

ADAPTIVE NUTRIENT MANAGEMENT TO ENHANCE THE SUSTAINABLE
PRODUCTION OF ROW CROPS

by

SOLOMON AMISSAH

(Under the Direction of Henry Yabbey Sintim)

ABSTRACT

Growers employ nutrient-sufficiency ranges (NSRs) after plant tissue analyses to ensure balanced nutrition, which is critical in soils of the Southeastern USA that are highly weathered with poor native fertility. A common NSR is the sufficiency range system by the Southern Cooperative Series Bulletin (SCSB), established from survey studies conducted across multiple locations, necessitating the need to test its validity in a controlled experiment. The timing of nutrient application is another important factor for row crops because of the potential to synchronize nutrient application with crop demand to ensure high yield and increase nutrient use efficiency (NUE). Nutrient availability for plant uptake is dependent on soil moisture, making the amount of soil water available, essential for crop growth and productivity. Thus, dry soils can reduce nutrient uptake due to the limited availability of water resulting from water stress.

A controlled experiment was conducted across three years to validate the lower threshold of the NSRs for corn established by the SCSB. Varying nutritional levels were induced through different nutrient application rates. Validity depended on samples within the same replication having similar relative biomass if all its nutrient elements satisfied the NSRs. The results showed that the NSRs of the SCSB were not valid under the conditions tested. 47.6% of the samples

satisfied the lower threshold of the NSRs, with 25.4% of those samples having relative biomass <50%. Another experiment investigated the benefits of secondary nutrient (SN) and micronutrient (MN) applications to the growth and development of corn. The results demonstrated that SN and MN were indeed limiting corn growth and that a yield of 12.5 Mg ha⁻¹ can be achieved with lower PN rates than currently recommended. An experiment to evaluate the impact of Early-season nutrient stress (E-stress) revealed that corn could not recover from early-season nutrient stress due to the reduction in biomass, nutrient uptake, and yield by the E-stress treatment. A similar study on cotton revealed that cotton can recover from E-stress with a marginal yield reduction because cotton exhibits plasticity in its growth.

INDEX WORDS: sufficiency range system, nutrient imbalance, essential plant nutrients, early season nutrient stress, irrigation scheduling, nutrient stress.

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Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2023

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DEDICATION

All thanks and adoration go to the Almighty God for life, strength, and motivation throughout this journey. This dissertation is dedicated to my Wife for her unflinching love, support, and understanding, without which these past four years would have been difficult. Next, I dedicate this work to my Mum for her love, support, and encouragement and in honor of my Dad for his love, support, and guidance.

ACKNOWLEDGEMENTS

I would like to sincerely thank my committee members (Glendon H. Harris, Miguel Cabrera, Dorcas H. Franklin, Juan C. Diaz-Perez, and Henry Y. Sintim) for their time and efforts toward completing this work. Special thanks go to my major professor, Dr. Henry Yabbey Sintim, for his confidence in selecting me to join his research program and his unwavering support, guidance, and training. Words cannot describe my immense gratitude and respect for the energy and time dedicated to my training and completing this dissertation. May God richly bless your efforts. I would also like to thank the Georgia Corn Commission for funding this project. Immense gratitude goes to Benjamin Kwadwo Agyei, Godfred Ankomah, and MD Ariful I. Sohag for their unwavering support during sample collection and processing.

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CHAPTER 1

INTRODUCTION

1.0. Background

The USA is the largest producer of corn, accounting for more than a third of the world's corn production. Corn serves as food for humans and livestock and the production of ethanol. It is a very important crop in the state of Georgia, as is the case throughout the country, with farmers in Georgia producing over 1.52 Mt each year (Roth et al., 2023). Corn is the eighth most valuable commodity in Georgia and the third most important row crop produced in the state, with an annual value of \$509.1 million in revenue to the agriculture sector (Kane, 2023). Corn is important for the livestock sector of the state, especially for the poultry industry, which is the most valuable agricultural commodity in the state, accounting for \$4.2 billion in revenue (Kane, 2023).

Cotton is another vital row crop to the economy of numerous countries worldwide. The USA is the third most important country for cotton in terms of production, after China and India, with an economic impact of \$600 billion worldwide (Najib et al., 2022). In the USA, Cotton provides more than \$120 billion annually to the economy. Georgia is the second largest producer of cotton in the USA, second only to Texas, planting 1290000 and harvesting 1280000 acres, with an average yield of 1051 kg ha⁻¹ in 2022 (Hand et al., 2023). Cotton is the second most valuable commodity in Georgia, accounting for \$1 billion in revenue to the agriculture sector and the most crucial row crop in terms of production value (Kane, 2023).

Plant nutrient elements are critical for the growth and development of plants. Essential processes in plants that govern the accumulation and partitioning of biomass and the general health of the plant are directly influenced by the supply of nutrients (Bagale, 2021; Pandey et al., 2021; Saleem et al., 2023). Nutrient elements are classified as either essential or beneficial depending on their importance to the plant. Plants cannot complete their lifecycle without essential nutrients and, as such, are indispensable to the growth and development of the plant (Pandey et al., 2021; Brown et al., 2022). Essential elements should have functions that cannot be performed by another element and should be involved directly with the metabolism of plants (Marschner, 2012; Brown et al., 2022). Beneficial nutrients do not satisfy the essentiality criteria but are essential in enhancing the resistance of plants to biotic and abiotic stresses, including drought, nutrient deficiency, and toxicity, salinity, and pathogens (Pilon-Smits et al., 2009; Chandel et al., 2010). Some beneficial nutrients are essential to specific plants and are thus not classified as essential since the nutrient element must be essential for many plants.

Currently, 17 nutrient elements are considered essential for plant production, including carbon (C), hydrogen (H), and oxygen (O), which are obtained from the environment and are considered non-mineral, nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), chlorine (Cl), boron (B), zinc (Zn), manganese (Mn), iron (Fe), copper (Cu), molybdenum (Mo), and nickel (Ni) (Morgan and Connolly, 2013; Kumar et al., 2021; Brown et al., 2022). N, P, K, Ca, S, and Mg are required in larger amounts and are referred to as macronutrients, serving as building blocks of important cellular components like chlorophyll, proteins, and nucleic acids (Hossner, 2008; Morgan and Connolly, 2013; Kumar et al., 2021). Though essential, micronutrients such as B, Zn, Mn, Fe, Cu, Mo, Cl, and Ni are required in smaller quantities for

plant growth and development. They serve as cofactors for enzymes that are responsible for catalyzing biochemical reactions. A typical example is the function of Mn in reactions catalyzed by enzymes, including phosphorylation, redox reactions, hydrolysis, and decarboxylation (Schmidt and Husted, 2019). Thus, an imbalance or deficiency in essential nutrients is likely to affect the plant's growth, leading to susceptibility to diseases, stunting of growth, and an eventual reduction in yield (Morgan and Connolly, 2013).

The Piedmont and Coastal Plains soils make up the majority of the soil types in Georgia. The soils are predominantly comprised of kaolinite clay minerals that are highly weathered (Swaby et al., 2016). The highly weathered soils in Georgia tend to leach nutrients beyond the reach of plant roots, causing yield and economic losses. Hence, fertilizer recommendation and the mode of application are crucial to ensuring high yield and profitability. Typically, fertilizer recommendations in Georgia, and some parts of the USA, depend on yield goal and the soil fertility status (Hand et al., 2023; Roth et al., 2023). The fertilizer recommendation in Georgia for corn and cotton is to split apply N to maximize N recovery. However, care must be taken to avoid deficiency leading to reduced yield or excessive N application, which can lead to boll rot, rank growth, delayed maturity, and a negative impact on cotton yield. Standard fertilizer application guidelines for corn do not recommend N fertilizer application after pollination. N fertilizer is recommended after this stage only if a severe deficiency of N is detected. All the P and K for corn and cotton should be applied preplant or at planting, with split application considered only on deep sands for corn and also in low K soils, high-yielding conditions, and in situations where leaf spot and K deficiencies have been reported. Regarding the secondary and micronutrient requirements of the

soil, fertilization with S, Mg, Zn, and B is also encouraged. These suggestions are all based on soil tests that will establish the soil's initial fertility level.

2.0. Significance of the study

In order to monitor the nutritional status and health of a plant, plant tissue analysis is critical. Along with soil tests, plant tissue analysis provides knowledge of the nutritional status of a plant for timely nutrient management (Baldock and Schulte, 1996). Despite the importance of plant tissue analysis, there should be an appropriate method of interpreting the results of the plant analysis for it to be useful. The commonest method of interpreting tissue results is the Sufficiency Range System because of its convenience and the ease with which it can be used (Campbell, 2000). This method was, however, established using survey studies conducted over several locations. The different biotic and abiotic factors prevailing in the different locations could confound the study's results. There is a need to conduct controlled experiments to validate the sufficiency ranges of the Southern Cooperative Series Bulletin #394 (SCSB). Corn is a high-input crop that requires soil fertility to be maintained at high levels to ensure successful production. Nutrient recommendations for high corn yields in the state of Georgia are usually based on primary nutrient application rates (Ciampitti et al., 2013), but secondary and micronutrient applications are also crucial for high corn yields because growth only occurs at the rate permitted by the most limiting factor, as illustrated by the "Law of the Minimum". This implies that corn could suffer yield losses as a result of either reduced or insufficient use of secondary and micronutrients (Liebig, 1855; Warsi and Dykhuizen, 2017). Therefore, research on the effects of secondary and micronutrients on corn development and yield is necessary.

According to research conducted by Bender et al. (2013) at two locations in Illinois, by the tasseling stage (VT), <70% of N, P, and K had been taken up by corn when compared to the total taken up at maturity (R6). By the V6 stage (six-leaf collar), less than 15% of N, P, and K had been taken up by corn when compared to the total taken up at R6 (Bender et al., 2013). This suggests low nutrient requirements for corn at the early stages of growth. Thus, it could be beneficial to omit nutrient application in the early season and apply it when demand is high.

Water has been established as an important input for corn production, which needs proper management to ensure the maximum possible yield when combined with the best fertilizer regime. Unsurprisingly, water was referred to as the single most crucial climatic factor influencing corn growth in Georgia (Djaman et al., 2013; Roth et al., 2023). Research conducted by Çakir (2004) observed that restricting water even once during one of the critical growth stages of corn (tasseling) was enough to cause about 20% yield loss in corn. Freshwater, being a limited natural resource, requires that vital measures be taken to determine the best irrigation schemes that will increase water-use efficiency in corn production (Rud et al., 2013; Ahmad et al., 2019). The lower water-holding capacity of most soils in Georgia also complicates nutrient management. Mobile nutrients are susceptible to leaching shortly after application under intensive irrigation cropping systems. Thus, the source of the fertilizer, the method and frequency of application, and the volume and mode of irrigation are critical factors to consider (Azad et al., 2020). Understanding the interaction between different irrigation and fertilizer application strategies will help inform best management practices for corn productivity in Georgia.

When compared to previous varieties, current cotton varieties are better able to take up and use nutrients, potentially conferring some level of tolerance to nutrient stress. Tolerance to nutrient

stress is especially desirable due to fluctuating fertilizer prices and supply in recent times. Increased fertilizer prices would lead to a reduction in the purchase and use of fertilizers. Also, as was observed in the literature for corn, research on nutrient uptake and partition has demonstrated that cotton nutrient requirement at the vegetative stage is low, increasing steadily towards the reproductive stage. Thus, synchronizing nutrient availability with crop demand will increase nutrient use efficiency and reduce environmental adverse effects (Esfandbod et al., 2017). It is essential to conduct a controlled experiment to evaluate the impact of reduced fertilizer application rates on the productivity of current cotton varieties.

3.0. Objectives

The overall goal of the dissertation is to evaluate approaches to enhance corn and cotton productivity in Georgia through effective water and nutrient management. The specific objectives of the research were to:

1. Validate the lower threshold of the nutrient sufficiency ranges (NSRs) for corn at the early growth stages.
2. Assess nutrient dynamics in corn when fertilized with or without secondary nutrients (SN) and micronutrients (MN) at different yield goals.
3. Determine the impact of SN and MN application on corn growth, development, and productivity.
4. Assess corn recovery from early-season nutrient stress under different soil moisture regimes.
5. Assess the impact on the productivity and quality of modern cotton varieties to varying degrees of nutrient stresses under different production conditions.

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CHAPTER 2

NUTRIENT SUFFICIENCY RANGES FOR CORN AT THE EARLY GROWTH STAGE: IMPLICATIONS FOR NUTRIENT MANAGEMENT

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Abstract

Growers rely on nutrient sufficiency ranges (NSRs) after plant tissue analysis to inform timely nutrient management decisions. The NSRs are typically established from survey studies across multiple locations, which could be confounded by several abiotic and biotic factors. We conducted field studies in 2020, 2021, and 2022 to validate the lower thresholds of the NSRs for corn (*Zea mays*) at the early growth stage, as reported in the Southern Cooperative Series Bulletin #394. We induced various corn nutritional levels by making different nutrient application rates. If the NSRs are valid, samples within the same replication that satisfy the NSRs of all nutrients should have similar biomass accumulation. The results showed that the NSRs were not valid under the conditions tested. In total, 47.6% of the samples satisfied all the lower thresholds of the NSRs, and 25.4% of those samples had relative biomass <50%, with relative biomass even as low as 24.2% observed. Moreover, 9.6% of the total samples had P and Cu levels that failed to meet the lower threshold but still had relative biomass $\geq 75\%$. The findings highlight the sensitivity of corn to nutrient imbalance and the need to optimize nutrient diagnostic methods at the early growth stage.

1.0. Introduction

Nutrient elements are indispensable for plant growth because they support critical metabolic functions in plants (Morgan and Connolly, 2013; Sintim et al., 2015; Brown et al., 2022). Without essential nutrients, plants cannot complete their life cycle (Arnon and Stout, 1939; Hanan, 1998; Morgan and Connolly, 2013). Moreover, the functions of essential nutrients are specific, indicating that the surplus of one nutrient element cannot substitute the deficiency of another nutrient element, as depicted by the “Law of the Minimum” and the “Law of the Optimum” (von Liebig, 1855; Liebscher, 1895; Arnon and Stout, 1939; Lemaire et al., 2019).

Maintaining adequate and balanced plant nutrition is crucial for crops to attain their genetic growth potential (Baldock and Schulte, 1996; Bojtor et al., 2021b; Aliyu et al., 2021).

As a high-input crop, corn (*Zea mays*) requires substantial nutrients and is also susceptible to nutrient imbalance (Mullins et al., 1998; Kaiser et al., 2016; Aliyu et al., 2021). Imbalanced nutrient supply affects nutrient uptake, utilization, and overall corn productivity (Karlen et al., 1988; Aliyu et al., 2021). Plant tissue analysis is a valuable method to monitor the nutritional health of crops. It complements soil tests to provide insight into the nutrient levels of plants at the time of sampling for timely nutrient management decisions (Baldock and Schulte, 1996; de Souza et al., 2020). An appropriate and convenient interpretation of plant tissue analysis results is needed for tissue analysis to be helpful as a management tool. Several methods are available to interpret plant tissue analysis results, which can be grouped into two major categories: (a) independent nutrient indices and (b) dependent nutrient indices (Baldock and Schulte, 1996).

A classic example of the independent nutrient indices is the sufficiency range system (SRS), an extension of the critical level approach (CLA). The CLA provides a single value for

every relevant nutrient, set at 90% to 95% of the maximum growth or yield of a nutrient response model (Munson and Nelson, 1990; Campbell, 2000). The SRS offers a significant advantage over the CLA by setting lower and upper threshold values for relevant nutrients, which indicate the optimum nutrient concentration levels to obtain maximum growth or yield. As nutrient concentration in plant tissues changes over the growing season, different threshold values are typically set in SRSs for the various growth stages. A classic example of the dependent nutrient indices is the Diagnostic and Recommendation Integrated System (DRIS), which calculates the ratio of all possible pairs of relevant nutrients and compares the ratios to that of high-yielding crops (Beaufils, 1973; Sumner, 1977; Aliyu et al., 2021). Standard scores are computed for each nutrient and averaged to obtain one index per nutrient. The DRIS prioritizes the relationship among nutrients rather than absolute concentrations and ranks the nutrients in their order of limitedness. Baldock and Schulte, (1996) proposed the Plant Analysis with Standardized Scores system, which integrated both the SRS and DRIS.

The SRS is one of the most common interpretative methods used by farmers because of its convenience and ease of adoption (Campbell, 2000; Blessitt, 2020). The lower and upper threshold values for every nutrient in SRSs were mainly based on subjective interpretation of plant analyses and survey studies across multiple locations (Campbell, 2000; Blessitt, 2020), which can be confounded by several abiotic and biotic factors that impact crop growth and productivity (Djaman et al., 2013; Amissah et al., 2023b). For instance, the mineralization of nutrients and subsequent crop uptake can be affected by rainfall, temperature, type of crop residues, and soil properties, such as the pH, aeration, and the structure and composition of microbial communities (Whalen, 2014; Shahzad et al., 2018, 2019b; Grzyb et al., 2020; Sintim et al., 2022a; b). Thus, several reports

have surmised that established threshold values in SRSs are not all-inclusive and absolute (Baldock and Schulte, 1996; Mitchell and Baker, 1997; Aliyu et al., 2021), but that needs to be validated.

The Southern Cooperative Series Bulletin (SCSB) #394 is a popular and valuable output of a regional project that provides nutrient sufficiency ranges (NSRs) for plant analyses in the southern region of the United States (Campbell, 2000). The NSRs, like any other, have not been validated in controlled experiments. Therefore, the objective of this study was to validate the lower threshold of the NSRs for corn at the early growth stages. The NSRs for corn at the early growth stage as reported in the SCSB #394 are 30–40 g N kg⁻¹, 3–5 g P kg⁻¹, 20–30 g K kg⁻¹, 2.5–8 g Ca kg⁻¹, 1.5–6 g Mg kg⁻¹, 1.5–4 g S kg⁻¹, 30–250 mg Fe kg⁻¹, 20–150 mg Mn kg⁻¹, 20–70 mg Zn kg⁻¹, 5–25 mg Cu kg⁻¹, 5–25 mg B kg⁻¹, and 0.1–2 mg Mo kg⁻¹ (Campbell, 2000). The early growth stage for corn in SCSB #394 represents plants that are >10 cm in height to tasseling.

A controlled experiment is needed to validate the threshold values, and all relevant nutrients must be validated simultaneously, which is very complicated to accomplish. To date, no management system exists to have nutrients accumulate precisely at specific levels. As plant nutrient uptake is regulated by several factors (Morgan and Connolly, 2013; Woli et al., 2019), there is no guarantee that plant tissues sampled at a particular stage will have all the nutrients within the sufficiency ranges, regardless of the nutrient management regime. Based on the explicit meaning of the NSRs, we posit that plant samples with all nutrients within the sufficiency ranges should accumulate similar biomass under a controlled field experiment, where nutrient levels are the only variables. We note that it would be a wrong inference to use yield to validate the sufficiency ranges at the early growth stage because yield can be confounded by several variables

post-sampling at the early growth stage. Moreover, it would be practically impossible to maintain those nutrient levels until harvest.

Field experiments were set up in 2020, 2021, and 2022 to assess the lower threshold of the NSRs for corn at the early growth stage as reported in the SCSB #394. Corn plants were maintained at various nutritional levels by imposing different fertilizer application regimes (Table 2.1) which constituted the experimental treatments. Plant tissue analyses were performed, along with measuring plant biomass. If the NSRs reported in the SCSB #394 are valid, we expected samples with all nutrient levels within the NSRs to have ~100% relative biomass.

2.0. Results and Discussion

2.1. Weather and Initial Soil Nutrients

The average minimum, mean, and maximum temperatures, as well as the total growing degree days (GDD), solar radiation, and rainfall received from planting to tissue sampling each year are reported in Table 2.1. The weather was relatively warmer in 2021 compared to 2020 and 2022, as shown by the greater minimum, mean, and maximum air temperature and the total GDD and solar radiation. Whereas temperature and GDD were greater in 2020 than in 2022, solar radiation was greater in 2022. Total rainfall during the growing period in the three years varied considerably, with 2021 receiving the highest and 2022 receiving the least rainfall.

The initial nutrient concentration of the soil varied with depth over the three years (Table 2.3). In general, there was nutrient stratification with the primary and secondary nutrients being concentrated in the top 0–15 cm depth than in the 15–30 cm depth, except in 2022, where the reverse was observed in P. Stratification of micronutrients was not very conspicuous, except in 2021 where more than 2-fold of Cu concentration was observed in the 15–30 cm depth as compared

to that observed at the top 0–15 cm depth. For the primary nutrients, N and P were greatest in 2020, whereas 2022 had the highest K level at the top 0–15 cm depth, and 2021 had the greatest K level at the 15–30 cm depth. Mg was greatest at both depths in 2022. Ca was substantially low at both depths in 2021 and the 15–30 cm depth in 2020. S was greatest in 2021 and 2022 at 0–15 cm and 15–30 cm depths, respectively. For the micronutrients, B was the least in 2021, and Zn and Mn were the least in 2022. Fe and Cu were substantially high in 2022 and 2021, respectively.

2.2. Validation of Reference Sufficiency Thresholds

A scatter plot of relative biomass vs. biomass is provided in Figure 2.1. In Figure 2.1a, samples with all nutrient concentrations satisfying the lower threshold of the reference sufficiency range for corn at the early growth stage in the SCSB are denoted as ‘Yes’, and ‘No’ for samples with at least one nutrient below the lower threshold. Figure 2.1b shows only samples denoted as ‘Yes’ in Figure 2.1a and differentiates the replications. The biomass of tissue samples collected at the V6-V7 ranged from 106 kg ha⁻¹ to 418 kg ha⁻¹ in 2020, from 148 kg ha⁻¹ to 563 kg ha⁻¹ in 2021, and from 59.2 kg ha⁻¹ to 702 kg ha⁻¹ in 2022. In general, there was a good distribution of samples across the entire biomass range in all three years. All samples satisfied the lower threshold of the NSRs in 2020, and 29% and 35% of samples satisfied the lower threshold in 2021 and 2022, respectively.

Within every replication, we expected samples that satisfied all the lower thresholds of the NSRs to have similar relative biomass unless (a) the lower thresholds of the NSRs were not valid or (b) there was a toxic level of a nutrient that impaired growth. The sufficiency range indicates the optimum level to achieve maximum growth, and additional nutrient accumulation could result in toxicity levels where plant growth is impacted (Havlin et al., 2005; Memon et al.,

2005; Lieth and Oki, 2019). Samples that satisfied the lower threshold of the NSRs had wide variations in relative biomass. In 2020, the minimum vs. maximum relative biomass within replications 1, 2, 3, and 4 were 39.2% vs. 66.8%, 42.3% vs. 75.9%, 61.0% vs. 100%, and 25.4% vs. 73.5%, respectively. In 2021, the minimum vs. maximum relative biomass within replications 1, 2, 3, and 4 were 43.1% vs. 97.7%, 34.2% vs. 53.2%, 46.8% vs. 68.3%, and 34.3% vs. 53.3%, respectively. In 2022, the minimum vs. maximum relative biomass within replications 1, 2, 3, and 4 were 41.8% vs. 76.5%, 52.0% vs. 74.9%, 24.2% vs. 87.2%, and 68.9% vs. 100%, respectively.

To ascertain potential toxicity effects, we compared the nutrient concentrations of samples that satisfied all the lower thresholds of the NSRs and had the minimum relative biomass in every replication with those with greater relative biomass. Of the 12 total samples (one per replication over three years), three had at least one nutrient that was the greatest within the replication, suggesting potential toxicity effects: treatment T7 in replications 2 (N, B, and Zn) and 3 (B) in 2020, and treatment T4 in replication 3 (Zn, Mn, and Cu) in 2021. The remaining nine samples, however, suggest that the lower threshold may not be valid. Moreover, 12 samples had P or Cu levels that failed to meet the lower threshold but still had relative biomass $\geq 75\%$. In 2021, treatment T2 of replication 1 had a Cu level of 4.0 mg kg^{-1} , below the lower threshold of 5.0 mg kg^{-1} , but it had a relative biomass of 100%. In 2022, treatment T4 of replication 4 had a P level of 2.6 g kg^{-1} , below the lower threshold of 3.0 g kg^{-1} , but it had a relative biomass of 86.1%. Additionally, the P (2.9 g kg^{-1}) and Cu (4.0 mg kg^{-1}) levels of treatment T4 of replication 2 were below the lower threshold, but it still had a relative biomass of 85.2%. Treatments T5 and T11 had Cu levels as low as 2.0 mg kg^{-1} but had relative biomass of 80.6% and 78.1%, respectively. The findings of this study suggest that either the lower thresholds of Cu and P are smaller than

recommended or they were not the most limited. They further highlight the inability of the SRS to account for nutrient interactions and the magnitude of the limitation of each nutrient (Liebscher, 1895; Beaufils, 1973; Baldock and Schulte, 1996).

2.3. Nutrient Dynamics

Radar plots of the minimum, maximum, and mean relative nutrient concentrations of samples with 0–25%, 25–50%, 50–75%, and 75–100% relative biomass are shown in Figure 2.2. Samples with 75–100% relative biomass had the greatest minimum N, K, S, B, and Zn levels (Figure 2.2a), suggesting that higher basal levels of those nutrients are needed to sustain good plant growth (Kovács and Vyn, 2017; Bojtor et al., 2021b). The samples with 75–100% relative biomass, however, had low minimum Mg, Ca, Fe, and Cu levels (Figure 2.2a). In contrast, samples with 0–25% relative biomass had distinctively greatest minimum Ca, Fe, and Cu levels, whereas those with 25–50% relative biomass had distinctively greater minimum Mg levels. The maximum Mg, Ca, Fe, and Cu levels were, however, also high in samples with 50–75% and 75–100% relative biomass (Figure 2.2b), suggesting nutrient deficiency or imbalance rather than toxicity of those nutrients, could explain the poorer growth in samples with 0–25% and 25–50% relative biomass. The mean nutrient levels were high for samples with 75–100% relative biomass, except for Ca and Cu (Figure 2.2c). Samples with 0–25% relative biomass had the lowest mean nutrient levels, except for Cu where it had the greatest concentration.

Table 2.4 shows the summary statistics of the nutrients of samples with 95–100% relative biomass. Except for P and Cu, the minimum levels of the nutrients amongst samples with 95–100% relative biomass (Table 2.4) were greater when compared to the lower threshold of the NSRs for corn at the early growth stage in the SCSB. The maximum levels of N, P, K, S, B, and Mo of

samples with 95–100% relative biomass were greater than the upper threshold of the NSRs for corn at the early growth stage in the SCSB. However, the samples with 95–100% relative biomass had lower Ca, Zn, Mn, Fe, and Cu than the upper threshold.

Pioneer conducted on-farm corn tissue sampling research in the United States and Canada in 2018, 2019, and 2020 (Blessitt, 2020). The study used 550 on-farm trials with an average yield of 16.9 to 29.8 Mg ha⁻¹ to establish NSRs for corn at the V6-V8, VT-R1, and R3-R5 growth stages. The V6-V8 NSRs derived were 38.0–41.0 g N kg⁻¹, 3.3–3.8 g P kg⁻¹, 29.7–33.8 g K kg⁻¹, 2.0–2.6 g Mg kg⁻¹, 4.7–5.7 g Ca kg⁻¹, 2.4–2.8 g S kg⁻¹, 10.2–14.3 mg B kg⁻¹, 31.0–39.7 mg Zn kg⁻¹, 66.8–94.9 mg Mn kg⁻¹, 168–207 mg Fe kg⁻¹, and 11.0–15.5 mg Cu kg⁻¹ (Blessitt, 2020). The sufficiency ranges reported by Blessitt (2020) are within the minimum and maximum nutrient levels of samples with 95–100% relative biomass in this study, except for B, Fe, and Cu. The lower and upper thresholds of B reported by Blessitt (2020) were lower than the minimum level observed in samples with 95–100% relative biomass in this study, whereas the upper thresholds of Fe and Cu reported by Blessitt (2020) were greater when compared to the maximum levels observed in samples with 95–100% relative biomass.

The relative biomass had significant correlations with N, P, K, S, B, Zn, Mn, and Mo; however, the correlations were generally weak (Table 2.5 and Figure 2.3), indicating that an increased concentration of plant nutrients does not necessarily lead to improved plant growth (Lieth and Oki, 2019; Aliyu et al., 2021). The correlation of relative biomass between only N, K, and S yielded Pearson correlation coefficients ≥ 0.3 . No significant negative correlation was observed between relative biomass and nutrients. Kovács and Vyn (2017) reported significant positive correlations between corn ear-leaf nutrient levels and biomass sampled at the mid-silking

stage, except for B, which yielded a significant negative correlation with biomass. However, the correlation was weak, with a Pearson correlation coefficient of -0.128 (Kovács and Vyn, 2017).

More significant correlations of the plant nutrients were observed, consistent with the findings of other studies (Kovács and Vyn, 2017; Bojtor et al., 2021b). In general, N and Mn had the maximum number of significant correlations with other nutrients (Table 2.5). N and Mn had significant correlations with all nutrients except N vs. Fe and Mn vs. Mo correlations that were not significant. Cu had significant correlations with nine other nutrients, and P, K, S, B, and Zn had significant correlations with eight other nutrients. The strongest positive correlation was between S and Zn, with a Pearson correlation coefficient of 0.82. There was no significant correlation between nutrients with a negative Pearson correlation coefficient, consistent with the observations of Bojtor et al. (2021).

2.4. Treatment Effects on Biomass and Nutrient Concentration

The nutrient rates had significant effects on the biomass ($p = 0.027$ in 2020; $p = 0.01$ in 2021; and $p < 0.001$ in 2022), and, as expected, treatment T12 (no nutrient application) consistently had the least biomass over the three years (Figure 2.4). Treatments T1, T5, T9, and T11 were not assessed in 2020, and there was only one replication for treatment T12, which was excluded from the statistical analyses. In general, increasing rates of N, P_2O_5 , and K_2O (T1 to T4 vs. T5 to T8) did not significantly increase biomass. In 2022, treatment T3 biomass was significantly lower than that of treatment T4. Treatment T3 did not receive any secondary nutrients, but it had similar rates of primary and micronutrients as treatment T4, highlighting the importance of secondary nutrients in corn growth (Kihara et al., 2017; Garba et al., 2020; Wang et al., 2020). As already noted, treatment T10 received greater rates of all nutrients than treatments T4 and T8. However, it had

similar biomass as those of treatments T4 and T8, except in 2020 when it had significantly lower biomass than treatment T4, and the biomass of treatment T8 was intermediate. The results in 2020 could be attributable to toxicity effects; the nutrient application rates of treatment T10 in 2020 were generally greater than those in 2021 and 2022 (Table 2.1). Nonetheless, in 2020, there was no single nutrient in treatment T10, where the concentration was overly high compared to any sample (Table 2.6). The level of B in 2020 seemed to be high (66.3 mg kg^{-1}), but a similar value (66.2 mg kg^{-1}) was observed in 2022.

The different nutrient rates applied also significantly affected plant tissue nutrient levels, but the trend was not consistent (Table 2.6). The high nutrient rates applied in treatment T10 in 2020 led to significantly greater N levels than those in treatments T2 and T7; however, no significant differences in N levels were observed between treatments in 2021, except for treatment T12. In 2022, treatments that received all forms of nutrients (treatments T4, T8, and T10) tended to have increased N levels. Differences in P levels were marginal in 2021 but significant in 2020 and 2022. In addition, the differences in K levels were marginal in 2020 and 2021 but significant in 2022. The lack of response in P levels in 2021 and K levels in 2020 and 2021 was unexpected as the initial soil levels were not overly high in P and K. For instance, the P level in 2020 was higher than in 2021, and also the K level in 2022 was greater than in 2020 and 2021. Ca levels were not affected by the different nutrient rates in all three years, and the Mg levels were not affected by the different nutrient rates in 2021 and 2022. The Mg level was significantly reduced in treatment T10 compared to treatment T2 in 2020. The effect of nutrient application rates on S was observed in all three years, with the impact being more evident in 2022. The S level was highest in treatment T8 and least in treatment T12. Significant differences in the micronutrient

levels due to the nutrient application rates were observed, except for Mn and Fe in 2020 and 2021. In general, the micronutrients accumulated more in treatments that received micronutrient application.

The marginal responses in corn biomass and nutrient levels to increased nutrient application rates could be attributed to low nutrient demand for corn at the early growth stage. It is estimated that <15% of nutrients are typically taken up by the V6 to V7 growth stage compared to the total nutrients taken up at physiological maturity (Bender et al., 2013; Ciampitti et al., 2013; Ciampitti and Vyn, 2013). These findings suggest the potential to synchronize nutrient applications with plant demand, maximizing corn's productivity and nutrient use efficiency (Roberts, 2007; Bender et al., 2013; Stewart et al., 2021).

3.0. Practical Implications

Figure 2.5 shows corn plants in treatments T2 and T9 exhibiting healthy and stunted growth, respectively. The healthy and stunted crops had all the nutrient levels satisfying the lower threshold of the SCSB's NSRs for corn at the early growth stage. Without the healthy plants, a grower would think there was nothing wrong with the stunted crops, given that the foliage was still green. More importantly, the NSRs of the SCSB would have also been unable to detect issues with the crop, given that the levels of all the nutrients satisfied the NSRs. Further studies to ascertain whether corn can fully recover from early season nutrient stress would help inform nutrient management decisions.

4.0. Materials and Methods

4.1. Experimental Site

The study was conducted at the University of Georgia Coastal Plains Experiment Station in Tifton, GA (31°31'06.5" N, 83°32'59.6" W). Tifton has a humid subtropical climate characterized by relatively high temperatures and evenly distributed precipitation. The annual average daily minimum, mean, and maximum air temperatures are 12.7, 19.0, and 25.2 °C, respectively, and the average annual precipitation is 1208 mm with an average of 109 rainy days (Georgia AEMN, 2023). The experimental field had a soil classified as Dothan sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) The soil had sand, silt, and clay content of 91.9%, 4.5%, and 3.6% at the top 0–15 cm depth, respectively, and 87.9%, 4.5%, and 7.6% at the 15–30 cm depth, respectively. Further, the soil pH and organic matter were 6.4 and 4.8 g kg⁻¹ at the top 0–15 cm depth, respectively, and 6.5 and 4.4 g kg⁻¹ at the 15–30 cm depth, respectively.

4.2. Field Experiment

Field experiments in 2020, 2021, and 2022 evaluated early-season corn growth impacted by various nutritional levels. The nutritional levels were induced by different nutrient application rates, which constituted the treatments (Table 2.1). Twelve treatments were assessed in 2021 and 2022, and eight treatments in 2020. Every year, Treatments T1 to T4 had similar N, P, and K (referred hereafter as primary nutrients) application rates, except that T2 received additional Mg, Ca, and S (referred hereafter as secondary nutrients), and T3 received additional B, Zn, Mn, Fe, Cu, and Mo (referred hereafter as micronutrients). Treatment T4 received both secondary and micronutrients. Treatments T5 to T8 received similar N, P, and K rates, but the rates were greater than those in treatments T1 to T4. Additionally, treatment T1 corresponded to T5, T2 to T6, T3 to

T7, and T4 to T8 regarding secondary and micronutrient application rates. Treatment T10 received primary, secondary, and micronutrients at greater rates than T8, whereas treatment T12 was a control, receiving no nutrient application. Treatments T9 and T11 were not assessed in 2020 but varied in 2021 and 2022. Treatment T9 received all primary, secondary, and micronutrients in 2021 and only N and P in 2022. Treatment T11 received N, P, K, and S in 2021 and N, P, K, S, and Zn in 2022. Different nutrient rates were used yearly based on initial nutrient levels, previous crops, and observations of the results from preceding years. Fertilizers as the primary sources of the different nutrients are listed in Table 2.7.

The treatments were laid out in a randomized complete block design with four replications, except for treatment T12 in 2020, which had only one replication embedded in the fourth replication. Each experimental plot was 9.1 m long and 5.5 m wide. Different research fields at the experimental site were used yearly; thus, treatment effects over the three years were not additive. The previous crop for the years 2020 and 2022 was peanut (*Arachis hypogaea*) and for the year 2021, it was cotton (*Gossypium hirsutum*). The field was prepared by harrowing, running a field cultivator, and making 20 cm deep furrows that were 91.4 cm apart. Pioneer hybrid P1870R was used every year, and it was planted at 88,958 seeds ha⁻¹ on 7 April, 12 April, and 25 March in 2020, 2021, and 2022, respectively. Glyphosate [N-(phosphonomethyl) glycine], Atrazine (2-chloro-4-ethyl amino-6-isopropyl amino-s -triazine), and Prowl [N-(1-ethyl propyl)-3,4-dimethyl-2,6-dinitrobenzenamine] were applied at manufacturer recommended rates to control weeds in the corn plots between the V3 and V4 growth stage. The plots were provided with supplemental water through overhead irrigation whenever the soil moisture reached 50% of the water-holding capacity of the soil.

4.3. Data Collection

Soil samples were collected from 0–15 cm and 15–30 cm depths before any field operations each year to determine the initial soil nutrient levels. The soil samples were air-dried, sieved through a 2-mm sieve, and then shipped to the Waters Agricultural Laboratories, Inc. in Camilla, GA, USA, for analyses. Nitrate-N was measured with the automated flow injection analysis system (FIAlyzer-1000, FIALab Instruments, Inc., Seattle, WA, USA) based on extraction in a 2 M KCl solution. Extractable P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu were measured with an inductively coupled plasma optical emission spectrophotometer (ICP-OES; iCAP™ 6000 Series, Thermo Fisher Scientific, Cambridge, UK) after extraction in Mehlich I solution.

Plant tissue samples were collected within a uniform 1-m long strip of every plot by the six- to seven-leaf collar stage (V6 to V7 growth stage) and sent directly to Waters Agricultural Laboratories, Inc. in Camilla, GA, for plant nutrient analyses. Plant samples at the V6-V7 growth stage were used because side-dress and other in-season nutrient applications are made around that stage or shortly after. Growers under non-irrigated conditions, or those who cannot inject fertilizers through their irrigation unit, cannot practically make nutrient applications after the V9-V10 stage. Thus, growers need to account for the time it will take to have the laboratory results and the time to plan and apply nutrients as needed.

For the nutrient analyses, plant samples were oven-dried to constant weight, pulverized, and sifted to <1 mm particle size. Total N was measured by dry combustion with LECO FP-528 Nitrogen Analyzer (LECO Corporation, St. Joseph, MI, USA). Total P, K, Ca, Mg, S, Fe, Mn, Zn, B, Cu, and Mo were measured with ICP-OES (iCAP™ 6000 Series, Thermo Fisher Scientific,

Cambridge, UK) after digestion with DigiBLOC 3000 digestion system (SCP Science, Montreal, QC, Canada) with HNO₃/H₂O₂ mixture.

Plant biomass was also determined for every plot by sampling aboveground plant samples within a uniform 1-m long strip of every plot at the same time that the plant tissue samples for nutrient analyses were collected. Weights of the aboveground plant samples were recorded after oven-drying at 78 °C to constant weight, and the values were used to compute plant biomass. In addition, relative biomass was calculated by dividing the biomass of every plot by the maximum biomass value obtained every year.

4.4. Statistical Analyses

The measured plant biomass and nutrient concentration data were analyzed with the linear mixed model using the ‘lme4’ package in R (Bates et al., 2015). As the number of treatments and nutrient rates varied over the three years, separate analyses were performed for each year. Assumptions of normality of residuals and homoscedasticity were assessed, and data transformation was performed with the Box-Cox transformation or square root transformation methods as appropriate. Means generated from the analysis were separated using the least square means and the adjusted Tukey multiple comparison procedure with the ‘emmeans’ package in R (Lenth et al., 2018). Correlation matrices were computed for the biomass and nutrient concentrations using the ‘agricolae’ package in R (Mendiburu, 2021). The significance level for all analyses was assessed at $p = 0.05$.

5.0. Conclusions

The nutrient sufficiency ranges (NSRs) for corn at the early growth stage in the SCSB were not valid under the conditions tested in this study. Of the total samples, 47.6% satisfied all the lower thresholds of the NSRs. A 25.4% of samples had relative biomass <50%, with relative biomass even as low as 24.2% recorded in 2022. The poor growth of some samples could not be attributed to nutrient toxicity because no nutrient level was excessive. Moreover, 9.6% of the total samples had P or Cu that failed to meet the lower threshold but still had relative biomass $\geq 75\%$, suggesting either the lower thresholds of P and Cu are smaller than recommended or they were not the most limited. The findings of the study highlight the inability of the NSRs of the SCSB to account for nutrient interactions and the magnitude of the limitations of every nutrient at the V6 to V7 stage.

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Tables

Table 2.1. Nutrient application rates imposed in 2020, 2021, and 2022.

Year	Treatments	Nutrient Rates Applied (kg ha ⁻¹)											
		N	P ₂ O ₅	K ₂ O	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
2020	T2	121	110	112	11.2	11.2	11.2	0	0	0	0	0	0
	T3	121	110	112	0.0	0.0	0.0	0.56	2.24	3.36	2.24	0.56	0.28
	T4	121	110	112	11.2	11.2	11.2	0.56	2.24	3.36	2.24	0.56	0.28
	T6	242	197	224	11.2	11.2	11.2	0	0	0	0	0	0
	T7	242	197	224	0	0	0	0.56	2.24	3.36	2.24	0.56	0.28
	T8	242	197	224	11.2	11.2	11.2	0.56	2.24	3.36	2.24	0.56	0.28
	T10	363	330	280	16.8	16.8	16.8	1.12	3.36	6.73	4.48	1.12	0.56
	T12	0	0	0	0	0	0	0	0	0	0	0	0
2021	T1	135	101	101	0	0	0	0	0	0	0	0	0
	T2	135	101	101	5.60	11.2	5.60	0	0	0	0	0	0
	T3	135	101	101	0	0	0	0.56	1.12	3.36	2.24	0.28	0.28
	T4	135	101	101	5.60	11.2	5.60	0.56	1.12	3.36	2.24	0.28	0.28
	T5	247	168	191	0	0	0	0	0	0	0	0	0
	T6	247	168	191	5.60	11.2	5.60	0	0	0	0	0	0
	T7	247	168	191	0.00	0.0	0.00	0.56	1.12	3.36	2.24	0.28	0.28
	T8	247	168	191	5.60	11.2	5.60	0.56	1.12	3.36	2.24	0.28	0.28
	T9	146	168	168	5.60	5.6	5.60	0.56	1.12	3.36	2.24	0.28	0.28
	T10	269	202	202	11.2	11.2	16.8	1.12	2.24	6.73	4.48	0.56	0.56
	T11	224	213	269	0	0	11.2	0	0	0	0	0	0
	T12	0	0	0	0	0	0	0	0	0	0	0	0
2022	T1	179	157	146	0	0	0	0	0	0	0	0	0
	T2	179	157	146	5.60	5.60	11.2	0	0	0	0	0	0
	T3	179	157	146	0	0	0	0.56	3.36	5.60	2.24	0.56	0.28
	T4	179	157	146	5.60	5.60	11.2	0.56	3.36	5.60	2.24	0.56	0.28
	T5	291	224	235	0	0	0	0	0	0	0	0	0
	T6	291	224	235	5.60	5.60	11.2	0	0	0	0	0	0
	T7	291	224	235	0	0	0	0.56	3.36	5.60	2.24	0.56	0.28
	T8	291	224	235	5.60	5.60	11.2	0.56	3.36	5.60	2.24	0.56	0.28
	T9	54	49	0	0	0	0	0	0	0	0	0	0
	T10	359	314	291	11.2	11.2	16.8	1.12	5.04	8.41	3.36	1.12	0.56
	T11	202	224	258	0	0	11.2	0	3.36	0	0	0	0
	T12	0	0	0	0	0	0	0	0	0	0	0	0

Table 2.2. Average minimum, mean, and maximum temperatures, total growing degree days (GDD), solar radiation, and rainfall received from planting to tissue sampling in 2020, 2021, and 2022.

Year	Minimum Temperature	Mean Temperature	Maximum Temperature	GDD	Solar Radiation	Rainfall
	°C				MJ m ⁻²	mm
2020	13.6	19.8	26.0	304	668	144
2021	14.0	20.1	26.3	374	796	190
2022	12.0	18.6	25.1	291	716	84.0

GDD: Growing degree days calculated with a base temperature of 10 °C.

Table 2.3. Initial nutrient status of the experimental field soil at 0–15 cm and 15–30 cm depths in 2020, 2021, and 2022.

Year	Soil Depth cm	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
		kg ha ⁻¹										
2020	0–15	20.1	58.3	90.8	101	881	7.85	0.41	3.25	8.22	12.0	0.49
	15–30	13.3	38.1	74.7	63.9	582	15.3	0.30	3.18	7.47	13.8	0.49
2021	0–15	5.12	30.3	119	77.3	644	42.0	0.22	3.59	8.97	16.8	1.12
	15–30	3.82	24.7	103	71.7	600	15.1	0.22	3.64	6.16	15.7	2.63
2022	0–15	9.53	15.3	134	161	1076	12.3	0.37	2.09	7.10	28.8	0.26
	15–30	6.70	22.8	82.2	148	986	23.5	0.34	2.76	5.60	30.6	0.26

N was measured as Nitrate-N after extraction with 2 M KCl solution. Soil P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu were measured after Mehlich I extraction.

Table 2.4. Summary statistics of the nutrients of samples with 95–100% relative biomass.

Statistics	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
	g kg ⁻¹						mg kg ⁻¹					
Min	34.4	3.00	28.5	1.60	3.90	2.80	16.0	26.0	44.0	149	4.00	0.69
Mean	40.7	4.40	37.8	2.02	5.22	3.26	22.2	34.2	61.4	165	6.60	9.5
Max	48.4	6.20	50.6	2.60	6.60	4.30	40.0	45.0	99.0	182	10.0	29.0
SD	5.45	1.15	8.0	0.34	0.97	0.60	10.3	6.91	23.1	12.5	2.41	11.2

Min: Minimum; Max: Maximum; SD: Standard deviation.

Table 2.5. *p*-values after Pearson correlation of the relative biomass (RB) and nutrient concentrations.

	RB	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
RB	1												
N	<0.001	1											
P	0.004	<0.001	1										
K	0.001	0.021	<0.001	1									
Mg	0.694	<0.001	0.159	0.602	1								
Ca	0.464	<0.001	0.989	0.158	<0.001	1							
S	<0.001	<0.001	<0.001	<0.001	0.059	0.082	1						
B	0.045	<0.001	<0.001	0.005	0.79	0.319	<0.001	1					
Zn	0.003	<0.001	<0.001	<0.001	0.483	0.698	<0.001	<0.001	1				
Mn	0.02	<0.001	<0.001	<0.001	0.018	0.018	<0.001	0.01	<0.001	1			
Fe	0.505	0.052	0.879	0.089	<0.001	<0.001	0.755	0.098	0.3	<0.001	1		
Cu	0.103	<0.001	<0.001	<0.001	0.012	0.178	<0.001	<0.001	<0.001	<0.001	0.255	1	
Mo	0.006	<0.001	<0.001	0.002	0.100	0.236	0.006	<0.001	<0.001	0.201	0.901	<0.001	1

Table 2.6. Nutrient treatment effects on nutrient concentration of corn samples collected at the V6-V7 stage from 2020 to 2022.

Treatment	N	P	g kg ⁻¹				mg kg ⁻¹					
			K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
2020												
T2	46.0 a	5.47 a	49.17 a	2.97 b	7.57 a	4.33 b	17.7 a	39.7 a	108.0 a	207.0 a	9.33 a	3.5 c
T3	48.4 ab	6.50 ab	47.17 a	2.67 ab	6.53 a	3.50 a	34.3 ab	41.3 a	95.0 a	186.0 a	11.67 ab	64.1 a
T4	46.2 a	5.87 a	48.57 a	2.57 ab	6.37 a	4.00 ab	45.0 bc	43.7 a	280.3 a	261.3 a	14.00 ab	15.8 b
T6	49.7 ab	6.73 ab	49.20 a	2.83 ab	6.87 a	4.37 b	19.3 a	39.3 a	118.3 a	209.7 a	10.33 ab	1.0 c
T7	49.1 ab	7.60 b	48.63 a	2.30 a	6.17 a	3.63 a	42.7 bc	43.7 a	116.7 a	236.7 a	15.00 b	79.0 a
T8	49.7 ab	6.07 ab	50.03 a	2.67 ab	6.90 a	4.40 b	57.0 bc	56.7 b	139.0 a	206.0 a	21.67 c	26.9 ab
T10	52.7 b	5.37 a	43.83 a	2.30 a	5.80 a	4.07 ab	66.3 c	49.0 ab	123.7 a	185.0 a	15.00 b	13.3 b
T12 *	38.3	5.50	41.7	2.400	7.400	2.9	20.0	32.0	84.0	161	9.00	3.27
<i>p</i> -value	0.001	0.003	0.132	0.007	0.132	<0.001	<0.001	0.001	0.281	0.766	<0.001	<0.001
2021												
T1	37.5 ab	3.52 a	33.50 a	1.95 a	6.20 a	2.80 ab	18.2 ab	30.0 a	56.0 a	181.8 a	4.25 ab	1.4 cd
T2	37.9 ab	3.48 a	33.35 a	1.95 a	5.42 a	2.80 ab	21.0 ab	30.5 a	47.8 a	165.8 a	4.00 ab	1.4 d
T3	37.2 ab	3.65 a	35.38 a	1.80 a	4.78 a	2.85 ab	23.2 ab	31.2 a	50.2 a	154.2 a	4.50 ab	5.6 ab
T4	35.6 ab	3.45 a	33.27 a	2.00 a	5.85 a	2.85 ab	24.2 ab	35.8 a	55.8 a	183.0 a	6.50 b	4.0 ab
T5	37.7 ab	3.50 a	33.77 a	1.90 a	5.70 a	2.75 ab	18.2 ab	29.0 a	46.0 a	166.8 a	4.50 ab	2.3 bcd
T6	37.4 ab	3.25 a	36.00 a	1.92 a	5.40 a	2.83 ab	18.8 ab	29.0 a	43.2 a	164.8 a	3.25 a	1.3 d
T7	37.5 ab	3.62 a	33.73 a	1.85 a	5.62 a	2.70 ab	29.2 a	30.2 a	53.8 a	162.8 a	4.25 ab	8.7 a
T8	37.2 ab	3.03 a	33.20 a	1.90 a	5.53 a	2.67 ab	23.2 ab	28.2 a	47.8 a	177.8 a	4.25 ab	2.8 abcd
T9	37.7 ab	3.28 a	33.80 a	2.02 a	6.42 a	3.02 b	27.0 a	33.8 a	56.2 a	183.2 a	5.25 ab	4.1 ab
T10	38.2 b	3.80 a	33.93 a	1.90 a	5.62 a	2.88 ab	25.5 a	31.2 a	53.0 a	176.2 a	4.50 ab	3.5 abc
T11	37.9 ab	3.65 a	32.73 a	1.95 a	5.95 a	2.72 ab	16.8 b	24.8 a	44.2 a	172.0 a	3.50 a	1.9 bcd
T12	32.1 a	3.25 a	31.48 a	2.10 a	6.58 a	2.53 a	23.0 ab	24.8 a	50.0 a	171.2 a	4.00 ab	2.1 bcd
<i>p</i> -value	0.046	0.658	0.112	0.318	0.068	0.052	0.001	0.017	0.321	0.4	0.012	<0.001
2022												
T1	42.3 ab	3.03 bc	35.93 cd	2.87 a	6.80 a	2.37 a	16.0 ab	24.3 abc	68.3 a	266.7 c	2.33 a	5.5 a
T2	42.4 ab	2.98 b	37.53 d	2.62 a	6.68 a	2.55 ab	27.2 ab	23.5 abc	60.5 a	259.8 bc	4.75 abc	11.5 ab
T3	43.9 bc	2.98 b	39.08 d	2.67 a	6.78 a	2.45 a	21.2 ab	23.2 abc	62.8 a	225.8 abc	4.25 abc	15.7 abc
T4	51.0 d	3.38 bcd	25.68 b	3.22 a	7.65 a	3.00 bcd	36.0 abc	27.5 bc	60.0 a	171.2 a	8.00 c	42.3 c
T5	42.8 abc	3.25 bcd	37.05 d	2.90 a	6.68 a	2.43 a	10.5 ab	21.0 ab	60.2 a	282.8 c	3.25 ab	4.8 a
T6	41.9 ab	2.90 b	36.92 d	2.70 a	6.75 a	2.60 ab	18.2 ab	22.2 ab	60.2 a	290.2 c	5.50 abc	7.4 ab
T7	42.1 ab	3.05 bc	37.83 d	2.85 a	6.58 a	2.38 a	20.2 ab	22.0 ab	56.0 a	258.8 bc	5.00 abc	19.1 abc
T8	54.6 d	3.88 cd	27.42 bc	2.25 a	7.22 a	3.25 d	39.0 bc	35.2 c	81.2 a	178.5 ab	7.25 bc	32.9 bc
T9	43.8 bc	3.60 bcd	14.28 a	2.83 a	8.03 a	2.72 abc	3.5 a	25.0 abc	97.2 a	246.0 abc	5.75 abc	1.5 a
T10	51.0 d	4.00 d	26.92 b	2.65 a	6.43 a	3.20 cd	66.2 c	31.8 bc	71.0 a	162.8 a	7.75 bc	27.9 abc
T11	49.3 cd	4.00 d	30.95 bcd	2.53 a	8.07 a	3.10 cd	5.0 a	27.5 bc	70.2 a	206.0 abc	4.25 abc	1.8 a
T12	36.8 a	1.82 a	27.10 bc	2.55 a	6.68 a	2.28 a	4.2 a	15.5 a	21.5 b	206.5 abc	6.00 abc	3.8 a
<i>p</i> -value	<0.001	<0.001	<0.001	0.395	0.010	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001

Within a study year, means not sharing any letter are significantly different using the least squares means

and adjusted Tukey multiple comparisons ($p < 0.05$). * Only one replication, and so it was excluded from

the statistical analyses

Table 2.7. Fertilizers used as the primary sources of the different nutrient elements.

N	Urea; Ammonium nitrate; Urea ammonium nitrate solution (UAN 32)
P	Di-ammonium phosphate; triple super phosphate; Ammonium polyphosphate solution
K	Potassium chloride; Potassium nitrate
Mg	Magnesium oxy-sulfate; Magnesium nitrate solution
Ca	Calcium chloride; Calcium sulfate; Calcium nitrate solution
S	Potassium sulfate; Epsom; Ammonium thiosulfate solution
B	Fertilizer borate; Borosol [®] 10 solution
Zn	Zinc oxysulfate; Zinc nitrate solution
Mn	Manganese sucrate; Manganese nitrate solution
Fe	Iron sucrate; chelated iron ethylenediaminetetraacetic acid; Iron nitrate solution
Cu	Copper sulfate; Copper nitrate solution
Mo	Sodium molybdate

Total nutrient rates applied accounted for the nutrient sources in other fertilizers as applicable.

Figures

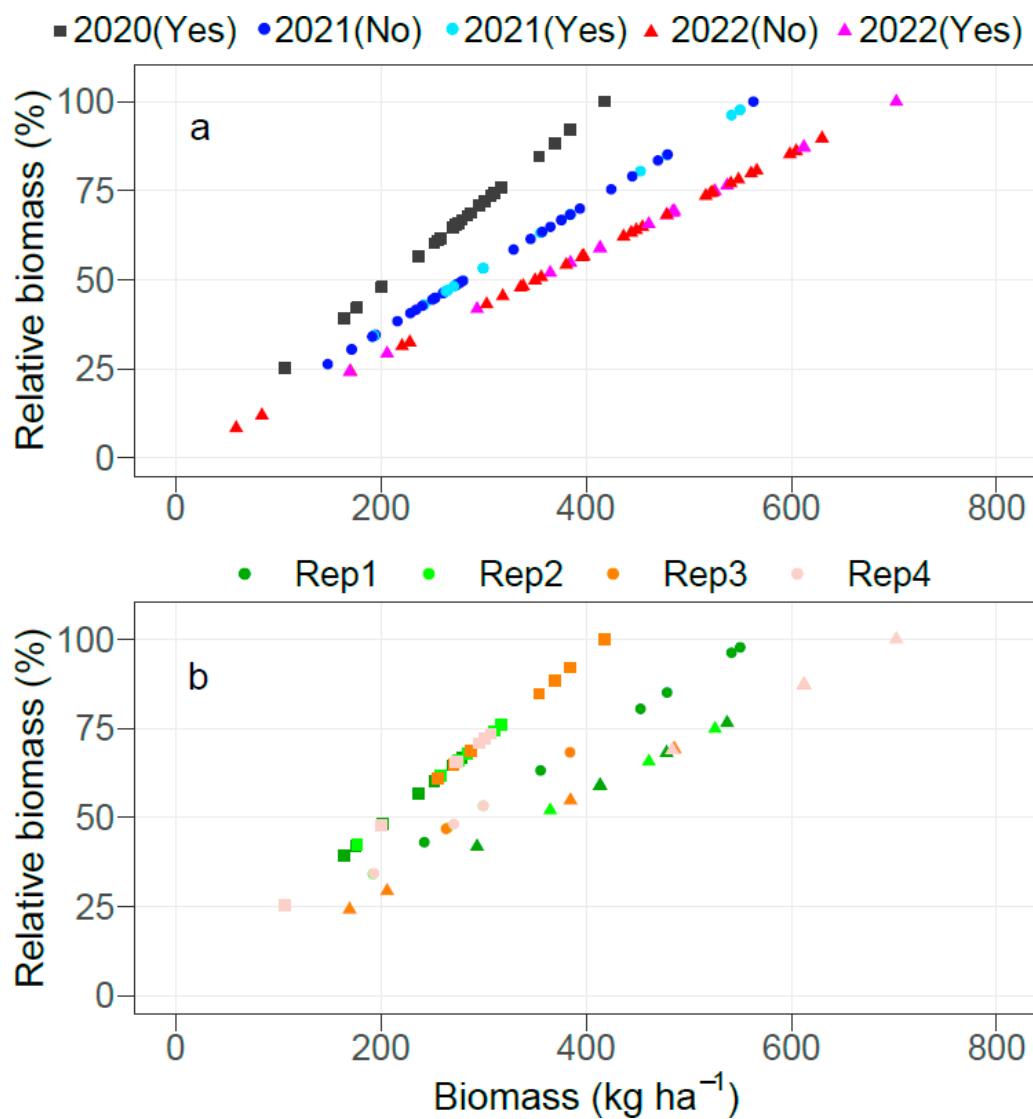


Figure 2.1. Scatter plot of relative biomass vs. biomass of corn sampled at the V6-V7 growth stage in 2020, 2021, and 2022. In (a), “Yes” refers to samples with all nutrient concentrations satisfying the lower thresholds of the reference sufficiency ranges for corn at the early growth stage in the Southern Cooperative Series Bulletin #394, whereas “No” refers to samples with at least one nutrient below the lower threshold; (b) shows only samples denoted as ‘Yes’ in (a), and the shapes in (b) denote the different years as noted for (a).

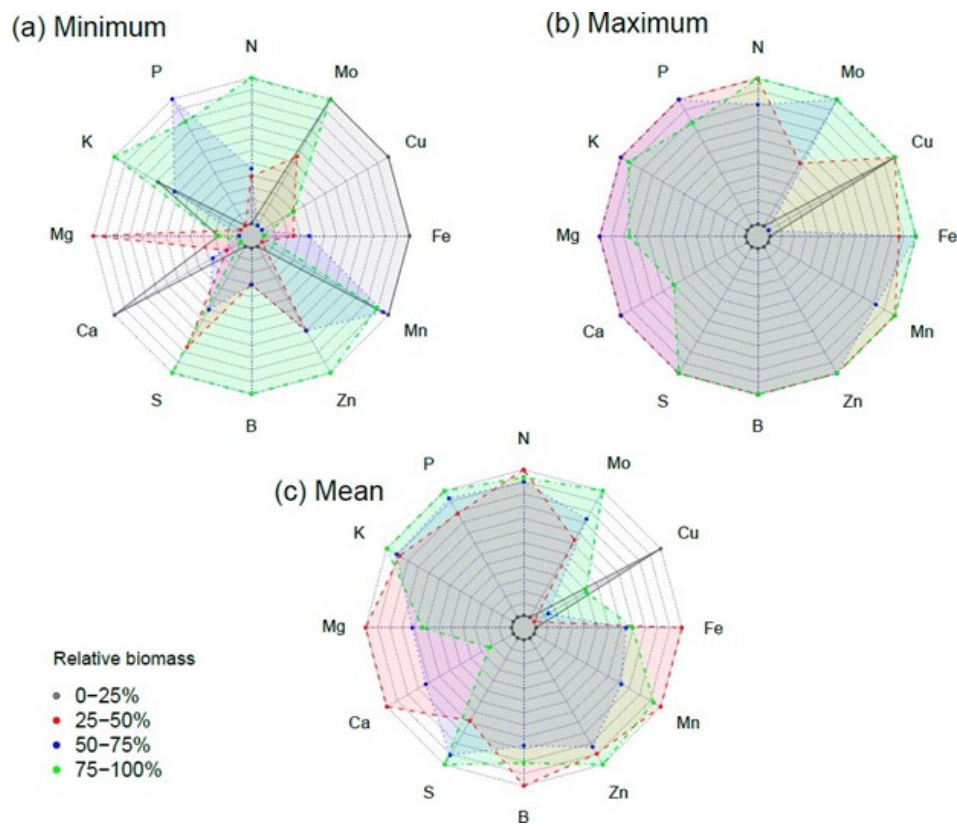


Figure 2.2. Radar plots of the minimum, maximum, and mean relative nutrient concentrations of corn samples with 0–25%, 25–50%, 50–75%, and 75–100% relative biomass for samples collected at the V6-V7 stage.

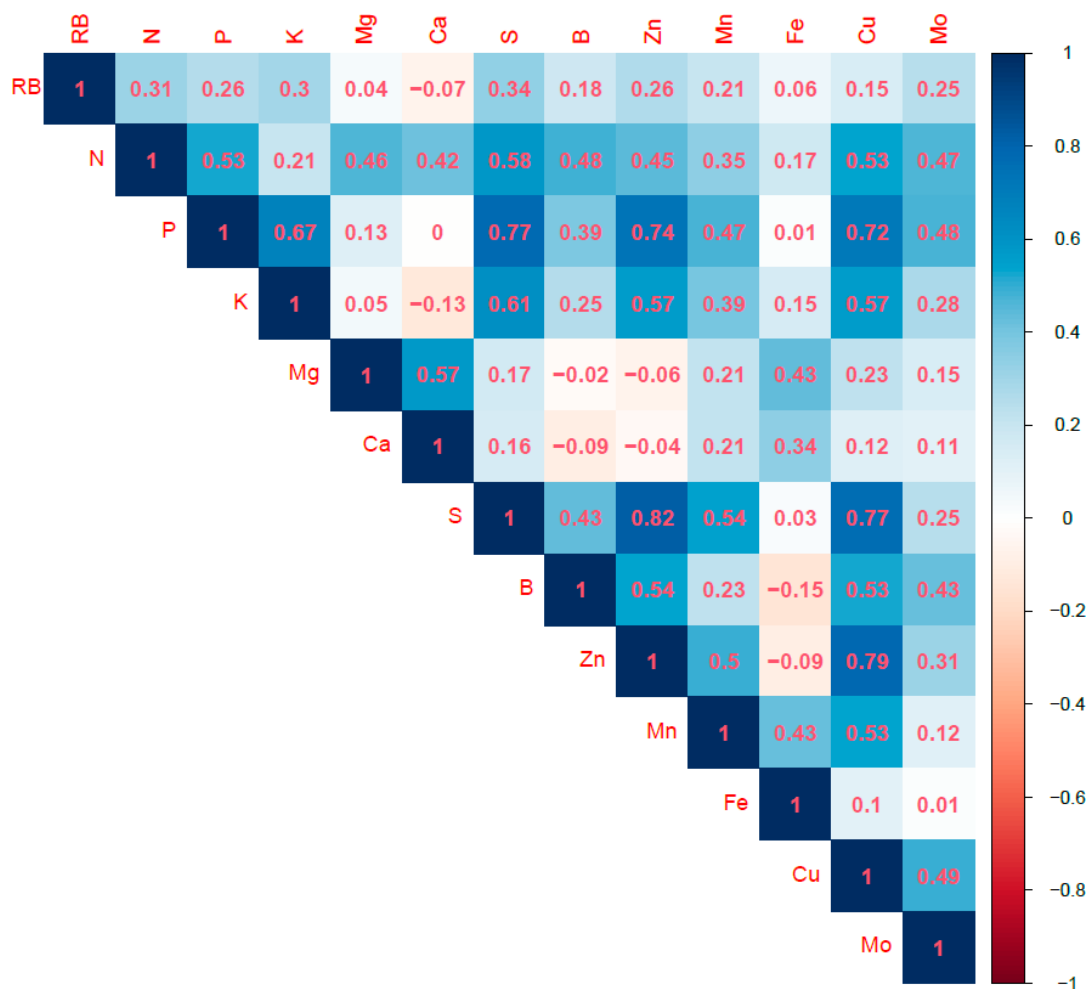


Figure 2.3. Pearson correlation coefficients of relative biomass (RB) and nutrient concentrations in corn samples collected at the V6-V7 stage.

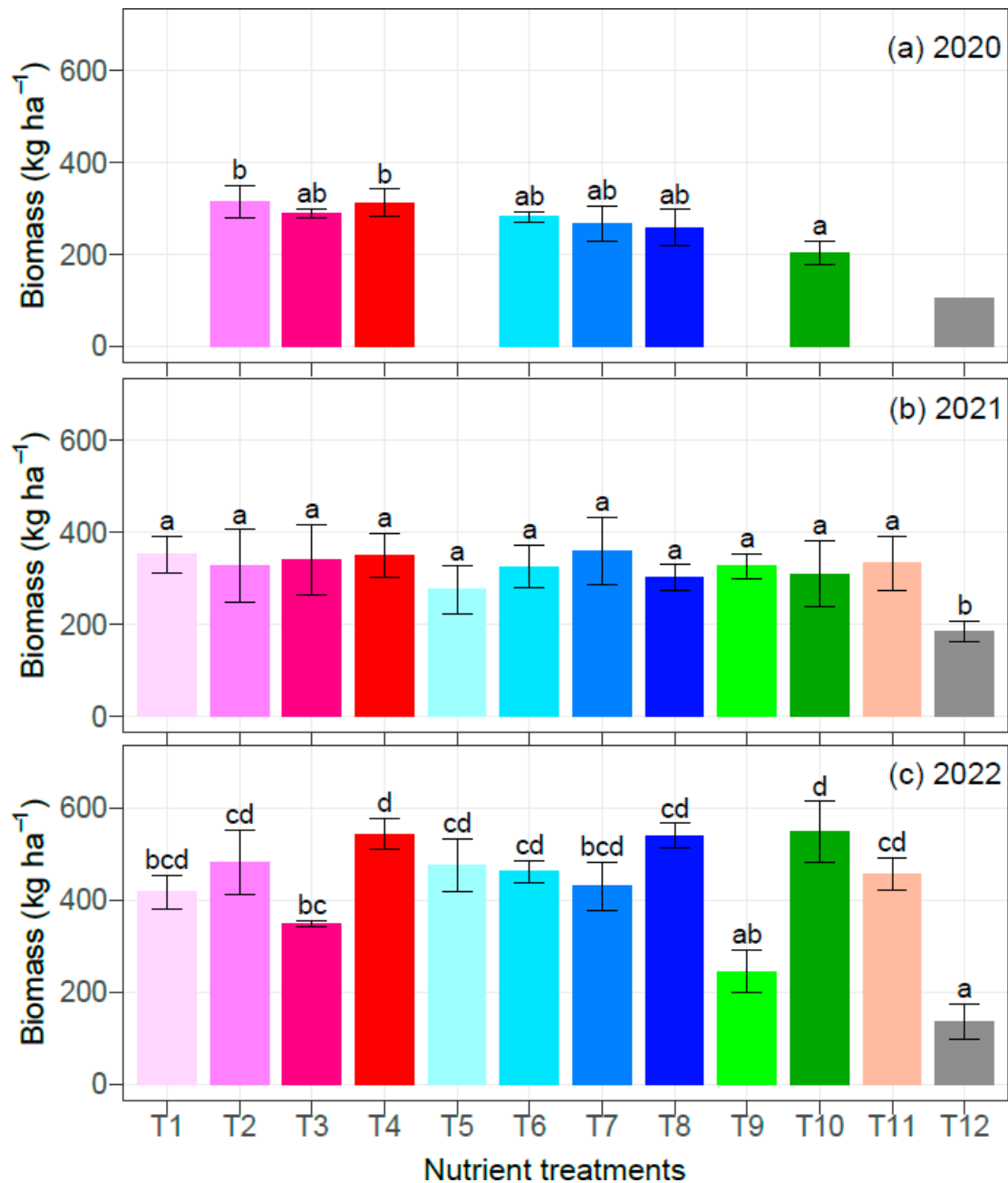


Figure 2.4. Nutrient treatment effects on biomass of corn collected at the V6-V7 stage from 2020 to 2022. Within a study year, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($p < 0.05$). Treatment T12 in 2020 had one replication, so it was excluded from the statistical analyses. Error bars indicate the standard deviation of the mean ($n = 4$).



Figure 2.5. Photo of the experimental field in 2022 showing corn plants in treatments T2 (healthy crops) and T9 (stunted crops). The stunted and healthy crops had all nutrient levels that satisfied the lower threshold of the nutrient sufficiency ranges for corn at the early growth stage reported in the Southern Cooperative Series Bulletin #394.

CHAPTER 3

SECONDARY AND MICRONUTRIENT APPLICATION EFFECTS ON CORN FERTILIZED FOR DIFFERENT YIELD GOALS UNDER HIGHLY-WEATHERED SOIL CONDITIONS

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Agronomy Journal.

Abstracts

Highly-weathered soils have low native fertility; thus, optimum nutrient management is critical, especially for a high-input crop such as corn (*Zea mays*). Field studies were established in Plains and Tifton, GA in the United States to assess secondary nutrient (SN; Mg, Ca, and S) and micronutrient (MN; B, Zn, Mn, Fe, Cu, and Mo) application effects on corn fertilized with primary nutrients (PN; N, P, and K) to achieve 12.5 Mg ha⁻¹ (low) and 25.1 Mg ha⁻¹ (high) yields. Both Plains and Tifton have Ultisol soil order, but whereas the Tifton soil has ≈ 30 cm of top sandy layer, the Plains soil has no top sandy layer. Differences in corn nutrient levels were observed at the V5-V7 stage but did not affect biomass accumulation. The 12.5 Mg ha⁻¹ target grain yield of the low PN rate was exceeded at both locations (by 19.0-26.6% in Plains and 6.3-19.7% in Tifton), irrespective of the SN or MN application. However, the 25.1 Mg ha⁻¹ target grain yield of the high PN rate was not achieved, with yields of 16.9-17.7 Mg ha⁻¹ in Plains and 15.7-17.1 Mg ha⁻¹ in Tifton obtained. The SN and MN applications improved corn yield under low and high PN rates. Overall, the results showed that SN and MN may be yield-limiting factors of corn in highly weathered soils, and also, low corn yield (≤ 12.5 Mg ha⁻¹) can be achieved with lower PN rates than currently recommended.

1.0. Introduction

Highly-weathered soils, such as Oxisols and Ultisols, are the predominant soils in tropical and subtropical regions (Juo S R and Franzluebbbers, 2003; Chesworth et al., 2008; Weil and Brady, 2017; Nunes et al., 2019). These soils have strong acidity, low clay activity, and poor native fertility. They are considered degraded soils because intense weathering of primary minerals has occurred, and abundant and well-distributed rainfall conditions have leached essential base cations. Moreover, warm temperatures and intensive rainfall conditions lead to the rapid mineralization of soil organic matter and residues returned to the soil. In the United States, Oxisols occupy approximately 0.02% of the land area and are restricted to Hawaii (USDA-NRCS, 1999). Ultisols, on the other hand, cover a much larger land area of the United States (9.2%) and are dominant in the southeastern United States (USDA-NRCS, 1999).

The state of Georgia (USA), where this study was conducted, has a sub-tropical climate characterized by hot and humid summers and cool to mild winters (Labosier et al., 2013; MacHmuller et al., 2015). Ultisols are the predominant soil order, and they have clay-enriched subsoil with a base saturation of less than 35% (Adams et al., 2019). In some areas of the state, the sandy topsoil layer has been eroded, causing the soils to have indistinct horizons (Coleman, 2007; Truman et al., 2010). The primary clay mineralogy is kaolinite, which is dominated by oxides of iron and aluminum (Soil Survey Staff; Truman et al., 2010; MacHmuller et al., 2015; Pincus et al., 2017). Sandy soils, abundant in quartz and kaolinite, have low cation exchange capacity (CEC) depending on the mineral present, with quartz having negligible to no CEC and that of kaolinite being $<16 \text{ cmol}_c \text{ kg}^{-1}$ (Sharma et al., 2015; Pincus et al., 2017; Weil and Brady, 2017; Kumari and Mohan, 2021). Ultisols have a characteristic low pH which can potentially limit the bioavailability

of plant nutrient elements like P (Goulding, 2016; Ratke et al., 2018). Liming and nutrient application are essential to sustaining crop productivity, especially for a high-input crop such as corn (*Zea mays*) (Chowdhury et al., 2021; Amissah et al., 2023a).

Nutrient management for corn in some areas of the United States is based on yield goals, and recommendations for higher yields are based on increasing only the primary nutrient (PN; N, P, and K) rates (Shapiro, 2008; Larson and Oldham, 2021; Harris and Sintim, 2022). In the state of Georgia, a standard S application of 11.2 kg ha⁻¹ is recommended, regardless of the yield goal (UGA-AESL, 2023). As Ultisols are natively acidic, liming with dolomitic lime is a common practice that, could supply adequate levels of Ca and Mg (Tiritan et al., 2016; Fatai et al., 2017; Thies, 2021; Harris and Sintim, 2022). While some forms of secondary nutrients (SNs) are applied, micronutrients (MNs) are not routinely applied, and thus, there is a need to evaluate whether MNs are yield-limiting factors of corn production in the state. Also, there is a need to determine whether increasing PN rates to achieve higher yields could elicit an imbalance in SNs and MNs in corn, which is critical because corn is susceptible to nutrient imbalances (Stewart et al., 2020, 2021; Aliyu et al., 2021; Amissah et al., 2023a).

The objectives of this study were to (a) assess nutrient dynamics in corn when fertilized with or without SN and MN at different yield goals, and (b) determine the impact of SN and MN application on corn growth, development, and productivity. The study was established at two locations in the state of Georgia (Plains and Tifton), with the Plains site having no top sandy soil layer, and the Tifton site having about 30 cm top sandy soil layer. We expected differences in the topsoil layer conditions to impact nutrient availability and overall corn productivity.

2.0. Materials and Methods

2.1. Experimental site

The research was conducted at the University of Georgia Southwest Georgia Research and Education Center in Plains, GA (32° 2'15.07"N, 84°22'31.75"W) and at the Coastal Plains Experiment Station in Tifton, GA (31°31'06.5"N, 83°32'59.6"W). The climate in Plains and Tifton is subtropical with characteristic high temperatures and evenly distributed precipitation. The annual average daily maximum, mean, and minimum air temperatures in Plains are 24.4 °C, 18.0 °C, and 11.4°C, respectively, with an annual rainfall of 1253 mm and 111 average rainy days, while the annual average daily maximum, mean, and minimum air temperatures in Tifton are 25.2 °C, 19.0 °C, and 12.7°C, respectively, with an annual rainfall of 1,208 mm and 109 average rainy days (Georgia AEMN, 2023).

The Plains study location had a soil mapped as Tifton sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) (USDA-NRCS, 2023), whereas the Tifton study location had a soil mapped as Dothan sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). In Plains, the sand, silt, and clay content of the soil were 57.3%, 7.20%, and 35.5% at the 0-15 cm depth, respectively, and 53.3%, 11.2%, and 35.5% at the 15-30 cm depth, respectively. Also, the organic matter content and soil pH in Plains were 16.1 g kg⁻¹ and 5.73 at 0-15 cm depth, respectively, and 15.1 g kg⁻¹ and 6.13 at 15-30 cm depth, respectively. In Tifton, the sand, silt, and clay content of the soil were 91.9%, 4.5%, and 3.6% at the 0-15 cm depth, respectively, and 87.9%, 4.5%, and 7.6% at the 15-30 cm depth, respectively. The organic matter content and soil pH were 4.8 g kg⁻¹ and 6.4 at 0-15 cm depth respectively, and 4.4 g kg⁻¹ and 6.5 at 15-30 cm depth, respectively.

2.2. Field experiment

Field experiments were established in 2020 and 2021 in Plains and 2020, 2021, and 2022 in Tifton to assess SN and MN application on corn fertilized with PN rates for 12.5 Mg ha⁻¹ (Low) and 25.1 Mg ha⁻¹ (High) yields. Different nutrient rates were used yearly based on initial nutrient levels and previous crops. Four SN and MN application regimes (SN-MN) were assessed: (1) no application of SN or MN (None), (2) the application of SN without MN (SN), (3) the application of MN without SN (MN), and (4) the application of SN and MN (SN+MN). The SN constituted the application of Mg, Ca, and S, and the MN constituted the application of B, Zn, Mn, Fe, Cu, and Mo. Table S3.1 lists the nutrient rates for the treatments that received low and high PN rates with SN+MN application, and Table S3.2 lists the fertilizers used as the major source of nutrients in the study. The same SN and MN rates were used for plots that received either SN or MN application alone. The treatments that did not receive the application of SN or MN were not assessed in Tifton in 2020 due to experimental constraints.

The experimental design was a two-factor (SN and MN) factorial design arranged in a randomized complete block design with four replications. The experimental plots for Tifton were 9.1 m long and 5.5 m wide, while those of Plains were 11 m long and 5.5 m wide. Treatment effects at both locations were not additive because different experimental fields at the research locations were used. The previous crop in 2020 and 2021 at Plains was peanut (*Arachis hypogaea*), whereas the previous crop in Tifton was peanut in 2020 and 2022, and cotton (*Gossypium spp.* L) in 2021. Field preparation was performed by harrowing, running a field cultivator, and creating 20 cm deep furrows 91.4 cm apart. Pioneer hybrid P1870R was used, and it was planted between March and April every year at 79,072 seeds ha⁻¹ in Plains and 88,958 seeds ha⁻¹ in Tifton.

Recommended rates of Glyphosate [N-(phosphonomethyl) glycine], Atrazine (2-chloro-4-ethyl amino-6-isopropyl amino-s -triazine), and Prowl [N-(1-ethyl propyl)-3,4-dimethyl-2,6-dinitrobenzenamine] were applied between the V3 and V4 stages of corn growth to control weeds. Supplemental irrigation was provided through an overhead irrigation system following standard irrigation scheduling recommendations by the University of Georgia Extension.

2.3. Data collection

The initial nutrient statuses of the experimental fields were determined from soils sampled at 0-15 cm and 15-30 cm depths. The soil samples were shipped to the Waters Agricultural Laboratories, Inc. in Camilla, GA for analysis after air drying and passing the dried samples through a 2-mm sieve. Nitrate-N was measured with the automated flow injection analysis system (FIAlyzer-1000, FIALab Instruments, Inc., Seattle, WA, United States) after extraction in a 2 M KCl solution. Measurement of extractable P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu was accomplished with an inductively coupled plasma optical emission spectrophotometer (ICP-OES; iCAP™ 6000 Series, Thermo Fisher Scientific, Cambridge, United Kingdom) after extraction in Mehlich I solution (Mylavarapu and Miller, 2014).

Plant tissue samples were collected at the vegetative (V5 to V7) and reproductive (VT to R1) growth stages and sent directly to Waters Agricultural Laboratories, Inc. in Camilla, GA for plant nutrient analyses following standard protocol. Total N was measured by dry combustion in a LECO FP-528 Nitrogen Analyzer (LECO Corporation, St. Joseph, MI, USA). The ICP-OES (iCAP™ 6000 Series, Thermo Fisher Scientific, Cambridge, UK) was used to measure total P, K, Ca, Mg, S, Fe, Mn, Zn, B, Cu, and Mo after digestion with DigiBLOC 3000 digestion system (SCP Science, Montreal, QC, Canada) with HNO₃/H₂O₂ mixture.

Plant biomass was also determined at the vegetative (between V5 and V7) and reproductive (between VT and R1) growth stages for every plot by sampling aboveground plant samples within a uniform 1-m long strip and oven-drying at 78°C to constant weight. Plant height (height of the tallest leaf from the soil surface); ear height (height of the base of the ear from the soil surface); ear length (length of the cob after removing the husk); ear diameter (measured from the center of the cob with the grain intact); and ear rows (the number of rows of corn grains on a cob) were determined at physiological maturity (R6 growth stage) from plants sampled within a uniform 1-m long strip. Corn stover and harvest index were determined from the same samples, where the stover constituted all aboveground dry biomass weight excluding the grains, and the harvest index was calculated as the dry grain weight divided by the total aboveground dry biomass weight. Grain yield was determined after harvesting the entire length of two rows of every plot with a plot combine, and adjusting the grain weight to 155 g kg⁻¹ moisture content.

2.4. Statistical analyses

Plant nutrient, growth, development, and yield data were analyzed with a linear mixed model using the “lme4” package in R (Bates et al., 2015). Separate statistical analyses were performed for each location because of differences in management practices, including the number of experimental years (two years in Plains and three years in Tifton). The PN rates and SN-MN application regimes were considered fixed effects, and year and block were considered random effects. Homoscedasticity of variance and normality of residual assumptions were tested and appropriate transformations with square root or Box-Cox transformation were applied as needed. Separation of means was achieved using the least square means and the adjusted Tukey multiple

comparison procedure with the ‘emmeans’ package in R (Lenth et al., 2022). Significance was assessed at $P = 0.05$ for all analyses.

3.0. Results

3.1. Weather and initial soil nutrients

Rainfall received during the experimental years and across the two locations varied from the long-term average (Figure 3.1c to 3.1j). The annual rainfall amounts in 2020 and 2021 in Plains were 1,554 mm and 1,395 mm, respectively, which are greater than the long-term average of 1,253 mm. Also, the annual rainfall amounts in 2020 and 2021 in Tifton (1,270 mm and 1,515 mm, respectively) were greater than the long-term average (1,208 mm). However, the annual rainfall received in 2022 in Tifton (1,104 mm) was lower than the long-term average. It was warmer during the experimental years than the long-term averages at both locations (Figure 3.1a, b). In Plains, the annual average temperature was 19.2 °C and 18.6 °C, respectively in 2020 and 2021, and in Tifton, the annual average temperature was 20.1 °C, 19.6 °C, and 19.7 °C, respectively, in 2020, 2021, and 2022. The long-term annual average temperature was 17.9 °C in Plains and 18.9 °C in Tifton.

The initial nutrient concentration of the soil varied with depth (Table 3.1). In general, there was a stratification of the PNs, with N, P, and K being concentrated more in the top 0-15 cm depth than in the 15-30 cm depth, except in 2022 in Tifton, where the reverse was observed for P. Stratification of SNs and MNs did not follow any particular trend across the different years at both locations. In Plains, except for P, which was considered low in both years, all the initial nutrient levels were above the low threshold according to the University of Georgia Extension soil test classification for corn (UGA-AESL, 2023). In Tifton, Mn was below the low threshold in 2020, P

and Mn were below the low threshold in 2021, and P, Zn, and Mn were below the low threshold in 2022.

3.2. Nutrient concentration at the vegetative and reproductive growth stages

The *P*-values of the main effects and interaction effects of PN and SN-MN application on nutrient concentration at the vegetative and reproductive stages are presented in Table S3.3. At the vegetative growth stage, the main effects of the PN application rate were not significant on the concentration of all nutrients measured, except the Mn level at Tifton where the high PN rate decreased the Mn level by 11.6% when compared to the low PN rate (Table 3.2). In Plains, the main effects of SN-MN application had significant effects on the P, Ca, and Mo levels, and the PN and SN-MN interaction effects were significant on the P and Ca levels. Applying SN, MN, or SN+MN did not affect the P and Ca levels under the high PN application, but they increased the P and Ca levels by 9.3-13.0% and 1.5-8.9%, respectively, under the low PN application. Also, under the low PN, applying MN or SN+MN tended to increase the Mo level (by 25.0-40.0%) at the vegetative growth stage in Plains, but the differences were not significant. However, under the high PN, the application of SN+MN led to a significant increase in the Mo level (by 59.4%) when compared to the application of SN without MN. In Tifton, the main effects of SN-MN application had significant effects on the Mg, B, Fe, Cu, and Mo levels at the vegetative growth stages, but the PN and SN-MN interaction effects were significant on just the Mg level (Table S3.3). The application of MN led to a 13.7% reduction in the Mg level compared to when neither SN nor MN was applied under low PN application, but MN application had no significant impact on the Mg level under the high PN application (Table 3.2). In general, the application of SN, MN, or SN+MN elevated the levels of B (43.7-68.0%), Cu (12.6-30.7%), and Mo (71.0-154%), but decreased the

level of Fe (3.8-12.0%) at the vegetative growth stage in Tifton. A notable observation was the high accumulation of Fe in Plains, which ranged from 939 mg kg⁻¹ to 1134 mg kg⁻¹. The Fe accumulation in Tifton ranged from 185 mg kg⁻¹ to 207 mg kg⁻¹.

At the reproductive growth stage, the main effects of PN application were not significant on the concentrations of all nutrients in Plains, but they were significant on the N, P, K, S, Zn, Mn, and Fe levels in Tifton (Table S3.3). Applying high PN increased the N, P, K, S, Zn, Mn, and Fe levels in Tifton by 7.1%, 10.0%, 8.4%, 6.6%, 5.2%, 28.6%, and 28.1%, respectively (Table 3.3). The high PN also decreased the Ca, Cu, and Mo levels in Tifton by 13.8%, 8.2%, and 14.6%, respectively, but as already noted, the differences were not significant. In Plains, the main effects of SN-MN application had significant effects on the N, B, Zn, Mn, Cu, and Mo levels, and the PN and SN-MN interaction effects were significant on the B and Mo levels. In Tifton, the main effects of SN-MN application had significant effects on all nutrients, except the P and K levels. However, the PN and SN-MN interaction effects were significant on just the N and Mn levels in Tifton.

3.3. Plant biomass at the vegetative and reproductive stages

Differences in nutrient accumulation at the vegetative growth stage did not significantly impact plant biomass measured at that stage. The main effects of PN and SN-MN application, and their interaction effects had no significant impact on the plant biomass at the vegetative stage in both Plains and Tifton (Table S3.4). On average, the biomass accumulated at the vegetative stage in Plains and Tifton were 0.34 kg ha⁻¹ and 0.40 kg ha⁻¹, respectively (Figure 3.2a, b). At the reproductive growth stage, the main effects of PN and SN-MN application were also not significant on the plant biomass at Plains and Tifton (Table S3.4). However, the interaction effects of PN and SN-MN applications were significant on the plant biomass at both locations. At the reproductive

growth stage in Plains, the SN, MN, or SN+MN application tended to decrease the plant biomass under the low PN, but they tended to increase the plant biomass under the high PN (Figure 3.2c). Significant differences in plant biomass at the reproductive growth stage in Plains were observed between the low and high PN applications when neither SN nor MN was applied. At the reproductive growth stage in Tifton, the application of SN increased plant biomass by 13.0% compared to the application of MN under the high PN rate (Figure 3.2d). However, no significant differences in plant biomass were observed between the SN, MN, and SM+MN applications under the low PN rate.

3.4. Plant height, grain yield, stover, harvest index, & TSW

Plant height in Plains was not significantly affected by the main effects of PN and SN-MN application, as well as their interaction effects (Table S3.4). The plant height in Plains was 263 cm, averaged over the two PN rates and the three SN-MN treatment factors (Figure 3.3a). The main effects of PN and SN-MN application were also not significant on the plant height in Tifton; however, the interaction effects of PN and SN-MN were significant on the plant height in Tifton (Table S3.4). No significant differences in plant height were observed under the high PN rates in Tifton. However, under the low PN rate, applying MN significantly increased the plant height compared to when neither SN nor MN was applied (Figure 3.3b).

The main effects of PN and SN-MN application were significant on the yield in both Plains and Tifton (Table S3.4). However, the interaction effects of PN and SN-MN application on yield were significant in Tifton but not in Plains. Averaged over the SN-MN application, the yields of the low and high PN application were 15.4 Mg ha⁻¹ and 17.3 Mg ha⁻¹ in Plains, respectively, and 14.5 Mg ha⁻¹ and 16.6 Mg ha⁻¹ in Tifton, respectively (Figure 3.3c, d). This reflects a yield increase

of 12.2% and 13.0% in Plains and Tifton respectively. In Plains, the application of SN and SN+MN tended to increase yield under both low (by 5.4% and 6.4%, respectively) and high (by 3.2% and 4.2%) PN application compared to when neither SN nor MN was applied. A similar trend was observed in Tifton, and the effects of SN and SN+MN application on yield were more evident under the low PN. Yields of SN and SN+MN were 13.6% and 10.4%, respectively, greater than when neither SN nor MN was applied under the low PN, and 2.3% and 6.0%, respectively, greater than when neither SN nor MN was applied under the high PN.

The main effects of PN application on stover were significant in both Plains and Tifton (Table S3.4). Also, the main effects of the SN-MN application were significant in Plains, and the interaction effects of PN and SN-MN application were significant in Tifton. The application of high PN caused a 6.64% and 5.43% increase in the stover in Plains and Tifton, respectively (Figure 3.3e, f). Averaged over the low and high PN, applying SN, MN, or SN+MN led to 5.3%, 8.8%, and 9.2% stover increase in Plains, respectively, and 5.4%, 1.7%, and 4.6% stover increase in Tifton, respectively. The harvest index was not significantly affected by PN and SN-MN application in Plains (Table S3.4 and Figure 3.3g). However, in Tifton, a significant increase in harvest index (by 2.0%) was observed from the application of SN+MN compared to when neither SN nor MN was applied under the high PN (Figure 3.3h). No significant differences in harvest indices were observed between the various SN-MN application treatments under the low PN rate in Tifton. For TSW, the main effects of PN application were significant in Plains and Tifton (Table S3.4). High PN application caused a 5.33% and 6.70% increase in the TSW, respectively, in Plains and Tifton compared to applying the low PN rate. SN or MN application significantly impacted

the TSW in Plains and Tifton. In general, the TSW tended to increase with SN, MN, or SN+MN application compared to when neither SN nor MN was applied (Figure 3.3i, j).

3.5. Ear development

The nutrient applications significantly affected ear length, ear diameter, and ear rows, but not the ear height (Table S3.4). The ear height was 109 cm in Plains and 107 cm in Tifton, averaged over the two PN rates and the three SN-MN factor treatments (Figure 3.4a, b). The main effects of SN-MN application were significant on the ear length at both locations, but not the main effects of PN application or the PN and SN-MN interaction effects. Averaged over the two PN rates, the ear length for SN, MN, and SN+MN application was 16.8 cm, 17.5 cm, and 16.7 cm, respectively, in Plains, and 17.5 cm, 16.7 cm, and 17.3 cm, respectively, in Tifton (Figure 3.4c, d). This compares to ear lengths of 17.2 cm and 16.9 cm when neither SN nor MN was applied in Plains and Tifton, respectively.

Significant differences in ear diameter were observed between the two PN rates at both locations. The high PN rate led to a 3.1% and 2.4% increase in ear diameter over the low PN rate in Plains and Tifton, respectively (Figure 3.4e, f). The main effects of SN-MN application were significant in Tifton but not in Plains, and the interaction effects of PN and SN-MN were not significant in both locations. The SN, MN, and SN+MN application led to a 3.1%, 2.8%, and 4.6% increase in the ear diameter, respectively, in Tifton, compared to when neither SN nor MN was applied. The average number of rows per ear was affected by the PN and SN-MN applications in Plains but not in Tifton. The average ear rows were 15.9 in Plains and 18.2 in Tifton (Figure 3.4g, h). In Plains, the high PN rate increased the ear rows by 3.8% over the low PN rate. Also, compared

to when neither SN nor Mn was applied, the application of SN, MN, or SN+MN increased the ear rows by 5.0%, 1.8%, and 5.8%, respectively.

4.0. Discussion

Despite observing significant differences in tissue nutrient concentration between treatments at the vegetative growth stage, it did not translate to significant differences in accumulated biomass. The lack of significant differences in biomass at the vegetative stage could partly be attributed to the low nutritional requirement of corn by the V5 to V7 growth stage, the initial soil nutrient levels, and the mineralization of crop residues. The nutritional requirement of corn by the V5 to V7 growth stage is low, typically <15% of the total taken up by maturity (Karlen et al., 1988; Bender et al., 2013; Ciampitti et al., 2013; Ciampitti and Vyn, 2013). As previously noted, according to the University of Georgia Extension soil test classification for corn, most of the initial soil nutrient levels were above the low threshold (UGA-AESL, 2023), which could have supplied adequate nutrients to the crop by the V5 to V7 growth stage. Moreover, the mineralization of the previous crop residues could have supplied additional nutrients (Sintim et al., 2015; Shahzad et al., 2018, 2019a; Torma et al., 2018) to meet the demand of the crop by the V5 to V7 growth stage, especially for P where the initial level was low at both locations. Torma et al. (2018) observed that 2–24 kg ha⁻¹ of P could be supplied to the soil by crop residues. Mineralization of crop residues is a biological process, and it depends on several abiotic and biotic factors, including the chemical composition of the crop residues; the structure and composition of microbial communities; soil properties; as well as weather conditions (Whalen, 2014; Arenberg and Arai, 2019; Shahzad et al., 2019b; Grzyb et al., 2020; Sintim et al., 2022a; Amissah et al., 2023b).

In contrast to the marginal differences in plant biomass between treatments at the vegetative stage, significant differences were observed between treatments at the reproductive stage, and the response varied with the PN application rate. For instance, in Plains, the SN, MN, or SN+MN application tended to decrease the plant biomass under the low PN rate at the reproductive stage, but they tended to increase the plant biomass under the high PN rate at the reproductive stage. The tissue concentration of all nutrients at the vegetative stage was above the lower threshold of the nutrient sufficiency ranges (NSRs) recommended in the Southern Cooperative Series Bulletin (SCSB) #394 (Campbell, 2000). This could partly explain why significant differences in plant growth were not observed at that stage despite significant differences in the nutrient concentration between the treatments. None of the nutrients were possibly at a limiting level. However, the tissue concentrations of the nutrients at the reproductive stage were not all above the lower threshold, especially all the N levels in Plains and the Ca levels of the high PN rate in Tifton. The reproductive stage is a period of increased nutrient demand by the crops, indicating why the varying fertility treatments impacted the plant biomass at that stage (Bender et al., 2013; Silva et al., 2018; Bojtor et al., 2021a).

The SCSB #394 is the output of a regional effort that provides NSRs for plant analyses in the southern region of the United States. The NSR system is a common interpretative method of plant tissue test results, which sets lower and upper threshold values for relevant nutrients. Values within the NSRs indicate the optimum nutrient concentration levels to obtain maximum growth or yield, and there are different threshold values for the different growth stages of crops due to changes in nutrient requirements and concentrations of plants (Campbell, 2000; Llanderal et al., 2021; Amissah et al., 2023a). For corn >10 cm in height to the tasseling stage, the NSRs of the

SCSB #394 are N (30-40 g kg⁻¹), P (3-5 g kg⁻¹), K (20-30 g kg⁻¹), Mg (1.5-6 g kg⁻¹), Ca (2.5-8 g kg⁻¹), S (1.5-4 g kg⁻¹), B (5-25 mg kg⁻¹), Zn (20-70 mg kg⁻¹), Mn (20-150 mg kg⁻¹), Fe (30-250 mg kg⁻¹), Cu (5-25 mg kg⁻¹), and Mo (0.1-2 mg kg⁻¹). At the tasseling/bloom stage, which corresponds to the VT to R1 growth stages, the NSRs of the SCSB #394 are N (28-40 g kg⁻¹), P (2.5-5 g kg⁻¹), K (18-30 g kg⁻¹), Mg (1.5-6 g kg⁻¹), Ca (2.5-8 g kg⁻¹), S (1.5-4 g kg⁻¹), B (5-25 mg kg⁻¹), Zn (20-70 mg kg⁻¹), Mn (15-150 mg kg⁻¹), Fe (30-250 mg kg⁻¹), Cu (5-25 mg kg⁻¹), and Mo (0.1-2 mg kg⁻¹).

Notably, the tissue concentration of Fe at the vegetative stage in Plains was 4-fold higher than the concentration observed in Tifton or the higher limit of the NSRs of the SCSB #394. This can be attributed to the abundance of oxides of Fe in the clay mineral in Plains (Trakoonyingcharoen et al., 2006; Fageria and Nascente, 2014; Weil and Brady, 2017). Oxides of Fe are prevalent in the clay minerals of highly weathered soils. As already mentioned, the soil in Plains has lost its top soil layer and has more clay than the soil in Tifton. The wide variation in tissue Fe concentration at the vegetative stage between Plains and Tifton was inconsistent with the differences in initial soil test Fe levels measured after extraction with the Mehlich I reagent. In fact, the initial soil test Fe level in 2022 in Tifton was even greater than all the levels reported for Plains, highlighting the inability of soil test Fe analyses, after extraction with the Mehlich I reagent, to discriminate Fe availability for plant uptake. However, it must be noted that nutrient availability and subsequent uptake and assimilation by crops are governed by complex biotic and abiotic factors (Morgan and Connolly, 2013; Sintim et al., 2016; Fan et al., 2021).

The Fe level at the vegetative stage tended to rather decrease with MN application, which was consistent across the two locations. The results could be due to the complexation of Fe by B

or Mo when micronutrients were applied (Liu et al., 2009; Van Eynde et al., 2020; Yang and Wang, 2021). Oxides of Fe including goethite and ferrihydrite often form complexes with B, reducing the bioavailability and concentration of Fe in the soil solution. Adsorption of B to Fe in acidic soils is often dominated by ferrihydrite due to its high specific surface area and small particle size (Brinza et al., 2019; Van Eynde et al., 2020). Studies also showed that Fe can adsorb Mo in highly weathered and acidic soils dominated by oxides of Fe and Al, thereby, reducing their availability to plants (Xu et al., 2013; Rutkowska et al., 2017; Brinza et al., 2019). The Mo level at the reproductive stage in Tifton, which has a top sandy layer, tended to accumulate the most when MN was applied without SN (Table 3.3). Also, the Mo levels were accumulated at very high levels in Tifton than in Plains (5.73-18.7 mg kg⁻¹ vs. 0.30-0.51 mg kg⁻¹ at the vegetative stage and 1.86-25.8 mg kg⁻¹ vs. 0.37-4.10 mg kg⁻¹ at the reproductive stage), indicating the potential complexation of Mo by the high Fe and Al oxides present in Plains.

Grain yields of the low PN rate at both locations exceeded the target yield of 12.5 Mg ha⁻¹ irrespective of SN or MN application, with the average grain yields ranging from 14.9 Mg ha⁻¹ to 15.8 Mg ha⁻¹ in Plains and 13.3 Mg ha⁻¹ to 15.1 Mg ha⁻¹ in Tifton. In contrast, the target yield of 25.1 Mg ha⁻¹ for the high PN rate was not achieved at any of the two locations, with average yields ranging from 16.9 Mg ha⁻¹ to 17.7 Mg ha⁻¹ in Plains and 15.7 Mg ha⁻¹ to 17.1 Mg ha⁻¹ in Tifton. As the average yield increase from high PN application (by 12.2% and 13.0% in Plains and Tifton, respectively) over the low PN was not 2-fold, the grain yield per unit N, P₂O₅, and K₂O applied reduced substantially. The grain yield per unit N, P₂O₅, and K₂O applied under the low PN rate was 65.5 kg ha⁻¹, 102 kg ha⁻¹, and 106 kg ha⁻¹ in Plains, respectively, and 58.9 kg ha⁻¹, 99.3 kg ha⁻¹, and 90.3 kg ha⁻¹ in Tifton, respectively. Under the high PN rate, the grain yield per unit N, P₂O₅,

and K_2O applied was 34.1 kg ha^{-1} , 60.2 kg ha^{-1} , and 46.5 kg ha^{-1} in Plains, respectively, and 31.8 kg ha^{-1} , 58.6 kg ha^{-1} , and 42.6 kg ha^{-1} in Tifton, respectively.

Corn yield potential exceeds 25.1 Mg ha^{-1} , as achieved on different occasions by growers on a much larger acreage than the experimental plots used in this study (NCGA, 2019). Thus, other factors besides nutrients might have limited the corn yield of the high PN rate in this study. According to the Law of the Minimum, growth is dictated not by total resources available, but by the scarcest resource. In other words, growth occurs at the rate permitted by the most limiting factor. Significant effects of SN and MN application on yield demonstrate their importance in corn production. Yield increase from SN and MN application were observed under both low PN and high PN rates, indicating that although SN and MN are required in small quantities compared to PN, their deficiency can limit corn yield potential (Chander et al., 2015; Njoroge et al., 2018).

5.0. Conclusions

Nutrient accumulation in corn by the V5 to V7 growth stage was at sufficient levels regardless of the PN rate and SN or MN application. Thus, significant differences in corn growth were not observed by the V5 to V7 growth stage despite significant differences in the nutrient concentration between treatments. In contrast, significant differences were observed between treatments at the reproductive stage, and the response varied with the PN rates. The SN, MN, or SN+MN application decreased the plant biomass under the low PN rate at the reproductive stage, but they increased the plant biomass under the high PN rate. The Fe accumulation at the vegetative stage in Plains was 4-fold higher than those observed in Tifton, but the magnitude of the difference was not observed in the soil test analyses by the Melich I extraction method.

The target grain yield of 12.5 Mg ha⁻¹ for the low PN rate was exceeded at both locations, irrespective of SN or MN application. However, applying high PN rates to achieve 25.1 Mg ha⁻¹ was not achieved, with average yields ranging from 16.9 Mg ha⁻¹ to 17.7 Mg ha⁻¹ in Plains and 15.7 Mg ha⁻¹ to 17.1 Mg ha⁻¹ in Tifton. The SN and MN applications improved corn yield under low and high PN rates. Compared to when neither SN nor MN was applied, the application of SN and MN led to an average yield increase of 6.4% and 4.2%, respectively, for the low and high PN rates in Plains, and 10.4% and 6.0%, respectively, for the low and high PN rates in Tifton. Overall, the results showed that SN and MN might be yield-limiting factors of corn in highly weathered soils, and also low corn yield (≤ 12.5 Mg ha⁻¹) can be achieved with lower PN rates than currently recommended. As this study assessed the interactive effects of different SN and MN nutrients, there is a need for further studies to assess the individual and interactive effects of the nutrients to elucidate the actual yield-limiting nutrients.

6.0. References

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Tables

Table 3.1: Initial nutrient levels of the experimental fields in Plains and Tifton at 0-15 cm and 15-30 cm depths.

Year	Soil depth (cm)	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
		kg ha ⁻¹										
----- Plains -----												
2020	0-15	9.30	21.30	172	229	832	35.9	0.97	3.81	46.3	22.4	1.42
	15-30	4.91	8.59	61.3	266	884	18.3	1.35	2.99	32.9	20.5	0.93
2021	0-15	9.39	29.7	170	221	865	5.04	0.84	3.36	27.5	16.3	0.67
	15-30	6.87	19.1	106	238	861	3.92	1.18	2.41	15.7	14.6	0.62
----- Tifton -----												
2020	0-15	20.1	58.3	90.8	101	881	7.85	0.41	3.25	8.22	12.0	0.49
	15-30	13.3	38.1	74.7	63.9	582	15.3	0.30	3.18	7.47	13.8	0.49
2021	0-15	5.12	30.3	119	77.3	644	42.0	0.22	3.59	8.97	16.8	1.12
	15-30	3.82	24.7	103	71.7	600	15.1	0.22	3.64	6.16	15.7	2.63
2022	0-15	9.53	15.3	134	161	1076	12.3	0.37	2.09	7.10	28.8	0.26
	15-30	6.70	22.8	82.2	148	986	23.5	0.34	2.76	5.60	30.6	0.26

Soil nitrate-N was measured after extraction with 2 M KCl solution, and soil P, K, Ca, Mg, S, Fe,

Mn, Zn, B, and Cu were measured after Mehlich I extraction.

Table 3.2: Effects of primary nutrient (PN; N, P, and K), secondary nutrient (SN; Mg, Ca, and S), and micronutrient (MN; B, Zn, Mn, Fe, Cu, and Mo) application on nutrient concentrations of corn leaf tissues sampled at the vegetative growth stage (between V5 and V7) in Plains and Tifton, GA.

PN	SN-MN	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
-----Plains-----													
PN-Low	None	34.8±1.2a	3.51±0.32a	43.6±3.6a	4.06±0.11a	2.92±0.26b	2.82±0.14a	9.19±0.20a	36.3±2.3a	87.0±5.6a	939±232a	19.4±2.7a	0.30±0.04ab
PN-Low	SN	35.1±1.4a	3.97±0.32b	42.9±3.5a	4.25±0.17a	3.06±0.24a	2.90±0.12a	9.62±0.32a	38.8±3.1a	96.7±9.1a	1024±274a	14.5±0.5a	0.35±0.05ab
PN-Low	MN	35.2±1.3a	3.84±0.31b	41.5±3.7a	4.17±0.06a	2.97±0.25a	2.84±0.11a	9.43±0.30a	35.2±1.8a	90.1±1.1a	914±166a	14.3±0.6a	0.40±0.05ab
PN-Low	SN+MN	34.2±1.4a	3.92±0.29b	43.2±3.6a	4.36±0.15a	3.18±0.30a	2.92±0.13a	9.62±0.18a	37.2±2.3a	96.1±3.5a	1099±218a	14.6±0.4a	0.42±0.03ab
PN-High	None	34.6±1.3a	3.90±0.28ab	42.7±3.4a	4.31±0.12a	3.17±0.30a	2.95±0.14a	9.62±0.18a	36.2±2.0a	95.6±3.1a	1098±218a	14.5±0.6a	0.35±0.06ab
PN-High	SN	33.9±1.5a	3.90±0.27ab	42.7±3.4a	4.30±0.11a	3.12±0.25a	2.92±0.14a	9.50±0.19a	37.7±2.6a	94.8±3.7a	1093±223a	14.2±0.7a	0.32±0.07a
PN-High	MN	34.6±1.3a	3.98±0.30b	44.4±4.0a	4.15±0.06a	3.07±0.26a	2.92±0.13a	9.50±0.27a	36.8±2.4a	91.5±2.8a	990±205a	14.5±0.7a	0.37±0.06ab
PN-High	SN+MN	35.1±1.0a	3.91±0.29b	43.3±3.7a	4.15±0.07a	3.02±0.28a	2.85±0.09a	9.62±0.32a	36.7±2.1a	117.3±20.2a	1134±257a	14.1±0.7a	0.51±0.09b
-----Tifton-----													
PN-Low	None	42.6±1.4a	4.24±0.43a	42.3±3.4a	6.48±0.22b	2.65±0.17a	2.76±0.10a	17.5±0.8ab	32.9±2.7a	70.7±5.2a	207±18b	5.03±0.75a	5.73±1.25a
PN-Low	SN	42.8±1.5a	4.12±0.45a	43.1±3.4a	5.85±0.29ab	2.45±0.13a	2.86±0.10a	25.1±3.3ab	35.0±4.0a	67.7±7.1ab	193±15ab	6.85±1.29ab	9.81±3.67ab
PN-Low	MN	43.2±1.4a	4.27±0.44a	44.9±3.3a	5.70±0.30a	2.50±0.16a	2.84±0.12a	24.7±2.8ab	32.9±2.8a	63.9±4.2ab	175±12a	6.01±0.81ab	11.1±2.95ab
PN-Low	SN+MN	41.9±1.6a	4.09±0.40a	42.6±3.4a	6.21±0.21ab	2.63±0.17a	2.86±0.11a	25.1±2.5ab	34.1±2.3a	72.0±8.9ab	189±13ab	6.68±0.61ab	12.89±3.97ab
PN-High	None	42.9±1.3a	4.60±0.53a	43.0±3.4a	6.02±0.27ab	2.60±0.16a	2.74±0.09a	14.6±1.1a	30.8±2.8a	61.3±4.3ab	203±23ab	5.46±0.75ab	6.03±1.62ab
PN-High	SN	42.6±1.6a	4.43±0.60a	44.1±3.3a	5.84±0.27ab	2.51±0.15a	2.82±0.09a	21.0±2.3ab	31.4±2.8a	58.6±4.2b	201±21ab	6.12±1.08ab	10.3±3.88ab
PN-High	MN	41.5±1.5a	4.55±0.55a	43.0±3.3a	6.00±0.24ab	2.55±0.17a	2.66±0.11a	23.7±2.8ab	31.2±2.7a	58.8±3.1b	185±18ab	5.79±0.65ab	18.7±7.26b
PN-High	SN+MN	43.4±1.6a	4.37±0.55a	43.3±3.5a	5.87±0.24ab	2.47±0.15a	2.85±0.10a	28.8±3.5b	34.6±3.3a	66.9±5.5ab	187±14ab	7.03±0.93b	12.8±3.73ab

Within every location and nutrient element, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean ± standard error. PN-Low and PN-High refer to N, P, and K rates fertilized to achieve 12.5 Mg ha⁻¹ and 25.1 Mg ha⁻¹ yield, respectively.

Table 3.3: Effects of primary nutrient (PN; N, P, and K), secondary nutrient (SN; Mg, Ca, and S), and micronutrient (MN; B, Zn, Mn, Fe, Cu, and Mo) application on nutrient concentrations of corn leaf tissues sampled at the reproductive growth stage (between VT and R1) in Plains and Tifton, GA.

PN	SN-MN	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
----- g kg ⁻¹ -----							----- mg kg ⁻¹ -----						
----- Plains -----													
PN-Low	None	26.6±1.0a	3.56±0.11a	26.5±1.8a	3.32±0.16a	2.99±0.22a	1.74±0.08a	11.7±1.0d	31.9±1.5b	55.8±2.4a	193±20a	8.1±0.4a	1.43±0.49ab
PN-Low	SN	25.7±1.3a	3.41±0.12a	26.3±1.6a	3.08±0.16a	2.74±0.20a	1.74±0.07a	12.2±0.9cd	33.3±2.4ab	57.5±3.7a	175±19a	8.5±0.6a	0.64±0.22ab
PN-Low	MN	25.1±1.0a	3.40±0.12a	26.9±1.7a	3.10±0.14a	2.84±0.21a	1.81±0.08a	12.6±1.1bcd	43.9±8.2ab	64.8±5.3a	185±21a	9.1±0.5ab	0.66±0.22ab
PN-Low	SN+MN	26.0±1.1a	3.51±0.14a	27.6±2.1a	3.08±0.20a	2.85±0.25a	1.81±0.10a	17.4±2.4a	41.0±3.2a	62.7±4.3a	194±19a	9.9±0.5ab	4.10±1.39c
PN-High	None	27.4±1.0a	3.54±0.15a	27.2±1.9a	3.19±0.17a	2.70±0.22a	1.83±0.09a	13.2±1.3bcd	34.7±2.3ab	66.7±3.9a	181±16a	9.3±0.7ab	0.37±0.09a
PN-High	SN	24.9±1.5a	3.30±0.18a	26.8±1.9a	3.04±0.13a	2.81±0.22a	1.75±0.08a	12.7±0.7bcd	35.6±2.8ab	60.2±4.4a	194±28a	8.8±0.6ab	2.81±1.07abc
PN-High	MN	25.8±1.0a	3.51±0.12a	27.0±1.8a	3.16±0.14a	2.83±0.20a	1.80±0.08a	14.8±0.9ab	37.6±2.1ab	62.2±3.0a	187±24a	9.7±0.5ab	1.37±0.43abc
PN-High	SN+MN	26.8±1.2a	3.50±0.12a	27.2±2.0a	3.05±0.22a	2.67±0.23a	1.86±0.08a	15.1±1.5abc	38.8±2.0ab	70.8±5.1a	209±25a	10.8±0.8b	2.16±0.74bc
----- Tifton -----													
PN-Low	None	27.7±1.2a	3.89±0.19a	24.2±0.8a	4.93±0.39a	2.68±0.24a	1.80±0.07a	8.1±1.0a	29.7±2.2ab	44.0±4.7cd	103±2a	6.98±0.37ab	3.91±0.96a
PN-Low	SN	28.2±1.2ab	3.92±0.15a	24.3±0.8a	4.51±0.38a	2.80±0.25a	1.97±0.06bc	8.9±0.9a	28.6±2.5a	42.3±3.5d	95±3b	6.51±0.45ab	4.54±2.32a
PN-Low	MN	28.4±1.1ab	4.04±0.20ab	24.1±0.8a	4.59±0.48a	2.76±0.28a	1.80±0.06a	13.4±0.7c	33.3±2.7bcd	57.1±8.5abcd	105±4a	7.84±0.57b	25.8±4.97b
PN-Low	SN+MN	29.9±1.1bc	3.97±0.16a	24.2±0.9a	4.71±0.42a	2.91±0.25a	2.00±0.08bc	14.3±1.3c	35.8±2.6d	44.4±5.3d	102±2a	7.81±0.65b	14.4±3.62b
PN-High	None	30.2±1.2bc	4.41±0.09bc	26.4±0.4a	4.78±0.38a	2.43±0.12a	1.97±0.07abc	8.4±0.7a	30.9±2.4abc	56.4±3.1abc	190±39a	6.26±0.37ab	3.73±0.97a
PN-High	SN	31.5±1.1c	4.27±0.14abc	26.5±0.6a	4.57±0.38a	2.45±0.12a	2.09±0.06c	9.9±0.8ab	31.1±2.7abc	53.5±3.3bcd	108±4ab	5.60±0.27a	1.86±0.60a
PN-High	MN	29.9±1.4bc	4.49±0.20c	26.3±0.4a	4.74±0.42a	2.42±0.13a	1.93±0.10ab	13.2±0.9bc	34.7±2.5cd	60.3±6.8ab	110±3a	7.48±0.61b	24.2±4.65b
PN-High	SN+MN	30.7±1.4c	4.24±0.09abc	25.7±0.6a	4.68±0.38a	2.49±0.07a	2.08±0.09bc	17.6±2.0c	37.4±2.7d	71.5±5.3a	112±4a	7.60±0.62b	12.8±1.94b

Within every location and nutrient element, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean ± standard error. PN-Low and PN-High refer to N, P, and K rates fertilized to achieve 12.5 Mg ha⁻¹ and 25.1 Mg ha⁻¹ yield, respectively.

Figures

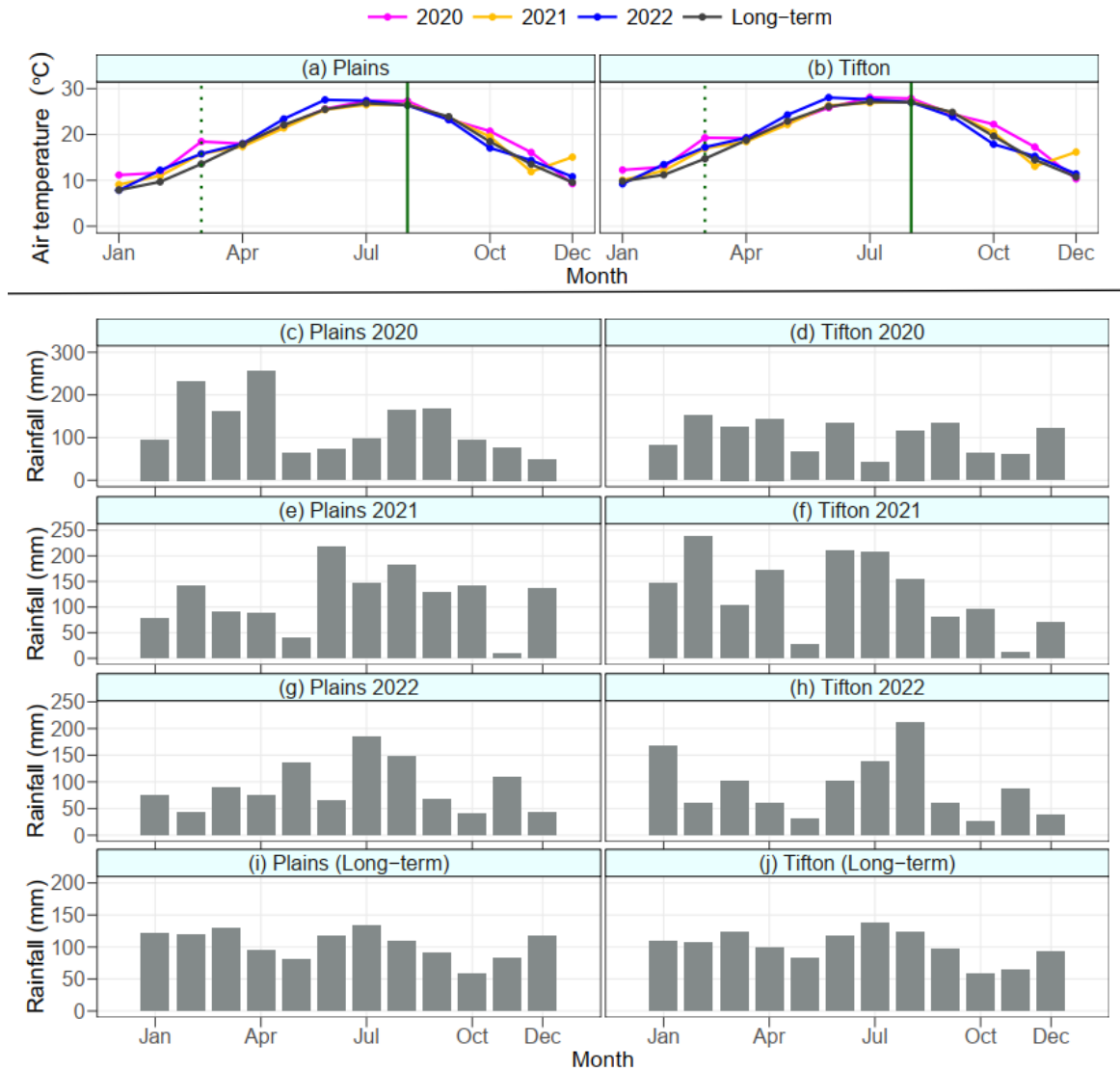


Figure 3.1: Monthly average temperature in Plains and Tifton (a,b) as well as the monthly total rainfall in Plains and Tifton, GA in 2020 (c,d), 2021 (e,f), and 2022 (g,h). Long-term refers to data from 1956 to 2016 in Plains and 1923 to 2016 in Tifton (i, j). Dotted and solid green vertical lines indicate the typical months of planting and harvesting corn in Georgia, respectively.

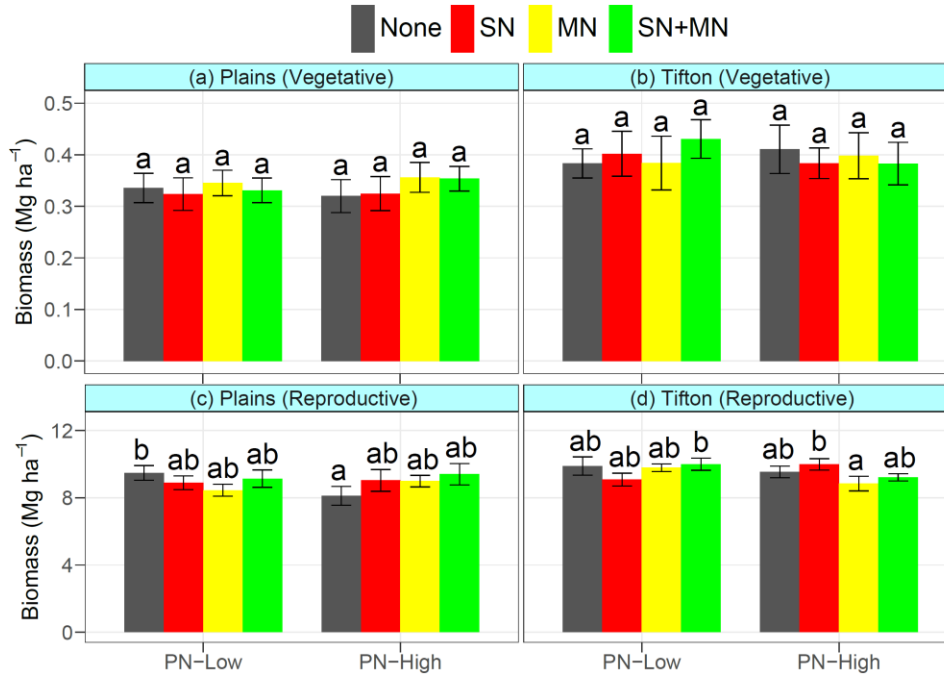


Figure 3.2: Effects of primary nutrient (PN; N, P, and K), secondary nutrient (SN; Mg, Ca, and S), and micronutrient (MN; B, Zn, Mn, Fe, Cu, and Mo) application on aboveground biomass of corn at the vegetative (between V5 and V7) and reproductive (between VT and R1) growth stages in Plains and Tifton, GA. Within every location and growth stage, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean. PN-Low and PN-High refer to N, P, and K rates fertilized to achieve 12.5 Mg ha⁻¹ and 25.1 Mg ha⁻¹ yield, respectively.

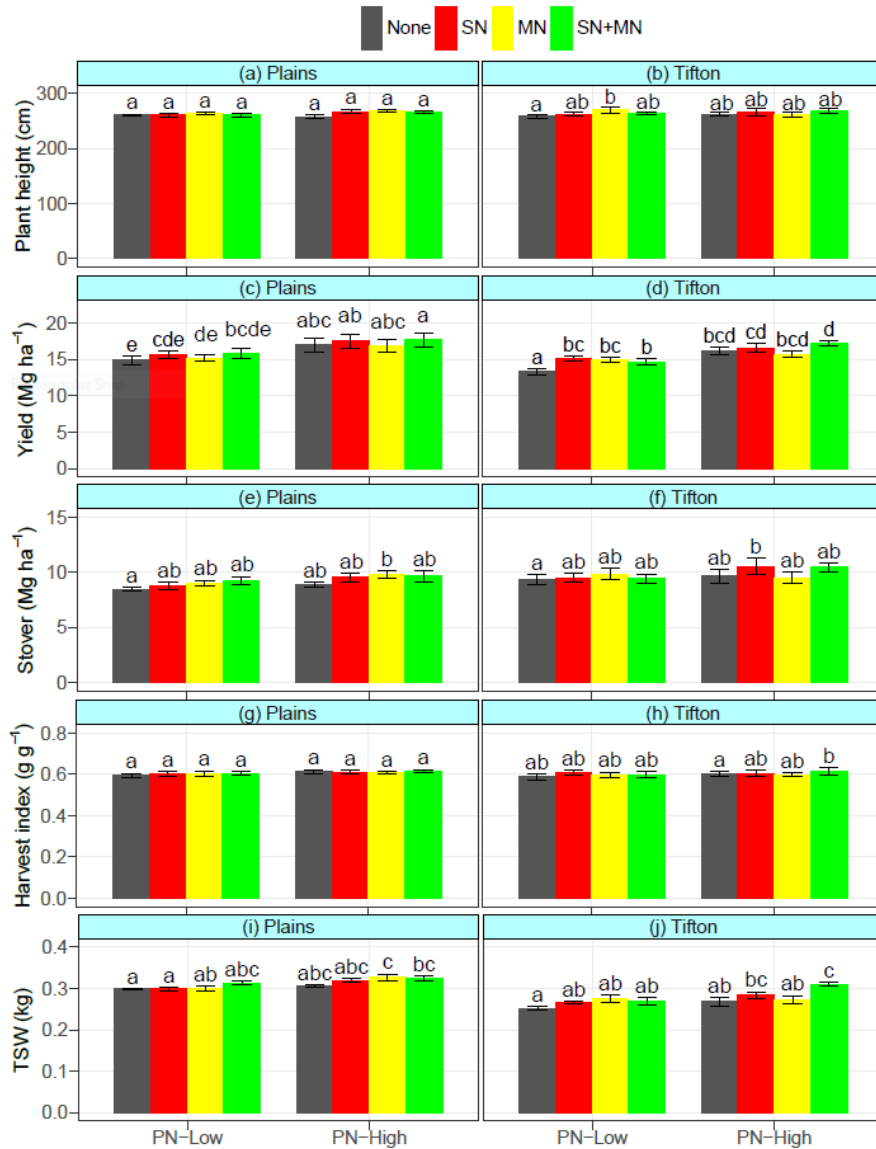


Figure 3.3: Effects of primary nutrient (PN; N, P, and K), secondary nutrient (SN; Mg, Ca, and S), and micronutrient (MN; B, Zn, Mn, Fe, Cu, and Mo) application on plant height, grain yield, stover, harvest index, and thousand seed weight (TSW) of corn in Plains and Tifton, GA. Within every location and growth stage, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean. PN-Low and PN-High refer to N, P, and K rates fertilized to achieve 12.5 Mg ha⁻¹ and 25.1 Mg ha⁻¹ yield, respectively.

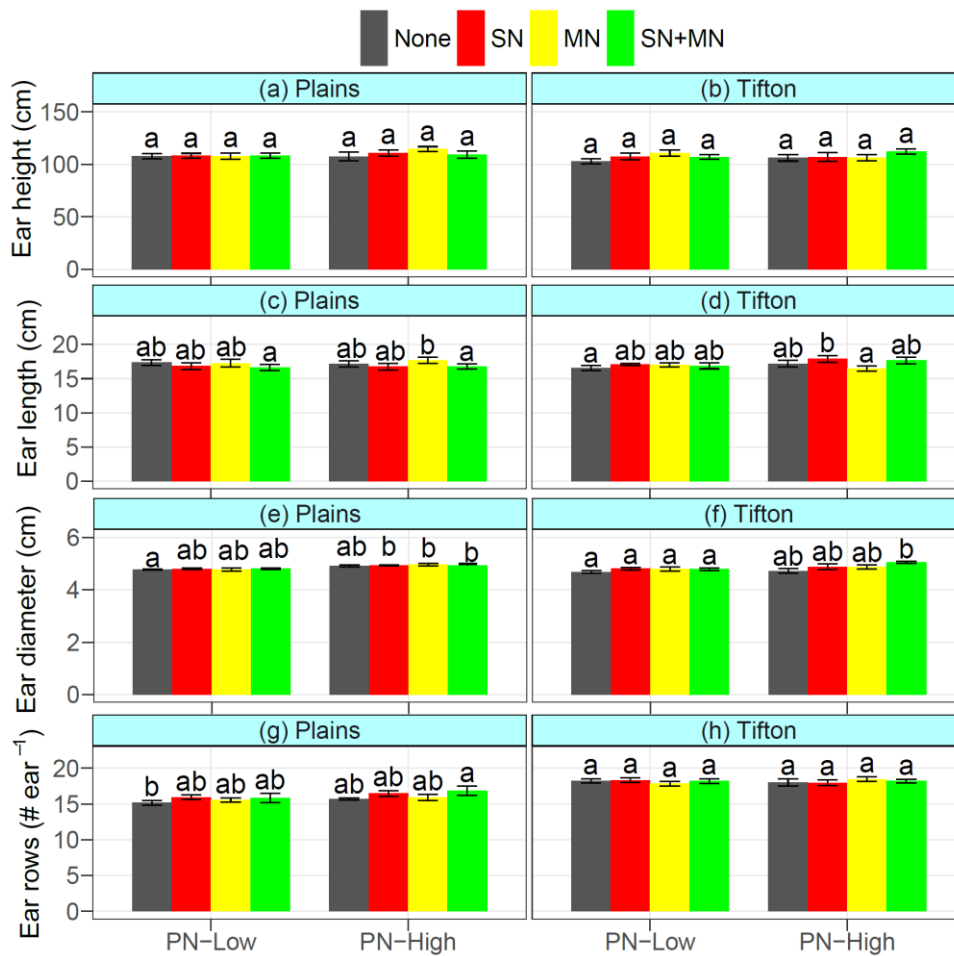


Figure 3.4: Effects of primary nutrient (PN; N, P, and K), secondary nutrient (SN; Mg, Ca, and S), and micronutrient (MN; B, Zn, Mn, Fe, Cu, and Mo) application on ear development (ear height, ear length, ear diameter, and ear rows) in Plains and Tifton, GA. Within every location and growth stage, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars represent standard errors of the mean. PN-Low and PN-High refer to N, P, and K rates fertilized to achieve 12.5 Mg ha^{-1} and 25.1 Mg ha^{-1} yield, respectively.

Supplemental Tables

Table S3.1: Total nutrient rates (kg ha^{-1}) imposed for the low and high primary nutrient (PN) treatments that received both secondary and micronutrients in Plains and Tifton.

Year	PN	N	P ₂ O ₅	K ₂ O	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
----- Plains -----													
2020	Low	235	157	150	11.2	22.4	16.8	0.6	3.4	5.6	5.6	0.6	0.6
	High	504	291	151	11.2	22.4	16.8	0.6	3.4	5.6	5.6	0.6	0.6
2021	Low	235	146	152	11.2	22.4	22.4	0.6	3.4	5.6	5.6	1.1	0.6
	High	504	280	153	11.2	22.4	22.4	0.6	3.4	5.6	5.6	1.1	0.6
----- Tifton -----													
2020	Low	235	135	153	16.8	22.4	22.4	1.1	3.4	9.0	5.6	1.1	0.6
	High	504	269	154	16.8	22.4	22.4	1.1	3.4	9.0	5.6	1.1	0.6
2021	Low	269	146	155	22.4	33.6	16.8	1.1	3.4	9.0	5.6	0.6	0.6
	High	538	280	156	22.4	33.6	16.8	1.1	3.4	9.0	5.6	0.6	0.6
2022	Low	235	157	157	17.2	16.8	22.4	1.1	4.5	11.2	5.6	1.1	0.6
	High	504	291	381	17.2	16.8	22.4	1.1	4.5	11.2	5.6	1.1	0.6

Table S3.2: Source of nutrients used in the study.

N	Urea; Ammonium nitrate; Urea ammonium nitrate solution (UAN 32)
P	Di-ammonium phosphate; Triple super phosphate; Ammonium polyphosphate solution
K	Potassium chloride; Potassium nitrate
Mg	Magnesium oxy-sulfate; Magnesium nitrate solution
Ca	Calcium chloride; Calcium nitrate solution
S	Potassium sulfate; Epsom; Ammonium thiosulfate solution
B	Fertilizer borate; Borosol [®] 10 solution
Zn	Zinc oxysulfate; Zinc nitrate solution
Mn	Manganese sucrate; Manganese nitrate solution
Fe	Iron sucrate; Chelated iron ethylenediaminetetraacetic acid; Iron nitrate solution
Cu	Copper sulfate; Copper nitrate solution
Mo	Sodium molybdate

Table S3.3: *P*-values of the main effects and interaction effects of primary nutrient (PN; N, P, and K), secondary nutrient (SN; Mg, Ca, and S), and micronutrient (MN; B, Zn, Mn, Fe, Cu, and Mo) application on nutrient concentrations of corn leaf tissues sampled at the vegetative growth stage in Plains (between V5 and V6) and Tifton (between V6 and V7), as well as the reproductive growth stage (between VT and R1) in Plains and Tifton.

Source	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
----- Vegetative (Plains) -----												
PN	0.792	0.191	0.818	0.808	0.167	0.541	0.426	0.914	0.207	0.412	0.251	0.942
SN-MN	0.973	0.015	0.422	0.561	0.014	0.948	0.620	0.127	0.150	0.720	0.061	0.004
PN x SN-MN	0.204	0.040	0.187	0.055	0.000	0.241	0.483	0.644	0.512	0.804	0.218	0.244
----- Vegetative (Tifton) -----												
PN	0.952	0.265	0.806	0.362	0.625	0.211	0.507	0.084	0.025	0.633	0.965	0.531
SN-MN	0.959	0.166	0.384	0.016	0.095	0.136	<0.000	0.132	0.255	0.014	0.008	0.026
PN x SN-MN	0.178	0.926	0.299	0.034	0.196	0.434	0.432	0.757	0.787	0.718	0.676	0.835
----- Reproductive (Plains) -----												
PN	0.213	0.766	0.530	0.630	0.078	0.273	0.073	0.504	0.282	0.567	0.055	0.818
SN-MN	0.013	0.086	0.381	0.066	0.514	0.139	<0.000	0.001	0.040	0.466	0.002	<0.000
PN x SN-MN	0.417	0.631	0.694	0.701	0.079	0.649	0.027	0.600	0.095	0.664	0.770	0.007
----- Reproductive (Tifton) -----												
PN	<0.000	0.001	0.010	0.837	0.229	0.004	0.070	0.045	0.001	0.007	0.068	0.259
SN-MN	0.006	0.249	0.377	0.010	0.012	<0.000	<0.000	<0.000	0.010	<0.000	<0.000	<0.000
PN x SN-MN	0.011	0.428	0.470	0.342	0.879	0.544	0.328	0.891	0.002	0.371	0.765	0.944

† Bold texts highlight significant effect terms ($P < 0.05$).

Table S3.4: *P*-values of the main effects and interaction effects of primary nutrient (PN; N, P, and K), secondary nutrient (SN; Mg, Ca, and S), and micronutrient (MN; B, Zn, Mn, Fe, Cu, and Mo) application on corn growth, yield, and development in Plains and Tifton.

Source	Biomass (vegeta.)	Biomass (reprod.)	Plant height	Yield	Stover	Harvest index	TSW	Ear height	Ear length	Ear diameter	Ear rows
-----Plains-----											
PN	0.640	0.866	0.124	0.001 [†]	0.030	0.067	0.003	0.630	0.685	<0.000	0.026
SN-MN	0.309	0.216	0.085	0.007	0.046	0.700	0.016	0.208	0.006	0.573	0.049
PN x SN-MN	0.620	0.015	0.331	0.763	0.809	0.428	0.207	0.061	0.459	0.746	0.673
-----Tifton-----											
PN	0.437	0.186	0.397	<0.000	0.007	0.700	0.003	0.427	0.085	0.001	0.575
SN-MN	0.707	0.806	0.697	<0.000	0.487	0.005	0.001	0.442	0.016	0.007	0.964
PN x SN-MN	0.375	0.029	0.037	0.015	0.024	0.162	0.015	0.416	0.053	0.148	0.162

[†] Bold texts highlight significant effect terms ($P < 0.05$). TSW: Thousand seed weight.

CHAPTER 4

ASSESSING CORN RESPONSE TO EARLY SEASON NUTRIENT STRESS UNDER DIFFERENT SOIL MOISTURE REGIMES TO INFORM ADAPTIVE NUTRIENT MANAGEMENT

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Abstract

Adaptive nutrient management synchronizes nutrient supply with crop demand to improve nutrient use efficiency and crop productivity. Corn (*Zea mays*) biomass accumulation and nutrient uptake by the V6 growth stage is low, <5% and <15% of the total at maturity, respectively. Assessing corn recovery from early season nutrient stress could help formulate adaptive nutrient management strategies. Field studies were conducted to evaluate corn performance when no fertilizer application is made until the V6 growth stage, and thereafter, applying fertilizer rates as those in non-stressed conditions. Thus, the early season nutrient stress and non-stress conditions received the same amount of nutrients. As the availability of nutrients for plant uptake is largely dependent on soil moisture, corn recovery from the early season nutrient stress was assessed under different soil moisture regimes induced via irrigation scheduling at 50% and 80% field capacity under overhead and subsurface irrigation systems. Peanut was the previous crop under all conditions, and the fields were under cereal rye (*Secale cereale*) cover crop. At the V6 growth stage, the nutrient concentrations of the early season-stressed crops, except for Cu, were above the minimum threshold of sufficiency ranges reported for corn. However, the crops showed poor growth, with biomass accumulation being more than 2× lower than non-stressed crops. Moreover, corn recovery from the stress was low. Compared to non-stress conditions, the early season nutrient stress caused 1.58 Mg ha⁻¹ to 3.4 Mg ha⁻¹ yield reduction, translating to 11.7% to 37.6% yield reduction. The findings highlight the susceptibility of corn to nutrient stress in the early season, and therefore, ample nutrient supply in the early season is critical even in adaptive nutrient management systems.

1.0. Introduction

Optimum plant nutrition is required to sustain plant health and productivity, especially for a high-input crop such as corn (*Zea mays*). The application of fertilizer to meet plant nutritional needs is critical in regions with highly weathered soil conditions. Oxisols and Ultisols, for instance, are highly weathered soils commonly found in tropical and subtropical regions. They are characterized by low organic matter, strong acidity, and poor native fertility because of rapid mineralization rates, intense weathering of primary minerals, and leaching of essential base cations (Juo and Franzluebbers, 2003; Chesworth et al., 2008; Weil and Brady, 2017; Nunes et al., 2019). This makes fertilizer a major input cost in corn production in the region. Moreover, instability in the supply and prices of fertilizers observed in recent years poses much concern (Singh and Tan, 2022; Amissah et al., 2023b). Several fertilizers exceeded record prices in 2008, affecting growers' profit margins (Singh and Tan, 2022).

Therefore, fertilizer application needs to be optimized to minimize nutrient loss and sustain crop productivity. Adaptive nutrient management optimizes nutrient application by synchronizing nutrient supply with crop demand. Crop nutrient requirements are low at the initial stages of growth, increasing towards the reproductive stage (Bender et al., 2013; Ciampitti and Vyn, 2014). A study conducted at two locations in the state of Illinois in the United States showed that by the V6 growth stage, <15% of primary, secondary, and micronutrients had been taken up by corn when compared to the total taken up at maturity (Bender et al., 2013). Also, biomass accumulation by the V6 stage was <5%. Synchronizing nutrient application with crop demand could increase nutrient use efficiency and minimize nutrient losses through runoff, leaching, ammonia

volatilization, and denitrification (Esfandbod et al., 2017; Shahzad et al., 2018, 2019a; Amissah et al., 2023a).

In conventional nutrient management, almost all the fertilizer rates are applied before planting or at the initial stages of planting, except for nitrogen, which is usually split applied. In the southeast United States, with characteristic high rainfall and temperatures, fertilizers applied at the initial stages of growth are susceptible to losses, especially when the vegetation cover is minimal. Knowledge of corn recovery to early season nutrient stress could be used to better synchronize nutrient application with crop demand. In the state of Georgia, where this study was conducted, corn follows peanut (*Arachis hypogaea*) in a typical rotation. Moreover, the state has a sub-tropical climate, characterized by warm and wet conditions, which could rapidly mineralize peanut crop residues and potentially supply adequate nutrients at the early growth stages (Balkcom et al., 2004).

The availability of nutrients to plants for uptake depends on the amount of water in the soil. Dry soil conditions can reduce nutrient uptake because water carries nutrients to plants (Pan et al., 2011; Sintim et al., 2015, 2016; Kusi et al., 2021b). Water stress at the developmental stages of corn is likely to affect plant performance, including plant biomass, ear length, and number of grains per ear, ultimately resulting in yield reduction (Bista et al., 2018; Wang et al., 2019; Sah et al., 2020). The objective of the study was to assess corn recovery from early-season nutrient stress under different soil moisture regimes. The different soil moisture regimes were induced by irrigation triggered when the soil water content was at 50% field capacity (FC-50) and 80% field capacity (FC-80). Also, the study was established under overhead irrigation and subsurface drip irrigation (SSDI) systems. We expected corn to respond differently to early-season nutrient stress under the various irrigation scheduling and application methods.

2.0. Materials and Methods

2.1. Experimental Site

Field experiments were established in 2021 and 2022 at the University of Georgia Stripling Irrigation Research Park in Camilla, GA (31°16'45.86"N, 84°17'29.65" W). The soil at the experimental site was Lucy loamy sand, classified as Loamy, kaolinitic, thermic Arenic Kandiudults, with an average sand, silt, and clay content of 90.7%, 3.2%, and 6.1%, respectively, at the 0-15 cm depth. The climate at the experimental site is subtropical, having average annual maximum, mean, and minimum air temperatures of 26.0°C, 19.4°C, and 12.8°C, respectively, with an annual rainfall of 1,314 mm and 98 average rainy days (Georgia AEMN, 2023). The minimum, average, and maximum air temperatures were 10.3°C, 20°C, and 27.7°C, respectively, in 2021, and 9.10°C, 19.7°C, and 28.1°C, respectively, in 2022. Annual rainfall was 1,419 mm in 2021 and 1,100 mm in 2022. Total rainfall received during the corn growing season (between planting and harvest) was 791 mm in 2021 and 629 mm in 2022.

2.2. Experimental Approach

The field experiment entailed two irrigation scheduling thresholds (FC-50 and FC-80), and two nutrient stress conditions [early season nutrient stress (E-stress) and non-nutrient stress (N-stress)]. The treatment factors were laid in a split-plot randomized complete block design with four replications, and the experiment was established under SSDI and overhead irrigation systems that were 50 m apart in 2021 and 200 m apart in 2022. The irrigation schedules were the main plot factors while the nutrient stress levels were the subplot factors.

The N-stress entailed periodic nutrient application to ensure plant tissue nutrient levels were within recommended sufficiency levels for corn (Campbell, 2000). The E-stress entailed no nutrient application until the V6 growth stage, after which the plots received a similar nutrient

application as the N-stress. The nutrient rates not supplied to the E-stress at the early stage were provided between the V6 and V7 growth stages. Thus, both nutrient stress levels received the same nutrient rates. Granular sources of nutrients were used as pre-plant fertilizer sources, whereas in-season nutrient applications were by use of liquid side-dress applicators and injection through irrigation systems. Nutrient rates and main nutrient sources applied are presented in Table S4.1.

Irrigation schedule was determined by utilizing Teros 12 moisture sensors (METER Group, Inc., Pullman, WA, USA) installed at (a) 10 cm deep and 15 cm to the side of plant row, (b) 20 cm deep and 15 cm to the side of plant row, and (c) 30 cm deep and 25 cm to the side of plant row to monitor soil moisture dynamics. The sensors were connected to a Zentra datalogger which was used to wirelessly transmit hourly soil moisture data. The available water holding capacity of the soil was calculated as the difference in water content at -33 kPa and -1500 kPa (Klute, 1986). Table 4.1 provides the amount of irrigation water supplied under the different irrigation scheduling and application methods.

2.3. Experimental Field Management

A lateral irrigation unit was used for the overhead irrigation system, and had variable rate irrigation application capability. The SSDI system was set up by installing Netafim Typhoon drip tapes (Netafim Irrigation, Inc., Fresno, CA, USA) in the middle of plant rows at 30 cm soil depth. The fields were under cereal rye (*Secale cereale*) cover crop, and peanut was the previous cash crop in both years. The cover crop was terminated by spraying Glyphosate [N-(phosphonomethyl) glycine] at the manufacturer-recommended rates, and the fields were prepared by strip-tilling to a depth of 30.5–45.7 cm before planting in March each year. The plot size was 12.2 m long by 5.49 m wide under the SSDI and 12.8 m long by 7.32 m wide under the overhead irrigation. Corn hybrid A6499STX by AgriGold was used, and it was planted at a rate of 88,958 seeds ha⁻¹ and row spacing

of 91.4 cm. Standard recommendations by the University of Georgia Cooperative Extension were followed to control pests and weeds.

2.4. Data Collection

Initial nutrient levels of the soil were determined by sampling soils at 0-15 cm depth and sending them to the Waters Agricultural Laboratories, Inc. for analyses following standard procedures. Nitrate-N was measured with the automated flow injection analysis system (FIAlyzer-1000, FIALab Instruments, Inc., Seattle, WA, USA) after extraction in a 2 M KCl solution. Extractable P, K, Ca, Mg, Fe, Mn, Zn, B, and Cu were measured with an inductively coupled plasma optical emission spectrophotometer (ICP-OES; iCAP™ 6000 Series, Thermo Fisher Scientific, Cambridge, United Kingdom) after extraction with Mehlich I solution, and S measured after extraction with monocalcium phosphate.

Before nutrient application in the E-stress plots, aboveground tissue samples were collected at the V6 growth stage within a uniform 1-m long strip of every plot and dried in an oven to constant weight to determine plant biomass. Nutrient analyses of the biomass samples were performed at the H.SINTIM LAB of the University of Georgia campus in Tifton, GA, following standard procedures. A 2400 Series II CHNS/O Elemental Analyzer (PerkinElmer U.S. LLC, Shelton, CT, USA) was used to measure the total N. Also, Avio 200 ICP-OES (PerkinElmer U.S. LLC, Shelton, CT, USA) was used to measure total P, K, Ca, Mg, S, Fe, Mn, Zn, B, Cu, and Mo after sample digestion in nitric acid and hydrogen peroxide mixture using DigiPREP MS digestion block (SCP Science, Montreal, QC, Canada). Plant height (measured from the soil surface to the tallest leaf); ear height (measured from the soil surface to the base of the ear); ear length (length of the cob); ear diameter (measured from the center of the cob with grain intact); and ear rows

(number of rows of corn grains on the cobs); and thousand seed weight (TSW) were determined at physiological maturity from plants within a uniform 1-m long strip. Also, the plants were partitioned into seeds and stover and dried in an oven to constant weight, and the weights were used to calculate the harvest index. The entire length of two rows of every plot was harvested with a plot combine harvester to obtain the seed weight and moisture content. The seed yield was determined at 155 g kg⁻¹ moisture content.

2.5. Statistical Analyses

The collected data was analyzed using a linear mixed model with the ‘lme4’ package in R (Bates et al., 2015). Separate statistical analyses were performed for the studies under the overhead irrigation and SSDI systems. The irrigation scheduling and nutrient stress factors were considered fixed effects, and year and block were considered random effects. Homoscedasticity of variance and assumptions of normality of residuals were assessed, and where appropriate, data transformation was performed using the Box-Cox transformation or the square root transformation methods. Separation of means was performed using the least square means and adjusted Tukey multiple comparison procedures with the ‘emmeans’ package in R (Lenth, 2018); significance level of all analyses was assessed at $P = 0.05$.

3.0. Results and Discussion

3.1. Initial Soil Nutrients

Initial nutrient concentrations of the soil are presented in Table 4.2. In general, the initial NO₃-N levels were low despite peanut, a legume, being the previous crop. However, the initial levels of the other nutrients were above the low threshold of the soil test classification for corn by the University of Georgia Extension, except for Zn in 2021 in the SSDI field (UGA-AESL, 2023).

Nitrogen is normally not included in routine soil tests in the region because available forms of nitrogen do not accumulate (Kissel and Sonon, 2008; Hurisso et al., 2018). The sandy nature and high rainfall conditions in the region cause the available forms of nitrogen to readily leach, which could explain why low initial NO₃-N levels were observed. Moreover, rye cover crops could have depleted the soil of NO₃-N. In addition, soils were sampled in late February, when temperatures were still low; thus, the peanut crop residuals may not have been sufficiently mineralized by the time of sampling (Grzyb et al., 2020; Shahzad et al., 2022; Amissah et al., 2023b). Mineralization of crop residues depends on several abiotic and biotic factors, including temperature, rainfall, soil properties, the chemical composition of crop residues, and the structure and composition of microbial communities (Whalen, 2014; Shahzad et al., 2019b; Grzyb et al., 2020; Sintim et al., 2022a; b).

3.2. Soil Water Dynamics

In 2021, the moisture sensors were initially installed at just the 20-cm and 30-cm soil depths. However, the sensors could not detect low rainfall events well. Thus, additional sensors and data loggers were obtained and installed at the 10-cm soil depth, except for the FC-80 treatment under the SSDI system due to limited supply. Soil moisture recharge at the 30-cm depth of the overhead irrigation at FC-50 was low during the mid-season in 2021. This triggered more irrigation, and thus, the difference in irrigation water amount between the FC-50 and FC-80 of the overhead system was lower in 2021 than in 2022 (54 mm vs. 206 mm). Under the SSDI system, when soil moisture values of the sensors installed at 10 cm depth in 2021 and at 10 cm and 20 cm depths in 2022 are compared with those installed at the 30 cm depth, it can be seen that the sensors at the shallower depths could not detect irrigation events (Figures 4.1). The sensors were, however,

able to detect rainfall events, demonstrating that the sensors were functional. As a result, the topsoil layer of the SSDI field was mostly below the permanent wilting point during the growing season, regardless of the irrigation scheduling threshold. In general, water content at the topsoil layer of the overhead irrigation was higher than those in the SSDI, except for a single occasion when the water content under the FC-50 went below the permanent wilting point in 2022. This was due to a technical constraint that delayed irrigation at the experiment station.

The inability of the soil moisture sensors at the topsoil layer to detect irrigation events under the SSDI system could be attributed to the configuration of the soil profile. The field has a top sandy layer underlaid by kaolinite clay minerals in the subsoil. Clay minerals have a larger surface area and more negative matric potential than sand (Jury and Horton, 2004). The drip tapes were installed at a 30-cm depth, which was at the interface of the sandy and clayey soil layer. Thus, the irrigation water would preferentially move downwards due to the higher capillarity of the clay layer and the downward exertion of the force of gravity (Abu-Zeid and El-Aal, 2017; Kroes et al., 2018; Rambabu et al., 2023). Irrigation water will only redistribute upwards to maintain equilibrium under very wet subsoil conditions.

3.3. Tissue Nutrient Concentration at the Vegetative Stage

The *P*-values of the main effects and interaction effects of irrigation schedule and nutrient stress on the concentration of plant nutrients at the vegetative stage are presented in Table S4.2. The effects of the irrigation schedule on nutrient concentration were significant for only N under both the overhead and SSDI. Averaged across the fertility treatments under both irrigation scheduling methods, the FC-80 had a higher nutrient concentration, with a 6.07% and 7.65% increase in nutrient concentration under the overhead and SSDI, respectively, compared to the FC-

50 (Table 4.3). The effects of nutrient stress on nutrient concentration were significant for N, P, Mg, Ca, Zn, Mn, and Mo under the overhead irrigation and for N, Ca, B, Zn, Mn, Cu, Fe, and Mo under the SSDI. The E-stress increased the concentrations of Mg, Ca, and Mo by 14.0%, 13.1%, and 30.5%, respectively, under the overhead irrigation and the concentrations of Ca, B, and Mo by 15.6%, 14.0%, and 63.3%, respectively, under the SSDI. In contrast, the N-stress increased the concentrations of N, P, Zn, and Mn by 26.4%, 22.3%, 28.7%, and 100%, respectively, under the overhead irrigation and N, Zn, Mn, Cu, and Fe by 17.2%, 20.6%, 35.7%, 55.7%, and 20.7%, respectively, under the SSDI (Table 4.2). The interaction between irrigation schedule and nutrient stress was significant for only N under the overhead irrigation method, with a greater reduction in N concentration from E-stress being more severe under the FC-50 than under the FC-80 (24.3% vs. 17.4%). Similar observations were made under the SSDI (17.7% vs. 12.0%), except the interaction term was not significant.

The greater reduction in N concentration from E-stress under the FC-50 could suggest water content at 50% of the soil's field capacity was not sufficient to solubilize a lot of N. Water stress can drastically reduce the concentration of N since the amount of nutrients a plant can take depends on the volume of water available (Saud et al., 2017; Plett et al., 2020). The E-stress had almost all the plant tissue nutrient concentrations above the low threshold of the reference nutrient sufficiency ranges (NSRs) reported in the Southern Cooperative Series Bulletin (SCSB) #394 (Campbell, 2000), a publication of a regional collaboration that provides nutrient sufficiency ranges (NSRs) for plant analyses in the southern region of the United States (Campbell, 2000). Only Cu, under the E-stress of the FC-80 for both overhead irrigation and SSDI, had concentrations below the NSRs reported in the SCSB publication.

Nutrient concentration is affected by biomass accumulation, and hence, crops with good growth could have lower nutrient concentrations than those with poor growth, even though the actual nutrient uptake may be greater. The effect is commonly termed as ‘dilution effect.’ Nutrient concentration alone is therefore not an adequate way to compare nutrient availability to crops. Research work by Amissah et al., (2023a) to assess the nutrient sufficiency ranges of corn in the SCSB publication showed some plots had >95% relative biomass at the V6-V7 growth stage even though the Cu levels were below the lower threshold. The findings highlighted that corn can tolerate lower Cu levels than reported. Moreover, Amissah et al. (2023a) observed that 25.4% of samples that had all nutrient concentrations above the lower threshold even had relative biomass <50%, and the effects were not due to the accumulation of nutrients at toxic levels. Thus, the thresholds of some nutrients can be higher or lower than what is currently reported, especially with the breeding of new corn varieties that are high-yielding and expected to require more nutrients (Bender et al., 2013).

3.4. Biomass and Nutrient Uptake at the Vegetative Stage

The *P*-values of the main effects and interaction effects of irrigation schedule and nutrient stress on plant biomass and nutrient uptake at the vegetative stage are presented in Table S4.3. The effects of the nutrient stress on biomass were significant for both the overhead irrigation and the SSDI. The effects of the irrigation schedule and the interaction effects between the irrigation schedule and nutrient stress were not significant. Averaged over the irrigation schedule, the biomass of N-stress was 2× greater than the biomass of E-stress under the overhead irrigation, and 2.6× greater under the SSDI (Table 4.4). Figure S4.1 is a drone image of the SSDI field, showing poor growth in the E-stress plots. The effects of E-stress under the SSDI were more severe than under the

overhead irrigation, likely because of dry conditions experienced at the topsoil layer of the SSDI field. Water regulates the transport of nutrients to the plant (Smethurst, 2004; Plett et al., 2020). Water stress will therefore lead to reduced uptake of water and nutrients and subsequently impact stomatal opening and absorption of carbon dioxide for photosynthesis. The effect will reduce growth, resulting in reduced biomass accumulation and partitioning (Chatzistathis and Therios, 2013; Bárzana and Carvajal, 2020; Pandey et al., 2021; Yan et al., 2023).

In contrast to the results observed for nutrient concentration at the vegetative stage, the effects of nutrient stress on nutrient uptake were significant for all nutrients under both the overhead irrigation and the SSDI (Table 4.4). Under both irrigation scheduling methods, the E-stress caused a reduction in nutrient uptake. Irrigation scheduling had a significant impact on the uptake of N, K, Mg, and Ca under overhead irrigation but not under the SSDI (Table 4.3). The interaction of irrigation scheduling and nutrient stress did not have a significant impact on nutrient uptake at the vegetative stage. Under the overhead irrigation, the E-stress caused a general reduction in nutrients. The nutrient uptake for the FC-50 irrigation scheduling method was higher than the FC-80, with the differences being significant for the N, K, Mg, and Ca under the overhead irrigation system. A similar trend was observed under the SSDI except for the uptake of S, Zn, and Cu where they were rather higher under the FC-80.

Reduction in nutrient uptake for the E-stress suggests the residual nutrients in the soil and mineralization of the peanut crop residues could not supply adequate nutrients to the crop by the V6 growth stage where nutrient requirement by corn was still relatively low. Nutrient uptake of corn by the V6 growth stage was reported to be <15% of the total taken up by maturity (Karlen et al., 1988; Bender et al., 2013; Ciampitti and Vyn, 2013; Ciampitti et al., 2013a). Despite the reduced nutrient requirement of corn in the early season, nutrient supply must be optimum to

sustain plant health and growth because nutrient stress at any of the developmental stages of corn can affect biomass accumulation (Bender et al., 2013; Ciampitti et al., 2013b). In contrast to corn, early-season nutrient stress in cotton (no nutrient application from planting to the square stage) did not affect plant growth and yield in a study conducted at the experimental site (Amissah et al., 2023b). Unlike corn, cotton is an indeterminate crop and can exhibit a high degree of plasticity in growth (Atkin et al., 2006; Rochester et al., 2012; Li et al., 2020; Kusi et al., 2021a; Amissah et al., 2023b).

3.5. Yield and Growth Parameters at Maturity

The interaction effects of irrigation schedule and nutrient stress were not significant on seed yield under both the overhead irrigation and SSDI systems (Table S4.4). The main effects of the irrigation schedule on seed yield were significant under just the SSDI system, but the main effects of nutrient stress on seed yield were significant under both the overhead and SSDI systems. The E-stress caused a yield reduction of 1.58 Mg ha⁻¹ (11.7%) and 1.86 Mg ha⁻¹ (13.0%), respectively, for the FC-50 and FC-80 under the overhead irrigation system and 2.95 Mg ha⁻¹ (38.2%) and 3.4 Mg ha⁻¹ (37.6%), respectively, for the FC-50 and FC-80 under the SSDI when compared to the N-stress (Figure 4.2a, b). Under the SSDI, the FC-50 caused a 3.07 Mg ha⁻¹ (16.7%) reduction in seed yield when compared to the FC-80. Also, under the overhead irrigation, the FC-50 caused a 1.79 Mg ha⁻¹ (5.9%) reduction in seed yield compared to the FC-80, but the difference was not significant as already noted.

Unlike seed yield, the main effects of the irrigation schedule were not significant on the plant height under both the overhead irrigation and SSDI systems. The main effects of nutrient stress were, however, significant on the plant height under the SSDI system (Table S4.4). The E-

stress significantly decreased plant height compared to the N-stress under both FC-50 (by 9.38%) and FC-80 (by 6.43%) (Figure 4.2c, d). Under the overhead irrigation, the FC-80 also resulted in increased plant height compared to the FC-50, albeit the differences were not significant. The main effects of nutrient stress were significant on the stover under both the overhead irrigation and SSDI systems, but the main effects of the irrigation schedule were significant under just the SSDI system (Table S4.4). Compared to the N-stress, the E-stress decreased the stover by 29.9% (FC-50) and 21.9% (FC-80) under the overhead irrigation and by 34.6% (FC-50) and 31.6% (FC-80) under the SSDI (Figure 4.2e, f).

In contrast, the E-stress increased the harvest index over the N-stress under both the overhead irrigation and SSDI systems (Table S4.4 and Figure 4.2g, h). Although the differences were statistically significant, the magnitude was relatively marginal, with the E-stress increasing harvest index over the N-stress by just 3.3% (FC-50) and 2.8% (FC-80) under the overhead irrigation and by 3.1% (FC-50) and 3.9% (FC-80) under the SSDI (Figure 4.2e, f). The main effects of the irrigation schedule and the interaction effects of the irrigation schedule and nutrient stress were not significant on the TSW under both the overhead irrigation and SSDI systems (Table S4.4). However, the main effects of nutrient stress were significant on the TSW under the SSDI. The E-stress decreased the TSW by 7.77% under the FC-50 and by 4.80% under the FC-80 compared to the N-stress.

In general, the seed yield and plant development parameters were better under the overhead irrigation than under the SSDI. However, statistical inference could not be made to establish causation because they were established in different fields. Notwithstanding, we expected the dry conditions of the topsoil layer under the SSDI field, evident by the soil moisture sensors, to affect plant growth and productivity (Akıncı and Lösel, 2012; Bárzana and Carvajal, 2020; Sah et al.,

2020). The soil moisture sensors at the 10-cm depth of the SSDI field showed that the water content was below the permanent wilting point for a prolonged period. Reduced nutrient uptake due to drought stress can result in a reduction in cell expansion, stunted growth, and increased susceptibility to pests and diseases, all of which will eventually lead to reduced biomass, yield, stover, harvest index, and TSW as observed in this study (Hussain et al., 2019; Bárzana and Carvajal, 2020).

The inability of corn to fully recover from the early season nutrient stress, as evidenced by the reduced seed yield and poor plant development in the E-stress, highlights the sensitivity of corn in the early season because it transitions through its developmental stages quickly (Roth et al., 2023). The effects of E-stress were more prominent under the SSDI system than under the overhead irrigation, possibly due to the combined effects of nutrient and moisture stress. When compared to the N-stress, the E-stress reduced grain yield by 38.2% and 37.7%, respectively, under the FC-50 and FC-80 of the SSDI field, whereas the yield reduction of E-stress in the overhead irrigation field was 11.7% and 13%, respectively, under the FC-50 and FC-80. The E-stress, however, resulted in a higher harvest index than the N-stress. Harvest index is a measure of the efficiency of plant biomass partitioned to the grain (Smith et al., 2018; Porker et al., 2020). Prevailing environmental conditions can cause an increase or decrease in the harvest index of corn. Generally, crops survive stress by reducing the length of the vegetative stage, which limits the growth of the vegetative parts to partition photo-assimilates to the seeds (Unkovich et al., 2010; Cohen et al., 2021).

3.6. Ear Development

The main effects of irrigation schedule and the interaction effects of irrigation schedule and nutrient stress were not significant on the ear height, ear length, ear diameter, and ear rows. However, the main effects of nutrient stress had significant impacts on ear length, ear diameter, and ear rows under the overhead irrigation and on the ear diameter and ear rows under the SSDI (Table S4.4). Compared to the N-stress, the E-stress resulted in a general reduction in all the measured ear development parameters, ranging from 1.7% to 20% reduction in ear height, 2.4% to 8.7% reduction in ear length, 6.2% to 11.4% reduction in ear rows, and 2.6% to 5.9% reduction in ear diameter across the overhead irrigation and SSDI systems (Figure 4.3). The results indicate the early season nutrient stress affected the source and sink dynamics. The use of nutrients entails uptake, assimilation, translocation, and remobilization during senescence (Masclaux-Daubresse et al., 2010; Sintim et al., 2015, 2016). As already mentioned, nutrient stress can cause the plant to shorten the vegetative stage and progress to the reproductive stage (Unkovich et al., 2010; Cohen et al., 2021). Thus, plants may not accumulate adequate nutrients at the vegetative stage to translocate and remobilize, which could subsequently impact the ear development of corn, as observed in the E-stress plots.

4.0. Conclusions

The findings of the study show that corn is susceptible to nutrient stress in the early season. Moreover, the recovery of corn from early season nutrient stress was low, with 11.7% to 37.6% yield reduction when compared to non-nutrient stress conditions. The recovery of corn from the early season nutrient stress was also poorer under dryer soil moisture conditions. This study assessed a no fertilizer application condition in the early season until the V6 growth stage. Thus,

residual soil nutrients, which were within adequate levels except for N and Zn, were not adequate to support the initial growth of corn. Also, the mineralization of peanut residues did not supply ample nutrients even though the nutrient demand for corn by the V6 stage is low. Adequate nutrient supply at the early season growth stage is required to avoid any form of stress in corn. Excess nutrient supply, however, will be vulnerable to losses, especially mobile nutrients and those with high fixation potential in the soil. Thus, further studies are recommended to optimize the nutrient supply for corn at the initial growth stages for effective adaptive nutrient management.

5.0. References

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Tables

Table 4.1. Irrigation water supplied (in mm) under the different irrigation scheduling and application methods in 2021 and 2022.

Irrigation	----- FC-50 -----		----- FC-80 -----	
	2021	2022	2021	2022
Overhead	172	240	226	446
SSDI	117	244	189	470

SSDI: Subsurface drip irrigation; FC-50: Irrigation triggered at 50% field capacity; FC-80: Irrigation triggered at 80% field capacity.

Table 4.2. Initial nutrient status of the overhead and subsurface drip irrigation (SSDI) experimental field soil at 0-15 cm depth in 2021 and 2022.

Year	NO ₃ -N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
----- Overhead (kg ha ⁻¹) -----											
2021	2.04	81.5	152	103	980	9.20	0.60	5.30	40.1	28.0	0.80
2022	1.96	81.5	152	103	979	9.25	0.62	5.30	40.1	28.0	0.78
----- SSDI (kg ha ⁻¹) -----											
2021	1.60	38.1	76.8	62.7	800	10.1	0.28	1.35	19.6	10.1	4.99
2022	0.78	119	106	121	1131	24.6	0.31	6.11	43.1	26.1	1.12

Soil NO₃-N was measured after extraction with 2 M KCl solution; soil P, K, Ca, Mg, Fe, Mn, Zn, B, and Cu were measured after Mehlich I extraction; and soil S was measured after extraction with monocalcium phosphate.

Table 4.3: Effects of irrigation schedule and nutrient stress on nutrient concentrations of corn biomass sampled at the vegetative stage under overhead irrigation and SSDI systems.

Irrigation schedule	Nutrient stress	g kg ⁻¹						mg kg ⁻¹					
		N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
----- Overhead -----													
FC-50	E-stress	34.6±1.3a	4.00±0.12ab	55.61±0.93a	2.38±0.12b	6.65±0.24a	2.28±0.19a	11.1±0.4a	25.9±1.7a	75.4±5.2a	81.9±10.3a	5.18±0.48a	2.91±0.41b
FC-50	R-stress	45.7±1.6c	4.63±0.32bc	56.15±1.26a	2.05±0.12a	5.85±0.13ab	2.36±0.18a	10.8±0.4a	32.1±2.8b	151.4±31.5b	89.8±16.3a	5.68±0.13a	2.09±0.43a
FC-80	E-stress	38.5±2.2b	3.79±0.08a	55.85±1.42a	2.34±0.11ab	6.50±0.20a	2.27±0.16a	11.3±0.3a	24.1±2.0a	73.0±4.1a	78.2±16.1a	4.90±0.38a	2.63±0.42ab
FC-80	R-stress	46.6±1.8c	4.89±0.29c	57.10±1.55a	2.09±0.18ab	5.77±0.31b	2.32±0.18a	10.7±0.5a	32.3±2.6b	145.5±35.1b	87.7±15.6a	5.56±0.26a	2.15±0.39a
----- SSDI -----													
FC-50	E-stress	34.9±2.2a	4.45±0.18a	47.7±2.1b	2.58±0.23a	6.65±0.56b	2.11±0.13a	17.2±0.7c	28.1±4.6a	102.2±6.4a	75.5±9.6a	5.42±0.72ab	2.87±0.24b
FC-50	R-stress	42.4±1.0bc	4.75±0.09a	49.1±1.3a	2.49±0.20a	5.58±0.25a	2.18±0.14a	14.6±0.7a	31.7±4.8b	151.5±24.9b	91.9±7.6b	6.72±1.08ab	1.86±0.26a
FC-80	E-stress	39.0±0.9ab	4.40±0.18a	46.0±2.0b	2.61±0.22a	6.44±0.55b	2.22±0.19a	16.2±0.6bc	26.7±3.6a	93.1±12.6a	78.0±8.1a	4.93±0.33a	3.04±0.26b
FC-80	R-stress	44.3±1.7c	4.55±0.20a	48.9±2.1a	2.40±0.17a	5.74±0.30a	2.36±0.19a	14.8±0.4ab	34.3±6.5b	152.7±32.7b	93.3±8.2b	7.33±1.14b	1.76±0.29a

Within the irrigation application method (overhead or SSDI) and nutrient element, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean \pm standard error. SSDI: Subsurface drip irrigation; FC-50: Irrigation triggered at 50% field capacity; FC-80: Irrigation triggered at 80% field capacity; E-stress: early season nutrient stress; R-stress: reduced nutrient stress.

Table 4.4: Effects of irrigation schedule and nutrient stress on corn biomass and nutrient uptake at the vegetative stage under overhead irrigation and SSDI systems.

Irrigation schedule	Nutrient stress	Biomass	kg ha ⁻¹											
			N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
----- Overhead -----														
FC-50	E-stress	214±25a	7.55±1.1a	0.85±0.10a	11.9±1.4a	0.52±0.08ab	1.39±0.13a	0.46±0.03a	2.38±0.29a	5.34±0.54a	15.6±1.4a	16.0±1.4a	1.14±0.20a	0.68±0.16ab
FC-50	R-stress	483±38b	21.8±1.3c	2.29±0.29b	27.0±1.9c	0.98±0.07c	2.81±0.19c	1.16±0.16b	5.22±0.44b	15.9±2.23b	78.6±19.5b	45.1±9.5b	2.77±0.26b	0.93±0.14b
FC-80	E-stress	197±20a	7.71±1.0a	0.75±0.08a	10.9±1.1a	0.42±0.09a	1.29±0.15a	0.43±0.04a	2.24±0.26a	4.54±0.35a	14.0±1.2a	14.3±2.7a	0.95±0.11a	0.55±0.13a
FC-80	R-stress	356±22b	14.5±2.3b	1.76±0.17b	20.3±1.4b	0.74±0.08bc	2.05±0.18b	0.82±0.08b	3.80±0.30b	11.5±1.12b	46.4±13.5ab	31.3±6.0ab	1.98±0.17b	0.76±0.14ab
----- SSDI -----														
FC-50	E-stress	176±31a	6.09±1.4a	0.79±0.15a	8.69±1.71a	0.41±0.05a	1.11±0.17a	0.35±0.05a	2.92±0.43a	4.21±0.48a	17.8±2.86a	13.8±3.3a	0.86±0.10a	0.53±0.12ab
FC-50	R-stress	443±41b	15.3±2.5b	2.10±0.19b	21.58±1.87b	1.15±0.19b	2.52±0.31b	1.00±0.15b	6.57±0.81b	15.08±3.24b	71.9±16.33b	40.2±4.8b	3.22±0.76b	0.79±0.10b
FC-80	E-stress	153±20a	5.52±1.1a	0.66±0.07a	7.25±1.14a	0.38±0.03a	0.94±0.10a	0.32±0.03a	2.43±0.26a	3.64±0.19a	14.4±2.38a	12.9±2.5a	0.73±0.08a	0.48±0.09a
FC-80	R-stress	417±45b	15.0±2.6b	1.94±0.28b	20.05±1.86b	1.03±0.16b	2.46±0.38b	1.04±0.18b	6.25±0.80b	16.2±4.32b	70.4±19.63b	38.8±5.7b	3.38±0.78b	0.66±0.07ab

Within the irrigation application method (overhead or SSDI) and nutrient element, means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Values represent the mean ± standard error. SSDI: Subsurface drip irrigation; FC-50: Irrigation triggered at 50% field capacity; FC-80: Irrigation triggered at 80% field capacity; E-stress: early season nutrient stress; R-stress: reduced nutrient stress.

Figures

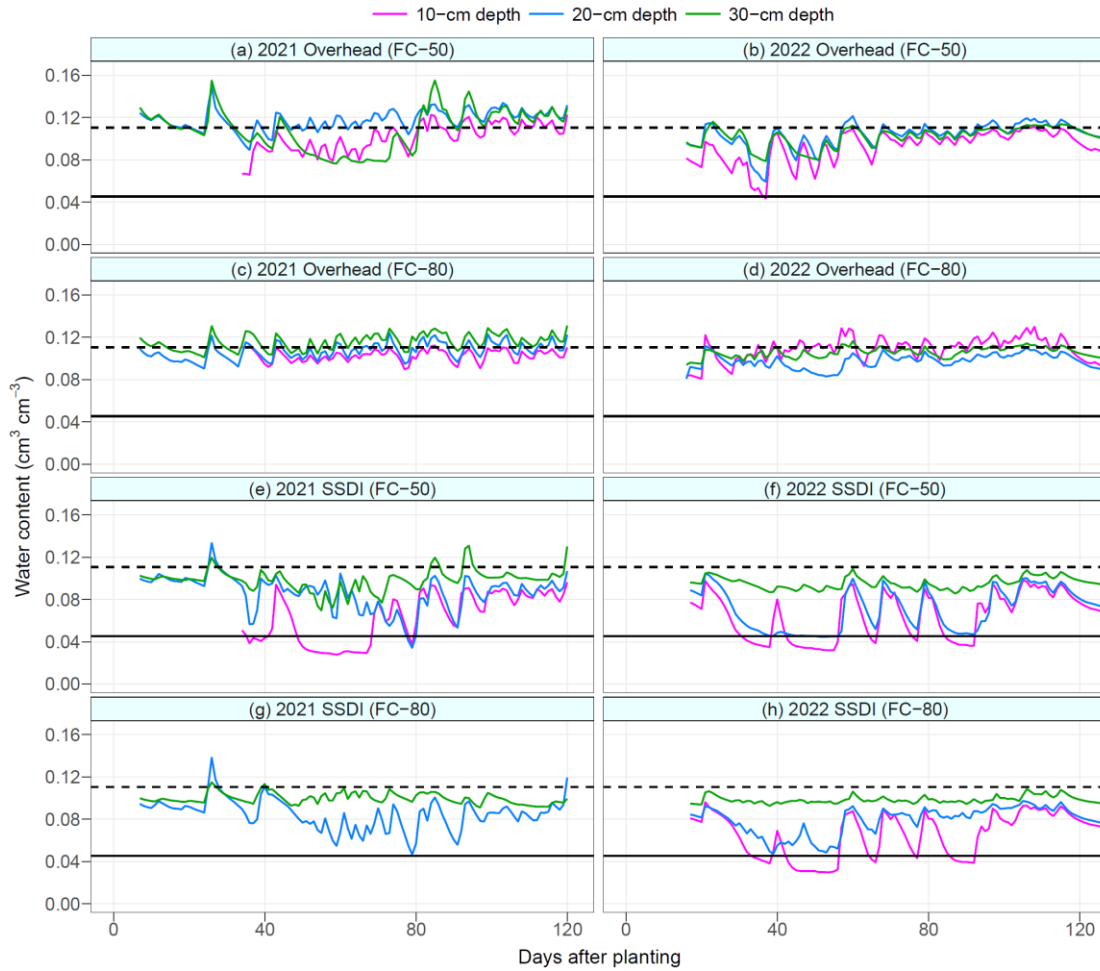


Figure 4.1. Mean daily soil water content at 10-cm, 20-cm, and 30-cm depths in 2021 (a, c, e, and g) and 2022 (b, d, f, and h). Black solid and dashed horizontal lines indicate the soil's permanent wilting point and field capacity, respectively. SSDI: Subsurface drip irrigation; FC-50: Irrigation triggered at 50% field capacity; FC-80: Irrigation triggered at 80% field capacity.

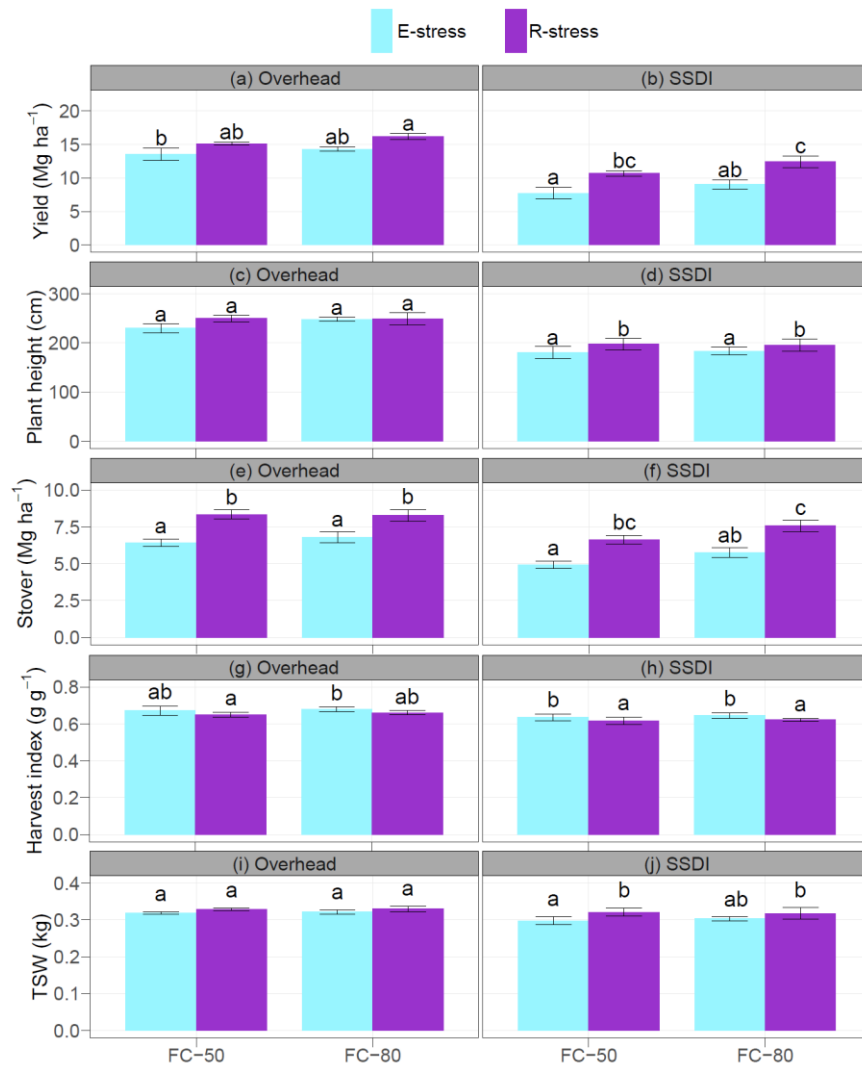


Figure 4.2: Effects of irrigation schedule and nutrient stress on corn yield and growth parameters at maturity under overhead irrigation and SSDI systems. Within the irrigation application method (overhead or SSDI) and measurement variable, bar plots of means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars indicate standard errors of the mean ($n = 4$). SSDI: Subsurface drip irrigation; FC-50: Irrigation triggered at 50% field capacity; FC-80: Irrigation triggered at 80% field capacity; E-stress: early season nutrient stress; R-stress: reduced nutrient stress; TSW: Thousand seed weight.

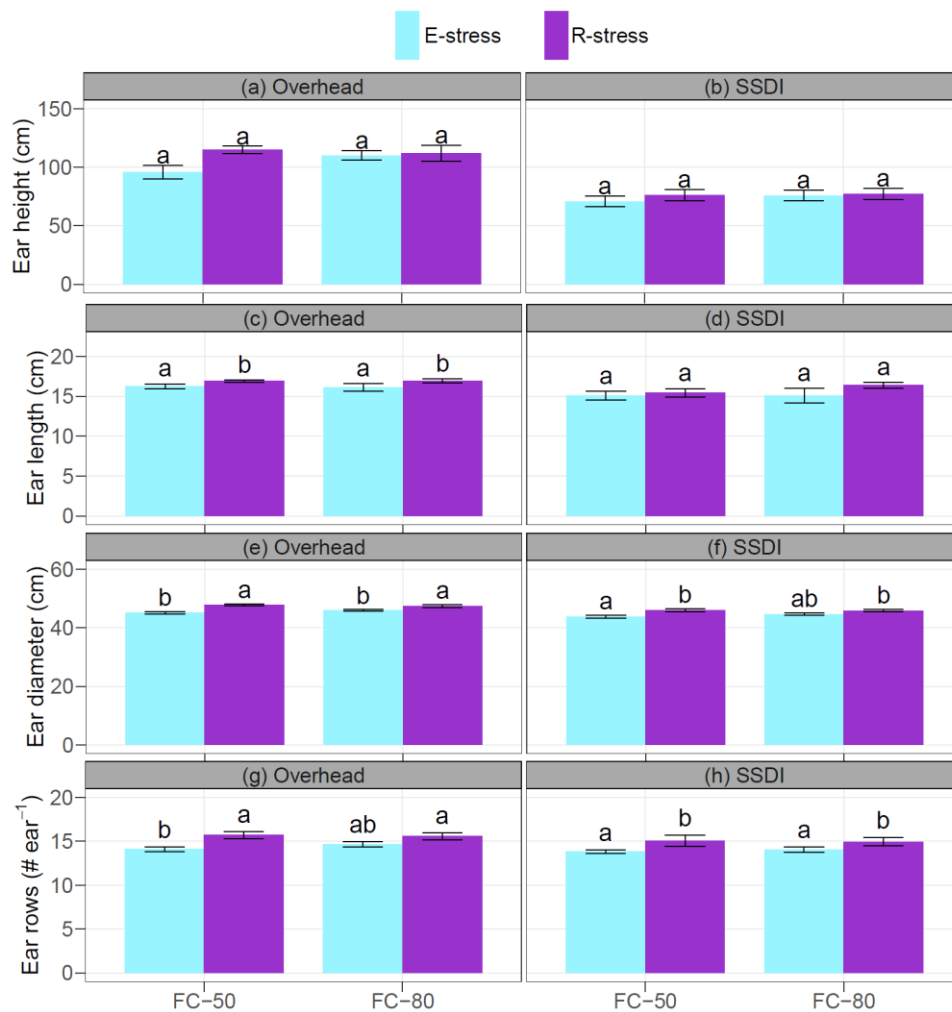


Figure 4.3: Effects of irrigation schedule and nutrient stress on corn ear development under overhead irrigation and SSDI systems. Within the irrigation application method (overhead or SSDI) and measurement variable, bar plots of means not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparisons ($P < 0.05$). Error bars indicate standard errors of the mean ($n = 4$). SSDI: Subsurface drip irrigation; FC-50: Irrigation triggered at 50% field capacity; FC-80: Irrigation triggered at 80% field capacity; E-stress: early season nutrient stress; R-stress: reduced nutrient stress.

Supplemental tables

Table S4.1: Total nutrient rates and main nutrient sources applied in 2021 and 2022.

Nutrients	Rates in 2021 kg ha ⁻¹	Rates in 2022 kg ha ⁻¹	Main nutrient sources
N	336	303	Urea; Urea ammonium nitrate solution
P ₂ O ₅	252	121	Diammonium phosphate; Ammonium polyphosphate solution
K ₂ O	280	280	Potassium chloride; Potassium nitrate
Mg	5.60	5.60	Magnesium oxy-sulfate; Magnesium nitrate solution
Ca	11.2	5.60	Calcium chloride; Calcium sulfate; Calcium nitrate solution
S	11.2	11.2	Potassium sulfate; Ammonium thiosulfate solution
B	0.56	1.12	Fertilizer borate derived from Ulexite; Borosol [®] 10 solution
Zn	1.12	1.68	Zinc oxysulfate; Zinc nitrate solution
Mn	1.68	3.36	Manganese sucrate; Manganese nitrate solution
Fe	1.68	2.24	Iron sucrate; Iron nitrate solution
Cu	0.56	0.56	Copper sulfate; Copper nitrate solution
Mo	0.00	0.22	Sodium molybdate solution

Table S4.2: *P*-values of the main effects and interaction effects of irrigation scheduling and nutrient stress on nutrient concentrations of corn biomass sampled at the vegetative stage under overhead irrigation and SSDI systems.

Effects	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
----- Overhead -----												
IS	0.046	0.927	0.669	0.833	0.641	0.787	0.972	0.597	0.943	0.499	0.617	0.587
NS	0.000	0.001	0.305	0.003	0.001	0.393	0.287	0.000	0.000	0.088	0.382	0.001
IS×NS	0.020	0.243	0.676	0.386	0.855	0.882	0.738	0.520	0.934	0.706	0.660	0.277
----- SSDI -----												
IS	0.024	0.477	0.610	0.869	0.939	0.137	0.333	0.795	0.654	0.907	0.701	0.895
NS	0.000	0.077	0.232	0.267	0.029	0.222	0.000	0.026	0.013	0.003	0.006	0.000
IS × NS	0.590	0.491	0.611	0.660	0.604	0.662	0.153	0.401	0.709	0.296	0.913	0.384

Bold texts highlight significant effects ($P < 0.05$). SSDI: Subsurface drip irrigation; IS:

Irrigation schedule; NS: Nutrient stress.

Table S4.3: *P*-values of the main effects and interaction effects of irrigation scheduling and nutrient stress on biomass and nutrient uptake of corn sampled at the vegetative stage under overhead irrigation and SSDI systems.

Effects	Biomass	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu	Mo
----- Overhead -----													
IS	0.051	0.039	0.140	0.035	0.032	0.037	0.059	0.071	0.063	0.142	0.121	0.062	0.051
NS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
IS×NS	0.125	0.019	0.402	0.069	0.333	0.125	0.112	0.131	0.264	0.156	0.193	0.253	0.781
----- SSDI -----													
IS	0.514	0.788	0.434	0.433	0.525	0.599	0.848	0.487	0.890	0.513	0.825	0.896	0.334
NS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
IS×NS	0.963	0.926	0.929	0.935	0.821	0.809	0.870	0.813	0.775	0.767	0.913	0.714	0.570

Bold texts highlight significant effects ($P < 0.05$). SSDI: Subsurface drip irrigation; IS:

Irrigation schedule; NS: Nutrient stress.

Table S4.4: *P*-values of the main effects and interaction effects of irrigation scheduling and nutrient stress on growth and yield parameters of corn under overhead irrigation and SSDI systems.

Effects	Seed yield	Plant height	Stover	Harvest index	TSW	Ear height	Ear length	Ear diameter	Ear rows
----- Overhead -----									
IS	0.099	0.354	0.660	0.584	0.937	0.301	0.841	0.323	0.382
NS	0.003	0.244	0.000	0.003	0.145	0.065	0.023	0.000	0.000
IS×NS	0.913	0.298	0.581	0.909	0.852	0.120	0.971	0.063	0.111
----- SSDI -----									
IS	0.039	0.337	0.034	0.795	0.867	0.445	0.243	0.426	0.892
NS	0.000	0.029	0.000	0.018	0.008	0.400	0.148	0.002	0.012
IS×NS	0.831	0.132	0.878	0.621	0.421	0.611	0.444	0.267	0.682

Bold texts highlight significant effects ($P < 0.05$). SSDI: Subsurface drip irrigation; IS:

Irrigation schedule; NS: Nutrient stress; TSW: Thousand seed weight.

Supplemental figures



Figure S4.1. Drone image of the subsurface drip irrigation field showing poor growth of the early season nutrient stress plots. The early season nutrient stress plots received no nutrient application until the V6 growth stage.

CHAPTER 5

EARLY AND LATE SEASON NUTRIENT STRESS CONDITIONS: IMPACT ON COTTON

PRODUCTIVITY AND QUALITY

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Abstract

Modern cotton (*Gossypium* spp. L) cultivars are efficient in nutrient uptake and utilization and, thus, may potentially tolerate nutrient stress. Early- and late-season nutrient stress (E-stress and L-stress, respectively) effects on cotton productivity and quality were assessed under different production conditions in Camilla and Midville, GA, USA. The E-stress received no nutrient application in the early season, but the full rates were split-applied equally at the initiation of squares and the second week of bloom stages. The L-stress received 30%–40% of the full nutrient rates only at the initial stage of planting. The effects of nutrient stress on cotton productivity and fiber quality were inconsistent across the different production conditions. Compared to the full nutrient rate, the E-stress did not adversely impact cotton yield, but rather, it improved the lint and cottonseed yields under one production condition by 17.5% and 19.3%, respectively. Averaged across all production conditions, the L-stress decreased the lint and cottonseed yields by 34.4% and 36.2%, respectively. The minimal effects of E-stress on cotton suggest nutrient rates at the early season could be reduced and more tailored rates, informed by soil and plant tissue analyses, applied shortly before the reproductive phase.

1.0. Introduction

Cotton (*Gossypium spp.* L) is a valuable industrial crop that contributes substantially to the agricultural economy of many countries. The Food and Agriculture Organization of the United Nations estimated the world's seed cotton (unginned cotton) production in 2020 to be 83.1 million t, which was valued at \$52 billion (FAOSTAT, 2022). The USA ranks third in cotton production in the world, behind China and India. In 2021, about 4.54 million ha of cotton was planted in the USA, and the top three leading producing states were Texas, Georgia, and Arkansas in descending order (USDA-NASS, 2019). Lint and cottonseed are the two valuable industrial products of cotton, with lint being more valuable. In 2021, lint and cottonseed production value in the USA was \$7.46 billion and \$1.32 billion, respectively. Thus, cotton production management is mainly geared towards enhancing the productivity and quality of lint.

The average cotton lint yield in the USA has increased by 25.6% in the past 30 years, with a yield of 0.73 Mg ha⁻¹ in 1991 and 0.92 Mg ha⁻¹ in 2021 (USDA-NASS, 2019). The increase in cotton lint yield can largely be attributable to improved agronomic practices and better performance of modern cultivars (Constable and Bange, 2015; Daystar et al., 2017; Shaheen et al., 2021). Rochester and Constable (Rochester and Constable, 2015) compared cotton cultivars released in 2006 with those released in 1973. The authors observed a 40% increase in lint yield in the 2006 cultivars. Also, the N, P, and K use efficiencies of the 2006 cultivars increased by 20%, 23%, and 24%, respectively, compared to those of the 1973 cultivars (Rochester and Constable, 2015). In a two-year field study in New Deal, TX, the average lint yields of cotton cultivar PM HS26 (released in 1990), FM 958 (released in 2000), and DP 1646 (released in 2016) were reported to be 1.11 Mg ha⁻¹, 1.26 Mg ha⁻¹, and 1.34 Mg ha⁻¹, respectively (Pabuayon et al., 2020).

The authors also observed that the 2016 and 2000 cultivars efficiently partitioned and remobilized essential nutrients more than the 1990 cultivars.

The efficient utilization of nutrients by modern cultivars could potentially confer better tolerance to nutrient stress, which would be desirable. There has been instability in the supply and prices of fertilizers over the past couple of years, with most fertilizers exceeding record prices in 2008. Lessons from the 2008 volatility in fertilizer prices suggest that farmers may not be willing to buy the usual tonnage of fertilizers at high price levels (Singh and Tan, 2022). It is therefore important to determine the impact of reduced fertilizer application rates on the productivity and quality of modern cotton varieties. The high fertilizer prices in 2008 may have contributed to the reduced cotton lint yield in succeeding years. The average cotton lint yield in the USA in 2007 was 0.88 Mg ha⁻¹, but it dropped to 0.81 Mg ha⁻¹ and 0.78 Mg ha⁻¹, respectively, in 2008 and 2009 (USDA-NASS, 2019).

While low fertilizer application could impact cotton productivity, supplying more nutrients than needed could have adverse implications on the environment, such as acidification of soils, eutrophication in aquatic systems, and ozone layer depletion (Townsend et al., 2003; Shahzad et al., 2018). Nutrient uptake and partition studies show that nutrient requirement in cotton is minimal at the vegetative stage and then increases rapidly at the reproductive stage (Bassett et al., 1970; Rochester et al., 2012; Pabuayon et al., 2020). Synchronizing nutrient availability with crop demand could potentially increase nutrient use efficiency and reduce nutrient loss through ammonia volatilization, denitrification, runoff, and leaching (Mandal et al., 2016; Esfandbod et al., 2017; Shahzad et al., 2019a). However, standard nutrient management guidelines suggest the application of all recommended fertilizer rates before or at the initial stages of planting, except for

N which is often split-applied. The minimal vegetation cover, coupled with high rainfall and temperature conditions, make fertilizers applied in the early season susceptible to losses.

Determining the response of modern cotton cultivars to no fertilizer application during the early season growth could inform adaptive nutrient management strategies. Residual nutrients in the soil and crop residues could meet the nutritional demand for cotton at the early season growth stage (Russell, 1977; Sintim et al., 2016; Torma et al., 2018). The objective of this study was therefore to assess the impact on the productivity and quality of modern cotton varieties to varying degrees of nutrient stresses under different production conditions.

2.0. Materials and Methods

2.1. Experimental site

The research was conducted at the University of Georgia Stripling Irrigation Research Park in Camilla, GA (31°16'45.86"N, 84°17'29.65" W) and the Southeast Georgia Research and Education Center in Midville, GA (32°52'54.72"N, 82°12'54.07"W). Both sites have a humid subtropical climate, with annual average daily minimum, mean, and maximum air temperatures of 12.8°C, 19.4°C, and 26.0°C, respectively, in Camilla and 11.3°C, 18.0°C, and 24.6°C, respectively, in Midville (Georgia AEMN, 2023). The average annual precipitation in Camilla is 1,314 mm, with 98 average rainy days, and the average annual precipitation in Midville is 1,146 mm, with 102 average rainy days (Georgia AEMN, 2023).

Air temperature over the two years of the study followed a similar pattern across the two locations. However, it was relatively warmer in Camilla compared to Midville, with the average minimum, mean, and maximum air temperatures of 13.7°C, 19.9°C, and 26.1°C, respectively, in Camilla, and 12.4°C, 18.5°C, and 24.6°C, respectively, in Midville (Figure 5.1). In addition,

rainfall received was relatively greater in Camilla, with an annual rainfall of 1,378 mm in 2020 and 1,384 mm in 2021. Annual rainfall in Midville was 1,318 mm in 2020 and 1,099 in 2021. Rainfall received between the planting and harvest of cotton was 547 mm and 776 mm in 2020 and 2021, respectively, in Camilla, and 482 mm and 532 mm, respectively, in 2020 and 2021 in Midville.

The experimental field in Camilla had a Lucy loamy sand, classified as Loamy, kaolinitic, thermic Arenic Kandiudults, whereas the field in Midville had a Dothan loamy sand, classified as fine-loamy, kaolinitic, thermic Plinthic Kandiudults. The average sand, silt, and clay content at the top 15 cm depth of the experimental field soils were 90.7%, 3.2%, and 6.1%, respectively, in Camilla, and 90.9%, 5.1%, and 4.0%, respectively, in Midville. Also, the average soil pH and organic matter within 0-15 cm depth were 6.51 and 2.90 g kg⁻¹ in Camilla, respectively, and 6.40 and 4.67 g kg⁻¹ in Midville, respectively.

2.2. Field experiment

Field experiments were established in 2020 and 2021 to evaluate early- and late-season nutrient stress (E-stress and L-stress) effects on cotton productivity and quality under different production conditions at the two locations. A reduced nutrient stress condition (R-stress) and standard fertility constituted the control treatments. In Camilla, the experiment was established under sub-surface drip irrigation (SSDI) systems in 2020 and 2021, and under an overhead irrigation system in only 2021. In Midville, the experiment was established under rainfed conditions in 2020 and 2021, and under an overhead irrigation system in only 2021, constituting six production conditions across the two locations. The two production conditions at both locations in 2021 were on separate fields (~100 m apart in Camilla and ~300 apart in Midville). The four

treatments were assessed under each production condition, except for the Midville 2020 rainfed condition where the standard fertility was not assessed.

The standard fertility treatment referred to nutrient recommendations (Table 5.1) by the University of Georgia Agricultural and Environmental Services Laboratories to make 1,681 kg ha⁻¹ lint yield under irrigated conditions and 1,121 kg ha⁻¹ lint yield under rainfed conditions (UGA-AESL, 2022). The rates were based on the initial soil nutrient status of the experimental fields (Table 5.2). Nutrients reported as essential for cotton are N, P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu (Campbell, 2000). To ensure minimal nutrient stress, the application of some rates of all the essential nutrients was made to the R-stress plots (Table 5.1). In Camilla, the R-stress plots received 30% of the full nutrient rates at the early stage of planting, another 30% each at square initiation and the second week of bloom (2-WoB) stages, and the remaining 10% at the 6-WoB stage. In Midville, the R-stress plots received 40% of the full nutrient rates at the early stage of planting, and 30% each at square initiation and the 2-WoB stages.

The E-stress at both locations was induced by not making any nutrient application until the initiation of squares, after which the full nutrient rates specified for the R-stress were split-applied equally at the initiation of squares and the 2-WoB stages. Thus, the E-stress received the same nutrient application rates as the R-stress. The L-stress in Camilla was induced by applying only 40% of the full nutrient rates specified for the R-stress at the early stage of planting, whereas the L-stress in Midville was induced by applying only 30% of the full nutrient rates specified for the R-stress at the early stage of planting. Table S5.1 lists the nutrient sources applied. Granular fertilizer sources were used at both locations, except the Camilla SSDI conditions where liquid fertilizer sources were applied via fertigation at the 2-WoB and 6-WoB stages. The treatments were laid out in a randomized complete block design with four replications and plot dimensions

(width × length) of 5.5 m × 11.0 m for the Camilla SSDI condition, 7.3 m × 12.2 m for the Camilla overhead irrigation condition, and 7.3 m × 9.1 m for all conditions in Midville.

2.3. Plot management

Previous cash crops were peanut (*Arachis hypogaea*) and corn (*Zea mays*) for the 2020 and 2021 seasons, respectively, in Camilla and peanut for all seasons in Midville. All sites were under cereal rye (*Secale cereale*) cover crop, and the fields were prepared by strip-tilling to 30.5- 45.7 cm depth. Deltapine[®] cotton variety DP 1646 B2XF (released in 2016) was used in Camilla and Stoneville[®] cotton variety ST 4550 GLTP (released in 2019) was used in Midville, and they were planted at 107,639 seeds ha⁻¹ and 91.4 cm row spacing. The SSDI system constituted a Netafim Typhoon drip tape (Netafim Irrigation, Inc., Fresno, CA, USA), with 46 cm emitter spacing and 1.5 l hr⁻¹ discharge rate, installed at the middle of every row (46 cm to the side of plant rows). The drip tapes at every other middle of the plant rows were used for irrigation in this study (one drip tape line serviced two plant rows), as per common grower practice. The overhead irrigation was a lateral irrigation system in Camilla and a center pivot irrigation system in Midville. Irrigation amounts were 200 mm (Camilla 2020 SSDI), 132 mm (Camilla 2021 SSDI), 184 mm (Camilla 2021 overhead), and 95.3 mm (Midville 2021 overhead), which depended on rainfall, location, and irrigation method. Weed and pest control and the use of growth regulators and defoliant followed standard recommendations by the University of Georgia Cooperative Extension (Whitaker et al., 2020; Hand et al., 2021).

2.4. Data collection

Initial soil nutrient levels within the top 15 cm depth were analyzed following standard protocols by Waters Agricultural Laboratories, Inc. The soil samples were collected with a 2.86

cm diameter AMS soil recovery probe (AMS Inc., American Falls, ID, USA). Nitrate-N was measured, after extraction in a 2 M KCl solution, with the automated flow injection analysis system (FIAlyzer-1000, FIALab Instruments, Inc., Seattle, WA, USA), and extractable P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu were measured, after extraction in Mehlich I solution, with an inductively coupled plasma optical emission spectrophotometer (ICP-OES; iCAP™ 6000 Series, Thermo Fisher Scientific, Cambridge, United Kingdom).

Aboveground plant tissues were sampled at square initiation, 2-WoB, and 7-WoB stages, and shortly before harvest (after defoliation), except for the Midville location where samples were not collected at the 7-WoB stage. At every sampling stage, the aboveground biomass was collected from a 1-meter strip of a non-harvest row, ensuring a minimum of 1-meter buffer during subsequent sampling. The samples were oven-dried at 78°C to obtain constant weight, after which the weights were recorded and used to calculate biomass accumulation. Plant height, the number of main stem nodes per plant, the total number of bolls per plant, the number of harvestable bolls per plant, and seed cotton per boll were determined at physiological maturity from five plants selected randomly within non-harvest rows of each plot.

Harvesting was performed mechanically by sampling entire two rows of every plot with a cotton picker, and weights of the seed cotton were measured. Thereafter, the seed cotton samples were ginned at the University of Georgia Micro Gin in Tifton, GA to determine the gin turnout, which was used to calculate the lint and cottonseed yields. Fiber samples were transported to the USDA classing office in Macon, GA to measure fiber quality parameters, including fiber length, fiber strength, uniformity, micronaire, reflectance (RD), and yellowness (+b), following standard protocol (CI, 2018).

2.5. Statistical analyses

Separate statistical analyses were performed for each location because of differences in the level of nutrient stress imposed. Except for the biomass data, plant growth, yield, and fiber quality data were analyzed with the linear mixed model using the “lme4” package in R (Bates et al., 2015). The nutrient stress and production conditions were considered fixed effects, and block was considered random effects. The biomass data were analyzed as repeated measure analyses using the “lme4” package in R (Bates et al., 2015). The sampling time was assigned as a within-plot factor variable, nutrient stress as between-plot factor variable, and block as a random term.

Normality of residuals, homoscedasticity of variance, and sphericity assumptions were tested, and appropriate transformations (square root and Box-Cox transformation methods) and corrections (Greenhouse-Geisser and Huynh–Feldt correction methods) were applied as appropriate. Mean separations were performed using the least square means and the adjusted Tukey multiple comparison procedure with the ‘emmeans’ package in R (Lenth et al., 2018). The significance level for all analyses was assessed at $P = 0.05$.

3.0. Results

3.1. Lint yield, gin turnout, and seed cotton

The main effects of nutrient stress were significant on cotton lint yield, gin turnout, cottonseed yield, and the seed cotton weight per boll in Camilla, but the effects were only significant on lint yield and cottonseed yield in Midville (Tables S5.2). Also, the interaction effects of nutrient stress and production conditions were significant on lint yield, cottonseed yield, and seed cotton weight per boll in Camilla, but their effects were not significant on those variables in Midville. Compared to the R-stress, the E-stress did not cause a significant reduction in lint yield,

but rather, it significantly increased the lint yield by 17.5% under Camilla 2021 SSDI condition (Figures 5.2a and 5.2b). In contrast, the L-stress led to a significant reduction in lint yield in four production conditions compared to the R-stress. The yield reductions were 41.7%, 33.3%, 69.4%, and 45.4%, respectively, under Camilla 2021 SSDI, Camilla 2021 overhead irrigation, Midville 2020 rainfed, and Midville 2021 rainfed conditions. Compared to R-stress, the standard fertility underperformed, but the differences were not significant, except under Camilla 2021 overhead condition (20.6% lower lint yield). Averaged over all production conditions across the two locations, the lint yield was 1.29 Mg ha⁻¹, 0.97 Mg ha⁻¹, 1.30 Mg ha⁻¹, and 1.15 Mg ha⁻¹ for the E-stress, L-stress, R-stress, and the standard fertility, respectively.

While the effects of nutrient stress on gin turnout were statistically significant under all production conditions in Camilla, the magnitude of the differences was small, with gin turnout ranging from 39.9% to 41.3% under Camilla 2020 SSDI, 42.2% to 43.7% under Camilla 2021 SSDI, and 42.3% to 44.5% under Camilla 2021 overhead irrigation (Figure 5.2c and 5.2d). Thus, the effects of nutrient stress on cottonseed yield (Figures 5.2e and 5.2f) followed the same trend as the effects on lint yield. Averaged over all production conditions across the two locations, the cottonseed yield was 1.87 Mg ha⁻¹, 1.37 Mg ha⁻¹, 1.86 Mg ha⁻¹, and 1.59 Mg ha⁻¹, respectively, for the E-stress, L-stress, R-stress, and the standard fertility. The seed cotton weight per boll, however, did not follow the same trend as the lint and cottonseed yields, with significant differences between nutrient treatments observed under Camilla 2020 SSDI condition only (Figure 5.2g and 5.2h). The seed cotton weight per boll under Camilla 2020 SSDI condition was least in the standard fertility (3.30 g kg⁻¹) and greatest in R-stress (5.12 g kg⁻¹).

3.2. Plant height, nodes, and boll development

Compared to R-stress, plant height was significantly reduced by L-stress under Camilla 2021 SSDI (25.0% reduction) and Midville 2021 rainfed (13.6% reduction) conditions (Figures 5.3a and 5.3b). The effects of E-stress were minimal on plant height. The E-stress had a similar plant height as the R-stress and standard fertility. Also, the number of main stem nodes was impacted by L-stress but not by E-stress (Figures 5.3c and 5.3d). A significant reduction in the number of main stem nodes occurred under the overhead irrigation conditions at both locations in 2021. The L-stress reduced the number of main stem nodes by 23.9% and 15.0%, respectively, under the overhead irrigation conditions in Camilla 2021 and Midville 2021. Compared to the E-stress and R-stress, the standard fertility had 21.3% and 17.7% lower number of main stem nodes, respectively, under the Camilla 2021 overhead irrigation condition. The total (Figures 5.3e and 5.3f) and harvestable (Figures 5.3g and 5.3h) number of bolls were both significantly reduced by L-stress under Camilla 2021 SSDI conditions but not under any production conditions in Midville. Compared to the R-stress, the reduction was very severe, being 76.8% and 78.8% for the total and harvestable numbers of bolls, respectively. The E-stress, however, did not have a significant impact on the total and harvestable numbers of bolls, and also the R-stress had similar total and harvestable numbers of bolls as the standard fertility.

3.3. Biomass accumulation

The effects of nutrient stress on biomass accumulation over time are shown in Table S5.3 and Figure 5.4. As already mentioned, biomass samples were collected at square initiation, 2-WoB, 7-WoB, and shortly before harvest, except for the Midville location, where the samples were not

collected at the 7-WoB stage. As expected, biomass accumulation significantly increased over the growth stages under all production conditions at the two locations. However, nutrient stress affected biomass accumulation at only the harvest stage. Significant differences were observed under all conditions in 2021 but not in 2020. Compared to R-stress, the E-stress did not affect biomass accumulation, whereas the L-stress and standard fertility significantly reduced biomass accumulation under four and one conditions, respectively. Averaged over all production conditions across the two locations, the E-stress, L-stress, R-stress, and standard fertility had total aboveground biomass of 11.7 Mg ha⁻¹, 8.82 Mg ha⁻¹, 12.2 Mg ha⁻¹, and 10.4 Mg ha⁻¹, respectively.

3.4. Fiber quality

The effects of nutrient stress on fiber quality indicators across the different production conditions are shown in Table S5.3 and Table 5.4. Overall, the magnitude of the differences in fiber quality indicators among the nutrient treatments was minimal, even though some of the test statistics were significant. Compared to the R-stress, the E-stress did not affect fiber length and strength, whereas the L-stress significantly reduced the fiber length and strength under Camilla 2021 SSDI condition only. The reduction was 4.23% and 2.02% for the fiber length and strength, respectively. Averaged over all production conditions across the two locations, the E-stress, L-stress, R-stress, and standard fertility had fiber lengths of 3.02 cm, 2.96 cm, 3.01 cm, and 2.97 cm, respectively, and a fiber strength of 31.1 g tex⁻¹, 30.6 g tex⁻¹, 30.9 g tex⁻¹, and 30.7 g tex⁻¹, respectively. The fiber uniformity was significantly increased in E-stress over the R-stress and standard fertility under Camilla 2021 overhead irrigation condition. It was also significantly increased in the E-stress over the R-stress and L-stress under the Midville 2021 rainfed condition. The E-stress, however, tended to decrease the micronaire, with an average reduction of 2.23%

when compared to the R-stress. The average micronaire across all production conditions at the two locations was 4.47, 4.57, 4.57, and 4.55 for the E-stress, L-stress, R-stress, and standard fertility, respectively. The RD was not significantly affected by nutrient stress under any production condition. In contrast to the RD, the +b was significantly reduced in the L-stress, the effect being more obvious under Camilla 2020 SSDI and Midville 2021 rainfed conditions. The average +b under all conditions was 7.60%, 7.39%, 7.55%, and 7.53% for the E-stress, L-stress, R-stress, and standard fertility, respectively.

4.0. Discussion

The residual soil nutrients, which were within the typical range (UGA-AESL, 2022), may have met the nutritional needs of the crop by the square stage, as depicted by the lack of significant impact of E-stress on the total aboveground biomass accumulated at the square stage at all production conditions. Cotton nutritional demand in the early season is reported to be low (Bassett et al., 1970; Rochester et al., 2012; Pabuayon et al., 2020). Bassett et al. (Bassett et al., 1970) observed that at the first flower stage, the N, P, K, Ca, and Mg accumulated in the aboveground components of cotton were < 15% of the total. Also, 2-4% of the total seasonal aboveground biomass had accumulated at the square stage (Bassett et al., 1970). The average aboveground biomass accumulated by the square stage in this study was 8.2% of that accumulated by harvest. Besides residual soil nutrients, the mineralization of crop residues and organic matter is another good source of nutrients for crops (Myers et al., 1994; Sintim et al., 2015; De Neve, 2017). However, organic matter at the experimental sites was low to have contributed to any appreciable levels of nutrients (2.90 g kg⁻¹ in Camilla and 4.67 g kg⁻¹ in Midville).

Besides biomass accumulation, the E-stress had no impact on cotton yield, which is consistent with observations made from previous studies that investigated the one-time application of nutrients in cotton (Yang et al., 2012; Luo et al., 2020). In general, the application of N, P, and K at only the first flower stage was reported to maximize nutrient utilization while minimizing the impact on the environment (Yang et al., 2012; Luo et al., 2020). The standard fertility received lower rates of nutrients than the E-stress and R-stress. Compared to the E-stress and R-stress, the standard fertility underperformed, with statistical significance in lint and cottonseed yields observed in Camilla 2021 under both the SSDI and overhead irrigation conditions. While modern cotton cultivars have better nutrient use efficiencies (Rochester and Constable, 2015; Pabuayon et al., 2020), the observations of this study indicate that they also respond to high nutrient levels. The L-stress received just 30-40% of the nutrient rate of the R-stress, which was applied one time at the early stage of planting. The results showed the L-stress had significantly lower lint and cottonseed yields than the R-stress under four out of the six production conditions tested in this study. Compared to the standard fertility, the L-stress had significantly lower lint and cottonseed yields under just one (Camilla 2021 SSDI condition) out of the five production conditions. As already mentioned, the standard fertility was not tested under the Midville 2020 rainfed condition.

Effects of nutrient stress on cotton fiber quality were not consistent across the different production conditions. Where significant, the E-stress tended to increase the fiber length, fiber strength, and uniformity, which was desirable. However, it decreased the micronaire and increased the +b, reflecting poor quality. In contrast, the L-stress tended to decrease the +b. Reported effects of nutrient application on cotton fiber quality are often inconsistent and vary across locations and cultivars (Sui et al., 2017; Kusi et al., 2021; van der Sluijs, 2022). Findings from a study that evaluated seven cotton cultivars under 33 environments in Georgia, showed that production

conditions that enhanced yield also led to improved fiber quality (Snider et al., 2013). The E-stress and R-stress had the greatest lint yield but had undesirable micronaire and +b properties, which could be due to the high N rates applied. Sui et al. (Sui et al., 2017) observed a negative correlation between +b and leaf N content. Overall, however, the magnitude of the differences in the fiber quality indicators observed in this study was small and did not affect the grading class.

The global textile market is competitive and fiber quality is critical to ensuring good prices. Moreover, fiber quality affects manufacturing processes and the ultimate use of cotton fiber. Of the fiber quality indicators, color has the highest contribution to the price of cotton (Chakraborty et al., 2000; van der Sluijs, 2022). Chakraborty et al. (2000) reported that color, cleanliness, micronaire, length, and strength contributed 30%, 23%, 22%, 20%, and 5%, respectively, to the price premium paid toward cotton fiber quality. According to Mcveigh (Mcveigh, 2017), a drop from Middling (31) to Strict Low Middling (41) can cause Australian farmers to lose about \$760 ha⁻¹. In the USA, the annual cotton price statistics report for the 2021-2022 season by the USDA-AMS showed quotations for color 41, leaf 4, staple 34, micronaire 35-36 and 43-49, strength of 27.0-28.9 g tex⁻¹, and uniformity of 81% to be ~\$2.52 kg⁻¹ (USDA-AMS, 2022). The quotation for a better cotton fiber quality (color 31, leaf 3, staple 34, micronaire 35-36 and 43-49, strength of 27.0-28.9 g tex⁻¹, and uniformity of 81%) increased by ~2.29 cents kg⁻¹ (USDA-AMS, 2022).

5.0. Conclusions

Cotton yield was not adversely impacted by E-stress. However, the L-stress significantly reduced the lint and cottonseed yields under four and one production conditions, when compared to the R-stress and standard fertility, respectively. The E-stress and R-stress had better lint and cottonseed yield than the standard fertility, indicating modern cultivars can respond to high

nutrient levels. Significant nutrient stress effects on fiber quality were observed but the magnitude of the differences was small and it did not affect the grading class. The minimal impact of E-stress on cotton yield and quality in this study suggests that the rates of nutrients often applied in the early season can be reduced. More tailored nutrient application rates, based on soil and plant tissue analyses, could then be applied shortly before the reproductive phase of the crop. Such a system will help optimize crop nutrition by synchronizing nutrient availability with crop demand.

6.0. References

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Tables

Table 5.1. Full nutrient application rates (in kg ha⁻¹) for the standard recommendation and reduced nutrient stress (R-stress) treatments imposed in Camilla and Midville, GA, under different production conditions.

Nutrient elements	----- Camilla -----						----- Midville -----					
	---SSDI (2020)---		---SSDI (2021)---		--Overhead (2021)--		Rainfed (2020)	--Rainfed (2021)--		--Overhead (2021)--		
	Standard	R-stress	Standard	R-stress	Standard	R-stress	R-stress	Standard	R-stress	Standard	R-stress	
N	84.1	118	106	84.1	118	106	67.3	50.4	78.5	84.1	118	
P ₂ O ₅	0.00	101	44.8	0.00	101	44.8	56.0	33.6	67.3	78.5	101	
K ₂ O	112	168	101	112	168	101	112	33.6	84.1	135	140	
Mg	0.00	33.6	0.00	0.00	33.6	0.00	28.0	0.00	5.60	0.00	5.60	
Ca	0.00	5.60	0.00	0.00	5.60	0.00	5.60	0.00	11.2	0.00	22.4	
S	11.2	22.4	11.2	11.2	22.4	11.2	11.2	11.2	11.2	11.2	11.2	
B	0.56	2.24	0.56	0.56	2.24	0.56	2.24	0.56	0.56	0.56	1.12	
Zn	0.00	2.24	0.00	0.00	2.24	0.00	2.24	0.00	1.12	0.00	2.24	
Mn	0.00	1.12	0.00	0.00	1.12	0.00	1.12	0.00	2.24	11.2	5.60	
Fe	0.00	1.12	0.00	0.00	1.12	0.00	0.56	0.00	2.24	0.00	2.24	
Cu	0.00	0.56	0.00	0.00	0.56	0.00	0.56	0.00	0.56	0.00	0.56	

SSDI: Sub-surface drip irrigation.

Table 5.2. Initial nutrient status of the experimental field soil in Camilla and Midville under different production conditions.

Soil depth	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
----- kg ha ⁻¹ -----											
----- Camilla -----											
SSDI (2020)	8.47	82.3	92.0	62.2	955	5.04	0.22	4.6	28.2	36	0.9
SSDI (2021)	2.69	81.6	107	127	907	28	0.45	6.05	13.5	10.1	1.01
Overhead (2021)	0.90	49.3	58.8	95.0	762	28.1	0.45	6.15	15.1	12.3	2.13
----- Midville -----											
Rainfed (2020)	3.49	75.7	81.6	67.7	971	32.4	0.22	5.62	20.2	37.1	0.67
Rainfed (2021)	2.73	68.4	184	166	864	37.9	0.67	7.64	15.6	17.2	0.45
Overhead (2021)	6.97	51.6	71.2	91	716	31.2	0.45	5.9	6.39	19.3	1.01

Soil samples were collected from 0-15 cm depth with a 2.86 cm diameter AMS soil recovery probe (AMS Inc., American Falls, ID, USA). N was measured as Nitrate-N after extraction with 2 M KCl solution, whereas P, K, Ca, Mg, S, Fe, Mn, Zn, B, and Cu were measured after Mehlich I extraction. SSDI: Sub-surface drip irrigation.

Table 5.3. Nutrient stress effects on cotton fiber quality in Camilla and Midville under different production conditions.

Nutrient stress	Fiber length cm	Fiber strength g tex ⁻¹	Uniformity %	Micronaire	Rd %	+b
----- Camilla (SSDI 2020) -----						
E-stress	3.20±0.01a	30.5±0.3a	81.9±0.8a	4.08±0.07a	74.9±0.2a	7.80±0.07a
L-stress	3.21±0.01a	30.5±0.3a	81.1±0.1a	4.32±0.07b	75.8±0.2a	7.42±0.15b
R-stress	3.19±0.03a	30.6±0.1a	81.5±0.3a	4.22±0.07ab	73.5±0.4a	7.58±0.09b
Standard	3.17±0.04a	30.1±0.2a	81.6±0.8a	4.20±0.09ab	74.3±0.9a	7.47±0.12b
----- Camilla (SSDI 2021) -----						
E-stress	3.10±0.01b	30.5±0.6a	82.3±0.3a	4.55±0.03a	74.0±0.4a	6.92±0.07a
L-stress	2.95±0.02a	29.7±0.3ab	81.6±0.4a	4.67±0.03a	75.9±0.9a	6.83±0.23a
R-stress	3.08±0.02b	30.3±0.1a	81.7±0.2a	4.65±0.03a	74.2±0.3a	6.85±0.06a
Standard	2.96±0.02a	29.3±0.3b	81.6±0.2a	4.60±0.00a	73.6±0.2a	7.03±0.15a
----- Camilla (Overhead 2021) -----						
E-stress	3.04±0.01c	27.8±0.2a	82.1±0.2a	4.60±0.04ab	74.7±0.7a	6.92±0.14a
L-stress	2.93±0.02ab	27.0±0.4a	81.7±0.2ab	4.58±0.05ab	74.3±0.6a	6.78±0.05a
R-stress	2.99±0.02bc	27.8±0.3a	81.4±0.2b	4.68±0.03b	73.6±0.9a	6.97±0.12a
Standard	2.90±0.03a	27.3±0.3a	81.3±0.4b	4.47±0.06a	74.7±0.6a	6.95±0.06a
----- Midville (Rainfed 2020) -----						
E-stress	2.90±0.03a	32.2±0.4a	83.3±0.3a	4.55±0.12a	77.8±0.2a	7.88±0.22a
L-stress	2.93±0.04a	32.5±0.4a	83.2±0.4a	4.65±0.03a	77.5±0.1a	7.85±0.13a
R-stress	2.98±0.02a	33.0±0.8a	83.5±0.3a	4.47±0.07a	77.7±0.2a	8.18±0.12a
Standard	na	na	na	na	na	na
----- Midville (Rainfed 2021) -----						
E-stress	2.94±0.03b	32.6±0.6a	83.3±0.2a	4.62±0.13a	76.7±0.3a	8.10±0.09b
L-stress	2.81±0.04a	30.9±0.5a	82.4±0.2b	4.70±0.00a	76.0±0.2a	7.55±0.06a
R-stress	2.89±0.02ab	31.9±0.2a	82.5±0.3b	4.70±0.07a	75.7±0.1a	7.90±0.08ab
Standard	2.88±0.03ab	31.9±0.5a	83.0±0.4ab	4.72±0.05a	76.2±0.2a	7.75±0.18ab
----- Midville (Overhead 2021) -----						
E-stress	2.94±0.03a	32.8±0.2a	83.0±0.4a	4.42±0.09a	77.4±0.2a	7.97±0.23a
L-stress	2.95±0.03a	33.2±0.8a	83.4±0.2a	4.53±0.09ab	77.8±0.0a	7.92±0.25a
R-stress	2.91±0.02a	32.0±0.1a	83.2±0.3a	4.70±0.04ab	78.1±0.2a	7.85±0.09a
Standard	2.92±0.03a	32.3±0.4a	83.5±0.5a	4.80±0.17b	77.6±0.2a	7.82±0.03a

Within location and production conditions, means of nutrient stress treatments not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison procedure ($P < 0.05$). Values represent the mean ± standard error. SSDI: Sub-surface drip irrigation; na: Not available.

Figures

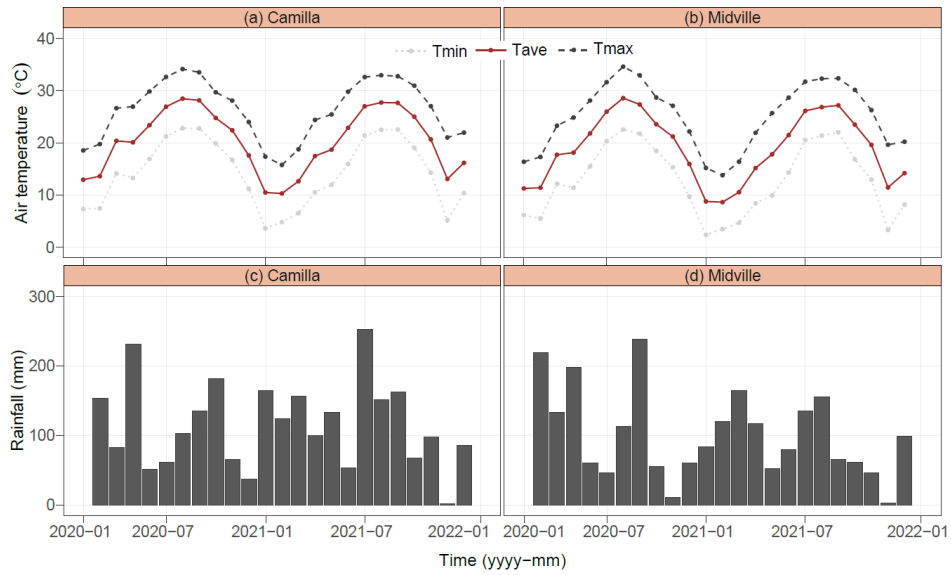


Figure 5.1. (a,b) Monthly minimum (Tmin), mean (Tave), and maximum (Tmax) air temperature, as well as (c,d) monthly total precipitation in Camilla and Midville, GA from January 1, 2020, to December 31, 2021.

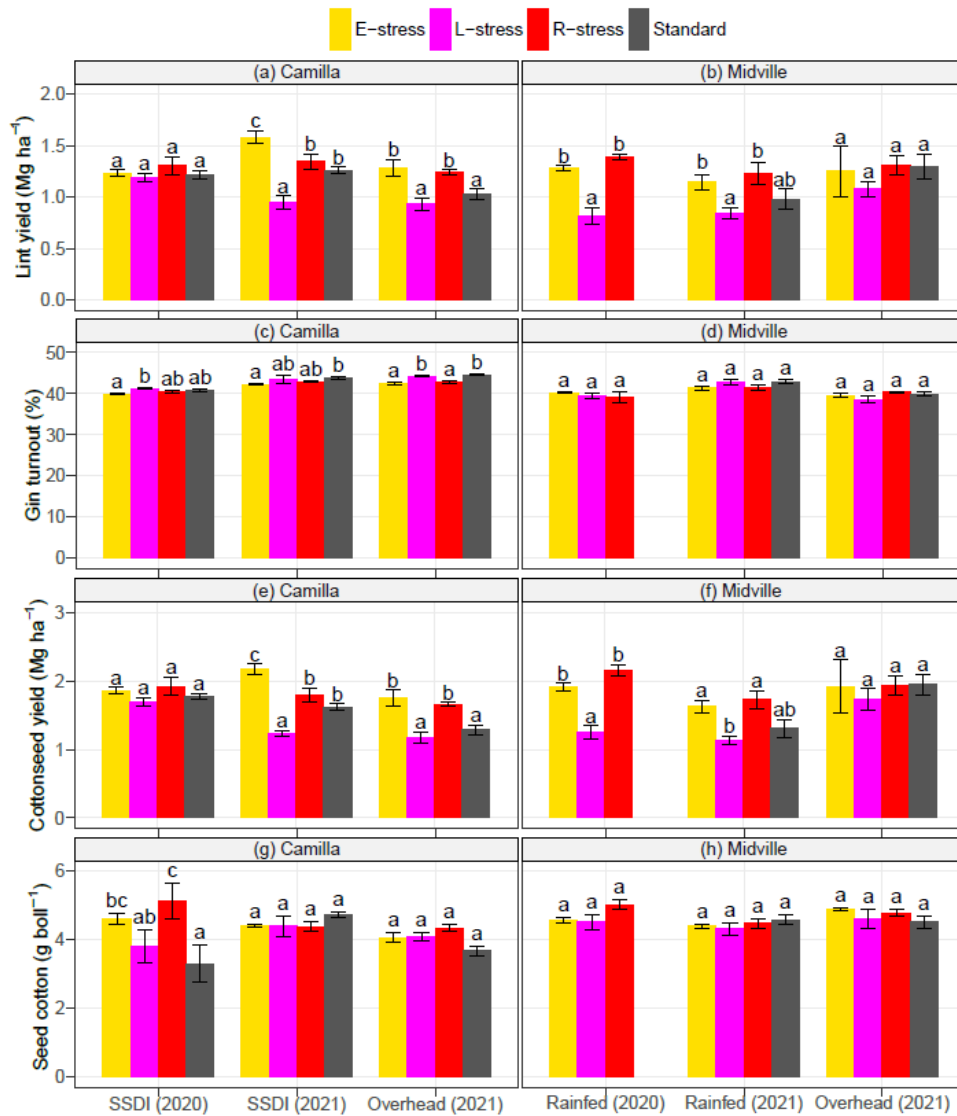


Figure 5.2. Nutrient stress effects on lint yield, gin turnout, cottonseed yield, and seed cotton yield per boll in Camilla and Midville, GA under different production conditions. Within location and production conditions, means of nutrient stress treatments not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison procedure ($P < 0.05$). Error bars indicate the standard error of the mean ($n = 4$). SSDI: Sub-surface drip irrigation.

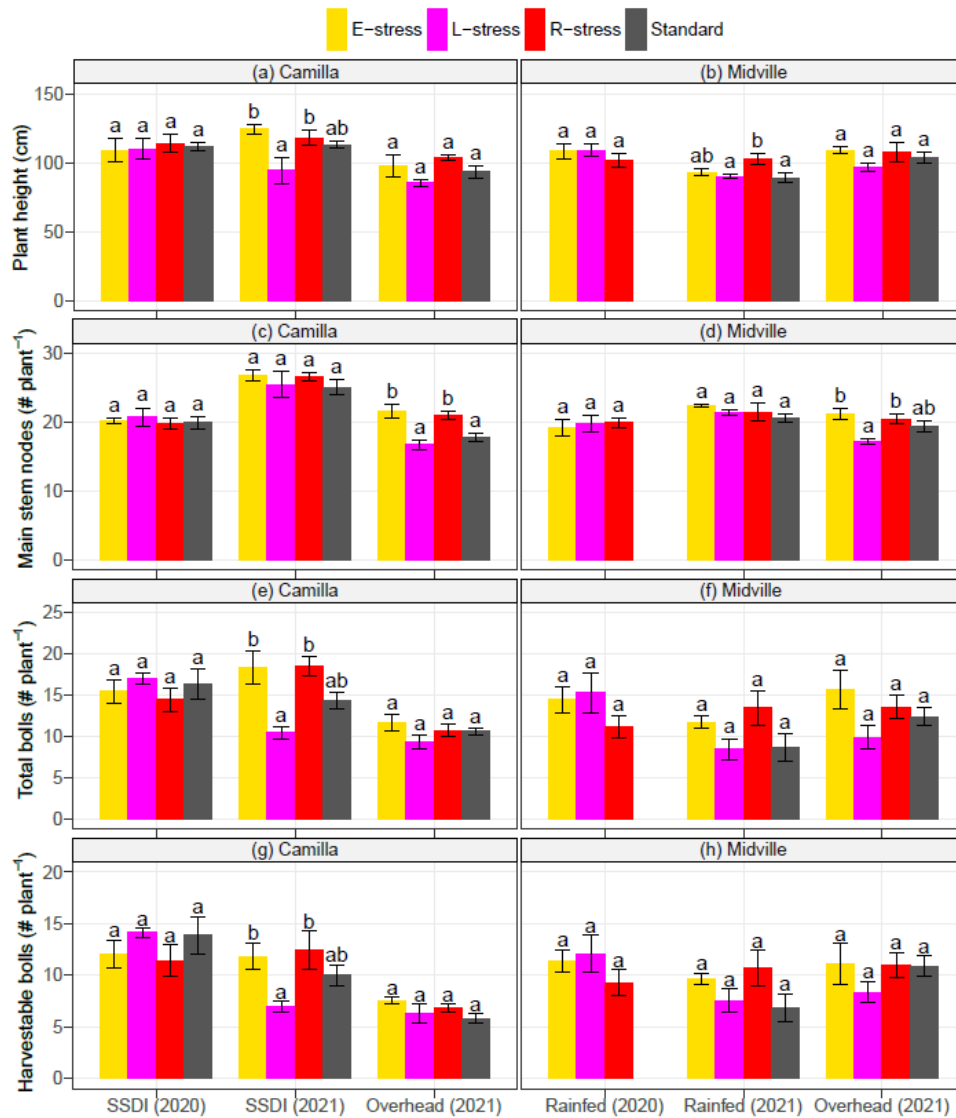


Figure 5.3. Nutrient stress effects on plant height, main stem nodes, and total and harvestable number of bolls in Camilla and Midville, GA under different production conditions. Within location and production conditions, means of nutrient stress treatments not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison procedure ($P < 0.05$). Error bars indicate the standard error of the mean ($n = 4$). SSDI: Sub-surface drip irrigation.

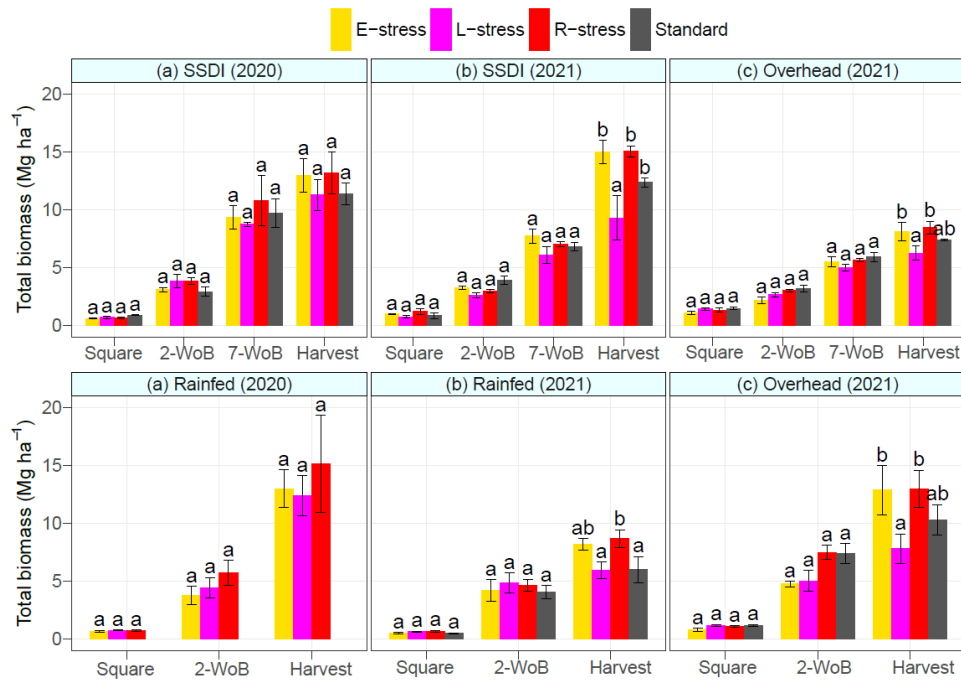


Figure 5.4. Nutrient stress effects on the total aboveground biomass in Camilla and Midville, GA under different production conditions. Within production conditions and growth stage, means of nutrient stress treatments not sharing any letter are significantly different using the least squares means and adjusted Tukey multiple comparison procedure ($P < 0.05$). Error bars indicate the standard error of the mean ($n = 4$). SSDI: Sub-surface drip irrigation; WoB: Week of bloom.

Supplemental Tables

Table S5.1: Fertilizers applied as the main sources of the different nutrient elements in Camilla and Midville.

Nutrient	Camilla SSDI	Camilla overhead and Midville rainfed and overhead
N	Urea	Urea
P	Di-ammonium phosphate; Haifa MAP™	Di-ammonium phosphate
K	Potassium chloride; Potassium nitrate	Potassium chloride
Mg	Magnesium oxy-sulfate; Magnesium nitrate solution	Magnesium oxy-sulfate
Ca	Calcium chloride; Calcium sulfate; Calcium nitrate solution	Calcium chloride; Calcium sulfate
S	Potassium sulfate; Epsom; Ammonium thiosulfate solution	Potassium sulfate; Epsom
B	Fertilizer borate; Borosol® 10 solution	Fertilizer borate
Zn	Zinc oxysulfate; Zinc nitrate solution	Zinc oxysulfate
Mn	Manganese sucrate; Manganese nitrate solution	Manganese sucrate
Fe	Iron sucrate; Iron nitrate solution	Iron sucrate
Cu	Copper sulfate; Copper nitrate solution	Copper sulfate

Table S5.2: *P*-values of the main effects and interaction effects of nutrient stress and production conditions on the growth and productivity of cotton in Camilla and Midville.

Source	Lint yield	Gin turnout	Cottonseed yield	Seed cotton per boll	Plant height	Main stem nodes	Total bolls	Harvestable bolls
----- Camilla -----								
Nutrient stress (NS)	<0.001	<0.001	<0.001	0.002	0.010	0.014	0.068	0.694
Condition (C)	0.472	0.004	0.141	0.697	0.700	0.007	0.215	0.015
NS x C	0.001	0.401	0.001	0.003	0.198	0.034	0.004	0.030
----- Midville -----								
Nutrient stress (NS)	<0.001	0.858	<0.001	0.164	0.056	0.083	0.058	0.360
Condition (C)	0.358	0.229	0.322	0.430	0.677	0.523	0.401	0.541
NS x C	0.380	0.055	0.052	0.212	0.040	0.048	0.102	0.220

† Bold texts highlight significant effect terms ($P < 0.05$).

Table S5.3: *P*-values of the main effects and interaction effects of nutrient stress and growth stage on biomass accumulation of cotton in Camilla and Midville under different production conditions.

Source	----- Camilla -----			----- Midville -----		
	SSDI (2020)	SSDI (2021)	Overhead (2021)	Rainfed (2020)	Rainfed (2021)	Overhead (2021)
	----- Leaf blade -----					
Nutrient stress (NS)	0.621	0.047	0.752	0.752	0.476	0.163
Growth stage (GS)	<0.001 [†]	<0.001	<0.001	<0.001	<0.001	<0.001
NS x GS	0.331	0.274	0.172	0.477	0.672	0.282
	----- Stem + petiole -----					
Nutrient stress (NS)	0.849	0.049	0.005	0.548	0.599	0.026
Growth stage (GS)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
NS x GS	0.713	0.361	0.462	0.357	0.905	0.038
	----- Reproductive tissues -----					
Nutrient stress (NS)	0.802	0.212	0.416	0.345	0.463	0.020
Growth stage (GS)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
NS x GS	0.780	0.001	0.049	0.107	0.463	0.020
	----- Total biomass -----					
Nutrient stress (NS)	0.759	0.046	0.043	0.509	0.779	0.024
Growth stage (GS)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
NS x GS	0.537	0.132	0.289	0.660	0.924	0.037

[†] Bold texts highlight significant effect terms ($P < 0.05$). SSDI: Sub-surface drip irrigation.

Table S5.4: *P*-values of the main effects and interaction effects of nutrient stress and production conditions on the fiber quality of cotton in Camilla and Midville.

Source	Fiber length	Fiber strength	Uniformity	Micronaire	Rd	+b
----- Camilla -----						
Nutrient stress (NS)	<0.001	0.032	0.006	0.001	0.244	0.033
Condition (C)	0.001	<0.001	0.059	0.005	0.748	0.819
NS x C	0.024	0.640	0.062	0.101	0.980	0.340
----- Midville -----						
Nutrient stress (NS)	0.513	0.879	0.320	0.298	0.445	0.411
Condition (C)	0.334	0.323	1.000	0.404	0.524	0.008
NS x C	0.038	0.200	0.135	0.054	0.397	0.003

† Bold texts highlight significant effect terms ($P < 0.05$).

CHAPTER 6

CONCLUSIONS AND IMPLICATIONS

The dissertation sought to investigate adaptive water and nutrient management strategies to enhance the sustainable production of row crops. The major conclusions of the dissertation include the following:

1. Chapter Two: Nutrient Sufficiency Ranges for Corn at The Early Growth Stage: Implications for Nutrient Management.

Results from this study suggest that nutrient sufficiency ranges of the Southern Cooperative Series Bulletin (SCSB) for corn were not valid. This is because although 47.6% of the samples satisfied the lower threshold of the interpretative method, 25.4% of them recorded relative biomass less than 50%. In another instance, 9.6% of the samples that had P or Cu not satisfying the lower threshold of the SCSB had relative biomass greater than 75%.

The findings of the research demonstrate the inability of the NSRs of the SCSB to detect nutrient interactions. The inability of the SCSB to detect differences between stressed plants and healthy plants suggests that it can't be relied on to monitor nutrient stress and inform nutrient application at the V6 stage. The marginal response of plants to greater nutrient application rates also demonstrates the low nutrient requirement of corn at the early growth stage.

2. Chapter Three: Secondary and Micronutrient Application Effects on Corn Fertilized for Different Yield Goals under Highly-weathered Soil Conditions.

Regardless of the treatments tested, nutrient concentrations in the plant tissues were all sufficient at the V5 to V7 stage. As a result, despite significant differences observed in the nutrient concentration between treatments at the V5 to V7 stage, it did not translate to significant differences in plant growth at that stage. At the reproductive stage, however, significant differences in nutrient concentration resulted in differences in plant growth.

Fe concentration in the plant tissues at the vegetative stage in Plains was 4 times higher than what was observed in Tifton. This huge difference was however not evident in the initial soil test analysis by the Mehlich I extraction method.

Applying SN and MN led to an increase in corn yield under both low and high PN rates. The application of SN and MN resulted in yield increments of 6.4% for the low PN and 4.2% for the high PN rates in Plains and 10.4% for the low PN and 6.0% for the high PN rates in Tifton compared to when neither SN nor MN were applied.

The yield target of 12.5 Mg ha⁻¹ was surpassed in both Plains and Tifton regardless of the SN or MN application while the target for 25.1 Mg ha⁻¹ was not achieved. These demonstrate that SN and MN might be limiting yield in highly weathered soil conditions when not included in the nutrient application regime. Also, a yield target of 12.5 Mg ha⁻¹ or lower can be achieved with lower PN nutrient rates than the current recommendations suggest.

3. Chapter Four: Assessing Corn Response to Early Season Nutrient Stress under Different Soil Moisture Regimes to Inform Adaptive Nutrient Management.

Corn is susceptible to nutrient stress and could not recover from early season nutrient stress. Early season nutrient stress caused a yield reduction of 11.7% to 37.6% compared to the non-nutrient stress treatment. Significant reductions in nutrient uptake, biomass, and yield suggest that residual soil nutrients were not adequate to support the initial growth of corn. Also, the

mineralization of peanut residues could ample nutrients at the early stages of growth despite low nutrient demand for corn at the initial stages of growth. Thus, adequate nutrient supply is required by corn during early season growth to avoid any form of stress. Care must also be taken to avoid losses due to excess nutrient supply, especially for mobile nutrients and nutrients that can easily be fixed.

4. Chapter Five: Early and Late Season Nutrient Stress Conditions: Impact on Cotton Productivity and Quality.

Nutrient stress impact on cotton on the productivity of cotton was not consistent across the production conditions. E-stress caused an improvement of 17.5% and 19.3% in lint and cottonseed yield respectively under one of the production conditions compared to the full nutrient rate. Also, the E-stress did not have an adverse impact on cotton yield. In contrast, the L-stress treatment reduced the lint and cottonseed yields by 34.4% and 36.2% when averaged across the production condition. Since the impact of E-stress on cotton was marginal, it suggests that nutrient application rates at the early season growth of cotton can be reduced and with the help of soil and plant tissue analyses, synchronized with crop demand and applied prior to the onset of the reproductive phase of cotton.