) BC
269	135.5 (14.7)	94.1 (11.3) BC	54.2 (3.0) C	50.0 (12.9) ABC	100.0 (5.8) ABC	94.6 (4.6) CD
336	128.7 (16.0)	128.9 (6.0) CD	46.4 (2.5) BC	53.1 (6.0) BC	101.0 (10.4) ABC	100.8 (6.7) CD
403	141.8 (36.4)	142.3 (16.8) D	45.2 (9.2) BC	55.4 (8.6) BC	122.3 (8.9) C	115.7 (9.4) D
470	148.1 (17.3)	147.3 (13.8) D	55.7 (3.4) C	67.2 (10.0) C	111.9 (22.8) BC	110.7 (9.8) D
	R6 Grain Nitrogen Uptake					
	mg N ha^{-1}					
N_Rate	Iron_Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	83.7 (15.8) A	73.5 (18.5) A	17.5 (6.6) A	32.8 (5.0) A	70.9 (9.7) A	55.5 (2.1) A
67	88.2 (8.0) A	138.3 (7.7) B	46.0 (7.1) AB	86.3 (9.5) AB	121.5 (24.5) AB	79.9 (6.8) A
134	120.9 (15.8) AB	192.1 (9.9) BC	85.8 (15.9) BCD	114.9 (24.1) AB	177.0 (17.4) B	128.6 (4.9) B
201	129.3 (15.5) AB	190.0 (9.8) BC	78.6 (8.8) BD	117.8 (33.2) AB	185.1 (18.8) B	175.9 (7.6) C
269	149.4 (30.6) AB	197.0 (3.6) C	133.9 (22.8) C	142.7 (16.0) B	195.2 (8.4) B	181.1 (8.6) C
336	154.1 (26.9) AB	204.7 (13.7) C	138.2 (6.8) C	133.6 (32.2) B	182.2 (18.6) B	182.1 (6.4) C
403	140.5 (37.4) AB	200.7 (5.9) C	90.8 (27.9) BCD	152.0 (19.6) B	204.2 (9.0) B	201.2 (6.5) C
470	192.1 (11.8) B	205.5 (13.0) C	128.5 (10.2) CD	176.2 (33.1) B	192.1 (26.5) B	190.3 (4.0) C
	R6 Whole Plant Nitrogen Uptake					
	mg N ha^{-1}					
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	151.2 (34.7) A	119.9 (24.2) A	38.8 (6.5) A	54.9 (6.2) A	119.0 (11.8) A	101.4 (4.9) A
67	158.6 (12.2) A	195.7 (12.4) AB	80.4 (5.5) AB	121.2 (13.5) AB	184.9 (35.5) AB	132.5 (10.0) A
134	201.8 (22.9) AB	267.7 (16.4) BC	127.8 (18.3) BC	154.8 (24.7) AB	231.8 (12.1) ABC	192.9 (7.6) B
201	237.5 (39.7) AB	285.7 (8.3) CD	120.3 (10.4) BC	157.8 (41.5) AB	248.7 (24.7) ABC	257.6 (10.1) C
269	284.9 (30.0) AB	291.1 (9.2) CD	188.1 (25.6) C	192.7 (28.1) B	295.3 (8.8) BC	277.4 (12.2) CD
336	282.7 (36.5) AB	333.6 (8.9) CD	184.7 (7.2) C	186.7 (33.3) B	291.4 (12.1) BC	282.9 (11.3) CD
403	282.3 (70.6) AB	344.0 (22.1) CD	136.0 (36.7) BC	207.4 (27.7) B	326.4 (16.7) C	316.9 (14.7) D
470	340.3 (16.3) B	352.8 (23.0) D	184.1 (13.5) C	242.2 (47.0) B	303.9 (49.0) BC	300.4 (12.7) CD

Table 2.13 Nitrogen recovery efficiency, nitrogen physiological efficiency, nitrogen agronomic efficiency, and nitrogen internal efficiency by nitrogen rate for each of the six experimental locations. Different capital letters within a column within a nitrogen use efficiency metric indicate significant difference between nitrogen rates within a given location at an alpha level of 0.05.

	Nitrogen Recovery Efficiency kg N Uptake kg N Applied^{-1}					
N_Rate	Iron_Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
67	0.49 (0.2)	1.13 (0.51)	0.6 (0.13) AB	0.99 (0.19) A	0.98 (0.63)	0.53 (0.2)
134	0.61 (0.24)	1.1 (0.24)	0.66 (0.1) A	0.78 (0.15) AB	0.79 (0.18)	0.72 (0.07)
201	0.43 (0.21)	0.82 (0.19)	0.4 (0.04) ABC	0.54 (0.19) AB	0.74 (0.12)	0.8 (0.04)
269	0.5 (0.18)	0.64 (0.1)	0.56 (0.09) ABC	0.51 (0.1) AB	0.66 (0.07)	0.68 (0.05)
336	0.39 (0.12)	0.64 (0.07)	0.43 (0.01) ABC	0.39 (0.08) B	0.5 (0.03)	0.55 (0.03)
403	0.45 (0.2)	0.53 (0.05)	0.24 (0.08) C	0.38 (0.06) B	0.51 (0.05)	0.55 (0.04)
470	0.4 (0.09)	0.50 (0.06)	0.31 (0.02) BC	0.41 (0.09) B	0.39 (0.09)	0.43 (0.03)

	Nitrogen Physiological Efficiency kg Yield kg N Uptake^{-1}					
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
67	49.74 (6.98)	61.41 (18.46)	91 (35.34)	63.89 (12.48)	49.88 (10.86)	80.04 (9.88) A
134	54.69 (22.99)	51.47 (10.58)	84.07 (11.93)	67.14 (1.23)	41.23 (7.93)	77.41 (6.58) A
201	81.03 (47.66)	48.84 (11.28)	100.14 (10.3)	101.88 (39.55)	58.03 (12.63)	56.26 (4.03) AB
269	77.56 (43.04)	46.31 (4.71)	73.75 (13.31)	74.25 (6.71)	38.44 (1.57)	56.57 (4.07) AB
336	37 (14.02)	38.72 (3.86)	77.00 (2.16)	89.72 (33.24)	49.49 (9.6)	52.69 (5.63) AB
403	53.4 (33.13)	34.1 (1.66)	115.21 (29.01)	68.62 (3.66)	40.82 (4.73)	49.81 (3.88) B
470	24.38 (9.31)	35.57 (2.73)	72.88 (6.48)	55.71 (12.72)	63.81 (29.82)	54.67 (8.47) AB

	Nitrogen Agronomic Efficiency kg Yield kg N Applied^{-1}					
N Rate	Iron Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
67	43.7 (5.5) A	67.4 (21.2) A	45.5 (6.4) AB	68.3 (21.7) A	54.0 (8.7) A	52.1 (7.6) A
134	40.1 (7.5) AB	49.1 (5.5) AB	54.5 (7.8) A	52.9 (11.1) A	34.4 (13.5) AB	51.1 (2.5) A
201	21.1 (3.9) BC	36.4 (6.4) AB	39.9 (4.8) AB	40.6 (7.5) A	41.7 (2.2) AB	43.6 (1.1) AB
269	19.8 (2.1) C	29.0 (4.5) AB	37.4 (2.9) B	36.0 (4.1) A	25.1 (2.6) AB	36.6 (1.3) BC
336	13.7 (0.7) C	24.2 (2.7) B	33.4 (1.2) BC	27.2 (2.7) A	25.3 (6.5) AB	27.8 (2.3) CD
403	11.0 (4.1) C	18.0 (1.5) B	22.1 (2.0) C	25.7 (3.6) A	20.5 (2.2) B	25.8 (0.6) CD
470	8.2 (2.7) C	17.6 (2.3) B	22.1 (1.1) C	21.7 (4.7) A	17.5 (1.8) B	21.1 (0.9) D

	Nitrogen Internal Efficiency kg Yield kg N Uptake^{-1}					
N_Rate	Iron_Horse	Midville	Ponder	RDC Con	RDC Strip	Stripling
0	56.6 (1.7)	59.6 (3.2) AB	39.9 (9.8) A	59.1 (3.4)	58.9 (2.3) A	55.1 (1.2) A
67	55.5 (1.7)	70.8 (0.9) AB	65.1 (1.9) B	71.2 (1.1)	65.3 (1.0) AB	59.9 (1.6) AB
134	59.9 (2.6)	71.9 (0.7) A	66.1 (3.0) B	73.2 (3.1)	69.4 (0.5) B	66.8 (1.9) BC
201	54.5 (5.2)	66.4 (1.5) AB	65.0 (2.1) B	73.4 (2.3)	69.7 (1.5) AB	68.3 (1.5) C
269	51.1 (5.8)	67.9 (2.6) AB	69.7 (3.2) B	75.1 (2.3)	66.1 (1.6) AB	65.3 (0.8) BC
336	53.7 (3.4)	61.2 (2.4) AB	74.8 (1.3) B	67.8 (7.5)	62.4 (2.7) AB	64.7 (1.4) BC
403	50.6 (5.7)	58.9 (3.7) AB	64.1 (4.3) B	73.4 (1.0)	62.6 (1.0) AB	64.2 (1.7) BC
470	56.8 (3.4)	58.4 (1.8) B	69.7 (0.4) B	72.9 (0.7)	64.2 (1.9) AB	64.5 (3.1) BC

CHAPTER 3. EVALUATING IRRIGATION SCHEDULING METHODS AND THEIR INFLUENCE ON OPTIMAL NITROGEN RATES AND CORN PRODUCTIVITY[1]

[1] Winkler et al., 2024. To be submitted to a peer-reviewed journal.

Highlights

1. This study compares three irrigation scheduling methods - checkbook, half-checkbook, and SI CropFit app - and their impact on optimal N rates and corn productivity.
2. EONR has the potential to improve profitability relative to the CYG nitrogen recommendation method.
3. Nitrogen rate, rather than irrigation scheduling, predominantly influenced NUE metrics and biomass production in this study
4. The half-checkbook method showed greater grain nitrogen uptake compared to other methods, suggesting that reduced irrigation can sometimes enhance nitrogen assimilation

Abstract

This study evaluates the impact of three distinct irrigation scheduling methods on optimal nitrogen (N) rates, corn productivity, and nitrogen use efficiency in a single-site trial conducted in Camilla, Georgia. Water availability and efficient N management are key factors influencing corn yield, yet achieving a balance between the two remains challenging. Traditional irrigation scheduling, such as the University of Georgia's checkbook method, provides crop water needs at growth stages but does not consider real-time variability in soil moisture and weather conditions. This study contrasts the checkbook method, a modified half-checkbook approach (providing half the water input), and the SI CropFit app, which combines real-time weather data with soil data and modeled crop growth stage data to optimize irrigation timing. We assessed these methods' effects on crop yield, AONR, EONR, and multiple crop growth and NUE metrics, including N recovery efficiency and N agronomic efficiency. Both AONR and EONR varied between irrigation methods, with the checkbook method producing the highest AONR and the half-

checkbook the lowest, indicating the potential yield cost of reduced irrigation. EONR, reflecting profitability and environmental sustainability, was consistently lower than AONR, with AONR producing marginal yield gains insufficient to justify additional N input. This supports the utility of EONR over the CYG method, which often over- or underestimates N requirements, potentially leading to excess application and environmental risks. The findings of this study revealed that corn yield components, biomass production and N uptake generally increased with N rate, while irrigation method had minimal impact on these variables, except for grain N uptake. The SI CropFit app, though designed to adjust to environmental variability, showed no significant advantage in NUE measures over the other methods, highlighting that N rate rather than irrigation scheduling primarily affects NUE. However, the half-checkbook method unexpectedly resulted in higher grain N uptake, suggesting that moderate irrigation reduction may sometimes enhance nitrogen uptake efficiency. Despite these insights, limitations include having just one study location for one year. Expanding trials across diverse locations as well as incorporating long-term evaluations would enhance the applicability of these findings. The findings from this study underscore that, while N rate strongly influences NUE and yield, incorporating real-time data for irrigation scheduling, such as the SI CropFit app, could optimize resource use. This study will help inform adaptive irrigation and fertilization strategies aimed at improving profitability and sustainability for corn production in the Southeast U.S.

3.1 Introduction

Water is a fundamental resource in agriculture, playing a crucial role in determining crop productivity, particularly in regions where rainfall is inconsistent or insufficient (Traore et al., 2000). In Georgia, corn production often faces challenges related to water availability, making irrigation an essential practice for ensuring optimal growth and yield (Orfanou et al., 2019).

However, the efficiency of irrigation is not just about providing enough water but also about applying it at the right time and in the right amount to meet the crop's needs (Payero et al., 2009). Effective irrigation scheduling can significantly impact not only water use efficiency but also the effectiveness of other critical inputs, such as N fertilizers.

Nitrogen is a vital nutrient for corn, influencing its growth, development, and final yield. However, nitrogen's effectiveness is closely tied to water availability. Adequate water ensures that N is dissolved and made available for plant uptake, but too much or too little water can lead to N losses through leaching, denitrification, or volatilization, reducing its efficiency and potentially harming the environment. Therefore, optimizing irrigation practices is key to maximizing nitrogen use efficiency (NUE) and, by extension, corn productivity (Baker, J. 2001).

Traditionally, irrigation scheduling in Georgia has followed the University of Georgia's "checkbook" method, which recommends water applications based on crop growth stages and estimated evapotranspiration rates. While this method provides a straightforward approach to irrigation management, it may not always account for the variability in weather conditions, soil moisture levels, and crop water needs throughout the growing season (Porter et al., 2015). As a result, there is a need to explore alternative irrigation scheduling methods that can respond to real-time conditions and improve both water and N management.

This study explores the impact of different irrigation scheduling methods on optimal N rates and corn productivity. The study was conducted at the Stripling Irrigation Research Park in Camilla, Georgia, where three distinct irrigation scheduling methods were tested: the standard checkbook method, a modified half-checkbook method, and an innovative approach using the SI (Smart Irrigation) CropFit app. The checkbook method serves as the control, providing a baseline for comparison. The half-checkbook method, which applies water at half the recommended rate, is designed to assess the effects of reduced water input on corn performance. The SI CropFit app monitors soil moisture by utilizing precipitation data and estimating daily crop water usage. It provides push notifications to alert users when irrigation is advised or when the crop is nearing a new growth stage.

By conducting this research in a controlled field environment with precise monitoring of water and N inputs, the study aims to provide valuable insights into the interaction between irrigation practices and N management. Understanding these interactions is crucial for developing strategies that not only enhance crop productivity but also improve resource use efficiency, thereby supporting the sustainability of corn farming in Georgia.

The findings from this study are expected to contribute to the ongoing efforts to refine irrigation and N management practices. By identifying the most effective irrigation scheduling methods, this research could lead to recommendations that help farmers optimize their water and N use, reducing costs, and minimizing environmental impacts while maintaining or even increasing corn yields.

The overarching goal of this study was to compare irrigation scheduling methods and their impact on optimal N rates for corn and corn growth, development, and yield. To achieve the intended goal of this study, the following specific objectives were developed:

1. Assess the effect of irrigation scheduling method on AONR and EONR compared to the CYG method.
2. Gauge the impact of irrigation scheduling method on corn yield, yield components, NUE parameters, and end-of-season stalk nitrate results.

3.2 Materials and Methods

3.2.1 Site Description and Experimental Design

This study consisted of three N rate trials conducted in a single field at Stripling Irrigation Research Park (31.279307, -84.295330) in Camilla, Georgia in 2023. The N rate trials were arranged in a randomized complete block design within an irrigation scheduling treatment, each with its own irrigation scheduling method. Each N rate trial consisted of seven replications of eight N rate treatments (described below). Plot dimensions were 3.7 meters by 7.6 meters. The primary soil type at Stripling Irrigation Research Park is Lucy Loamy Sand. Figure 3.1 is a plot map for the trials at Stripling Irrigation Research Park.

3.2.2 Cultural Practices

3.2.2.1 Tillage:

Strip tillage was used for the studies at Stripling Irrigation Research Park. This is the predominant practice used by the superintendent of Stripling Irrigation Research Park and is representative of many growers in the region. Strips were created using a two-row ripper stripper a week prior to planting. Strips were then freshened on the day of planting using a separate strip-till implement that did not have ripper shanks.

3.2.2.2 Fertility, and Pest Management:

Soil fertility samples were collected from the field by the farm manager. Phosphorus and potassium applications were then tailored based on the results of these samples, following the UGA fertility guidelines. The primary phosphorus source used was diammonium phosphate (18-46-0) and the primary potassium source was muriate of potash (0-0-60). The preplant P and K application equaled 112 kg of P ha^{-1} and 252 kg of K ha^{-1}. Unfortunately, the farm manager was unable to obtain triple superphosphate. Thus, given the need for phosphorus based on soil tests, the plots received approximately 40 kg N ha^{-1} via preplant fertilizer that was applied uniformly across the field and was not included within our nitrogen because it was applied weeks before planting and the N in diammonium phosphate readily nitrifies and in the sandy soils found at the Stripling Irrigation Research Park could easily have been lost prior to corn planting.

Weed management practices included preemergence and post-emergence herbicide applications based on UGA guidelines in the 2023 Georgia Pest Management Handbook. For this trial weed management included a preemergence applications consisting of 1.16 L ha^{-1} of Dual II Magnum (S-Metolachlor) and 2.35 L ha^{-1} of atrazine 4L. The Post-emergence application included 1.16 L ha^{-1} of Dual II Magnum, 3.51 L ha^{-1} of atrazine 4L, and 2.35 L ha^{-1} of Roundup PowerMAX II (Glyphosate). Insecticide and fungicide applications were not necessary based on UGA developed thresholds outlined in the 2023 Georgia Pest Management Handbook.

3.2.2.3 Irrigation Management:

Water is quite often a limiting factor for corn growth in Georgia; therefore, we wanted to observe the effect of different irrigation scheduling methods on corn growth and yield. The primary method of scheduling irrigation across Georgia is based on the University of Georgia (UGA) checkbook recommendations (Roth et al., 2023); thus, it was included as a treatment in this trial. However, the lateral irrigation system in the field at Stripling Irrigation Research Park where these trials took place allows for the observation of multiple irrigation scheduling methods within the same field. At the recommendation of the superintendent and University of Georgia Extension Irrigation Specialist Dr. Wes Porter, the irrigation treatments were set up in blocks with the N rate trials built within them (Figure 3.1).

The three irrigation treatments that were implemented include:

1. *Checkbook Method:* The checkbook method involves determining irrigation needs based on crop water requirements at different growth stages. This approach considers factors

such as crop evapotranspiration to schedule irrigation and optimize water use efficiency. This treatment followed the standard UGA checkbook recommendations.

2. *Half Checkbook Method:* Irrigation was applied at half the rate compared to the standard checkbook method. This treatment aimed to evaluate the impact of reduced water inputs on crop performance and N rate recommendations.
3. *SI CropFit App:* An innovative approach integrating real-time weather data with crop growth stage information to optimize irrigation scheduling. The SI CropFit app provides precise and timely irrigation recommendations tailored to the specific needs of the crop and prevailing environmental conditions.

3.2.2.4 Nitrogen Management:

We utilized 8 total N rates ranging from 0 to 470 kilograms per hectare in 67 kg ha^{-1} increments (Table 3.1). Each 67 kg ha^{-} increment in N rate corresponds to a projected increase of 3.14 Mg ha^{-1} in yield based on the current yield goal recommendation of 21.4 kg N Mg grain^{-1}. At planting (April 10, 2023), 67 kg N ha^{-1} was applied using the Precision Planting Conceal 2x0x2 starter N application system, positioning the N 5 cm to the side of the furrow at seed depth on both sides of the furrow. The remaining N was applied on May 4, 2023, at the V3 corn growth stage using a custom sidedress applicator, which employed opening discs to create a shallow furrow approximately 5 centimeters from the row on both sides. Liquid UAN was then dribbled into this furrow. The N source utilized as both starter and sidedress in this study was a liquid 24-0-0-3S fertilizer, which was a blend of urea ammonium nitrate (28-0-0), BASF's 19E fertilizer (19-0-0), and ammonium thiosulfate (12-0-0-26S). Application rates at both timings were controlled using a Precision Planting vApplyHD system.

3.2.2.5 Planting and Harvest:

Planting occurred on April 10, 2023. Planting operations were conducted using a 4-row Harvest International planter outfitted with precision planting equipment to ensure accuracy and uniformity across all sites. The planter was equipped with the following precision planting components: DeltaForce automated downforce control, vSet seed meters, vDrive electronic seed meter drive, BullsEye seed tubes, Conceal banded N placement, and vApplyHD liquid control system. These state-of-the-art technologies were chosen to optimize planting precision and facilitate consistent seed placement and N application.

Corn was seeded at 79,000 seeds per hectare in 91centimeter rows with an average inter-plant spacing of approximately 12 centimeters. This spacing aligns with common practices among farmers in Georgia and was selected to represent real-world agricultural conditions accurately. The hybrid utilized for this study was Pioneer 1622VYHR, chosen for its suitability to the region's conditions and farming practices.

Harvest occurred on August 29, 2023 using a plot combine equipped with a calibrated HarvestMaster GrainGage, allowing for the measurement of yield, test weight, and harvest moisture. For each plot, the center two rows were designated for yield data collection to minimize edge effects and allow some buffer between N rate treatments.

3.2.3 Sampling and Data Collection

3.2.3.1 Weather Data

Weather data will be collected from automated weather stations installed at each site location, ensuring accurate and consistent meteorological measurements throughout the study period. Cumulative and monthly total precipitation and irrigation can be seen in Table 3.1 and Figure 3.2.

3.2.3.2 Plant Sampling and Analysis

At the R6 growth stage, plant samples were collected from four replications at each experimental location. Specifically, two plants were randomly selected from three separate locations within each plot to ensure representative sampling. Stand counts for each plot were also conducted at each of the three sampling locations to assess plant density and uniformity.

The collected plant samples were separated into three fractions: stalk nitrate samples, remaining stover, and grain. Stalk nitrate samples were collected by excising a 20-centimeter segment from the stalk, specifically from 15 to 35 centimeters above the base of the plant. Grain was separated from cobs using an ALMACO Maizer SES. Prior to further processing the grain, yield components were evaluated, including kernels per ear and weight per kernel. Subsequently, all plant fractions were dried at 60°C to a constant weight to remove moisture content. Once dried, the samples were weighed to determine biomass. Following biomass determination, the samples were ground to pass through a 1mm sieve for further analysis.

Nitrogen concentration in the ground samples was analyzed via dry combustion analysis. This analysis provides precise measurements of N concentration in each plant fraction. The N concentration was multiplied by the biomass of each fraction to determine the total N content. To determine the whole plant N uptake, we added the total N content from each plant fraction (grain N + Stover N + Stalk Sample N). The results from these analyses were used to calculate various measures of NUE. Additionally, stalk nitrate samples will undergo standard stalk nitrate testing procedures. Specifically, 0.5g of the ground stalk material will be extracted with 50ml of distilled water. The resulting solution will then be analyzed colorimetrically for nitrate content using an autoanalyzer with the cadmium reduction method.

3.2.3.3 Nitrogen Use Efficiency Calculations

The inclusion of a zero N treatment in this study allowed us to utilize N fertilizer recovery efficiency, nitrogen physiological efficiency, nitrogen agronomic efficiency, and nitrogen internal efficiency as our measures of NUE, which were calculated using the following equations.

Nitrogen Fertilizer-N Recovery Efficiency

$$NRE_{=} \frac{Plant\ N_f - Plant\ N_0}{Fertilizer\ N} \times 100$$

where NRE is fertilizer-N recovery efficiency, Plant N_f is whole plant N uptake in the fertilized plot, Plant N_0 is whole plant N uptake in the zero N plot, and Fertilizer N is the total amount of N fertilizer applied to the fertilized plot.

Nitrogen Physiological Efficiency

$$NPE = \frac{Yield_f - Yield_0}{Plant\ N_f - Plant\ N_0}$$

where NPE is physiological efficiency, $Yield_f$ is grain yield in the fertilized plot, and $Yield_0$ is grain yield in the zero N plot.

Nitrogen Agronomic Efficiency

$$NAE = RE_{fert} \times PE$$

where AE is agronomic efficiency.

Nitrogen Internal Efficiency

$$NIE = \frac{Yield\ _f}{Plant\ N_f}$$

3.2.4 Statistical Analysis

For the determination of AONR and EONR, we employed the model averaging method described by Miguez and Poffenbarger (2022). Briefly, this method involves fitting linear plateau and quadratic plateau N response models to the yield data and then using weighted averages of fit to derive an average model. AONR and EONR are then computed from this average model. AONR is defined as the breakpoint of the model and EONR is defined as the point at which the slope of the response curve falls below the chosen fertilizer to grain price ratio. Using this method of model averaging helps mitigate negative bias in prediction that can occur with linear plateau models and positive bias in prediction that can occur with quadratic plateau models. For this study a fertilizer to grain price ratio of 5.6, which is common in the literature was utilized, considering a fertilizer price of $1.10 per kg and a grain price of $0.197 per kg.

For the analysis of grain yield, stover, grain, and whole plant biomass and N uptake, stover and grain N concentration, thousand kernel weight (TKW), kernels per ear (KPE), nitrogen fertilizer recovery efficiency (NRE), nitrogen physiological efficiency (NPE), nitrogen agronomic efficiency (NAE), and nitrogen internal efficiency (NIE), we conducted Analysis of Variance (ANOVA) using the Agricolae package in the R statistical environment. In this study, irrigation treatment, N rate, and the interaction between the two were treated as fixed effects and block was considered as a random effect and nested within irrigation treatment. When the ANOVA model yielded significant results, a least significant difference (LSD) test was employed for the separation of means. This allowed for the identification of statistically significant differences between treatment means. An alpha level of 0.05 was used for all means comparisons.

3.3 Results and Discussion

The overarching goal of this study was to investigate the inter-relationship between irrigation scheduling method and N application rate with regards to varying measures of corn growth and NUE. In this study, three irrigation scheduling methods were investigated including the checkbook method, the half-checkbook method, and the SI CropFit App. The checkbook method recommends irrigation based on weekly crop water needs at different growth stage intervals as estimated by plant evapotranspiration and is the method for scheduling irrigation currently recommended by several land-grant universities (Lundstrom and Stegman, 1988; Tubbs et al., 2024; Da Cunha Leme Filho et al., 2020; Wright et al., 1991; Scherer and Steele, 2024; Werner 1993). Essentially, the proportion of weekly crop water needs not met by precipitation are added via irrigation in this method. The half-checkbook method utilized in this study is simply the weekly recommended crop water needs as identified by the checkbook method cut in half. Finally, the SI CropFit App also recommends irrigation based on crop water requirements and estimated evapotranspiration at specific growth stages. However, one advantage of the SI CropFit App over the traditional checkbook method is that it incorporates real-time weather data to account for fluctuations in temperature, rainfall, and other environmental factors that might affect soil moisture. This advanced approach ensures that crops receive water when needed and helps avoid unnecessary water use while maintaining optimal crop production.

The primary objective of this study was to evaluate the efficacy of the CYG method under differing irrigation scheduling regimes and to assess the influence of irrigation scheduling method on AONR and EONR. The importance of this study is highlighted by the dearth of literature on this topic. In the case of both AONR and EONR in this study the greatest values were observed for the checkbook irrigation method and the lowest values were observed in the half-checkbook irrigation method. AONR is defined as the N rate required to achieve maximum corn grain yield. In this study, estimated AONR ranged from 239 kg N ha^{-1} to 317 kg N ha^{-1} and estimated yield at AONR (YAONR) ranged from 14.02 to 14.92 Mg ha^{-1} (Table 3.3). This equates to a 78 kg N ha^{-1} spread in AONR but just a 0.90 Mg ha^{-1} spread in YAONR amongst irrigation scheduling methods. Large ranges in AONR are commonly observed in the literature. For example, Oglesby et al. (2022) reported a 108 kg N ha^{-1} range in AONR, while Kaur et al. (2024) observed a 112 kg N ha^{-1} range in AONR; however, neither of these studies incorporated varying irrigation methods along with their N rate trials. In a Minnesota study, Maharjan et al. (2016) reported a 13 kg N ha^{-1} difference in AONR between a fully irrigated treatment and a water stressed treatment. Based on the current recommended CYG N rate (21.4 kg N Mg^{-1} grain), the N rate recommendation to achieve YAONR in this study would range from 301 to 320 kg N ha^{-1} which is quite a bit greater than the estimated AONR (Table 3.3).

In contrast to AONR, EONR aims to optimize profitability and is defined as the N rate at which the revenue gained from an additional unit of yield no longer outweighs the cost of the additional N fertilizer required to produce that yield. In this study, estimated EONR ranged from 227 kg N ha^{-1} to 292 kg N ha^{-1} and estimated yield at EONR (YEONR) ranged from 13.93 to 14.80 Mg ha^{-1} (Table 3.3). On average, EONR was 6.3% (18.3 N ha^{-1}) less than AONR but YEONR was just 0.11 Mg ha^{-1} (0.7%) less than YAONR (Table 3.3). The marginal difference between yields raises questions about the economic benefit of applying N rates beyond the EONR, given the potential environmental costs of N leaching and runoff (Raun et al., 2017; Rodriguez et al., 2019). To put into perspective the importance of utilizing a N recommendation tool such as EONR over the CYG, if a fertilizer of \$1.10 kg^{-1} N and a grain price of \$0.197 kg^{-1} grain is utilized when calculating EONR, this equates to an average reduction in fertilizer price of \$51.37 ha^{-1} and a reduction in grain revenue of \$21.67 ha^{-1}. So, utilizing EONR in this study could have resulted in \$29.70 ha^{-1} greater profit relative to the CYG at YAONR.

In this study, the CYG method over estimated both AONR and EONR across all three irrigation scheduling methods. Previous studies commonly report that the CYG method often results in improper (too high or too low) N fertilizer applications for corn growth. In a Midwest U.S. study, Ransom et al. (2020) reported that CYG methods only estimate N rates within 30 kg N ha^{-1} of the EONR 20 - 41% of the time, while Oglesby et al. (2022) reported that the CYG method over estimated AONR and EONR 86% of the time. The results observed in this study suggest that a one-size-fits-all to recommendations is inadequate and that more detailed methods that account for variation and factors such as geography, climate, and crop management could be explored.

The secondary objective of this study was to investigate the influence of irrigation scheduling method and N rate on common measures of corn growth and NUE efficiency. In this study there was no significant effect of irrigation method on any of our measured variables except grain nitrogen uptake (GNU) (Table 3.4). Additionally, there was a significant interaction between nitrogen rate and irrigation method for thousand kernel weight (TKW). For all other variables (except plan population and nitrogen recovery efficiency [NRE]) the main effect of N was significant and thus in the discussion portion of this paper all variables were averaged across irrigation methods except for GNU and TKW.

3.3.1 Corn Yield and Yield Components

In this study, there was a general trend for yield to increase as N rate increased. Specifically for yield, all treatments from the 0 to 201 kg N ha^{-1} treatments increased with every increasing N rate, while the 269 kg N ha^{-1} treatment was similar to both the 201 and 336 kg N ha^{-1} treatment and the 403 and 470 kg N ha^{-1} treatments were only similar with the 336 kg N ha^{-1} treatment. In contrast to the current study, Dahal et al. (2020) found a significant effect of the interaction between their N rates and irrigation methods on corn grain yield. Specifically, Dahal et al. reported increasing yield with increasing N rate and greater yields with greater crop evapotranspiration water replacement rate. In this study, there was no significant effect of N rate, irrigation scheduling method, or the interaction between the two on plant population. For Kernels per ear (KPE), the 0 kg N ha^{-1} treatment was significantly less than the 67 kg N ha^{-1} treatment, which was significantly less than the 134 kg N ha^{-1} treatment. The 134 kg N ha^{-1} treatment was significantly less than the 269, 403, and 470 kg N ha^{-1} treatment, while all treatments were similar to the 201 and 336 kg N ha^{-1} treatments. In contrast to the current study, Pandey et al. (2000) reported a significant interaction between irrigation and N rate, ears m^{-2} and kernels m^{-2} which when used in conjunction can derive KPE. Specifically, they observed a general trend for greater KPE with increasing N rate and a lower values of KPE as irrigation decreased.

A significant interaction between N rate and irrigation scheduling method was observed for TKW in this study (Table 3.4; Figure 3.3). In general, TKW increased with increasing N rate before plateauing around the 201 kg N ha^{-1} rate and there was also a slight but inconsistent trend for greater TKW in the checkbook and half-checkbook irrigations relative to the SI CropFit App. Our results are similar to findings in previous studies in terms of general increases in corn TKW with increasing N fertilizer rate (Moser et al., 2006; Abbasi et al., 2013; Pico et al., 2023). For instance, Cambouris et al. (2016) observed a 5 - 7% increase in TKW when N fertilizer rate increased from 0 to 150 kg N ha^{-1} while Imran et al. (2015) reported a 3-5% increase in TKW when N rate increased from 0 to 180 kg N ha^{-1}. In contrast to the current study, Krnjaja et al. (2021) found no consistent response in TKW to increasing N fertilizer rate. The impact of irrigation on TKW was inconsistent in this study. However, in the literature it is commonly reported that as the amount of irrigation water applied increases, both TKW and KPE increase (Eck, 1986; Moteva et al., 2016; Karasu et al., 2015; Lack et al., 2012). Specifically, Karasu et al. (2015) observed that 34% increase in KPE and 18% increase in TKW when irrigation increased from 0% evapotranspiration replacement to 125% evapotranspiration replacement. Likewise, Lack et al. (2012) observed a 36% increase in KPE and a 38% increase in TKW when irrigation increased from 60% to 100% evapotranspiration replacement. The results of this study, coupled with those of previous literature, suggest that N fertilizer application rate can have a significant impact on crop yield and yield components, and that irrigation can also have a significant impact on these factors under certain situations.

With regard to biomass production, N concentration, and N uptake there was a significant effect of N fertilizer application rate but not irrigation scheduling method or the interaction between the two factors. Stover biomass (Sbio) in the 0 kg N ha^{-1} treatment was significantly less than the 67 kg N ha^{-1} treatment, which was significantly less than the 134 kg N ha^{-1} treatment, which was significantly less than the 403 kg N ha^{-1} treatment, but both the 134 and 403 treatments were similar to the 201, 269, 336, and 470 kg N ha^{-1} treatments. Grain biomass (Gbio) significantly increased with increasing N rate from the 0 to 201 kg N ha^{-1} treatments after which there was no significant differences except for the 403 kg N ha^{-1} treatment being significantly greater than all treatments. Similar to Gbio, whole plant biomass (WPbio) significantly increased with increasing N rate from the 0 to 201 kg N ha^{-1} treatments after which there was no significant differences (Table 3.5). The positive response of biomass production to increasing N rate in this study is in agreement with previous literature that has reported increasing N rate tends to result in increased corn biomass production, as well as N concentration and N uptake (Irmak et al., 2023; Asibi et al., 2022; Chen et al., 2020; Biswas and Ma, 2016; Halvorson and Bartolo, 2014). In contrast to the current study, Benjamin et al. (2015) reported a significant effect of irrigation resulting in 20-150% greater biomass at the R1 growth stage when crop water needs were not restricted. Likewise, Gheysari et al. (2017) reported similar findings of total above ground biomass increases as irrigation deficit decreased. The findings of the current study suggest that irrigation scheduling has little effect on corn biomass production but N fertilizer application rate can significantly impact biomass production; however, previous literature has found that irrigation can have an impact on biomass production under certain circumstances prompting the need for further research on the topic.

In this study, N application rate but not irrigation scheduling method for the interaction between the two factors had a significant effect on both stover (SNC) and grain (GNC) N concentration. For SNC, there was a trend for decreasing N concentration between the 0 and 134 kg N ha^{-1} treatments, however SNC showed significant increases with increasing N rates beyond 134 kg N ha^{-1}. For GNC the 134 kg N ha^{-1} treatment was significantly greater than the 0 kg N ha^{-1} treatment and both were similar to the 67 kg N ha^{-1} treatment, while all three treatments were significantly less than the remaining treatments. The results of this study showed a significant trend for increased stover N uptake (SNU) with increasing N rate, with a 241% difference observed between the lowest and highest N rates. Similar to SMU, whole plant nitrogen uptake (WPNU) significantly increased with N rate from 0 to 201 kg N ha^{-1} treatments, while the 201 kg N ha^{-1} treatment was similar to the 269 and 336 kg N ha^{-1} treatments, and the 403 kg N ha^{-1} treatment was significantly greater than all treatments, except for the 470 kg N ha^{-1} treatment which it was similar to. For grain nitrogen uptake (GNU) there was a significant effect of both N rate and irrigation scheduling method but not the interaction of the two factors (Table 3.4). With regard to N fertilizer application rate, GNU significantly increased with increasing N rate from the 0 to 201 kg N ha^{-1} treatments after which there was no significant differences except for the 470 kg N ha^{-1} treatment being significantly greater than all treatments (Figure 3.4A). With regard to irrigation scheduling method, GNU significantly greater in the Half-Checkbook treatment compared to both the SI CropFit app and the Checkbook treatments (Figure 3.4B). Similar to the results for SNU and TNU from the current study, Hatlitligil et al. (1983) reported no significant effect of irrigation rate on corn N uptake. In contrast, Wang et al. (2017) reported a significant effect of irrigation on N uptake with greater uptake corresponding to greater amounts of irrigation. Finally, Hammad et al. (2016) reported a significant interaction of irrigation and N fertilizer rate for both GNC and TNU noting increased values for both variables as irrigation increased and as N application rate increased. The results of the current study combined with inconsistent literature on the effect of N rate and irrigation on corn N uptake suggests that more research is needed to understand the coupled effects of these two factors on corn N assimilation.

3.3.2 Nitrogen Use Efficiency

In this study four measures of corn NUE were evaluated included nitrogen fertilizer recovery efficiency (NRE), nitrogen physiological efficiency (NPE), nitrogen agronomic efficiency (NAE), and nitrogen internal efficiency (NIE). There was no significant effect of N rate or irrigation scheduling method on NRE in this study (Table 3.4). NPE was significantly affected by N rate and on average the 67 and 134 kg N ha^{-1} treatments were 46% greater than the remaining treatments (Table 3.4). In this study, NAE tended to decrease with increasing N fertilizer application rate. Specifically, the 269 kg N ha^{-1} treatment was significantly less than the 67 and 134 kg N ha^{-1} treatments, significantly greater than the 336 to 470 kg N ha^{-1} treatments, and similar to the 201 kg N ha^{-1} treatment. Finally, for NIE the 134 - 470 kg N ha^{-1} treatments were all similar, while the 0 kg N ha^{-1} treatment was significantly less than all other treatments except the 67 kg N ha^{-1} treatment. The results from the current study for NPE and NAE align with previous literature in that both measures of NUE tend to decrease as N fertilizer application rate increases (Ma et al., 2020; Zhang et al., 2020; Sindelar et al., 2015; Sawyer et al., 2017;

Bindhani et al., 2001; Biswas and Ma, 2016; Wortmann et al., 2011). However, the results for NRE and NIE are inconsistent and agree with the findings of some previous studies while disagreeing with others in terms of response to changing N rates (Walsh et al., 2012; Wortmann et al., 2011; Sindelar et al., 2016; Bindhani et al., 2001; Ciampitti and Vyn, 2011; Sindelar et al., 2015). Unlike the current study, Gholamhoseini et al. (2013) observed a significant interaction between irrigation frequency and N application rate on NUE (partial factor productivity which is similar to NAE) reporting that NUE increases with increasing irrigation frequency but decreases with increasing N fertilizer application rate. Likewise, Di Paolo and Rinaldi (2008) observed a significant effect of both N rate and irrigation on NUE and reported NUE increased with irrigation but decreased with increasing N application rate. However, similar to the current study, Wienhold et al. (1995) did not find a significant effect of irrigation rate on corn N use efficiency in a study utilizing ^{15}N-enriched fertilizer to evaluate N use. The findings of the current study suggest that N application rate is a driving factor controlling measures of NUE, however based on the findings of other researchers it is possible that irrigation could also affect NUE under certain circumstances. Thus, it is important that more research be conducted to better understand how the combination of these factors can influence NUE.

3.3.3 Limitations

This study offers important insights into the influence of irrigation scheduling methods on optimal N rates and corn productivity; however, some limitations should be acknowledged. The scope of irrigation scheduling methods was confined to three approaches: the standard checkbook method, a reduced half-checkbook method, and an innovative approach using the SI CropFit app. While these methods encompass both traditional and advanced technologies, the exclusion of other advanced techniques, such as sensor-based or remote-sensing systems, could limit the understanding of irrigation's effects on N dynamics and yield. Additionally, field trials were conducted at a single site, the Stripling Irrigation Research Park in Camilla, Georgia, which has a specific climate and soil type (Lucy Loamy Sand). This focus on a single location and soil type constrains the generalizability of the findings, as different regions with unique environmental and soil conditions could exhibit varied responses to irrigation scheduling. Conducting similar trials across a wider geographic range would enhance the applicability of these results.

The study's concentration on a single soil type also limits the extrapolation of these findings to other soil textures, which can affect water and nutrient retention and subsequently impact N leaching, water availability, and crop response. Seasonal and environmental variability, though partially accounted for through the SI CropFit app's real-time weather integration, was not extensively examined across multiple seasons or with a focus on inter-annual climate fluctuations. Such fluctuations, including changes in rainfall and temperature, could influence irrigation efficiency and N uptake.

Although the EONR was calculated to evaluate profitability, a broader economic analysis that includes costs associated with different irrigation methods, such as equipment, labor, and energy, would provide further insight into the economic implications of each approach. This analysis could illustrate potential cost savings from water conservation achieved through improved irrigation scheduling. Finally, this study was conducted over a single growing season, which precludes a comprehensive understanding of the cumulative effects of irrigation methods on NUE and long-term environmental outcomes, such as nitrate leaching and soil nutrient status. Long-term studies are essential for evaluating the sustainability and potential soil health impacts of varying irrigation and N management practices. Addressing these limitations in future research would expand the utility of these findings and support more robust N and water management recommendations across different environments and agricultural systems.

3.4 Conclusions

The primary purpose of this study was to evaluate the CYG N recommendation method under different irrigation scheduling methods and how irrigation scheduling method might influence AONR and EONR. The findings from this study underscore the influence that irrigation scheduling method can have on AONR and EONR. Specifically, the checkbook method resulted in the highest AONR, while the half-checkbook method showed the lowest, highlighting how reduced water input may may lead to greater crop water stress, thus necessitating lower N application rates to reach maximum yield potential.

In this study, it was observed that EONR, which balances profitability with environmental sustainability, was generally lower than AONR. This finding emphasizes that, while high N rates may increase yield, the marginal yield gains might not justify the environmental and economic costs. The use of EONR instead of traditional CYG recommendations has the potential to improve profitability while preventing over-application of N; thus, reducing the potential for environmental harm from N leaching and nitrous oxide emissions. This notion is supported by previous research which indicates that CYG methods often overestimate N requirement, which was observed in this study across irrigation treatments. Given these results, recommending the use of EONR may offer more sustainable N management strategies for corn growers in Georgia.

The secondary objective of this study was to evaluate the influence of irrigation scheduling method on different measures of crop growth and NUE. In this study, NUE was evaluated using four key metrics: NAE, NPE, NRE, and NIE. There was no significant effect of irrigation scheduling method on any of the measures of NUE evaluated in this study, however, N application rate did significantly influence three of the four metrics evaluated. Specifically, NAE and NPE declined as N rates increased, suggesting that while additional N may promote greater yield, excessive rates can lead to lower returns per unit of N applied. This highlights the need for balanced N application strategies to enhance efficiency, reduce costs, and mitigate environmental impacts associated with N losses.

Crop biomass production and N uptake were also evaluated in this study and it was observed that both increased with higher N rates but were largely unaffected by irrigation scheduling method, except for GNU. Surprisingly, the half-checkbook method resulted in greater GNU than either of the two other irrigation scheduling methods. This indicates that reduced irrigation can, in certain conditions, enhance N uptake. The findings from the study suggest that N rate remains a dominant factor in controlling crop growth, although irrigation scheduling method may contribute to more effective N assimilation under specific conditions.

Future research should build on these findings by examining the interactive effects of varying irrigation and N application rates across more locations throughout Georgia in order to better develop recommendations for corn growers. Expanding studies to include soil types, climate variations, and crop species could improve the understanding of how tailored irrigation and N management can enhance crop yields and resource use efficiency. Additionally, the use of real-time data from precision agriculture technologies, such as soil moisture sensors and remote sensing, shows promise in refining irrigation and N application, warranting further exploration. Such technology-enabled practices could support adaptive management strategies that respond dynamically to changing field conditions, further improving sustainability in corn production.

In all, this study demonstrates that while N rate remains a key factor for NUE and yield, the choice of irrigation scheduling method can play an important role under certain scenarios.

Implementing flexible irrigation scheduling methods like the SI CropFit app, which leverages real-time environmental data, could optimize water and N use in corn production, offering an alternative to traditional methods. These findings support a move towards more adaptive, data-driven irrigation and fertilization practices that could potentially reduce input costs, improve crop yield, and protect environmental resources.

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3.6 Tables and Figures

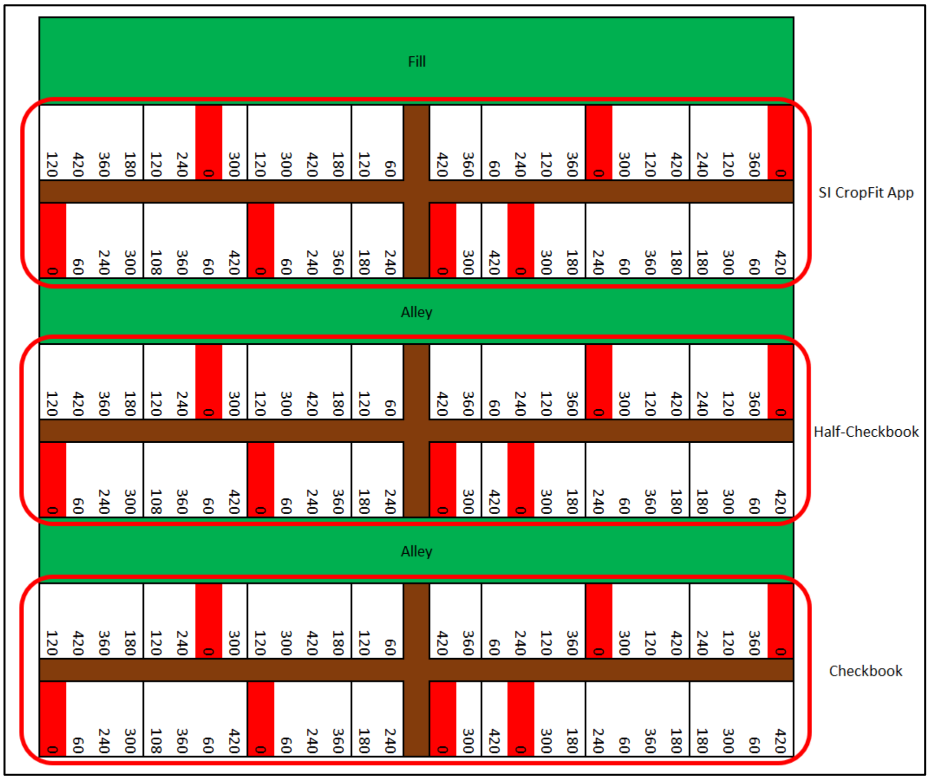

Figure 3.1 Plot map for the trials at Stripling Irrigation Research Park. Red boxes indicate the different irrigation scheduling methods. N rate trials are arranged in a randomized complete block design within each irrigation scheduling method treatment.

Table 3.1 Monthly total precipitation and irrigation for the checkbook, half-checkbook, and SI CropFit app at the Stripling Irrigation Research Park.

	Precipitation	Checkbook	Half-Checkbook	SI CropFit App	Total
Month	Cm H_2O				
April	3.82	-	-	-	3.82
May	3.90	2.75	1.38	2.75	10.78
June	7.12	4.50	3.75	3.75	19.12
July	4.40	5.25	2.25	3.00	14.90
August	1.84	-	-	-	1.84
Total	21.08	12.50	7.38	9.50	

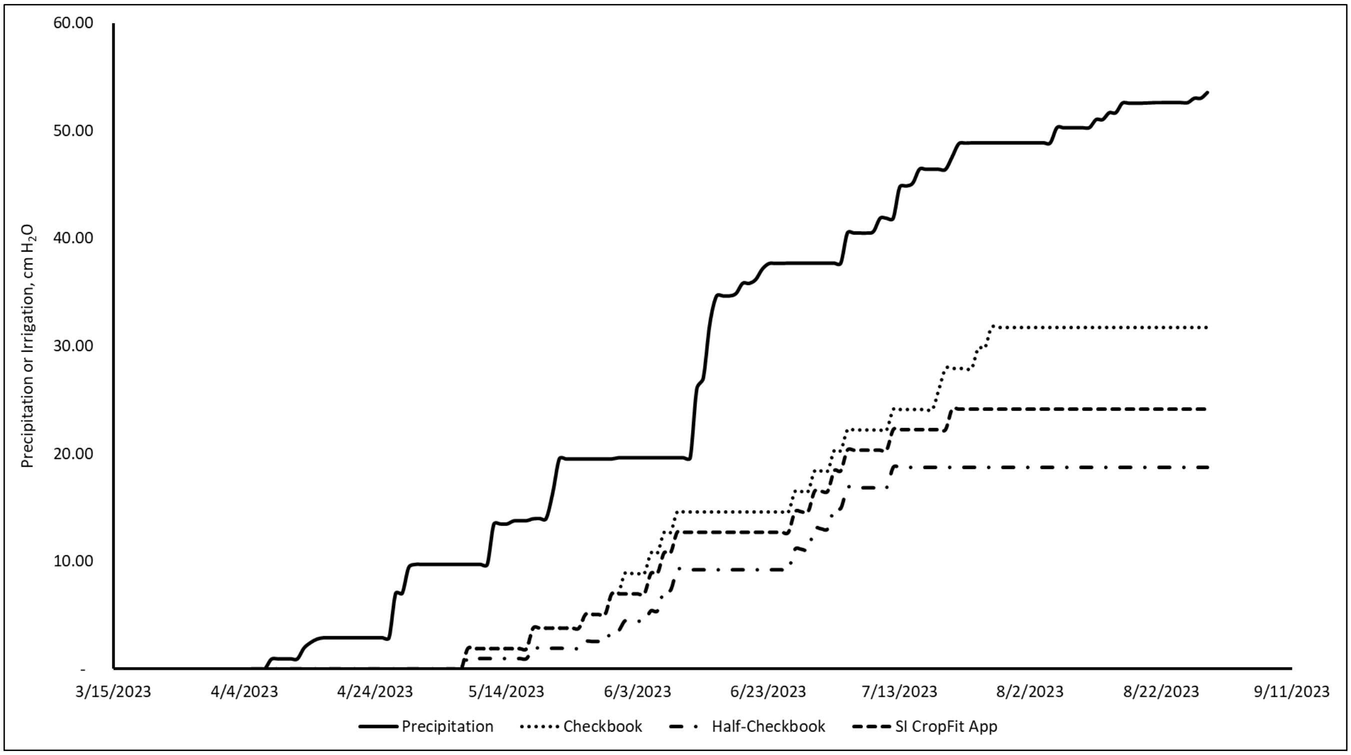

Figure 3.2 Cumulative precipitation and irrigation for the checkbook, half-checkbook, and SI CropFit app at Stripling Irrigation Research Park.

Table 3.2 Rate, timing, and placement for the eight nitrogen fertilizer treatments utilized across all irrigation scheduling methods.

	Nitrogen Fertilizer Applications							
	Kg N ha^{-1}							
Total N Rate	0	67	134	201	269	336	403	470
2x0x2 at Plant	0	67	67	67	67	67	67	67
Sidedress Injected	0	0	67	134	201	269	336	403

Table 3.3 Crop yield goal, agronomic optimum, and economic optimum N rates, yield at AONR and EONR, and current, agronomic optimum, and economic optimum yield goal Nitrogen rates by irrigation scheduling method at the Stripling location.

Irrigation Method	**CYG Rate†**	**AONR**	**EONR ‡**	**YAONR**	**YEONR**	**CYG**	**AOYG**	**EOYG**
	Kg N ha^{-1}			Mg ha^{-1}		Kg N Mg^{-1} Grain		
Checkbook	320	317	292	14.92	14.80		21.3	19.7
Half Checkbook	301	239	227	14.02	13.93	21.4	17.0	16.3
App	319	299	281	14.90	14.79		20.1	19.0

†Calculated as AONR yield multiplied by current CYG N rate recommendation of 21.4 kg N Mg^{-1} grain.

‡Calculated with fertilizer to grain price ratio of 5.6. Fertilizer price was \$1.10 kg^{-1} and grain price was \$0.197 kg^{-1}.

Table 3.4 ANOVA results for the sixteen corn growth and nitrogen use response variables measured at Stripling.

Variable	p-Value		
	N Rate	Irrigation Method	N Rate * Irrigation Method
Yield	0.000	0.682	0.518
Pop	0.108	0.590	0.182
TKW	0.000	1.000	0.010
KPE	0.000	0.771	0.862
Sbio	0.000	1.000	0.477
Gbio	0.000	0.401	0.725
Tbio	0.000	1.000	0.693
SNC	0.000	1.000	0.115
GNC	0.000	0.368	0.812
SNU	0.000	1.000	0.343
GNU	0.000	0.012	0.593
TNU	0.000	1.000	0.433
NRE	0.114	0.595	0.999
NPE	0.004	0.383	0.807
NAE	0.000	0.992	0.999
NIE	0.000	1.000	0.560

Table 3.5 Impact of nitrogen rate on yield, population, kernels per ear, stover biomass, grain biomass, whole plant biomass, stover nitrogen concentration, grain nitrogen concentration, stover nitrogen uptake, whole plant nitrogen uptake, nitrogen recovery efficiency, nitrogen physiological efficiency, nitrogen agronomic efficiency, and nitrogen internal efficiency at Stripling. Different capital letters within a row within a row indicate significant difference between nitrogen rates at an alpha level of 0.05.

		N Rate Treatment, kg N ha^{-1}							
Variable	Units	0	67	134	201	269	336	403	470
Yield	Mg ha^{-1}	4.91 (0.25) A	8.23 (0.33) B	11.60 (0.20) C	13.46 (0.18) D	14.46 (0.24) DE	14.06 (0.70) EF	15.13 (0.23) F	14.95 (0.29) F
Pop	1000 plants ha^{-1}	78.07 (0.69)	80.89 (1.64)	79.40 (1.27)	81.23 (0.95)	79.40 (0.88)	79.73 (0.85)	82.72 (2.32)	78.73 (0.76)
KPE	Kernels per Ear	307.81 (15.04) A	407.90 (24.30) B	562.35 (15.85) C	599.21 (20.91) CD	619.02 (24.33) D	594.99 (11.27) CD	645.96 (13.11) D	621.76 (12.61) D
Sbio	Kg ha^{-1}	6.55 (0.53) A	8.45 (0.38) B	10.54 (0.35) C	11.50 (0.40) CD	11.53 (0.31) CD	11.53 (0.25) CD	11.73 (0.69) D	11.66 (0.27) CD
Gbio	Kg ha^{-1}	5.84 (0.32) A	8.08 (0.45) B	12.28 (0.34) C	14.61 (0.50) D	14.98 (0.52) D	15.20 (0.28) D	16.50 (0.25) E	15.25 (0.38) D
WPbio	Kg ha^{-1}	12.38 (0.71) A	16.52 (0.78) B	22.82 (0.60) C	26.11 (0.77) D	26.55 (0.75) D	26.73 (0.44) D	28.23 (0.77) D	26.03 (1.25) D
SNC	%N	0.73 (0.03) BC	0.63 (0.02) AB	0.63 (0.03) A	0.74 (0.04) C	0.85 (0.04) D	0.89 (0.05) D	0.99 (0.05) E	1.07 (0.03) E
GNC	%N	0.96 (0.03) A	0.97 (0.04) AB	1.04 (0.02) B	1.19 (0.02) C	1.21 (0.03) C	1.20 (0.04) C	1.22 (0.04) C	1.26 (0.04) C
SNU	Kg N ha^{-1}	45.93 (3.20) A	52.60 (3.94) AB	64.36 (4.14) BC	82.03 (5.06) CD	94.62 (4.59) DE	100.75 (6.65) EF	115.67 (9.43) F	110.70 (9.81) EF
WPNU	Kg N ha^{-1}	101.42 (4.86) A	132.54 (9.97) B	192.92 (7.60) C	257.60 (9.71) D	277.37 (11.70) DE	282.86 (11.28) DE	316.85 (14.68) F	300.43 (12.14) EF
NRE	Kg kg^{-1}		0.53 (0.20)	0.72 (0.07)	0.80 (0.04)	0.68 (0.05)	0.55 (0.03)	0.55 (0.04)	0.43 (0.03)
NPE	Kg kg^{-1}		80.04 (8.07) A	77.41 (6.58) A	56.26 (3.86) B	56.57 (3.90) B	52.69 (5.63) B	49.81 (3.88) B	54.67 (8.11) B
NAE	Kg kg^{-1}		52.06 (7.56) A	51.08 (2.50) AB	43.60 (1.04) BC	36.56 (1.20) C	27.77 (2.32) D	25.78 (0.62) D	21.05 (0.89) D
NIE	Kg kg^{-1}	0.55 (0.01) A	0.60 (0.02) AB	0.67 (0.01) C	0.68 (0.02) C	0.65 (0.01) C	0.65 (0.01) BC	0.64 (0.02) BC	0.65 (0.03) BC

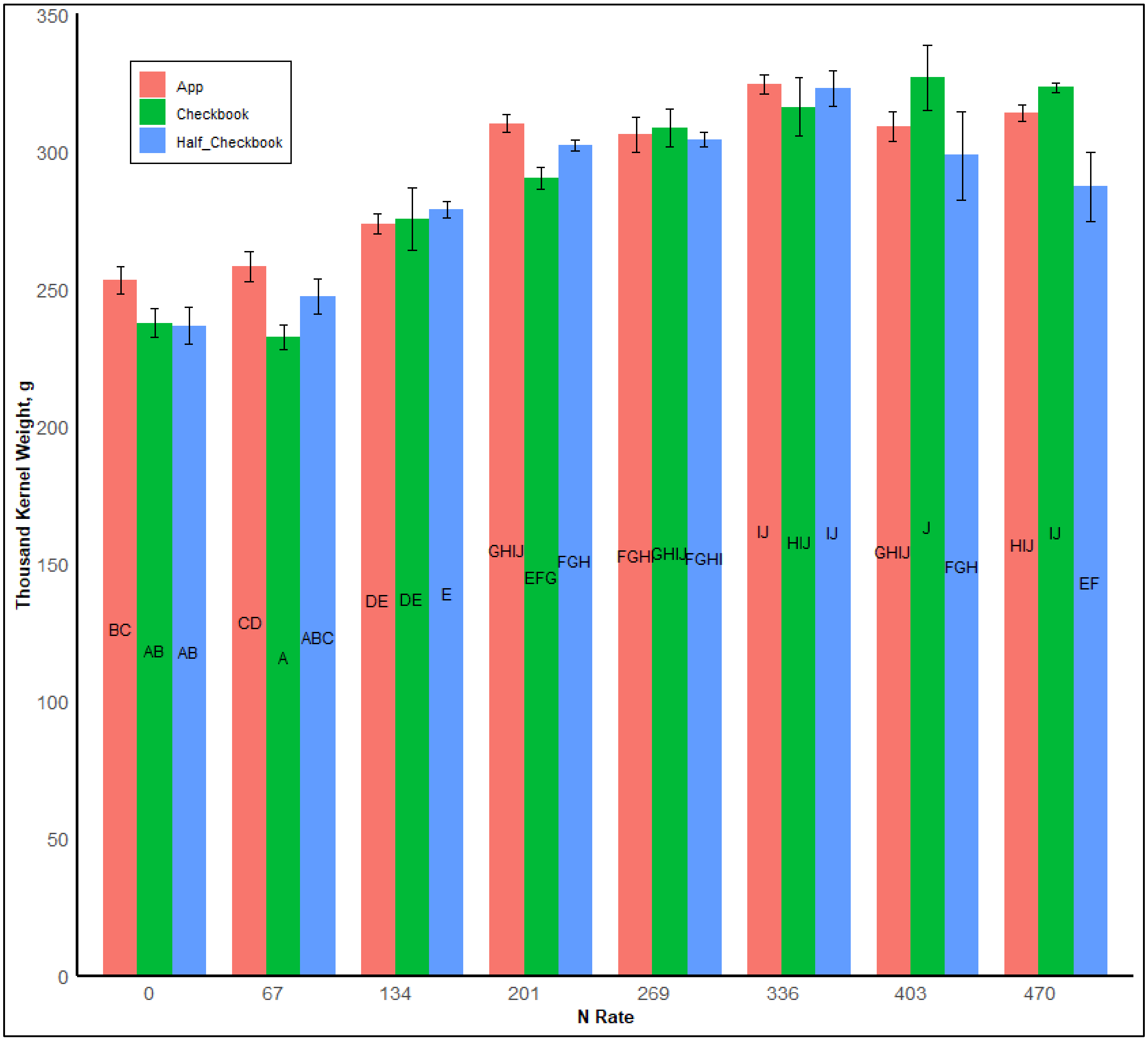

Figure 3.3 Influence of the interaction between nitrogen rate and irrigation on thousand kernel weight at Stripling. There was a significant interaction of nitrogen rate by irrigation scheduling method so, different capital letters indicate significant differences in thousand kernel weight between nitrogen rates and irrigation scheduling methods at an alpha level of 0.05.

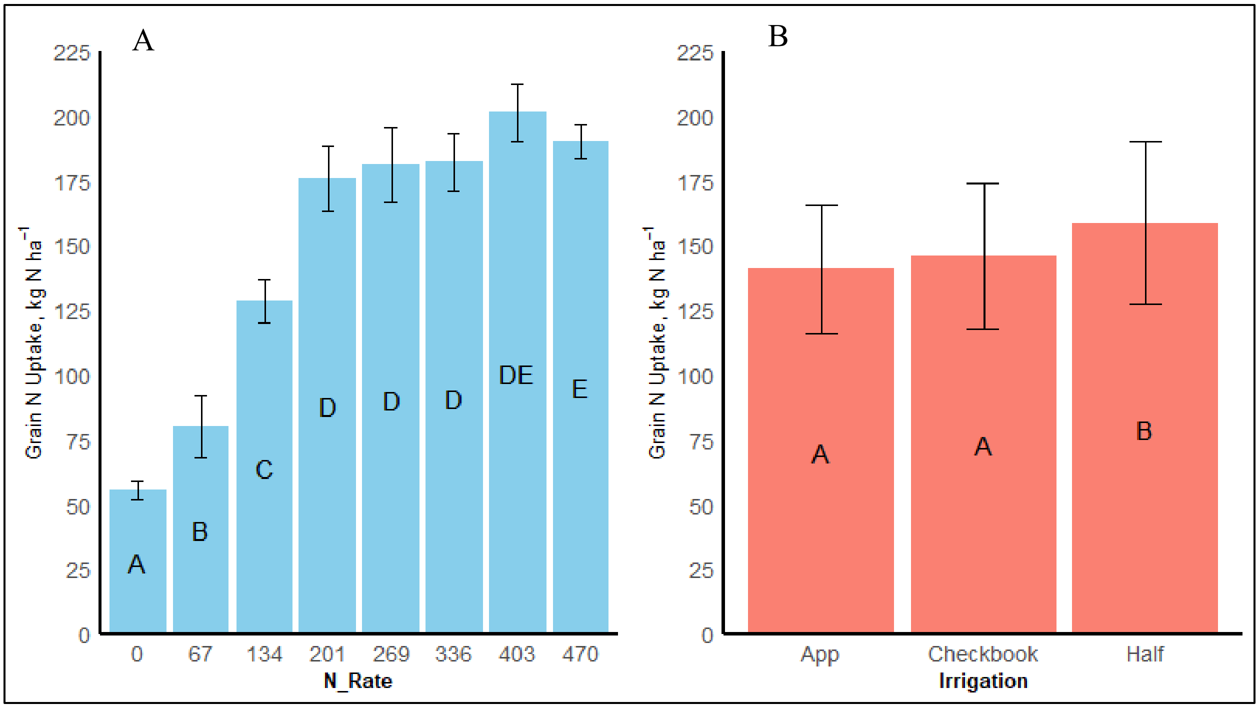

Figure 3.4 Impact of nitrogen rate and irrigation on grain nitrogen uptake at Stripling. In figure (A) different capital letters indicate significant differences in grain nitrogen uptake between nitrogen rates at an alpha level of 0.05. In figure (B) different capital letters indicate significant differences in grain nitrogen uptake between irrigation scheduling methods at an alpha level of 0.05.

CHAPTER 4. ASSESSING THE IMPACT OF CORN SEEDING DENSITIES ON GROWTH, DEVELOPMENT, AND YIELD IN THE STATE OF GEORGIA[1]

[1] Winkler et al., 2024. To be submitted to a peer-reviewed journal.

Highlights

1. Higher seeding densities increased biomass and nitrogen uptake but showed inconsistent yield responses.
2. Increasing seeding density generally translated to decreased thousand kernel weight, but no observable pattern was detected in kernels per ear.
3. Partial factor productivity and partial nitrogen balance tended to follow the pattern of nitrogen uptake with greater values associated with greater seeding density, but there was no observable trend in nitrogen utilization efficiency or nitrogen internal efficiency.

Abstract

This study investigates the effects of varied corn (Zea mays L.) seeding densities on growth, development, and yield in Georgia. Three trials were conducted with six seeding densities, ranging from 49,420 to 98,840 seeds per hectare. Key variables assessed included grain yield, biomass production, yield components, nitrogen uptake, nitrogen utilization efficiency (NUtE), partial factor productivity (PFP), partial nitrogen balance (PNB), and nitrogen internal efficiency (NIE). Results showed that higher seeding densities had the potential to increase whole plant biomass and nitrogen uptake by up to 10.7 Mg ha^{-1} and 78.2 kg N ha^{-1}, respectively, depending on location. Corn grain yield generally increased with increasing seeding density; however, the response varied across sites with yields ranging from 4.08 to 12.79 Mg ha^{-1}, suggesting that optimal density may be context-specific. Evaluation of corn yield components revealed that increasing seeding density generally translated to decreased thousand kernel weight, but no observable pattern was detected in kernels per ear. Evalauation of NUE metrics showed variable trends: PFP and PNB generally followed the trend of nitrogen uptake with greater values

associated with greater seeding density, but there was no observable trend in NUtE or NIE. Overall, these findings suggest that seeding density optimization is not a one-size-fits-all solution. To enhance corn yield and NUE under Georgia's unique agro-environmental conditions, further research across a greater number of locations within the state is recommended.

4.1 Introduction

Corn (*Zea mays* L.) remains a cornerstone of agricultural production in the United States, driven by its diverse applications in food, feed, and industrial sectors (Doebley et al., 2008). In regions like Georgia, optimizing corn yield is crucial not only for meeting production demands but also for ensuring the sustainability and economic viability of farming operations. Among the various factors influencing corn productivity, seeding density plays a pivotal role, directly affecting plant growth, development, and yield outcomes.

Seeding density refers to the number of plants established per unit area, is a critical management decision that influences light interception, nutrient uptake, and water use efficiency (Ping et al., 2008). The balance between too few and too many plants per unit area is delicate; while lower densities may underutilize available resources (Tokatlidis et al., 2010), excessively high densities can lead to competition among plants, reducing overall crop performance. Therefore, determining the optimal seeding density is essential for maximizing yield potential (Licht et al., 2016).

The interaction between seeding density and nitrogen (N) availability is particularly significant. Nitrogen is a key nutrient for corn, driving processes such as photosynthesis and protein synthesis, which are vital for plant growth and grain development (Anas et al., 2020; Mahmud et al., 2021). However, the efficiency with which N is utilized by the crop, Nitrogen Use Efficiency (NUE), can vary depending on plant population density. At optimal densities, corn plants can effectively capture and utilize available N, leading to higher yields. Conversely, at densities either too low or too high, NUE can be compromised, resulting in N losses or inadequate growth.

Within the state of Georgia, there is a variety of vast range of different growing conditions that adds complexity to the task of identifying the best seeding densities for corn. While existing guidelines provide general recommendations, site-specific research is needed to refine these guidelines and adapt them to the diverse conditions found within the state. This is needed for growers to optimize both yield and input efficiency in the face of economic and environmental challenges (Baker, 2008).

This study aims to address these issues by evaluating the impact of different corn seeding densities on growth, development, and yield in Georgia. By systematically varying seeding densities and maintaining a consistent N application rate across treatments, the study seeks to isolate the effects of plant population on yield components such as kernel number, kernel weight, and overall biomass production.

In conclusion, this study sets out to explore the critical role of seeding density in corn production, focusing on its impact on growth, development, and yield under the specific conditions found in Georgia. The study aims to enhance the precision of corn management practices, ultimately supporting the sustainability and profitability of agriculture in the region. The findings from this research are expected to provide valuable insights into the relationship between seeding density and corn performance in Georgia's unique agricultural environments. Moreover, the results will contribute to the broader understanding of how seeding density interacts with N management, informing future research and extension efforts aimed at improving corn production practices. By identifying the optimal seeding densities, this study aims to offer practical recommendations that can help farmers achieve higher yields with greater efficiency, reducing input costs and minimizing environmental impacts.

The overarching goal of this study was to compare corn seeding densities and their impact on corn growth, development, and yield. To achieve the intended goal of this study, the following specific objectives were developed:

1. Evaluate the effect of seeding density on corn yield.
2. Determine the optimal seeding rate for corn in Georgia.
3. Assess the impact of seeding density on corn yield, yield components, NUE parameters, and end-of-season stalk nitrate results.

4.2 Materials and Methods

4.2.1 Site Description and Experimental Design

This study consisted of three seeding density trials with two trials executed at the Plant Science Farm in Tifton, Georgia and one trial at the Gibbs Farm in Tifton, Georgia in 2023. They were arranged in a randomized complete block design consisting of six seeding density treatments ranging from 49,420 to 98,840 seeds ha^{-1} in increments of 9,884 seeds ha^{-1} replicated six times. Unfortunately, harvest at the Gibbs Farm was affected by a hurricane resulting in data only being available from four replications of the trial. Site details for each trial are provided in Table 4.1.

4.2.2 Cultural Practices

4.2.2.1 Tillage:

Conventional full-width tillage was utilized at the Gibbs Farm and for Plant Science Farm 2. Conventional tillage consisted of disking to a depth of 15 – 20cm followed by a pass with a field cultivator with rolling baskets to prepare the seedbed. Strip tillage was used for Plant

Science Farm 1. Strips tillage was conducted using a two-row ripper stripper. All tillage was completed within a week prior to planting.

4.2.2.2 Fertility, Pest, and Irrigation Management:

Soil fertility samples were collected from the field by the farm manager. Phosphorus and potassium applications were then tailored based on the results of these samples, following the UGA fertility guidelines. The primary phosphorus source used was diammonium phosphate (18-46-0) and the primary potassium source was muriate of potash (0-0-60). Unfortunately, the farm manager was unable to obtain triple superphosphate. Thus, given the need for phosphorus based on soil tests, the plots received a small amount of N via preplant fertilizer that was applied uniformly across the field.

Weed management practices included preemergence and post-emergence herbicide applications based on UGA guidelines in the 2023 Georgia Pest Management Handbook. For this trial weed management included a preemergence applications consisting of 1.16 L ha^{-1} of Dual II Magnum (S-Metolachlor) and 2.35 L ha^{-1} of atrazine 4L. The Post-emergence application included 1.16 L ha^{-1} of Dual II Magnum, 3.51 L ha^{-1} of atrazine 4L, 2.35 L ha^{-1} of Roundup PowerMAX II (Glyphosate), and 2.35 L ha^{-1} of Reckon 280SL (Glufosinate). Insecticide and fungicide applications were limited to necessity and followed UGA guidelines outlined in the 2023 Georgia Pest Management Handbook.

All locations were irrigated using center pivot systems. Irrigation scheduling across all locations was based on the University of Georgia checkbook recommendations (Roth et al., 2023). The checkbook method involves determining irrigation needs based on crop water requirements at different growth stages. This approach considers factors such as crop evapotranspiration to schedule irrigation and optimize water use efficiency.

4.2.2.3 Nitrogen Management:

To isolate the effects of seeding density on crop performance, a constant N application rate of 269 kg N ha^{-1} was applied to all treatments. At planting (Table 4.2), 67 kg N ha^{-1} was applied using the Precision Planting Conceal 2x0x2 starter N application system, positioning the N 5 cm to the side of the furrow at seed depth on both sides of the furrow. The remaining 202 kg N ha^{-1} was applied at the V3-V5 corn growth stage using a custom sidedress applicator, which employed opening discs to create a shallow furrow approximately 5 centimeters from the row on both sides. Liquid UAN was then dribbled into this furrow. The N source utilized as both starter and sidedress in this study was a liquid 24-0-0-3S fertilizer, which was a blend of urea ammonium nitrate (28-0-0), BASF's 19E fertilizer (19-0-0), and ammonium thiosulfate (12-0-0-26S). Application rates at both timings were controlled using a Precision Planting vApplyHD system.

4.2.2.4 Planting and Harvest:

Planting operations (Table 4.2) were conducted using a 4-row Harvest International planter outfitted with precision planting equipment to ensure accuracy and uniformity across all sites. The planter was equipped with the following precision planting components: DeltaForce automated downforce control, vSet seed meters, vDrive electronic seed meter drive, BullsEye seed tubes, Conceal banded N placement, and vApplyHD liquid control system. These state-of-the-art technologies were chosen to optimize planting precision and facilitate consistent seed placement and N application.

Corn was seeded in 91-centimeter rows which aligns with common practices amongst farmers in Georgia and was selected to represent real-world agricultural conditions accurately. The hybrid utilized at all locations was Pioneer 1622VYHR, chosen for its suitability to the region's conditions and farming practices. These trials consisted of 6 different seeding densities including 49,420 seeds ha^{-1}, 59,304 seeds ha^{-1}, 69,188 seeds ha^{-1}, 79,072 seeds ha^{-1}, 88,956 seeds ha^{-1}, and 98,840 seeds ha^{-1}

Harvest (Table 4.2) was conducted using a plot combine equipped with a calibrated HarvestMaster GrainGage, allowing for the measurement of yield, test weight, and harvest moisture. For each plot, the center two rows were designated for yield data collection to minimize edge effects and allow some buffer between N rate treatments. Unfortunately, at the Gibbs Farm a hurricane caused total loss of the crop prior to harvest; thus, yields from the Gibbs Farm were calculated from physiological maturity crop samples that were collected prior to the hurricane.

4.2.3 Sampling and Data Collection

4.2.3.1 Plant Sampling and Analysis

At the R6 growth stage, plant samples were collected from four replications at each experimental location. Specifically, two plants were randomly selected from three separate locations within each plot to ensure representative sampling. Stand counts for each plot were also conducted at each of the three sampling locations to assess plant density and uniformity.

The collected plant samples were separated into three fractions: stalk nitrate samples, remaining stover, and grain. Stalk nitrate samples were collected by excising a 20-centimeter segment from the stalk, specifically from 15 to 35 centimeters above the base of the plant. Grain was separated from cobs using an ALMACO Maizer SES. Prior to further processing the grain, yield components were evaluated, including kernels per ear and weight per kernel. Subsequently, all plant fractions were dried at 60°C to a constant weight to remove moisture content. Once dried, the samples were weighed to determine biomass. Following biomass determination, the samples were ground to pass through a 1mm sieve for further analysis.

Nitrogen concentration in the ground samples was analyzed via dry combustion analysis. This analysis provides precise measurements of N concentration in each plant fraction. The N concentration was multiplied by the biomass of each fraction to determine the total N content. To determine the whole plant N uptake, we added the total N content from each plant fraction (grain N + Stover N + Stalk Sample N). The results from these analyses were used to calculate various measures of NUE. Additionally, stalk nitrate samples will undergo standard stalk nitrate testing procedures. Specifically, 0.5g of the ground stalk material will be extracted with 50ml of distilled water. The resulting solution will then be analyzed colorimetrically for nitrate content using an autoanalyzer with the cadmium reduction method.

4.2.3.2 Nitrogen Use Efficiency Calculations

We did not include a zero N treatment in this study. Therefore, we could not use the most commonly evaluated measures of NUE including nitrogen fertilizer recovery efficiency, nitrogen physiological efficiency, nitrogen agronomic efficiency, and nitrogen internal efficiency. Instead, we utilized measures of NUE that can be calculated without the need for a zero N treatment. These measures include nitrogen utilization efficiency, partial nitrogen balance, and partial-factor productivity which were calculated using the following equations.

Nitrogen Utilization Efficiency

$$NUtE = \frac{Yield}{Plant\ N}$$

where NUtE is nitrogen utilization efficiency, Yield is grain yield from the plot, and Plant N is whole plant N uptake for the plot.

Partial Nitrogen Balance

$$PNB = \frac{Plant\ N}{Fertilizer\ N} \times 100$$

where PNB is N uptake efficiency and Fertilizer N is the total amount of N fertilizer applied to the plot.

Partial-Factor Productivity

$$PFP = \frac{Yield}{Fertilizer\ N}$$

where PFP is partial-factor productivity.

Nitrogen Internal Efficiency

$$NIE = \frac{Yield}{Plant\ N}$$

where NIE is nitrogen internal efficiency.

4.2.4 Statistical Analysis

For the analysis of yield, measures of NUE, and comparisons of yield components between treatments, we conducted Analysis of Variance (ANOVA) in the R statistical environment. When the ANOVA model yielded significant results, Tukey's Honestly Significant Difference (HSD) multiple comparisons test was employed for the separation of means. This allowed for the identification of statistically significant differences between treatment means, providing insight into the effects of N rate treatments on crop yield, NUE, and yield components.

For the analysis of grain yield, stover, grain, and whole plant biomass and N uptake, stover and grain N concentration, thousand kernel weight (TKW), kernels per ear (KPE), nitrogen utilization efficiency (NUtE), partial nitrogen balance (PNB), partial factor productivity (PFP), and nitrogen internal efficiency (NIE), we conducted Analysis of Variance (ANOVA) using the Agricolae package in the R statistical environment. In this study, seeding density was treated as a fixed effect and block was treated as a random effect. When the ANOVA model yielded significant results, a least significant difference (LSD) test was employed for the separation of means. This allowed for the identification of statistically significant differences between treatment means. An alpha level of 0.05 was used for all means comparisons.

4.3 Results and Discussions

Determining the ideal seeding density within a specific cropping system is key to achieving maximum corn grain yields, thus research is needed to provide growers with the necessary data to make informed decisions about seeding density in their production systems (Zhang et al., 2020; Stanslous et al., 2024). Corn grain yield generally increases with increasing plant density, which is often realized in the form of reduced per plant yield but increased overall yield within the field (Duncan, 1984). However, it is not uncommon to reach a point where competition for water, nutrients, and light become too great and the increase in grain yield no longer outweighs potential reductions in yield per plant (Duncan, 1984; Licht et al., 2016). Furthermore, corn yield response to plant density can be influenced by biotic and abiotic factors such as pest incidence, topography, and soil properties (Shanahan et al., 2004; Van Roekel and Coulter, 2012; Kaspar et al., 2004; Kravchenko and Bullock, 2000; Kravchenko et al., 2003; Papiernik et al., 2005; Licht et al., 2016). The current University of Georgia recommendation for corn seeding density is 69,200 to 88,900 seeds ha^{-1} (Tubbs et al., 2023), which is similar to seeding densities recommended by other states in the Southeastern U.S. (Sorensen et al., 2022; Plumblee et al., 2015; Williams et al., 2014) and the central U.S. Corn Belt (69,000 – 98,800 seeds ha^{-1}; Hoeft et al., 2000; Mueller and Sisson, 2013; Nafziger, 2012; Neilsen et al., 2015; Woli et al., 2014). This study was designed to observe the effect of seeding density on corn grain yields under irrigated conditions in Georgia. The results varied by trial location with each exhibiting similar yet unique responses to increasing seeding density.

4.3.1 Final Plant Stands

In this study, we achieved final plant stands approximately equal to our intended seeding rates at both the RDC Con and RDC Strip locations. However, our final plant stand counts at the Gibbs location showed that we did not achieve our desired seeding rates, thus the discussion of any results from the Gibbs location are made with this in mind. There are several possible reasons that the desired plant stands may not have been achieved at this location. First, it is possible that at the time of planting human and/or technological error could have resulted in plots not being seeded at the expected seeding densities. Second, due to the number of individuals collect plant stand and biomass samples it is possible that some of these individuals collected data from the wrong locations within the field which could have contributed to the results seen here as well (Table 4.3).

4.3.2 Seeding rate effect on corn yield

In this study we observed significant effects of seeding density on corn grain yield at all three experimental locations. In general, there was a trend for greater corn grain yields at the higher seeding densities, but the corn grain yield response to increased seeding density was inconsistent and did not necessarily follow a linear trend as hypothesized. Specifically, at Gibbs the 88.9 seeds ha^{-1} treatment had significantly greater corn grain yield than the 49.4 seeds ha^{-1} treatment, but both were similar to all remaining treatments. At the RDC Con location, the corn grain yield in the 98.8 seeds ha^{-1} treatment was significantly greater than the 49.4, 59.3, and 69.2 seeds ha^{-1} treatments and the 79.0 seeds ha^{-1} treatment also had significantly greater corn grain yield than the 49.4 and 69.2 seeds ha^{-1} treatments. Finally, at the RDC Strip location the 59.3, 88.9, and 98.8 seeds ha^{-1} treatments had significantly greater corn grain yield than the 49.4 and 69.2 seeds ha^{-1} treatments but had similar yield to the 79.0 seeds ha^{-1} treatment. Another interesting note on the corn grain yield results from this study is that the conventional tillage consistently outyielded the strip tillage, which is the opposite of the results observed by this researcher in N rate trials conducted within the same fields (Table 4.4). The results of this study are similar to those of previous studies which have found that increasing seeding density generally results greater corn grain yields (Bullock et al. 1998; Lowenberg-DeBoer 1999; Widdicombe and Thelen 2002). However, this relationship of increased corn grain yield with increasing seeding densities is not necessarily linear and is most commonly reported as a quadratic relationship. In contrast, Licht et al. (2016) reported a negative correlation between corn grain yield and increased seeding density. The negative correlation observed by Licht et al. (2016) and others could be due to factors outside the control of the corn producer resulting in incremental impacts on grain yield throughout the growing season such as soil water availability and storage, weather conditions, and heavy pest pressure (Baron et al., 2006; Ferreira & Teets, 2017; Williams & Boydston, 2013). Despite mixed conclusions regarding seeding density and corn grain yields within the literature one common theme persists, which is that seeding density must be considered on a location-by-location basis and that there is no one-size-fits-all answer to this question. The results of the current study confirm this and suggest that further research is needed regarding ideal corn seeding density in Georgia.

4.3.3 Seeding density influence on corn yield components

Corn grain yield is comprised of four primary components including plants per hectare (PPH), ears per plant (EPP), kernels per ear (KPE), and thousand kernel weight (TKW). In this study, the corn plants had an average of just one EPP, with very few having any kind of secondary ear and even fewer having harvestable secondary ears. Additionally, the independent variable in this study was seeding density, as this researcher was interested in how varying how

PPH might influence the other components of corn grain yield. Thus, our goal in this study was to quantify kernels per ear and kernel weight. In this study, no significant differences were observed in kernels per ear amongst the different seeding densities at any of the three locations (Table 4.6.). Furthermore, no significant differences were observed in TKW amongst the different seeding densities at the Gibbs locations. However, significant effects of seeding density on TKW was observed at the RDC Con and RDC Strip locations. At the RDC Con location, TKW in the 49.4 seeds ha^{-1} was significantly greater than the 88.9 seeds ha^{-1} treatment, but both were similar to all remaining treatments. At the RDC Strip location the 49.4 seeds ha^{-1} treatment had significantly greater TKW than the 79.0 and 99.8 seeds ha^{-1} treatments, but was similar to the 53.9, 69.2, and 88.9 seeds ha^{-1} treatment.

In the literature, there is extensive research regarding the effect of seeding density on corn yield components. In general, previous studies have reported decreased KPE and TKW in response to increasing seeding density (Madani et al., 2011; Millander et al., 2016; Van Roekel and Coulter, 2012; Bruns and Abbas, 2005). For instance, Madani et al. (2011) observed that KPE decreased by 12% from 874.6 to 767.4 when increasing plant density from 7 plants m^{-2} to 13 plants m^{-2}. Similarly, Millander et al. (2016) observed that KPE decreased by 25% and TKW decreased by 10% in increasing plant population from 65,000 plants ha^{-1} to 105,000 plants ha^{-1}. Likewise, Van Roekel and Coulter, (2012) observed a 15% decrease in kernel weight when increasing from 40,700 to 108,700 plants ha^{-1}. In a Stoneville, Mississippi study, Bruns and Abbas (2005) reported that increasing plant population from 71,760 plants ha^{-1} to 102,960 plants ha^{-1} resulted in an average 36% and 6% decrease in KPE and kernel weight, respectively. In the current study, there was an average reduction of 15% in KPE when increasing seeding density from 49,400 seeds ha^{-1} to 98.8 seeds ha^{-1}. However, unlike the previous studies, no significant trend was observed in TKW at any of the three locations in the current study. It is possible that this reduction could be a result of overcrowding leading to increased competition for resources such as light, nutrients, and water at higher plant densities.

4.3.4 Seeding density impact on measures of corn growth and nitrogen use efficiency

4.3.4.1 Seeding density impact on biomass production and Nitrogen Uptake

For this study, plant samples were taken at the R6 growth stage to examine the biomass production and N uptake. The samples were then broken down into stover and grain biomass, also examining whole plant biomass. There was no significant difference with stover biomass among any seeding density (Table 4.7) at the Gibbs location. At the RDC Con location the 49.4 was significantly less than the 59.3 and 69.2 seeding rate, while those two rates were significantly less than the 88.9 seeding rate, while the 79.0 and 98.8 seeding rates were similar to all rates except the 49.4 seeding rate. For RDC Strip, the 49.4 seeding rate was significantly less than all rates except the 59.3 seeding rate, which was similar to. While the 98.8 was similar to the 69.2, 79.0, and 88.9 seeding rate. For grain biomass, there was no significant difference among any population at the Gibbs location. For the RDC location, the 49.4 and 59.3 were significantly less than the 98.8 seeding rate, while all rates were similar to the 69.2, 79.0, and 88.9 seeding rate. At the RDC Strip till location, the 49.4 seeding rate was significantly less than the 69.3, 88.9, and 98.8 seeding rate. While the 98.8 was similar to the 79.0 and 88.9 seeding rate. Similarly, to the stover and grain biomass there was no significant differences for whole plant biomass among any population rate at the Gibbs location. The whole plant biomass at the RDC Con location, was very similar to the results to the grain biomass, as the 49.4 and 59.3 seeding rates were significantly less than the 88.9 and 98.8 population, while all treatments were similar to the 69.2 and 79.0 seeding rate. At the RDC Strip location the 49.4 treatment was less than the 79.0, 88.9, and 98.8 treatments, while they were similar to the 59.3 and 69.2 treatments. The 98.8 treatment was also similar to the 79.0 and 88.9 treatment (Table 4.8).

In the literature, there is a general trend for greater biomass and N uptake in corn with increasing plant densities. As N uptake is a function of plant biomass, it is expected that these two measures of plant growth would follow very similar trends. In this study, we observed that stover accounted for an average of 45% of the whole plant biomass, while grain accounted for the remaining 55%. Similarly, Kazula & Lauer (2018) found that corn biomass distribution among plant parts was around 52% grain and 48% stover. In the current study, corn stover, grain, and whole plant biomass tended to increase with increasing seeding density at the RDC Con and RDC Strip locations, though no trend was observed at the Gibbs location. This aligns with the findings of previous studies such as Hashemi et al. (2005), Ferreira et al. (2017), Ferreira et al. (2014) and Li et al. (2022) who all observed the greatest corn biomass production at the greatest seeding density used in their individual studies. It has been observed that increasing plant density actually leads to lower per plant biomass production, thus the observed increase in biomass with increasing seeding density is likely a function of increased plants per hectare leading to greater overall biomass than an increase in per-plant biomass production. Similar to biomass production, it is common within the literature to observe increase N uptake with increasing seeding density. For instance, Ferreira et al., 2017 found that N uptake followed the pattern of biomass production with greater N uptake occurring with increasing seeding density. Similarly, Shapiro and Wortmann (2006) observed increasing N uptake with increasing seeding density. In the current study, averaged across all locations, there was an average increase in whole plant N uptake of 28% when increasing seeding density from 49,400 seeds ha^{-1} to 98,800 seeds ha^{-1}. These results coupled with those in previous literature suggest that in scenarios where achieving the greatest biomass production and N uptake possible, such as silage production for livestock feed, it is advisable to utilize the high end of the local seeding density recommendations.

4.3.4.2 Impact of seeding density on measures of nitrogen use efficiency

In the most general of terms, NUE is a tool to measure the efficacy with which a crop utilizes applied N fertilizer. Many different formulas, each considering unique variables, exist to calculate NUE and can generally be classified as fertilizer-based, plant-based, soil based, isotope-based, ecology-based, or system-based (Congreves et al., 2021; Dobermann et al., 2007). Though NUE may seem like a simple idea, it is actually fairly complex when considering the various N sources that can contribute to crop production and that factors such as genetics, crop management, and weather can all influence NUE. While it could be argued that having multiple methods of calculating NUE could be beneficial for understanding NUE within different experimental designs, the counterpoint is that having multiple formulas dilutes the authority of any single definition for NUE. In this study we used a combination of fertilizer and plant-based measures of NUE, including Nitrogen utilization efficiency (NUtE), partial nitrogen balance (PNB), partial factor productivity (PFP), and nitrogen internal efficiency (NIE) to evaluate how well the corn utilized applied N fertilizer. These measures of NUE were selected because their calculation does not require a non-fertilized control, but they are very similar to more commonly used NUE formulas that include a non-fertilized control. Specifically, the formulas for calculating NUtE, PNB, and PFP are similar to nitrogen physiological efficiency (NPE), nitrogen recovery efficiency (NRE), and nitrogen agronomic efficiency (NAE), respectively, with the only difference being that NUtE, PNB, and PFP do not include a non-fertilized control. Furthermore, the calculation of NIE does not require fertilized control and thus would be the same whether in a situation like the current study or a study that included a non-fertilized control (Table 4.9).

Nitrogen utilization efficiency is defined by Ogawa et al. (2016) as the ability of a plant to convert absorbed N into biomass or yield. Most commonly, NUtE is calculated as the ratio of grain yield to N uptake by the plant. One limitation of NutE is that it cannot delineate between the contributions of soil N versus fertilizer N with regard to whole plant N uptake and yield production. At the Gibbs location there were no significant differences in NUtE among seeding densities. At the RDC Con location, NUtE in the 79,000 seeds ha^{-1} treatment was significantly greater than all other treatments. At the RDC Strip location, the 69.2 seeds ha^{-1} treatment was significantly less than the 59.3 and 88.9 seeds ha^{-1} treatments, while the 79.0 and 98.8 seeds ha^{-1} treatments were similar all treatments (Table 4.9).

Partial Nitrogen Balance is defined by Congreves et al., 2021 as a measure of NUE that compares the amount of N removed in the harvested crop to the amount of N applied. It is calculated by dividing the N output (in crop yield) by the total N input (fertilizer and other sources). This ratio provides insight into how effectively the N is utilized by the crop, highlighting the balance between N inputs and outputs to minimize environmental impacts while maintaining crop productivity. At Gibbs and RDC Con there was not any significant difference in PNB among any population rate. At the RDC Strip site the 49.4 and 59.3 seeding densities were significantly less than the 69.2 and 98.8 seeding densities, while the 79.0 and 88.9 seeding densities were similar to all remaining seeding densities (Table 4.9).

Partial factor productivity is defined by Dobermann (2007) as the ratio of the harvested crop yield to the amount of applied nutrient. It is a useful measure for farmers because it integrates the efficiency of both indigenous soil nutrients and the applied fertilizer. High PFP values indicate a good balance between soil nutrient supply and applied nutrient efficiency. In well-managed systems, PFP for N ranges from 40 to 80 kg of harvested product per kg of N applied (Dobermann 2007). At the Gibbs location, the 49.4 seeding rate was significantly less than the 88.9 seeding rate, while both rates were similar to the rest of the seeding densities. At RDC Con the 49.4 and 69.2 seeding densities were significantly less than the 79.0 and 98.8 seeding densities, while being similar to the 59.3 and 88.9 seeding densities. While the 98.8 seeding density was greater than the 49.4, 59.3, and 69.2 seeding density, but similar to the 79.0 and 88.9 seeding density. At the RDC Strip location the 59.3, 88.9, and 98.8 seeding density was significantly greater than the 49.4 and 69.2 seeding densities, but similar to the 79.0 seeding density. The 49.4 treatment was only similar to the 69.2 seeding density and significantly less than the rest of the treatments (Table 4.9).

Nitrogen Internal Efficiency is defined by Dobermann (2007), as the plant's ability to convert absorbed N, from both soil and fertilizer sources, into economic yield. Similarly to NPE, it is influenced by factors such as genotype, environmental conditions, and crop management practices. Higher NIE values may indicate N deficiency, while lower NIE values often signal suboptimal nutrient conversion due to environmental stresses or biotic pressures. The typical range for NIE in cereal crops is between 30 and 90 kg kg^{-1}, with 55 to 65 kg kg^{-1} being considered the optimal range for balanced nutrition (Dobermann, 2007). Similar to NPE, there was little significant response in NIE to increasing N rates in this study. In fact, there was no significant difference for nitrogen internal efficiency (NIE) among any seeding densities at the Gibbs and RDC Strip locations. At the RDC Con the 69.2 and 98.8 seeding densities was significantly greater than the 59.3 seeding density, while all three were similar to the remaining of the seeding densities (Table 4.9).

There is a dearth of literature regarding the influence of corn seeding density on measures of NUE, especially within the United States. Furthermore, of the literature from around the world that does exist, very little information is available about the specific measures of NUE utilized in this study with the majority focusing on NRE, NAE, and NPE (Yan et al., 2016; Tian et al., 2022; Guo et al., 2016). In a study conducted in Central China, Tian et al. (2022) observed a positive relationship of NIE with plant density at yields less than 10 Mg ha^{-1} and a negative relationship at yields above 10 Mg ha^{-1}. Additionally, Tian et al. (2022) observed the opposite trend for NRE with a negative relationship at yields below 10 Mg ha^{-1} and a positive relationship at yields above 10 Mg ha^{-1}. In their study, seeding densities of 82,500 ha^{-1} or greater were most commonly associated with yields of 10 Mg ha^{-1} and above. In the current study, no trend was observed in NIE with regards to increasing seeding density, and for PNB, which is related to NRE, there was no significant influence of seeding density though there was a general trend for greater PNB values with increased seeding density. In another study, Yan et al. (2016) observed no clear trend in NRE with regard to seeding density, reporting the greatest NRE at 7.5 plants m^{-2} and the lowest NRE at 6.0 plants m^{-2} with 9.0 plants m^{-2} in the middle. In another study conducted in China, Guo et al. (2016) found that PFP decreased by an average of 48% when seeding density was increased from 62,000 seeds ha^{-1} to 75,000 seeds ha^{-1}. In contrast to the results of Guo et al., the results of the current study showed a trend for increasing PFP with increasing seeding density. The lack of information available of the impact of seeding density on measures of NUE, especially within the United States and more specifically the Southeastern United States, highlights the relevance of the current study, but also suggests that research in this area should be expanded.

4.3.5 Limitations of Study

There were some limitations to the current study that may affect the generalizability and interpretation of the results. First, this study was carried out over a limited number of sites in Georgia; this provides insight into those local conditions but could limit the broader applicability of the results to other regions within the state and beyond. Unique soil types in combination with climatic factors and management practices peculiar could mean that outcomes in other regions and environments may differ widely.

At the Gibbs Farm site, several additional limitations were noted that may affect the interpretation of results from this study. Perhaps most notably, a hurricane severely impacted the site previous to R6 plant sampling and harvest, likely affecting the survivability of plants, uniformity of growth, and yield outcomes. This reduced the number of replicates that could be analyzed and significantly lowered the statistical power while maintaining the potential for bias in yield and biomass estimates due to environmental stress rather than seeding density effects alone.

Additionally, there were some difficulties in achieving target plant stands at Gibbs. It's unclear whether this was due to human or equipment error at planting time or to incorrect identification of the sampling areas within the field, though the latter would likely affect the consistency of the plots rather than the overall bias of them. Thus, any effects observed at this site may not accurately reflect the intended seeding densities, making strong conclusions about the specific density treatments difficult.

Since this study did not include a zero-nitrogen treatment, the most common metrics of NUE, such as NRE, NPE, and NAE, were unable to be calculated. NutE, PNB, and PFP were calculated in this study, although the lack of a non-fertilized control prevents the delineation of fertilizer N and soil N contributions to corn grain yield. Future trials, where a zero-nitrogen treatment is included, would enable more accurate calculations of NUE and contribute toward a more holistic view of N use over a range of seeding densities.

Finally, biomass and N uptake measurements were only collected at the R6 growth stage. Including measurements of these growth parameters at multiple growth stages in future studies could provide greater insight into how seeding density may effect plant growth and N uptake throughout the lifecycle of corn and help identify where competition effects of increased seeding densities may be greatest. This could aid in the development of more targeted seeding density by N management recommendations.

In all, this study provides useful data on corn seeding densities in Georgia, but it could have been improved by considering more variables, replicating at a greater number of locations throughout the state, and including a non-fertilized control treatment. Making these changes in future studies would generate data with greater applicability and provide a more nuanced understanding of the effects of seeding density on corn yield, growth, and NUE.

4.4 Conclusions

This study was conducted to determine the effects of different seeding densities on corn yield, growth, and NUE across three experimental sites in southern Georgia. Our results begin to illustrate the importance of management-specific management practices for maximum corn production, as the response of the measured variables to increasing seeding density was not linear, inconsistent, and likely influenced by site-specific management and environmental factors. The current study's results are in line with previous studies for many of the key variables that were measured, showing that increasing seeding density generally increases total yield, but only up to a certain limit, beyond which competition for resources such as nutrients and water limits further gains. However, each trial site illustrated different response patterns, underscoring the importance of site-specific data for making precise agricultural recommendations. For instance, the RDC Con and RDC Strip locations showed consistently increased grain yields at higher seeding densities, while the results from the Gibbs location showed no observable patter, likely due to both environmental variability and logistical limitations.

Interestingly, the trial results showed that while higher plant densities boosted whole plant biomass production and N uptake, this did not always translate to proportional increases in grain yield components, such as KPE and TKW. Variability in TKW across locations further supports the influence of environmental factors, as higher seeding densities can intensify competition for limited resources like water and light, potentially hindering kernel development. For farmers, this means that seeding density should be chosen in conjunction with the management of other factors, such as nutrient application and irrigation.

This study evaluated NUE through four key metrics: NUtE, PNB, PFP, and NIE, which showed varied responses across treatments, further highlighting both the potential and limitations of high seeding densities in terms of N management. The findings from this study indicated that greater seeding densities generally enhanced corn N uptake, though this did not always correspond to improved NUE. For instance, PFP and PNB values had a tendency to increase with increasing seeding density, reflecting a better uptake and conversion of applied N fertilizer to grain yield; however, NIE and NutE showed no consistent trends across locations. The results of this study suggest that seeding density optimization is likely needed on a site-by-site basis in order to achieve optimal NUE.

This study begins to highlight the challenges and trade-offs in optimizing corn production through seeding density management under Georgia's unique agricultural conditions. The lack of uniform responses across sites emphasizes the need for adaptive management strategies that account for farm-specific factors like tillage, crop rotation, and planting equipment. Current seeding density recommendations in Georgia tend to follow a “one-size-fits-all” approach, offering a wide range of potential densities for growers, which may hinder productivity and sustainability. To improve yield and NUE in Georgia corn production, it is essential to provide more accurate, site-specific seeding density recommendations through increased localized research across the state’s diverse agroecosystems. Such data-driven recommendations could empower growers and advisors to enhance yield potential, optimize NUE, and improve the economic and environmental sustainability of Georgia's corn production systems.

4.5 References

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4.6 Tables and Figures

Table 4.1 Location, farm name, field coordinates, tillage type, soil type, and plot size for each experimental location.

Location	Farm Name	Field Coordinates	Tillage Type	Soil Type	Plot Size
	RDC Strip	31.484979, -83.522342	Strip-Till	Tifton Loamy Sand	3.7m x 9.1m
Tifton	RDC Con	31.484979, -83.522342	Conventional Till	Tifton Loamy Sand	3.7m x 9.1m
	Gibbs Farm	31.431798, -83.583689	Conventional Till	Tifton Loamy Sand	3.7m x 9.1m

Table 4.2 Planting, sidedress, and harvest dates for the Gibbs, RDC Con, and RDC Strip experimental locations.

Farm	Planting Date	Sidedress Date	Harvest Date
RDC Strip	April 17, 2023	May 17, 2023	September 14, 2023
RDC Con	April 17, 2023	May 17, 2023	September 14, 2023
Gibbs Farm	April 20, 2023	May 15, 2023	September 10, 2023

Table 4.3 Final corn plant populations measured at the R6 growth stage for the Gibbs, RDC Strip, and RDC Con experimental locations. Different capital letters within a column indicate significant difference in plant population between seeding densities within a given location at an alpha level of 0.05.

	R6 Plant Population		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 seeds ha^{-1}	1000 plants ha^{-1}		
49.4	71.8 (12.4)	47.8 (5.0) A	47.8 (1.4) A
59.3	57.8 (6.1)	60.6 (2.2) B	60.3 (0.5) B
69.2	79.7 (6.8)	68.3 (2.6) BC	71.3 (1.0) BC
79.0	80.2 (8.6)	75.7 (3.2) CD	78.7 (0.6) CD
88.9	68.3 (8.5)	87.2 (1.3) DE	85.7 (2.4) D
98.8	71.8 (9.0)	90.2 (7.5) E	113.6 (8.3) E

Table 4.4 Corn grain yield by seeding density for each of the three experimental locations. Different capital letters within a column indicate significant difference in grain yield between seeding densities within a given location at an alpha level of 0.05.

	Corn Grain Yield		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 seeds ha^{-1}	Mg ha^{-1}		
49.4	4.93 (0.45) A	8.67 (0.18) A	4.08 (0.98) A
59.3	6.61 (0.91) AB	9.33 (0.96) AB	6.79 (0.71) C
69.2	6.63 (1.23) AB	8.79 (1.99) A	4.42 (1.19) AB
79.0	5.86 (0.65) AB	12.10 (0.84) BC	6.35 (1.55) BC
88.9	7.50 (0.39) B	11.78 (1.30) ABC	7.09 (0.66) C
98.8	6.59 (0.80) AB	12.79 (1.13) C	7.09 (0.47) C

Table 4.5 Thousand kernel weight by seeding density for each of the three experimental locations. Different capital letters within a column indicate significant difference in thousand kernel weight between seeding densities within a given location at an alpha level of 0.05.

	Thousand Kernel Weight		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}	g 1000 $seeds^{-1}$		
49.4	206.7 (26.0)	277.6 (9.0) A	304.4 (8.5) A
59.3	262.9 (6.1)	261.0 (17.5) AB	303.5 (3.6) AB
69.2	215.6 (31.8)	273.4 (5.6) AB	293.4 (9.2) AB
79.0	223.4 (28.9)	267.8 (7.0) AB	278.7 (11.8) BC
88.9	223.0 (37.7)	228.9 (17.8) B	280.4 (13.9) ABC
98.8	247.9 (16.2)	234.8 (10.5) AB	259.5 (7.2) C

Table 4.6 Kernels per ear by seeding density for each of the three experimental locations. Different capital letters within a column indicate significant difference in kernels per ear between seeding densities within a given location at an alpha level of 0.05.

Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		Kernels per Ear	
49.4	320.5 (102.7) A	723.9 (67.5)	798.2 (9.7)
59.3	525.8 (29.0) B	621.1 (86.0)	697.3 (100.4)
69.2	325.8 (50.9) A	728.8 (36.4)	666.0 (82.2)
79.0	343.2 (29.8) A	613.0 (106.7)	763.9 (6.9)
88.9	320.3 (85.0) A	656.5 (34.8)	668.3 (34.0)
98.8	450.5 (72.4) AB	670.8 (31.0)	643.0 (61.5)

Table 4.7 Corn R6 stover, grain, and whole plant biomass by seeding density for each of the six experimental locations. Different capital letters within a column within a biomass component indicate significant difference in biomass production between seeding densities within a given location at an alpha level of 0.05.

	Stover Biomass		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		$Mg\ ha^{-1}$	
49.4	4.95 (0.95)	7.72 (0.24) A	9.76 (0.54) A
59.3	6.13 (0.37)	8.97 (0.40) B	10.76 (0.43) AB
69.2	5.83 (0.55)	9.07 (0.19) B	11.97 (0.33) BC
79.0	5.66 (0.12)	9.18 (0.82) BC	11.82 (0.20) BC
88.9	5.27 (0.80)	10.34 (0.60) C	12.43 (0.87) BC
98.8	6.52 (0.85)	9.72 (0.26) BC	13.38 (0.91) C
	Grain Biomass		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		$Mg\ ha^{-1}$	
49.4	4.77 (1.60)	9.47 (0.82) A	11.64 (0.59) A
59.3	7.88 (0.54)	9.90 (1.63) A	12.77 (1.87) AB
69.2	5.74 (1.48)	13.07 (0.27) AB	14.08 (2.04) AB
79.0	5.92 (0.62)	12.43 (2.95) AB	16.77 (0.78) BC
88.9	5.67 (1.79)	13.26 (1.77) AB	16.00 (0.90) BC
98.8	7.92 (1.70)	13.98 (0.52) B	18.74 (1.56) C
	Whole Plant Biomass		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		$Mg\ ha^{-1}$	
49.4	10.85 (1.72)	17.20 (1.04) A	21.40 (0.83) A
59.3	14.02 (0.89)	18.87 (1.96) A	23.53 (1.76) AB
69.2	11.57 (2.00)	22.14 (0.33) AB	26.96 (2.10) ABC
79.0	11.59 (0.57)	21.61 (3.33) AB	28.58 (0.65) CD
88.9	10.94 (2.57)	23.60 (2.28) B	28.43 (1.44) BCD
98.8	14.45 (2.45)	23.71 (0.74) B	32.12 (2.46) D

Table 4.8 Corn R6 stover and grain nitrogen uptake by seeding density for each of the six experimental locations. Different capital letters within a column within a biomass component indicate significant difference in nitrogen uptake between seeding densities within a given location at an alpha level of 0.05.

	R6 Stover Nitrogen Uptake		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		kg N ha^{-1}	
49.4	57.9 (11.0)	94.2 (2.3)	96.5 (18.5)
59.3	64.8 (1.5)	114.1 (12.1)	91.3 (20.7)
69.2	63.9 (8.5)	112.8 (1.5)	120.6 (17.2)
79.0	62.5 (3.0)	112.9 (5.6)	101.5 (14.5)
88.9	59.7 (8.3)	119.1 (11.5)	114.9 (10.6)
98.8	78.7 (10.6)	119.2 (6.7)	119.8 (13.8)
	R6 Grain Nitrogen Uptake		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		kg N ha^{-1}	
49.4	85.0 (9.7)	118.1 (13.1)	152.3 (12.1) A
59.3	105.9 (7.2)	126.1 (24.1)	152.0 (19.3) A
69.2	81.2 (21.5)	167.0 (3.3)	190.1 (6.9) AB
79.0	84.6 (6.1)	148.0 (42.1)	191.2 (12.5) AB
88.9	74.9 (23.6)	152.7 (27.7)	179.4 (8.7) AB
98.8	111.4 (17.9)	168.5 (10.6)	207.3 (16.1) B
	R6 Whole Plant Nitrogen Uptake		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		kg N ha^{-1}	
49.4	126.6 (31.6)	212.4 (15.3)	248.8 (29.4) A
59.3	170.8 (7.4)	240.2 (35.2)	243.4 (6.2) A
69.2	145.1 (24.9)	279.9 (4.8)	323.6 (14.6) B
79.0	147.0 (8.3)	260.9 (47.7)	292.7 (26.8) AB
88.9	134.6 (31.3)	271.8 (38.6)	294.3 (15.9) AB
98.8	190.1 (28.1)	287.8 (16.2)	327.0 (26.5) B

Table 4.9 Nitrogen utilization efficiency, partial nitrogen balance, partial factor productivity and nitrogen internal efficiency by seeding density for each of the six experimental locations. Different capital letters within a column within a nitrogen use efficiency metric indicate significant difference between seeding densities within a given location at an alpha level of 0.05.

	Nitrogen Utilization Efficiency		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		kg N ha^{-1}	
49.4	56.1 (23.9)	41.4 (3.8) A	17.2 (5.3) AB
59.3	38.9 (5.5)	40.7 (5.1) A	28.0 (3.0) C
69.2	48.6 (8.4)	37.4 (1.1) A	11.5 (4.2) A
79.0	40.1 (4.5)	74.5 (17.4) B	21.9 (5.9) ABC
88.9	77.3 (32.2)	44.3 (4.4) A	24.1 (2.1) BC
98.8	36.9 (6.2)	44.6 (3.6) A	21.8 (1.0) ABC
	Partial Nitrogen Balance		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		kg N ha^{-1}	
49.4	0.47 (0.12)	0.79 (0.06)	0.92 (0.11) A
59.3	0.63 (0.03)	0.89 (0.13)	0.90 (0.02) A
69.2	0.54 (0.09)	0.86 (0.18)	1.20 (0.05) B
79.0	0.55 (0.03)	0.72 (0.18)	1.09 (0.10) AB
88.9	0.50 (0.12)	1.01 (0.14)	1.09 (0.06) AB
98.8	0.71 (0.10)	1.07 (0.06)	1.22 (0.10) B
	Partial Factor Productivity		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		kg N ha^{-1}	
49.4	18.3 (1.7) A	32.3 (0.7) A	15.2 (3.6) A
59.3	24.6 (3.4) AB	34.7 (3.6) AB	25.3 (2.7) C
69.2	24.6 (4.6) AB	32.7 (7.4) A	16.4 (4.4) AB
79.0	21.8 (2.4) AB	45.0 (3.1) BC	23.6 (5.8) BC
88.9	27.9 (1.5) B	43.8 (4.8) ABC	26.3 (2.5) C
98.8	24.5 (3.0) AB	47.5 (4.2) C	26.4 (1.7) C
	Nitrogen Internal Efficiency		
Seeding Density	**Gibbs**	**RDC Con**	**RDC Strip**
1000 Seeds ha^{-1}		kg N ha^{-1}	
49.4	60.2 (3.6)	55.3 (2.2) AB	62.2 (3.2)
59.3	61.8 (1.8)	51.0 (3.1) A	62.6 (8.0)
69.2	53.6 (6.5)	59.7 (0.2) B	59.0 (3.3)
79.0	57.4 (1.6)	55.6 (6.0) AB	65.8 (1.9)
88.9	48.0 (11.5)	55.4 (2.1) AB	61.1 (2.1)
98.8	58.4 (1.3)	58.5 (1.1) B	63.5 (2.2)

CHAPTER 5. CONCLUSION

The results of this study highlight the role of nitrogen (N) management, p irrigation scheduling, and seeding density have on enhancing corn productivity and sustainability in Georgia. In this thesis, three nitrogen recommendation methods were compared including Crop Yield Goal (CYG), Agronomic Optimum Nitrogen Rate (AONR), and Economic Optimum Nitrogen Rate (EONR). The findings of the thesis illustrate the limitations of traditional CYG recommendations, which often lead to inaccurate N applications, which results in increased input costs and potentially greater environmental impacts. The AONR and EONR methods both provided more precise recommendations for optimizing yield and profitability, though AONR may still risk over-fertilization in some scenarios. Improved nitrogen recommendation tools are essential to optimizing corn grain yield without excessive N application, aligning with sustainable agricultural goals and benefiting both the ecosystem and crop efficiency.

The investigation of irrigation scheduling in this thesis was less revealing than the nitrogen study, yet still provides valuable insights. Specifically, it was observed that irrigation scheduling method can influence AONR and EONR, with reduced water availability leading to lower overall AONR and EONR values, likely due to increased water stress impacting growth leading to less nitrogen needed to achieve maximum yield levels. While little significant differences were observed amongst crop growth and NUE variables measured in the irrigations study, this could be due to the fact that the study occurred at just one location for one year. Future research should build on these findings by examining the interactive effects of varying irrigation and nitrogen application rates across more locations throughout Georgia in order to better develop recommendations for corn growers. Beyond statistics, general observations from this study show the promise of the Smart Irrigation CropFit app to balance water needs with N requirements, resulting in more efficient irrigation that maintains crop productivity equal to the traditional checkbook method. These findings highlight that advanced, data-driven irrigation techniques may offer Georgia's farmers better control over water application, particularly critical if Georgia begins to face water resources issues.

Additionally, the evaluation of different seeding densities revealed a nuanced relationship between plant population, yield components, and NUE. As seeding density increased so too did yields, biomass production, and nitrogen uptake. However, the increase in biomass production and nitrogen uptake did not necessarily translate to a proportionally to thousand kernel weight or kernels per ear which suggest increases in yield with increased seeding density are likely of greater kernels and kernel weight per area than on a per plant basis. Similarly, the enhanced corn nitrogen uptake related to increased seeding density did not always correspond to improved NUE. Site-specific adjustments to seeding density can therefore be a powerful tool in maximizing both productivity and resource utilization, reducing the environmental footprint per unit of output.

This thesis contributes to the broader understanding of how site-specific and data-driven management practices can enhance agricultural sustainability and efficiency. These results encourage moving away from static N recommendation methods to more adaptive approaches that consider local soil, weather, and crop conditions. Future work could expand on this thesis by developing models for AONR and EONR that are regionally specific to the diverse agricultural zones of Georgia incorporating site-specific environmental, climatic, and management factors. Further, it may be worthwhile to explore the synergistic effects of irrigation management, nitrogen management, and seeding density on soil and crop resilience to generate more insightful recommendations for Georgia's corn growers.

In all, continued efforts at optimizing N rates, irrigation scheduling, and seeding density are foundational to achieving sustainable corn production in Georgia. In other words, farmers could reduce input costs, maintain or increase crop yields, and contribute to a more resilient agricultural system by aligning their agronomic practices with economic and environmental goals, thus paving the way for economic gains and environmental stewardship in future corn production.