FERTILIZER SCHEDULING EFFECTS ON CORN PRODUCTIVITY AND NUTRIENT UPTAKE UNDER SUBSURFACE DRIP IRRIGATION SYSTEM

by

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(Under the Direction of Henry Yabbey Sintim)

ABSTRACT

This study was conducted to investigate the effects of fertilizer and irrigation scheduling on corn yield, biomass and nutrient uptake under subsurface drip irrigation. Two irrigation regimes [irrigation at 50% field capacity (FC-50) and 80% field capacity (FC-80)] and three nutrient scheduling treatments [split application terminated at VT growth stage (NS-VT); split application terminated at R2 growth stage (NS-R2); and no fertilizer application till V6 growth stage, followed by split application till VT growth stage (ES-VT)] were evaluated. Irrigation regime did not significantly impact yield and biomass, however, nutrient scheduling considerably affected yield and biomass with ES-VT recording the lowest yield and biomass while NS-R2 recorded the highest yield and biomass. Nutrient uptake was not influenced by irrigation regime but was significantly influenced by nutrient scheduling.

INDEX WORDS: Field Capacity, irrigation regime, nutrient scheduling, subsurface drip irrigation, biomass, nutrient uptake, adaptive nutrient application, growth stage

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DEDICATION

I dedicate this thesis to my parents. My father, Mr. Kwabena Yeboah and my mother Mrs. Pomaa Mercy for their support and prayers throughout my time in graduate school. Without them, this would not be possible.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Corn (*Zea mays*) is the highest producing feed grain in the United States. Globally, the United States produces and exports the largest amount of corn annually (Ranum et al., 2014). In the 2018/2019 cropping season, an estimated 366 million Mg of corn was produced with an export of 53 million Mg (USDA-NASS, 2019). The unexported corn in the United States is used for animal feed, ethanol, human food, and other industrial purposes (USDA-ERS, 2020). The Midwest United States is the major corn-producing region in the country and is commonly referred to as the Corn Belt. The top five corn-producing states in the country are Iowa, Illinois, Nebraska, Minnesota, and Indiana, in descending order of production. The state of Georgia is not in the Corn Belt; however, corn is a very important commodity as it comes behind only cotton and peanut in the total area of row crop production. In 2019, corn planted for all purposes was estimated at 159,851 ha, with an economic value of $252 million. Total areas of peanut and cotton production in that same year were 273,163 ha and 566,560 ha, respectively, with economic values of $532 million and $894 million, respectively (USDA-NASS, 2019). According to the 2020 Ag Snapshots report on Georgia’s agricultural economy, corn contributed 2.81% to the total agricultural economy of the state of Georgia.

Corn nutrient dynamics

Corn is a high-input crop, requiring a considerable amount of nutrients and water to achieve a higher yield (Ciampitti et al., 2013; Ciampitti and Vyn, 2013; Karlen et al., 1988). The yield and total plant nutrient uptake in corn reported in two different studies are shown in Table 1. The yield obtained from both studies resulted from a complex interaction between crop variety (hybrid), environment, and management practices. Both studies were under irrigated conditions, but Ciampitti et al. (2013) used a more modern corn hybrid than that used by Karlen et al. (1988). In general, modern corn hybrids have high yield potential, but Karlen et al. (1988) obtained greater yield. Moreover, plant nutrient uptake obtained by Karlen et al. (1988) was greater than that of Ciampitti et al. (2013). Karlen et al. (1988) applied some rates of all the listed primary, secondary, and micro-nutrients, whereas Ciampitti et al. (2013) applied just primary nutrient fertilizer sources, suggesting the need for an extensive nutrient management program.

Table 1. Grain Yield and total plant nutrient uptake in corn by maturity growth stage

Source	Yield	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	Mg ha^{-1}	------------------------------- kg ha^{-1} -------------------------------										
[1]	19.3	386	70.0	370	59.0	44.0	40.0	0.13	0.14	1.90	0.90	0.80
[2, 3]	12.3	270	55.0	201	28.0	33.1	21.9	na	0.08	1.70	0.50	0.50

[1](Karlen et al., 1988); [2](Ciampitti and Vyn, 2013); [3](Ciampitti et al., 2013)

na: not analyzed.

The use of starter fertilizer in corn production is a common practice to provide early-season growth. However, increased early-season growth does not always translate into better yield, especially under warm soil conditions and medium to high soil nutrient test levels (Hoeft, 2000; Mallarino, 2015). In Georgia, corn production often follows peanut production, and the warm and wet conditions lead to rapid mineralization of the peanut crop residues that can supply ample nutrients at the early growth stages during corn production (Balkcom et al., 2004) . Tissue nutrient concentrations at the three and six-leaf collar stages (V3 and V6) of corn planted after peanut without fertilizer application in a preliminary study in Tifton, GA, are provided in Table 2. As can be seen, the concentration of all nutrients is well within the reference nutrient sufficiency ranges for corn by the University of Georgia Agricultural and Environmental Services Laboratories (AESL) and the Southern Cooperative Series Bulletin (SCSB). The initial soil test levels before planting in the preliminary study are provided in Table 3. In general, the rate of nutrient uptake in corn is high at the middle of the vegetative stage until the silking stage (Hanway, 1963; Ciampitti and Vyn, 2013; Ciampitti et al., 2013; Bender et al., 2013). A study conducted at two locations in Illinois showed that at the six-leaf collar stage, less than 15% of all the applied nutrients had been taken up by corn when compared to the total taken up at maturity (R6) (Bender et al., 2013). By the tasseling stage, less than 70% of N, P, and K had been taken up when compared to the total uptake at R6 (Bender et al., 2013). Maximum uptake in the leaf blades, stalk, and leaf sheaths occurred around (R2) for N, P, K, and S nutrients.

Table 2. Tissue nutrient concentration in corn that received no fertilizer application in a preliminary study in Tifton, GA in 2020

Nutrient	V3	V6	AESL*	SCSB*
	-------------------------------- g kg^{-1}---------------------------------			
N	5.68	3.83	3.00-5.00	3.00-4.00
P	0.81	0.55	0.25-0.45	0.30-0.50
K	5.08	4.17	2.00-2.50	2.00-3.00
Mg	0.25	0.24	0.13-0.30	0.15-0.60
Ca	0.59	0.74	0.25-0.50	0.25-0.80
S	0.36	0.24	0.17-0.50	0.15-0.40
	--------------------------------mg kg^{-1}-------------------------------			
B	12.0	20.0	4.00-25.0	5.00-25.0
Zn	38.0	32.0	15.0-60.0	20.0-70.0
Mn	50.0	84.0	15.0-300	20.0-150
Fe	210	161	30.0-200	30.0-250
Cu	6.50	9.00	3.00-15.0	5.00-25.0

*Reference nutrient sufficiency ranges for corn by the University of Georgia Agricultural and Environmental Services Laboratories (AESL) and the Southern Cooperative Series Bulletin (SCSB). The reference nutrient sufficiency ranges of AESL are based on those for irrigated corn. V3 and V6, refer to three and six-leaf collar stages, respectively.

Table 3. Soil test results before planting in the preliminary study in Tifton, GA in 2020

NO_3^-	NH_4^+	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
--kg ha^{-1}---											
15.6	0.04	5.28	90.8	881	101	7.85	0.41	0.48	11.9	8.18	3.25

The findings of these studies give indications of getting some benefits from late fertilizer application. Splitting fertilizer application to ensure nutrients are provided at the stages needed most by corn can potentially be beneficial to increase yield while reducing nutrient loss to the environment. Precise diagnosis of the nutrient needs through in-season soil and tissue analysis will allow for tailored nutrient management (Scharf et al., 2002). This is particularly important in the state of Georgia where the majority of farmed soils are highly weathered with low cation exchange capacity. Moreover, the state experiences intensive rainfall conditions during the early stages of the growing season, which leaches mobile nutrients from the soil. Understanding the effects of such early nutrient stress on corn is therefore critical for the development of nutrient management tools.

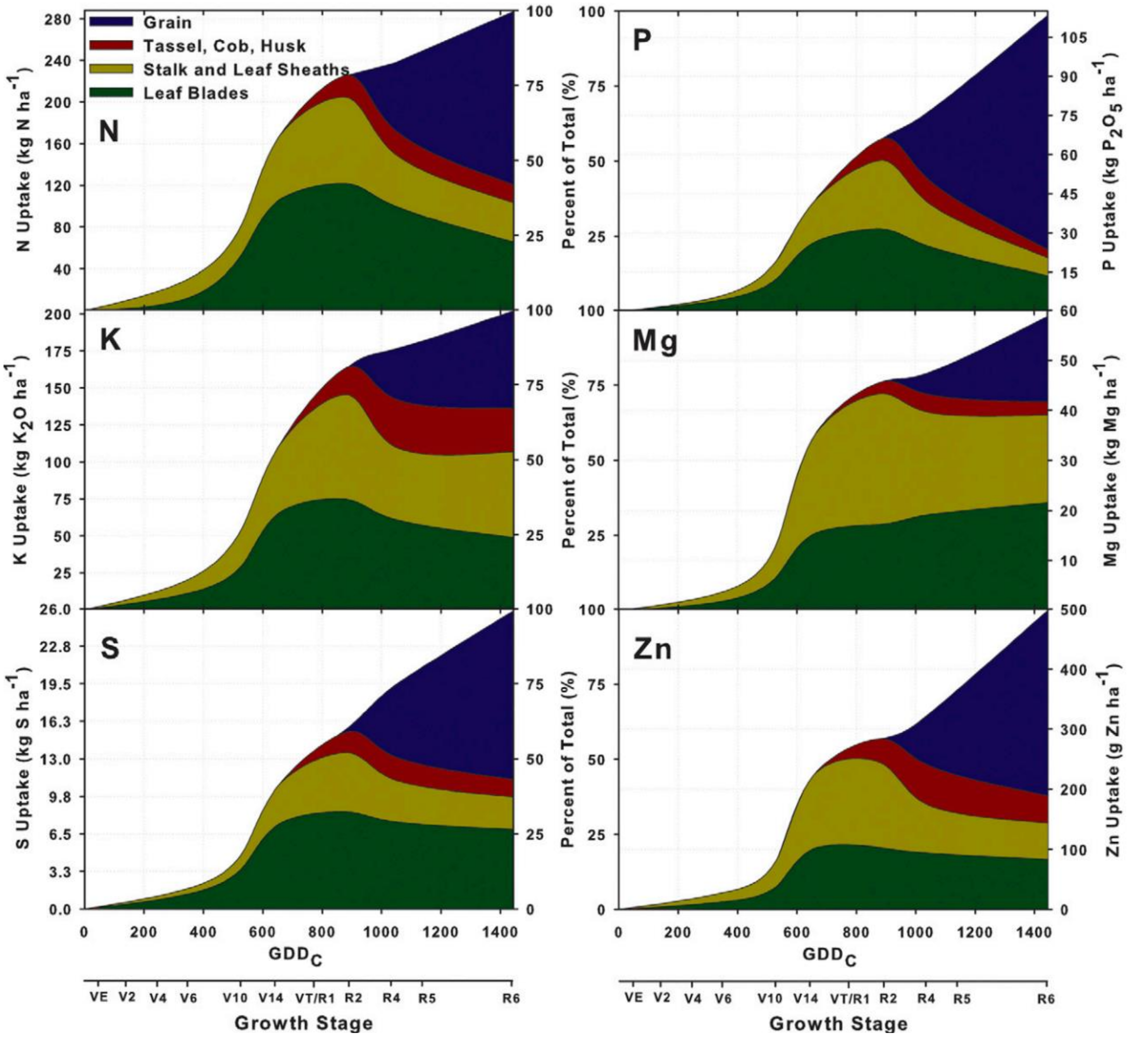

Figure 1. Seasonal accumulation and partitioning of nutrients in 12.0 Mg ha^{-1} average yield of corn reported by Bender et al. (2013)

Corn, like many vascular plants, requires about twelve essential nutrients [Nitrogen (N), Phosphorous (P), Potassium (K), Sulphur (S), Magnesium (Mg), Calcium (Ca), Zinc (Zn), Copper (Cu), Boron (B), Iron (Fe), Molybdenum (Mo), Manganese (Mn)] (Olson and Sander, 1988). Some nutrients are required in a larger amount (primary nutrients/macronutrients: N, P, and K), while those needed in relatively smaller quantities are referred to as secondary nutrients (Ca, Mg, and S) and micronutrients (Zn, Cu, B, Fe, Mo, and Mn). Nutrients could be available in substantial amounts based on native soil fertility and the crop rotation system adopted (Olson and Sander, 1988; Seifert et al., 2017). Studies showed that alfalfa (*Medicago sativa* L.) preceding corn can provide about 135 kg N ha^{-1} (Baldock and Musgrave, 1980; Stanger and Lauer, 2008). Pedersen and Lauer (2002) reported that soybean/corn rotation increased the grain yield of corn by 11% due to the availability of more residual N after soybean. However, most soils are deficient in some of the major nutrients required by corn (Ali et al., 2008), therefore, nutrient needed is mostly provided using fertilizers. In general, the amount of fertilizes to be applied is based on the yield goal and initial soil test results (Dobermann and Cassman, 2002; Shapiro et al., 2008) and fertilizer recommendations for corn defers among States in the U.S (Padgitt et al., 2000). Therefore, calculation of fertilizer requirement for corn must be based on local recommendation as excess application can cause lodging (Defra, 2010) and environmental pollution (Lupwayi et al., 2012; Ma et al., 2010) while applying less than the needed amount can reduce yield significantly (ten Berge et al., 2019).

The grain yield of corn is expected to increase with increasing nutrient levels, however, increasing the concentration of some plant nutrients may not always translate to higher yield. This is because each nutrient has a critical threshold that must be applied.

Nutrients levels above the threshold will result in luxury consumption and will not increase yield, on the other hand, nutrient levels lower than the threshold can potentially decrease corn yield (Barber and Olson, 1968). A study conducted by Wortmann et al. (2009) to investigate the effect of applied Phosphorous, Potassium and Sulphur on corn yield under irrigated conditions found out that, applying 40 kg K ha^{-1} resulted in a 0.2 Mg/ha decrease in grain yield, however, the 22 kg S ha^{-1} applied did not result in any significant yield increase. Another study by Inman et al. (2005) was conducted to evaluate the response of corn yield to different nitrogen rates. The lowest N rate applied was 56 kg N ha^{-1} while the highest amount of applied N was 268 kg N ha^{-1}. The results showed that, corn yield was significantly higher with increasing N. Similar N rate studies by (Abebe and Feyisa, 2017; Khan et al., 2018) reported significant increase in corn yield with higher levels of nitrogen. In as much yield generally increases with increasing levels of nitrogen fertilizer application, overapplication can potentially increase the probability of nitrate (NO_3—N) leaching below the root zone of corn (Mamo et al., 2003). Determining optimum fertilizer rate to attain optimal corn yield is practically difficult (Hawkins et al., 2007) because optimum fertilizer levels vary spatially due to variation in soil properties and interactions between environmental factors (Mamo et al., 2003).

Water dynamics in corn production

As a high input crop, corn also requires large quantities of water for its production. It is estimated that a grain yield of 12.5 Mg ha^{-1} will require about 87 liters of water per plant (Bruns, 2019). In areas with little rainfall, the water requirement for corn is provided through irrigation. Agricultural activities account for about 70% of total fresh water withdrawals and can be reach up to 95% in some developing countries (FAO, 2017). The increasing global population and rising income levels in most developed nations have resulted in increased demand for a higher standard of living (Kearney, 2010; UN DESA, 2015). As a result, there has been a shift in diet towards more meat and dairy products (Kearney, 2010). Concurrently, water requirements for non-agricultural purposes, such as household urban and industrial usage, have increased as well (Jensen et al., 2001). These situations have placed enormous pressure on global water resources (Rosegrant, 2016).

In many parts of the United States, irrigation water is becoming scarce due to decreasing groundwater levels (Mcguire, 2004). Shortage in water has led to government-imposed restrictions on irrigation in some parts of the United States like western Nebraska. Over time, these restrictions are bound to be more severe and widespread (Donk and Shaver, 2016). Water demand in most cities in Georgia is expected to increase as much as 100% by 2030 (Hess and Brown, 2018). Lake Lanier in the Chattahoochee river basin supply about 70% of the water needs of Atlanta and its metropolitan areas (Missimer et al., 2014). However, for over two decades, Lake Lanier has been in a protracted legal dispute between the state of Georgia and Florida based on the allocation of the water resources of the basin and other riparian factors (Missimer et al., 2014). To meet water needs, actions such as swapping roads and rail for water and seawater desalination have been adopted in some areas of Georgia (Missimer et al., 2014).

Against this background of water scarcity, and the need to meet global food demand more food has to be produced with less water. Thus, efficient irrigation scheduling/methods, such as deficit irrigation, surface drip irrigation (SDI), and subsurface drip irrigation (SSDI) have been introduced. Deficit irrigation is defined as the application of water below the evapotranspiration requirement of the crop (Fereres and Soriano, 2007).

Deficit irrigation has been investigated as a valuable and sustainable irrigation strategy that increases or stabilizes crop yield (Geerts and Raes, 2009). Many researchers have often concluded that the high efficiency and reduced cost associated with deficit irrigation can increase net farm income (M. H. Ali et al., 2007; English, 1990). Besides deficit irrigation, SDI and SSDI have been touted as efficient irrigation systems compared to center pivot or furrow irrigation systems (Donk and Shaver, 2016). On bigger corn farms, plants at areas farther from the pivot are normally subjected to prolonged periods of water stress compared to the plants very close to the starting point of the pivot due to the slow movement of the pivot. This setup can potentially cap yield, especially if crops are at the drought-sensitive stage of growth. However, SDI and SSDI systems avoid such water stress by supplying water to all the plants within a short time. Despite the enormous benefits of SDI and SSDI, application of irrigation water might be uneven along the pipes if it not well designed or installed.

Colaizzi et al. (2004) conducted a three-year study to compare three irrigation methods: SSDI, low-energy precision application, and spray irrigation under grain sorghum. In all three years, SSDI had a much higher yield than the yield of the other methods. Hassanli et al. (2009) investigated the effects of SDI, SSDI, and furrow irrigation on corn yield and water use efficiency. The results showed maximum water saving with SSDI, while furrow irrigation had the lowest water saving. The highest grain yield, 12.1 Mg ha^{-1} was obtained with SSDI, while the lowest yield 9.75 Mg ha^{-1}was obtained with furrow irrigation. Djaman et al. (2013) conducted a study with four irrigation treatments in Nebraska. The first treatment received the full amount of irrigation, treatments two and three received 15% and 30% less water, while the fourth treatment received 50% less water.

Treatment one had the highest grain yield, however, the yield was not significantly different from treatment two. Gadédjisso-tossou et al. (2020) conducted a study with three levels of irrigation. The first treatment received a full complement of irrigation, treatment two and three received 20% and 40% less water respectively. Grain yield was not significantly different between the first two treatments, but treatment two had a slightly higher water use efficiency.

Rationale

A close relationship exists between soil water and nutrient availability, therefore integrating effective water and nutrient management strategies is very important to optimize productivity and to maximize economic returns in corn production. Several studies that evaluate independently the effect of irrigation regimes and nutrient management have been extensively investigated. Studies that investigate how corn responds to varying level of water stress and nutrient scheduling often focus on the interaction between irrigation amount and the primary nutrients (N, P, and K). Further research is needed to demonstrate how corn will respond to different irrigation regimes amid varying nutrient application timings when all the essential nutrients (primary, secondary, and micro-nutrients) are supplied. The primary objectives of this research are as follows:

Objectives

1. To determine recovery of corn from an early-season nutrient stress condition.
2. To investigate corn response to late-season fertilizer application.
3. To assess the effect of water scheduling on corn under subsurface drip irrigation.

4. To understand corn nutrient uptake and water use efficiency under different moisture and irrigation management using subsurface drip irrigation.

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CHAPTER 2

CORN PRODUCTIVITY UNDER SUBSURFACE DRIP IRRIGATION SYSTEM: FERTILIZER AND IRRIGATION SCHEDULING EFFECTS

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ABSTRACT

Most farmers make their last fertilizer application by tasseling, however, some studies have suggested that, corn still needs nutrients after tasseling stage. Also, early season nutrient losses can be very under heavy rainfall and highly weathered soil conditions. The objective of this experiment was to quantify the effect of partial water and nutrient stress on corn yield and biomass production. Two irrigation treatments [irrigation at 50% field capacity (FC-50) and 80% field capacity (FC-80)] and three nutrient treatments [split application terminated at VT (NA-VT); split application terminated at R2 (NA-R2); and delayed application till V6 growth stage, followed by split application till VT (ES-VT)]. Grain yield of 12.5 and 13.6 Mg ha^{-1} obtained from the FC-50 and FC-80, respectively, and they were not significantly different. The NA-VT and NA-R2 treatments had similar yields (14.2 and 14.7 Mg ha^{-1}, respectively), and those yields were significantly greater than that of the ES-VT (10.2 Mg ha^{-1}). Total biomass was not affected by irrigation treatment, but was greater for NA-VT (19.5 Mg ha-1) and NA-R2 (19.8 Mg ha-1) than for ES-VT (10.1 Mg ha-1. In conclusion, early-stage (pre-plant and at planting) fertilizer application is critical in corn, but the benefit of post-tassel fertilizer application was not observed as hypothesized.

INTRODUCTION

Corn is very sensitive to nutrient stress; hence fall or early spring fertilizer application and the use of starter fertilizers are very common in most parts of the United States (Kaiser et al., 2016; Mullins et al., 1998). Early nutrient application, either spring or fall preplant fertilizers in corn, have been found to increase corn yield, height, and biomass (Gordon and Pierzynski, 2006; Mascagni and Boquet, 1996). In practice, the fertilization strategies of farmers vary among production systems (Fernandez et al., 2020). In the major corn-producing areas of the United States

(Illinois, Iowa, Indiana, and others), farmers apply about 75% of N fertilizer before planting while the remaining 25% is split applied as side-dress during the growing season (Cao et al., 2018; Jin et al., 2017). Typically, in the sandy Coastal Plains of Southern Georgia, about 30% of the required N is applied by planting with the remaining nitrogen split applied before or right after tasseling (Harris, 2020). However, all phosphorous fertilizers are applied preplant by broadcasting, or some of the rates are reserved and applied as starter fertilizer during planting (Barber and Olson, 1968; Harris, 2020). Potassium fertilization recommendation typically follows that of phosphorous, however, on deep sand soils, split application is recommended (Harris, 2020).

Most farmlands in Georgia are highly weathered with low organic matter and nutrient reserves, low soil pH, as well as low cation exchange capacity, which makes them susceptible to erosion (Rhoades et al., 1997). Under such conditions, nitrogen losses due to runoff and leaching are tremendous and it severely affects nutrient availability, thereby subjecting corn to nutrient stress during the late part of the season (Aulakh and Bijay-Singh, 1996). In the state of Georgia, corn is often planted between late February and Mid-May and harvested around mid-June and mid-September (Martinez et al., 2008). Farmers favors early planted corn as greater corn yields have been associated with early planted corn than the late-planted ones (Martinez et al., 2008). However, historical climate data shows that, the early part of the corn season in the Southern coastal plains is characterized heavy rainfall as shown by the monthly Normal precipitation data for two locations in Figure 2. Under such intensive rainfall, losses of mobile nutrients such as nitrogen and potassium can be very high and this can potentially induce nutrient stress, especially if most of the nutrients have been applied before such intensive rainfall events. Corn is predicted to set its yield by the V6-V8 stage based on a study conducted by Teal et al. (2006) using normalized difference vegetation index (NDVI) values during in-season growth. Previous studies evaluating early nutrient stress in corn production have provided mixed results. Scharf et al. (2002) evaluated the impact of delayed nitrogen application on yield and found out that delaying nitrogen application up to V11 did not statistically affect yield compared to when preplant and planting fertilizers were applied. In his study, the total nitrogen application rate was 225 kg ha^{-1}. However, Binder et al. (2000) working on corn deficiency and nitrogen application timing on a silty clay loam soil found out that delaying nitrogen application to the V6 stage was able to decrease corn yields up to 12% of the maximum grain yield obtained. Similarly, Walsh et al. (2012) evaluated multiple combinations of preplant and in-season nitrogen side-dress at three growth stages (V6, V10, VT) and the results showed that yield loss was significantly higher when nitrogen was delayed until V10-VT. Most studies investigating early nutrient stress in corn often focused on only the primary nutrients. It is therefore important to ascertain how corn will recover from early nutrient stress when all essential nutrients are provided in adequate amounts.

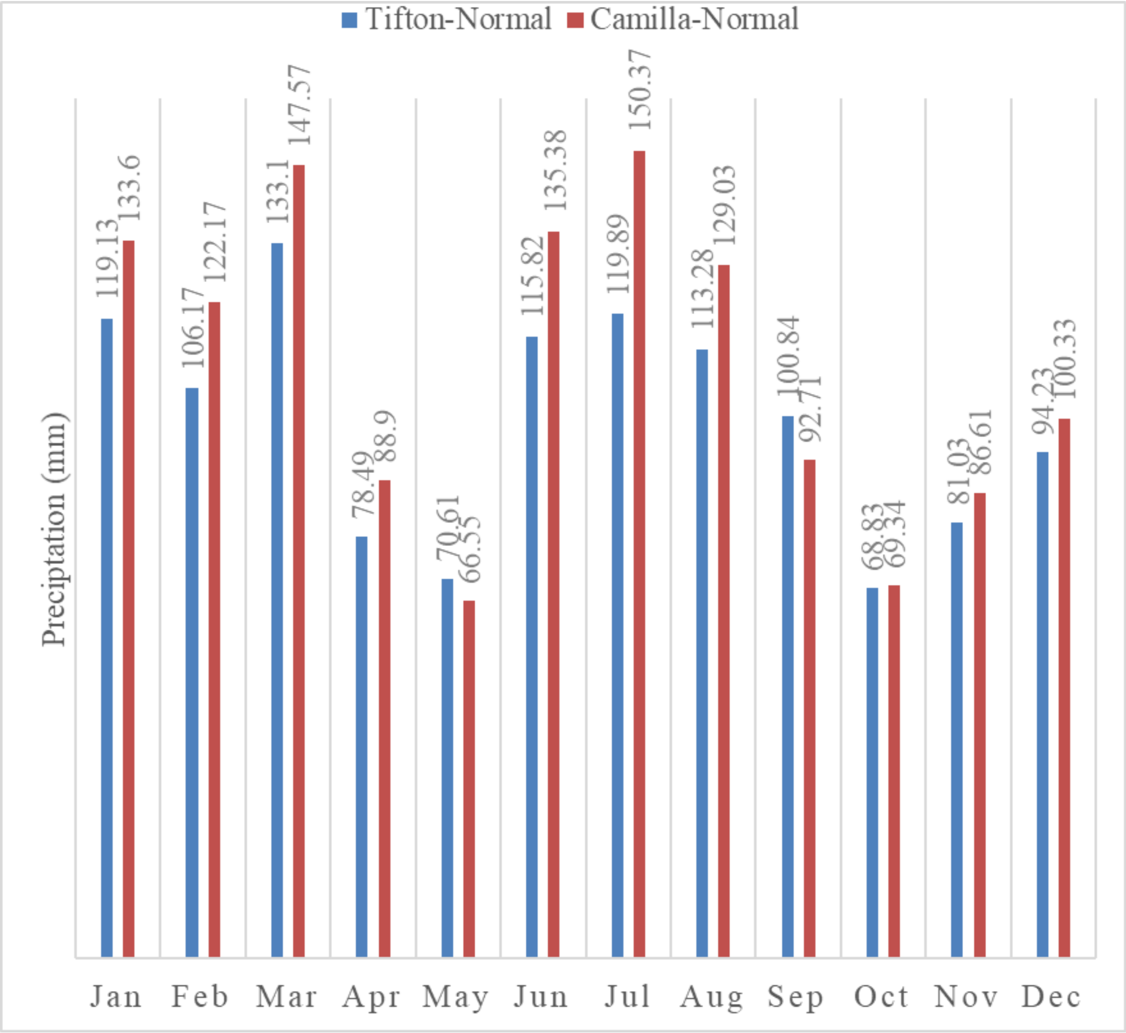

Figure 2. Monthly Precipitation-Normal for Tifton and Camilla

Studies show that corn accumulates nutrients such as nitrogen, potassium, magnesium, and other micronutrients in excess of 30% after the silking stage (Mueller and Vyn, 2016). In addition, observations from experimental plots show that corn plants stay green for a longer period during the late-season stage in well-fertilized plots than those in poorly fertilized plots. Therefore, late-season fertilizer application could be a possible fertilization strategy to alleviate nutrient stress, improve soil nutrient supply, and increase plant nutrient availability (Fernandez et al., 2020). However, those hypotheses need to be experimentally proven. As most of the farmlands in Georgia have natively acidic, the use of calcitic or dolomitic lime is recommended to correct low soil pH conditions (Harris, 2020). However, applying lime (calcium carbonate) can potentially fix a huge amount of the phosphorous applied at preplant and at planting, thus, making phosphorous less available to corn especially in the late season (Ibrikci et al., 2005). In order to reduce nutrient stress, increase corn yield and also improve nutrient recovery, greater synchrony in nutrient demand and nutrient supply is required during the growing season (Ciampitti and Vyn, 2012; Raun and Johnson, 1999).

Water stress affects the developmental and physiological processes in corn and can result in a severe reduction in biomass production and consequently grain yield, due to decreased kernel weight and the number of kernels per ear (Payero et al., 2009; Traore et al., 2000). Globally, agricultural activities use about 70% of fresh water for irrigation purposes (FAO, 2017) and in 2015, the amount of water used for irrigation in the United States was about 446,678 ML day^{-1}, representing 42% of the total water abstraction (Dieter et al., 2018). In recent years, water resources available for agricultural activities have decreased while drought and water regulation have limited the amount of irrigation water available in many areas of the United States (Hu et al., 2009). Under such circumstances, farmers have the option of either applying full irrigation water by decreasing the size of their farm or by applying less amount of irrigation water if they want to increase their farm size (Payero et al., 2009). Irrigating corn with less amount of water can create water shortage in the soil during some time in the season, and a decline in soil water can affect nutrient availability and adsorption by plant roots (Hu et al., 2009). Previous studies on nutrient stress and water dynamics in corn have predominantly focused on nitrogen application under different moisture regimes. There is limited information on how corn responds to partial nutrient stress under minimal irrigation conditions when all the required nutrients (primary, secondary, and micronutrients) are supplied in adequate amounts. The objectives of this study were to (a) determine how corn will recover from early-season nutrient stress, (b) investigate corn response to late-season fertilizer application, and (c) assess the effect of water scheduling on corn under subsurface drip irrigation.

MATERIALS AND METHODS

Study Site Details

The study was conducted during the 2020 growing season at the Stripling Irrigation Research Park located near Camilla, GA (31°16′43″N, 84°17′41″W, 53 m above sea level). The average annual precipitation at Camilla is about 1313 mm with about 98 rainy days per year (Georgia Weather Network, 2019). The soil at the experimental site is classified as Lucy loamy sand, with 0 to 5 percent slope. Maximum and minimum temperature, precipitation, and total solar radiation at the study site were obtained from an on-site weather station, which is part of the statewide Georgia Weather Network. Initial soil samples to two depths (0-15 cm and 15-30 cm) were taken and analyzed for soil chemical properties, following standard soil test procedures by the Waters Agricultural Laboratories Inc. in Camilla, GA (Soil Sampling - Soil Testing - Soil Analysis, n.d.). The experimental site was equipped with a subsurface drip irrigation system where the drip tapes were installed at 30 cm deep and 46 cm to the side of every plant row.

Treatment factors and experimental design

Two irrigation and three nutrient scheduling treatments were evaluated in this study. The irrigation scheduling treatments were based on when the soil water content depleted to 80% (FC-80) or 50% (FC-50) field capacity, at which times irrigation was applied to raise the soil water content to field capacity. The nutrient scheduling treatments were (a) nutrient application terminated at VT (NA-VT), (b) nutrient application terminated at R2/R3 (NA-R2), and (c) no fertilizer application until V6, after which, the plots received nutrient application until VT (ES-VT). The experimental design was a split-plot randomized complete block design with four replications. The two irrigation scheduling treatments were assigned to the main plots, and the three nutrient scheduling treatments were assigned to the subplots. Each subplot had six rows of corn 12 m long, with a row spacing of 0.91m.

Irrigation System Descriptions

The experiment was conducted under a subsurface drip irrigation system. A Netafim Typhoon drip tape with an inner diameter of 1.62 cm and a wall thickness of 0.038 cm was installed at the experimental site in 2016. The maximum pressure of the tapes was about 179 kpa and was installed at approximately 30 cm below the soil surface. Spacing between emitters was 46 cm which is common for laterals produced by commercial irrigation companies (Kandelous et al., 2011) and each emitter had a discharge rate of 1.5 L hr^{-1}. Drip tapes were placed 183 cm apart and located at the middle of every row and 45 cm away from the corn.

Irrigation Scheduling

Bulk soil samples were taken and used for the calibration of soil moisture sensors (Teros 12, METER Group, Inc., Pullman, WA, USA), following recommended procedure. The sensors were connected to a Zentra datalogger (METER Group, Inc., Pullman, WA, USA) and set up to collect hourly soil moisture data. The Zentra datalogger was equipped to transmit data via a cellular network, where the data could be downloaded remotely. The sensors were installed at (a) 20 cm depth and 15 cm to the side of the plant row, and at (b) 30 cm depth and 25 cm to the side of the plant row. The soil water content at 80% field capacity of the soil was estimated as 0.11 m^3 m^{-3}, whereas the soil water content at 50% field capacity of the soil was estimated as 0.092 m^3 m^{-3}. The available water holding capacity of the soil was calculated as the difference in water content at -

33 kPa and -1500 kPa (Klute, 1986). The irrigation treatments were imposed between the V6 and R6 stages, and the irrigation was triggered when the threshold for the sensors installed at 30 cm depth was reached. The sensors installed at the 20 cm depth did not detect irrigation events and could therefore not be used to trigger irrigation. This was likely due to the installation depth of the drip tapes (30 cm) and the coarse nature of the soil that limited capillary action.

Fertilizer Scheduling

Macro (N, P, and K), secondary (Ca, Mg, and S), and micro (Fe, Mn, Zn, B, Cu) nutrients were supplied based on the initial soil test results. The total nutrient application rates and schedule used for the treatment NA-VT are shown in Table 4. The treatment NA-R2 received the same fertilizer rates and schedule as the treatment NA-VT, plus an additional 10% of the total of all nutrients applied by the VT stage were supplied at the R2/R3 stage. The treatment ES-VT did not receive any fertilizer application until the V6 stage, after which it received nutrient application rate and schedule as the treatment NA-VT. All fertilizers supplied to the treatment NA-VT before the V6 stage were supplied to the treatment ES-VT between the V6 and V9 stages. Granular sources of fertilizer were used before the V6 stage, as either broadcast or side-dress application. After V6, liquid sources of fertilizer were used, and applied via injection through the drip tapes.

Table 4. Total nutrient application rate and schedule used for the non-early-stress nutrient application treatment terminated at VT (NA-VT).

Nutrient	Total rate (kg ha^{-1})	Proportion applied (%)			
		Preplant - planting	V3 – V6	V9 – V10	VT
N	404	15	45	20	20
P	202	50	50	0	0
K	235	40	40	10	10
Ca	22.4	50	50	0	0
Mg	16.8	50	50	0	0
S	16.8	50	50	0	0
Fe	4.5	50	50	0	0
B	2.2	50	50	0	0
Mn	4.5	50	50	0	0
Zn	3.4	50	50	0	0
Cu	1.1	50	50	0	0

Plot Management

The study was established on a research field that had been under strip-tillage for the previous five years. The previous cash prop was peanut (*Arachis hypogaea*), and rye (*Secale cereal*) was cultivated as a cover crop during the fall season. The rye cover crop was terminated in the spring of 2020 by spraying the recommended rate of glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine, Monsanto, St. Louis, MI]. After, the plots were strip-tilled to 30-cm depth with a chisel plow. The plots were demarcated according to the experimental design described previously. AgriGold corn hybrid A6499STX was planted at a rate of 88,958 seeds ha^{-1}. Pest and disease controls were performed to ensure plant health, according to the University of Georgia corn production guide.

Data collection and analysis

Six plants from one row harvested at V3, V6, VT/R1, R3/R4, and R6 growth stages were used to determine biomass production, and were partitioned into four components: 1) leaves; 2) stems and leaf sheath; 3) tassel, cob, and husk; 4) and seeds. The samples were dried in the oven at 65^{o}C until a constant weight was obtained, and then weighed to estimate biomass. We installed trail cameras (Spypoint Link-Micro 4G-LTE, Victoriaville, Québec, Canada) to facilitate the monitoring of growth and physiological stages of corn. At maturity, additional data, including yield, biomass, ear height, number of rows per ear, ear length, ear diameter, and 1000-seed weight were also determined.

Statistical Analysis

The analysis of variance conducted considered irrigation treatment and nutrient treatment as fixed effects, with blocks as a random effect. The data were analyzed with a linear mixed model using the "nlme" package in R software (Pinheiro et al., 2018). 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 software (Lenth, 2018). The significance level for all analyses was assessed at $P = 0.05$

RESULTS AND DISCUSSION

Initial Soil Characteristics

The initial physical and chemical properties of the soil at the experimental site are presented in Table 5. The initial soil pH of the field was similar across the two depths with an average value of 6.2. However, the soil organic matter tended to decrease with depth. Also, the initial levels of P, K, S, B, Fe, and Cu were relatively higher at the top 15 cm and decreased as the soil depth increased. Conversely, the initial levels of Mg, Ca, Zn, and Mn increased with depth. The initial levels of Ca, Mg, and S are fairly high, and this could be attributable to the residual nutrients from the gypsum and dolomitic lime applied in the previous year. The field received 1120 kg ha^{-1} of gypsum and dolomitic lime the prior year.

Grain Yield

All yield data are presented in Table 6 and means of yield are separated statistically. There were significant effects of irrigation and nutrients treatments, however, the interaction between irrigation and nutrient was not significant. The yield ranged from 8.8 Mg ha^{-1} (for FC-50 and ES-VT) to 14.8 Mg ha^{-1} (FC-80 and NA-VT). Yields for plots that were irrigated at 50% field capacity (FC-50) were lower than those of plots irrigated at 80% field capacity (FC-80), except for NA-VT, where the yield was similar, with average yield value of 14.2 Mg ha^{-1}. Plots under ES-VT always had lower yields compared to the yields of plots under NA-VT. The yield of plots under NA-R2 was always greater than the yield for plots under NA-VT. Statistically, plots under ES-VT irrigated at 50% field capacity had a significantly lower yield (8.8 Mg ha^{-1}) compared to the yield of NA-VT and NA-R2 plots (14.2 and 14.6 Mg ha^{-1}, respectively). However, the yields of plots irrigated at 80% field capacity had statistically similar yields irrespective of the nutrient scheduling treatment. The yield of FC-50 and FC-80 were not statistically different ($P < 0.05$), averaged over the three irrigation scheduling treatments. However, the yield of ES-VT was significantly lower ($P < 0.05$) from the yield of NA-VT and NA-R2).

Management strategies, such as fertilizer and irrigation scheduling, have been intensively studied in the quest to understand how to achieve higher corn yield while safeguarding the environment and using less water. Corn is very sensitive to nutrient stress during its growth stages. As shown in this study, partially stressed treatments produced yields lower than the treatment that was not stressed. Specifically, the yield of the early stressed nutrient treatments was significantly lower than the yields of no stressed treatments. This result is similar to previous studies conducted by Binder et al. (2000), where delaying nitrogen application till the V6 stage produced grain yield significantly lower than the treatments that received early fertilizer application. The yield of the late stressed treatment was not significantly different from the yield of the no stressed treatment, and this observation is similar to the observation made by Tarkalson et al. (2009).

Irrigation is crucial in corn production. As shown in this study, the yield of FC-80 was slightly greater than the yield of FC-50. Significant yield differences were not observed between the irrigation treatments because rainfall was high during the early stages of development giving the crop a good start. In July (which corresponded to the post silking and grain filling stage), rainfall events for almost half of the month provided an adequate amount of water to the corn. The results from this study are consistent with other studies (Djaman et al., 2013; Gadédjisso-tossou et al., 2020). In the latter study, supplying 50%, 60%, and 75% percent of the total irrigation requirement of corn on a silt loam soil provided a grain yield of 14.3, 14.9, and 15.0 Mg ha^{-1}, respectively, and these yields were not statistically different.

Yield Component

Yield components (ear diameter, ear length, number of rows per ear, and thousand seed weight) response to partial water and nutrient stress is presented in Table 7. Yield components were not significantly impacted by the irrigation treatment and there was no interaction between irrigation and nutrient treatments. FC-50 had ear diameter, ear length, number of rows per ear, and thousand seed weight of 45.9 mm, 15.9 cm, 15, 317 g, respectively, while the values of the same parameters for FC-80 were 46.6 mm, 16.4, 15, 327 g, respectively. The lack of an irrigation effect on yield components is in agreement with results of previous studies (Aydinsakir et al., 2013; Ertek and Kara, 2013). Karasu et al. (2015) observed that ear length and number of rows per ear obtained when irrigation was applied at 75% and 50% were not significantly different. Significant differences in ear length and the number of rows per ear were only observed when irrigation applied was 100% and over or below 25%. Marković et al. (2017) noted that applying irrigation at 60% and 80% field capacity did not significantly affect ear length, 1000 grain weight, and the number of rows per ear. The 1000-seed weights reported by Marković et al. (2017) were lower than what was obtained in this study and this can be attributed to differences in soil type and fertilization levels. The effect of partial nutrient stress on ear diameter, ear length, number of rows per ear, and thousand seed weight was significant. When nutrients were supplied starting from V6 (ES-VT), ear diameter, ear length, the number of rows per ear, and thousand seed weight were significantly reduced. However, beginning nutrient application from pre-plant and stopping at either VT (NA-VT) or R2 (NA-R2) did not affect ear diameter, ear length, number of rows per ear, and thousand seed weight even though values of these parameters were slightly higher for NA-R2. Ear diameter, ear length, number of rows per ear, and thousand seed weight of 42.4 mm, 14.6 cm, and 13, 286 g, respectively, for ES-VT, were about 12%,13%, 18%, and 16% lower than the average of the NA-VT and NA-R2. Yield components of the early stressed plots were significantly lower because the kernel and ear initiation in corn growth begin around V6/V7, hence nutrient stress before this stage significantly impacts these components (Abendroth et al., 2011; Corey, 2020). The treatments NA-VT and NA-R2 were statistically at par with the yield components, however, values were slightly higher in NA-R2. This is because starch accumulation in kernels starts around R1 through to R5 and Abendroth et al. (2011) mentioned that at R1, only about 40-45% of kernel weight and ear length have been formed. Thus, stress at late reproductive stages can cause a reduction in kernel weight and ear size. Results from this study are in corroboration with that of Keyro and Zenebe, (2019) who found that delaying nitrogen application up to the V6 stage significantly decreased yield components but observed no significant differences when nitrogen application was terminated at either VT or R2.

Biomass Accumulation

The rate of increase and the amount of biomass accumulated during corn growth differed among the various components (stems, leaf blade, tassel, cobs, grain); however, summing all components together for each treatment produced a response curve as shown in Figure 2. The x-axes represent the approximate growth stage (vegetative and reproductive) at which tissue samples were collected while the y-axes show cumulative biomass production scaled in kg ha^{-1}. The percentage of total biomass accumulated at each defined growth stage is shown along the curve. In this study, tissues were separated into four components (stems and leaf sheath, leaf blades, tassel and husk and cob, grain), these components are represented by the color lines. Stems and leaf sheath contains the largest amount of biomass among the vegetative components while grains have the highest among the reproductive parts.

Irrigation treatment did not significantly influence biomass accumulation as the total amount of biomass produced at the end of the growing season was statistically similar. The interaction effects of irrigation and nutrient scheduling were not significant, but the main effects of nutrient scheduling had a significant impact on biomass accumulation. As can be seen in plots 1a and 1b, irrigating at either FC-50 or FC-80 with early nutrient stress (ES-VT) produced total biomass of about (10, 000 and 10, 500 kg ha^{-1}). The percentage of biomass accumulated at a specific growth stage was also statistically similar, with most components reaching maximum weight around R2. Biomass accumulated for the early nutrient stress treatment (ES-VT) was significantly lower than the total biomass accumulated for the NA-VT and NA-R2. The maximum weight reached for ES-VT was about 10,500 kg ha^{-1} while the maximum for NA-VT and NA-R2 were about 20, 500 and

21,000 kg ha^{-1}, respectively. Statistically, no significant differences were observed between NA-VT and NA-R2. Studies by Abendroth et al. (2011) found that total above-ground biomass produced in corn can be in excess of 22,400 kg ha^{-1}, provided that all stressed factors are eliminated and the plants get an appreciable amount of sunlight. The biomass obtained in this study is low because the subsurface drip irrigation system may have induced some moisture stress, regardless of irrigation scheduling treatment.

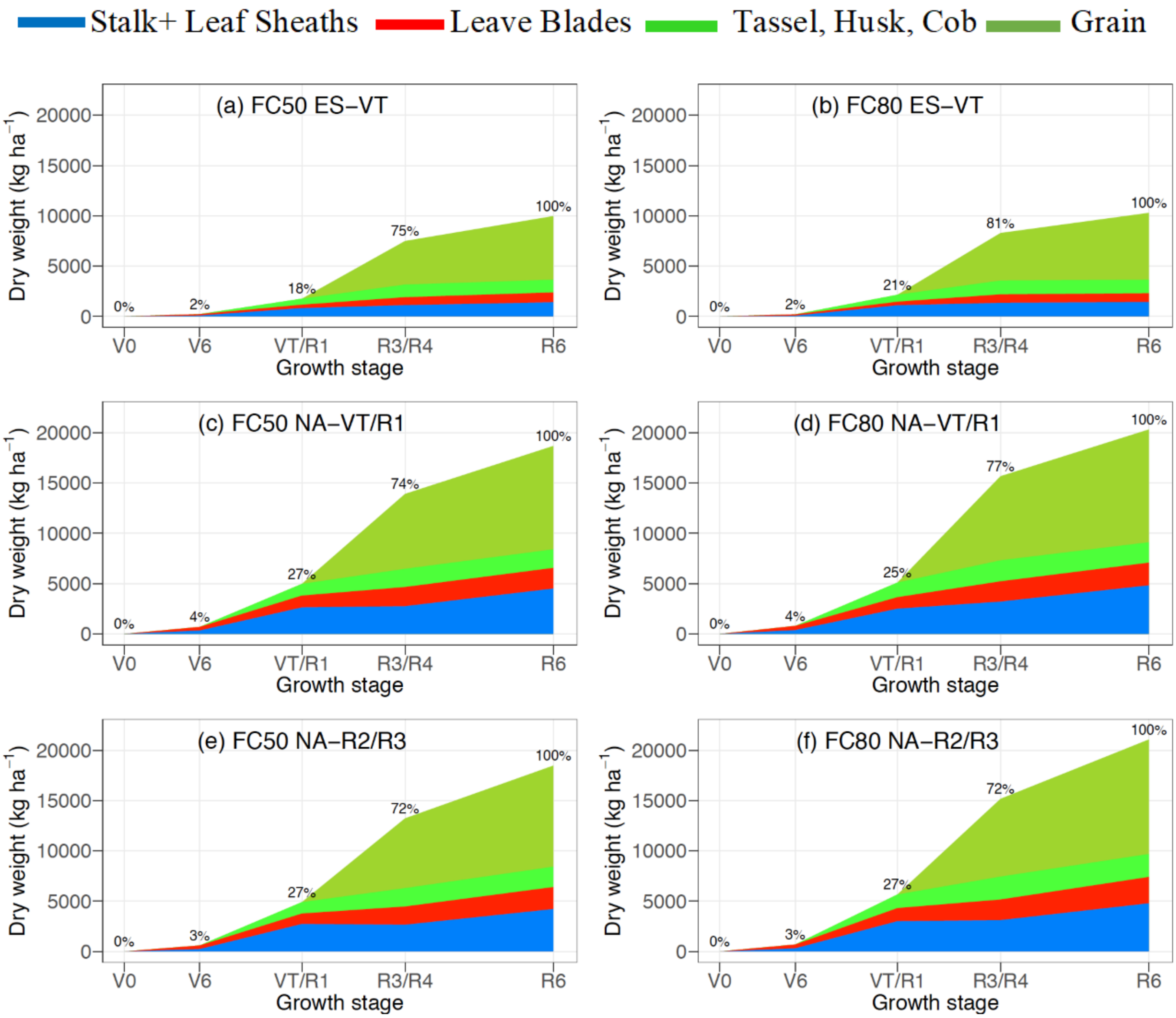

Figure 3. Cumulative biomass accumulation of each treatment combination over the growing season.

Table 5. Initial physical and chemical properties of the soil at the experimental site.

Soil depth (cm)	Texture	Sand (%)	Silt (%)	Clay (%)	Soil pH	Soil OM	P	K	Mg	Ca	S	B	Zn	Fe	Mn	Cu
						g kg^{-1}	kg ha^{-1}									
0-15	Sand	90.7	3.2	6.1	6.2	6.4	90.8	100	106	933	66.1	0.4	5.3	31.0	18.3	0.9
15-30	Loamy Sand	86.7	2.1	11.2	6.2	5.9	75.1	82.9	109	968	47.1	0.3	5.4	26.5	27.6	0.8

OM: Organic matter.

Table 6. Impact of partial water and nutrient stress effect on corn yield

Irrigation Treatment	Nutrient Treatment	Yield (Mg ha^{-1})
FC-50	ES-VT	8.8a
	NA-VT	14.2b
	NA-R2	14.b
FC-80	ES-VT	11.6a
	NA-VT	14.2b
	NA-R2	14.8b

Within irrigation treatment, means followed by different letters are significantly different ($P < 0.05$) according to Tukey's test.

Table 7. Impact of partial nutrient and water stress on corn yield components

Irrigation Treatment	Nutrient Treatment	Number of rows per ear	1000 Seed weight (g)	Ear length (cm)	Ear Diameter (mm)
FC-50	ES-VT	13a	274a	14.3a	42.3a
	NA-VT	15b	340c	16.5b	47.3b
	NA-R2	16b	338bc	17.0b	48.2b
FC-80	ES-VT	14a	297ab	15.0a	42.5a
	NA-VT	16b	337bc	16.8b	49.2b
	NA-R2	16b	348c	17.5b	48.1b

Within irrigation treatment, means followed by different letters are significantly different ($P < 0.05$) according to Tukey's test.

CONCLUSION

The level of irrigation employed in this study did not significantly affect the variables (yield, ear length, 1000 seed weight, ear diameter, number of rows per kernel, and biomass accumulation) that were assessed in this study. Specifically, grain yield and total biomass accumulation of plots that were irrigated at either 50% FC or 80% FC were statistically similar. This observation shows that amidst decreasing water availability, corn growers can produce considerably higher yields with a limited amount of irrigation. The impact of partial nutrient stress on yield, yield components, and biomass accumulation was tremendous in this study. Delaying nutrient application until V6 significantly decreased yield and biomass accumulation even though nutrient levels of some major nutrient elements were high at the start of the experiment. Applying nutrients after VT (NA-R2) slightly increased yield and biomass over the NA-VT, but it was not statistically significant. In conclusion, early-stage (pre-plant and at planting) fertilizer application is critical in corn, but the benefit of post-tassel fertilizer application was not observed as hypothesized.

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CHAPTER 3

NUTRIENT UPTAKE AND WATER USE EFFICIENCY OF CORN UNDER SUBSURFACE DRIP IRRIGATION

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ABSTRACT

Freshwater is a limited natural resource, and therefore there has been increased interest in more efficient irrigation systems. Subsurface drip irrigation (SSDI) is a very efficient irrigation method, but its performance could be compromised under coarse-textured soil conditions. This study evaluated two irrigation and three nutrient scheduling regimes under SSDI and a coarse-textured soil condition. SSDI induced severe moisture stress in the upper 20-cm layer, likely due to restricted capillary rise. The uptake of all applied nutrients was similar between plots irrigated when the soil moisture was at 50% and 80% field capacity; however, irrigation water use efficiency (IWUE) was greater in the former. Nutrient uptake in both grains and stover was considerably low when corn was subjected to early-season nutrient stress conditions. Applying 10% of fertilizer post the tassel growth stage did not translate into increased nutrient uptake and IWUE.

INTRODUCTION

Subsurface drip irrigation is an efficient irrigation system that reduces non-productive water losses due to evaporation, surface runoff, and deep percolation (Ayars et al., 2015; Evett et al., 2018; Kandelous and Simunek, 2010; Martínez and Reca, 2014). Subsurface drip irrigation enhances plant growth, increases yield, and improves crop quality because of the timely placement of water and nutrients in the crop root zone (Ayars et al., 2015). Subsurface drip irrigation promotes plant health because it ensures a drier canopy and reduced wetted soil surface, inhibiting the growth of fungal pathogens (Ayars et al., 2015). In the SDI system, the laterals are buried, resulting in a significant reduction in weed germination and development, particularly in the area between rows (Ayars et al., 2015). Subsequently, farming operations and the performance of agronomic management practices are facilitated since the drip laterals are buried, and damage due to farm equipment and field labor is minimized. There is also a less physical obstruction to farming activities (Martínez and Reca, 2014).

A study by Hernandez et al. (1991) examining nutrient uptake, biomass accumulation, and yield of corn under subsurface drip irrigation and surface sprinkler irrigation found out that phosphorous and potassium uptake was higher under subsurface drip irrigation relative to the surface application. Karam et al. (2003) conducted a two-year study to evaluate the effects of irrigation on yield and water use efficiency of corn under a subsurface drip irrigation. Two irrigation levels (irrigation at 100% field capacity and 60% field capacity) were tested, and the results showed greater irrigation water use efficiency for the irrigation at 60% field capacity (1.88 kg m^{-3}) than the water use efficiency of the irrigation at 100% field capacity (1.61 kg m^{-3}), averaged over the two years. Camp (1998) reviewed several studies comparing the yield of crops cultivated under subsurface drip irrigation and other surface irrigation methods. He concluded that in most cases, the yields of all the crops irrigated using a subsurface drip irrigation were either equal to or better than those under the different irrigation systems.

Despite the enormous benefits of subsurface drip irrigation, this method has several shortcomings (Martínez and Reca, 2014). It has been observed that rodents are often a problem with SDI as they chew the underground drip tapes, causing leaks that may result in non-uniform water distribution (Donk et al., 2012). More importantly, irrigating with a subsurface drip irrigation wets only a small soil volume (Lamm and Trooien, 2003). With a small fraction of the soil being wet, plant root growth and distribution are restricted, affecting nutrient and water uptake (Coelho and Or, 1999). Depending on the soil type and how the drip laterals are installed, the wetting pattern under a subsurface system will be different as the distribution of water across the root zone is affected by the hydraulic soil property, spacing and depth of emitters and laterals, and the discharge rate of the emitters (Kandelous and Simunek, 2010). Past studies on subsurface drip irrigation have often focused on understanding how different irrigation amounts affect yield, biomass, and water use efficiency (Colaizzi et al., 2004; Payero et al., 2009; Payero et al., 2008). Unfortunately, there is limited information on how corn responds to varying irrigation amounts under different nutrient management. This study was conducted to understand corn nutrient uptake and water use efficiency under different moisture and irrigation management using subsurface drip irrigation.

MATERIALS AND METHODS

Study Site Details

The study was conducted during the 2020 growing season at the Stripling Irrigation Research Park located near Camilla, GA (31°16′43″N, 84°17′41″W, 53 m above sea level). The average annual precipitation at Camilla is about 1313 mm with about 98 rainy days per year (Georgia Weather Network, 2019). The soil at the experimental site is classified as Lucy loamy sand, with 0 to 5 percent slope. Maximum and minimum temperature, precipitation, and total solar radiation at the study site were obtained from an on-site weather station, which is part of the statewide Georgia Weather Network. Initial soil samples to two depths (0-15 cm and 15-30 cm) were taken and analyzed for soil chemical properties, following standard soil test procedures by the Waters Agricultural Laboratories Inc. in Camilla, GA (Soil Sampling - Soil Testing - Soil Analysis, n.d.). The experimental site was equipped with a subsurface drip irrigation system where the drip tapes were installed at 30 cm deep and 45 cm to the side of every plant row.

Treatment Factors and Experimental Design

Two irrigation and three nutrient scheduling treatments were evaluated in this study. The irrigation scheduling treatments were based on when the soil water content depleted to 80% (FC-80) or 50% (FC-50) field capacity, at which times irrigation was applied to raise the soil water content to field capacity. The nutrient scheduling treatments were (a) nutrient application terminated at VT (NA-VT), (b) nutrient application terminated at R2/R3 (NA-R2), and (c) no fertilizer application until V6, after which, the plots received nutrient application until VT (ES-VT). The experimental design was a split-plot randomized complete block design with four replications. The two irrigation scheduling treatments were assigned to the main plots, and the three nutrient scheduling treatments were assigned to the subplots. Each subplot had six rows of corn 12 m long, with a row spacing of 0.91m.

Irrigation System Descriptions

The experiment was conducted under a subsurface drip irrigation system. A Netafim Typhoon drip tape with an inner diameter of 1.62 cm and a wall thickness of 0.038 cm was installed at the experimental site in 2016. The maximum pressure of the tapes was about 179 kpa and was installed at approximately 30 cm below the soil surface. Spacing between emitters was 46 cm which is common for laterals produced by commercial irrigation companies (Kandelous et al., 2011) and each emitter had a discharge rate of 1.5 L hr^{-1}. Drip tapes were placed 183 cm apart and located at the middle of every row and 45 cm away from the corn.

Irrigation Scheduling

Bulk soil samples were taken and used for the calibration of soil moisture sensors (Teros 12, METER Group, Inc., Pullman, WA, USA), following recommended procedure. The sensors were connected to a Zentra datalogger (METER Group, Inc., Pullman, WA, USA) and set up to collect hourly soil moisture data. The Zentra datalogger was equipped to transmit data via a cellular network, where the data could be downloaded remotely. The sensors were installed at (a) 20 cm depth and 15 cm to the side of the plant row, and at (b) 30 cm depth and 25 cm to the side of the plant row. The soil water content at 80% field capacity of the soil was estimated as 0.083 m^3 m^{-3}, whereas the soil water content at 50% field capacity of the soil was estimated as 0.069 m^3 m^{-3}. The available water holding capacity of the soil was calculated as the difference in water content at -33 kPa and -1500 kPa (Klute, 1986). The irrigation treatments were imposed between the V6 and R6 stages, and the irrigation was triggered when the threshold for the sensors installed at 30 cm depth was reached. The sensors installed at the 20 cm depth did not detect irrigation events and could therefore not be used to trigger irrigation. This was likely due to the installation depth of the drip tapes (30 cm) and the coarse nature of the soil that limited capillary action.

Fertilizer Scheduling

Macro (N, P, and K), secondary (Ca, Mg, and S), and micro (Fe, Mn, Zn, B, Cu) nutrients were supplied based on the initial soil test results. The total nutrient application rates and schedule used for the treatment NA-VT are shown in Table 4. The treatment NA-R2 received the same fertilizer rates and schedule as the treatment NA-VT, plus an additional 10% of the total of all nutrients applied by the VT stage were supplied at the R2/R3 stage. The treatment ES-VT did not receive any fertilizer application until the V6 stage, after which it received nutrient application rate and schedule as the treatment NA-VT. All fertilizers supplied to the treatment NA-VT before the V6 stage were supplied to the treatment ES-VT between the V6 and V9 stages. Granular sources of fertilizer were used before the V6 stage, as either broadcast or side-dress application. After V6, liquid sources of fertilizer were used, and applied via injection through the drip tapes.

Table 4. Total nutrient application rate and schedule used for the non-early-stress nutrient application treatment terminated at VT (NA-VT).

Nutrient	Total rate (kg ha^{-1})	Proportion applied (%)			
		Preplant - planting	V3 – V6	V9 – V10	VT
N	404	15	45	20	20
P	202	50	50	0	0
K	235	40	40	10	10
Ca	22.4	50	50	0	0
Mg	16.8	50	50	0	0
S	16.8	50	50	0	0
Fe	4.5	50	50	0	0
B	2.2	50	50	0	0
Mn	4.5	50	50	0	0
Zn	3.4	50	50	0	0
Cu	1.1	50	50	0	0

Plot Management

The study was established on a research field that had been under strip-tillage for the previous five years. The previous cash prop was peanut (*Arachis hypogaea*), and rye (*Secale cereal*) was cultivated as a cover crop during the fall season. The rye cover crop was terminated in the spring of 2020 by spraying the recommended rate of glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine, Monsanto, St. Louis, MI]. After, the plots were strip-tilled to 30-cm depth with a chisel plow. The plots were demarcated according to the experimental design described previously. AgriGold corn hybrid A6499STX was planted at a rate of 88,958 seeds ha^{-1}. Pest and disease controls were performed to ensure plant health, according to the University of Georgia corn production guide.

Data Collection

Plant tissue samples were collected at the R6 growth stage to estimate the crop biomass of the different tissues. Six plants were harvested at physiological maturity within one meter of the second row of each plot, and the samples were separated into stover and grain. The partitioned samples were dried in the oven at 65^{o}C until a constant weight was obtained and then weighed to estimate the biomass weight. The tissue samples were taken to the Waters Agricultural Laboratories Inc. in Camilla, GA to determine the nutrient levels, which were then used to calculate nutrient uptake. The total amount of irrigation water applied for each irrigation treatment was determined at the end of the season by summing the irrigation events for each treatment

Statistical Analysis

The analysis of variance conducted considered irrigation treatment and nutrient treatment as fixed effects, with blocks as a random effect. The data were analyzed with a linear mixed model using the “nlme” package in R software (Pinheiro et al., 2018). 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 software (Lenth, 2018). The significance level for all analyses was assessed at $P = 0.05$.

RESULTS AND DISCUSSION

Initial Soil Characteristics

The physical and chemical properties of the soil at the experimental site determined at the beginning of the study are presented in Table 5. The initial soil pH of the field was similar across the two depths with an average soil pH of 6.2. However, the soil organic matter tended to decrease with depth. Also, the initial levels of P, K, S, B, Fe, and Cu were relatively higher at the top 15 cm and they decreased as the soil depth increased. Conversely, the initial levels of Mg, Ca, Zn, and Mn increased with depth. The initial levels of Ca, Mg, and S are fairly high, and this could be attributable to the residual nutrients from the gypsum and dolomitic lime applied in the previous year. The field received 1120 kg ha^{-1} of gypsum and dolomitic lime the prior year.

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Table 5 Initial physical and chemical properties of the soil at the experimental site

Soil depth (cm)	Texture	Sand (%)	Silt (%)	Clay (%)	Soil pH	Soil OM	P	K	Mg	Ca	S	B	Zn	Fe	Mn	Cu
						g kg^{-1}	← kg ha^{-1} →									
0-15	Sand	90.7	3.2	6.1	6.2	6.4	90.8	100	106	933	66.1	0.4	5.3	31.0	18.3	0.9
15-30	Loamy Sand	86.7	2.1	11.2	6.2	5.9	75.1	82.9	109	968	47.1	0.3	5.4	26.5	27.6	0.8

OM: Organic matter.

Weather Conditions During the Growing Season

Weather data, such as the maximum and minimum temperature, precipitation, and solar radiation were critical factors in this study. Specifically, precipitation data were recorded daily and this was important because the amount of precipitation influenced the irrigation frequency. The daily minimum and maximum temperature were important for calculating accumulative growing degree days (GDDs) over the season. GDDs were necessary for determining the growth stage of corn since the growth stage was used to schedule fertilizer application and to determine when to initiate and terminate irrigation. Table 6 shows the monthly minimum and maximum temperature (°C), precipitation (mm), and solar radiation (MJ m^{-2}) measurements taken during the growing season (University of Georgia Weather Systems, GA).

The highest average monthly temperature (34.1 °C) was recorded in July, which was towards the end of the season. The lowest average monthly temperature (13 °C) was recorded early season in April. Higher late temperature in corn may not necessary affect yield as corn is either matured or nearing maturity at this stage (Norwood, 2001). Averaged monthly precipitation over the growing season was 116 mm and only April and August had rainfall more than the average. May and June tended to be the dry months during the growing season, with 51.6 mm and 55.4 mm rainfall, respectively. The highest average monthly solar radiation (22 MJ m^{-2}) was recorded in May and it coincided with the month that had the least amount of rainfall. The lowest solar radiation (18.7 MJ m^{-2}) was recorded in August, which was the month that received the second-highest amount of rainfall.

Table 8. Weather conditions at the experimental site during the growing season.

Month	Avg temp (°C)		Precipitation (mm)	Number of rainy days	Ave. solar radiation (MJ m^{-2})
	Max	Min			
April	26.8	13.2	231	9	19.3
May	29.6	16.5	51.6	10	22.1
June	32.5	21.1	55.4	9	19.6
July	34.1	22.7	108	14	19.7
August	33.5	22.8	134	15	18.7

Soil Moisture Dynamics

The soil water content response to the cumulative irrigation applied in both irrigation treatments during the growing season is shown in Figure 3 and the daily rainfall event is showed in Figure 4. The sensors were first installed at 20 cm depth; however, we noticed that they did not detect irrigation regimes. As already noted, this was likely because the drip tapes were distant from the sensors, and the coarse nature of the soil restricted the capillary rise of water through the soil. Subsequently, an additional set of sensors were then installed at 30 depth, which explains the gap with no data for the 30 cm depth at the beginning of the experiment. The sensors at the 20-cm depth responded to rainfall regimes, indicating that they were not defective. The sensor at 30-cm depth did not respond to rainfall events, therefore, rainfall events recorded during the season is depicted by moisture variations of the sensor at 20-cm depth. It rained for a total of 46 days during the growing season. The wettest day recorded 110.7 mm of rainfall and occurred on April 23 and as shown, the sensor at 20-cm depth recorded values above the field capacity. As expected, irrigation events were frequent under FC-80, as shown by the higher number of rises and falls. The total amount of irrigation water applied were 325 mm and 490 mm for FC-50 and FC-80 respectively.

The inadequate capillary rise of water through the soil led to extremely dry conditions of the soil in the shallow depths as rainfall distribution was not frequent during the growing season. In other words, the subsurface drip irrigation system was not able to replenish the topsoil profile with water upon irrigation. This can be seen from Figure 3, where the sensors at 20-cm depth even exceed the permanent wilting point in some instances. This condition could adversely affect corn performance as a large surface area of the roots did not have contact with soil moisture.

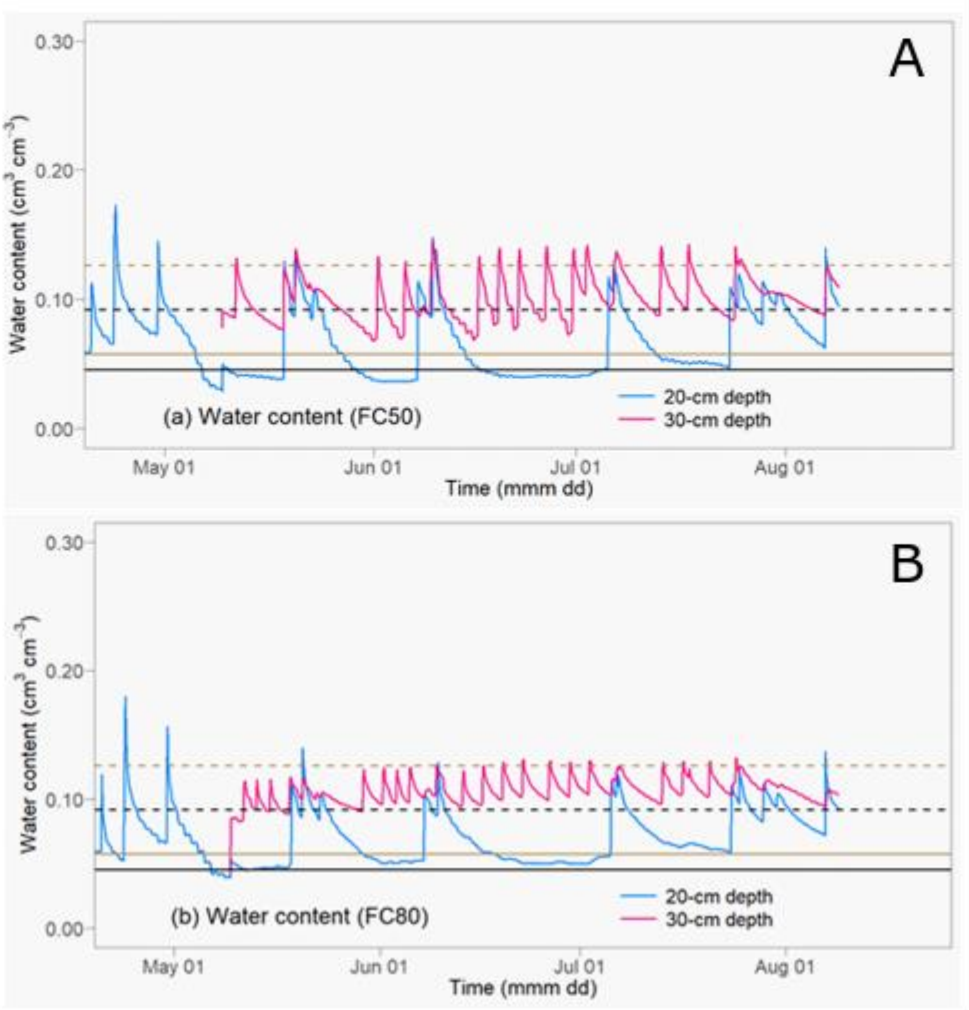

Figure 4. Hourly soil water content at 20 cm and 30 cm depth for the main plot treatments FC-50 (A) and FC-80 (B). The solid black and brown lines indicate permanent wilting points (PWP) for the soil at 20 cm and 30 cm depth, respectively, and the dotted black and brown lines indicate field capacity (FC) of the soil at 20 cm and 30 cm depth, respectively.

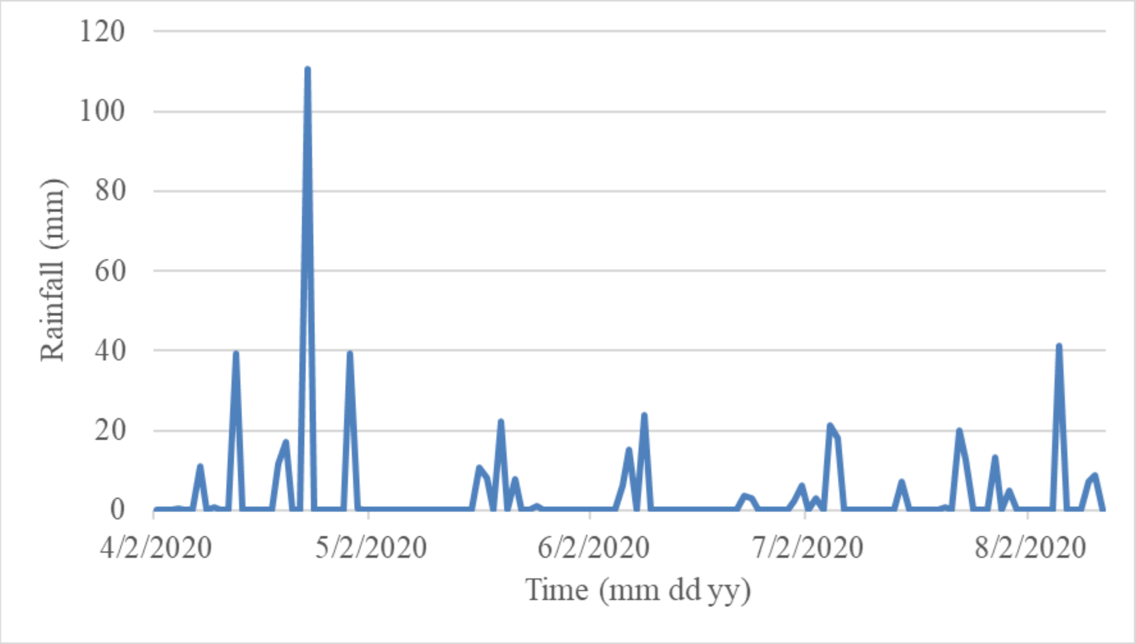

Figure 5. Daily rainfall recorded during the growing season

Nutrient Uptake

The uptake of all applied nutrients (N, P, K, Mg, Ca, S, B, Zn, Mn, Fe, and Cu) in the grain and stover harvested at physiological maturity is presented (Table 7 and 8). Analysis of the results showed that the interactions between irrigation frequency and nutrient management were not significant; hence the effect of only the main treatments are presented. Generally, the uptake of N, P, K was very high compared to the uptake of the secondary nutrients (Mg, Ca, S) and micronutrient uptake (B, Zn, Mn, Fe, Cu). The results also revealed that the uptake of most nutritional elements was higher in the stover except for N, P, and S, which happened to be higher in the grain. Among the main treatments, grain N uptake ranged between 98-149 kg ha^{-1} with the highest uptake recorded for NA-VT, while N uptake in the stover was between 34.5-98.2 kg ha^{-1} and NA-R2 had the highest uptake. The uptake of P in the grain was almost twice the amount in the stover with a range of 22.2-35.0 kg ha^{-1} for grain and 5.8-16.4 kg ha^{-1} for stover. Most of the K taken up by the corn was stored in the stover as uptake was three times higher in the stover than in the grain with a range of 29.0-49.1 kg ha^{-1} in the grain and 56.8-137 kg ha^{-1} in the stover. Uptake of secondary nutrients was similar between grain and stover except for calcium which was low in the grain. Among the micronutrients, the uptake of Zn, Mn, and Fe was comparatively higher than those of B, and Cu. Except for Zn, the uptake of all the micronutrients was greater in the stover than in the grain. The mean separation revealed that nutrient uptake among irrigation treatments was not statistically different; however, in most instances, plants under FC-80 irrigation had slightly higher nutrient uptake. On the other hand, nutrient management significantly impacted the uptake of all the nutrients applied. Results showed that nutrient uptake was significantly lower in plants that received fertilizer starting from V6 (ES-VT), while uptake was mostly similar among plants fertilized under NA-VT and NA-R2.

Soil moisture plays a critical role in the concentration of nutrients in soil solution; therefore, a vital function exists between plant nutrient uptake and the status of soil water (Djaman et al., 2013; Misra and Tyler, 2000). Higher nutrient uptake levels have mainly been observed under adequate or fully irrigated conditions, while lower nutrient uptake is typical under water-limiting conditions. Regardless of irrigation scheduling, the crops experienced some level of moisture stress. This could partly confound treatment response and could also explain why there were limited differences, due to irrigation scheduling, in nutrient uptake in this study. In contrast, other studies have observed lower nutrient uptake with decreasing irrigation amounts (Djaman et al., 2013; Faloye et al., 2020; Setiyono et al., 2010). Lower nutrient uptake under water stress is usually due to decreased nutrient transport by mass flow and diffusion (Seiffert et al., 1995).

Fertility management had a significant effect on the uptake of all applied nutritional elements investigated in this study. No differences were found between NA-VT and NA-R2 treatments, but the ES-VT treatment resulted in lower nutrient uptake. These results indicate that corn is not able to tolerate early-season nutrient stress. The ES-VT received the same amounts of nutrients as the NA-VT. Thus, intensive rainfall conditions during the early stages of the growing season, which is prevalent in the state of Georgia, could induce early-season nutrient stress by leaching important mobile nutrients from the soil. We understand that the early-season nutrient stress in this study was a worst-case scenario where no fertilizer application was made until the V6 stage. It is important to also note that the initial soil nutrient levels (Table 5) were in the moderate to high levels, except for N that was not measured.

Irrigation Water Use Efficiency

The impact of irrigation and nutrient scheduling on irrigation water use efficiency (IWUE) is summarized in Figures 4 and 5. The main effects of irrigation scheduling and fertilizer application regimes significantly affected IWUE; however, the interaction between irrigation and nutrient scheduling was not significant ($P < 0.05$). Specifically, irrigating the corn plants at 50% field capacity (FC-50) had IWUE averaging (3.80 Mg ha^{-1} mm^{-1}), making it 25% more efficient than corn plants under FC-80 with an average IWUE of (2.80 Mg ha^{-1} mm^{-1}). Under the different fertilizer application regimes, the highest IWUE of 3.80 Mg ha^{-1} mm^{-1} was recorded for NA-R2, and this was statistically similar to the IWUE of 3.60 Mg ha^{-1} mm^{-1} for NA-VT. The least IWUE among the nutrient scheduling was 2.50 Mg ha^{-1} mm^{-1}, which was observed under ES-VT. The IWUE for ES-VT was about 30% less than the IWUE of the other nutrient treatments.

Effective water delivery to the root zone of plants can significantly reduce water requirements for crop production and improve irrigation water use efficiency (Demie et al., 2010). The IWUE of this study was estimated by dividing grain yield by the total amount of irrigation water supplied for each treatment. In the experiment, the grain yield obtained was similar between the two irrigation regimes; however, the total amount of irrigation water given (490 mm) for FC-80 was significantly higher than the amount of irrigation water (325 mm) provided for FC-50. The increased amount of water used in FC-80 could partially account for the lower IWUE observed because more irrigation water did not correspond to an increased corn yield. Observations in this study agree with the results of other studies (Chaichi et al., 2015; Djaman and Irmak, 2012; Irmak et al., 2016).

Plant nutrients play a crucial role in improving water use efficiency under limited water conditions; therefore, ensuring adequate nutrient supply throughout the growing season is an important strategy to enhance water use efficiency (Waraich et al., 2011). The IWUE of the well-fertilized plots (NA-VT and NA-R2) were high because nutrients were adequately supplied. Research has shown that an adequate amount of N and Mg facilitates light interception by chlorophyll. P is essential in accumulating energy for carbohydrate build-up, while K helps regulate the stomata. Therefore, well-fertilized corn plants are expected to produce more biomass and grain for every unit of irrigation water used than a nutrient-deficient corn plant (Waraich et al., 2011). IWUE of the ES-VT nutrient treatment was low because biomass and grain production was reduced due to the early-season nutrient stress. Moreover, studies have found that N and P stress causes a reduction in the hydraulic conductivity of the roots cell, leading to lower water absorption and a subsequent decrease in water use efficiency (Radin and Matthews, 1989).

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The impact of irrigation and nutrient scheduling on irrigation water use efficiency (IWUE) is summarized in Figures 4 and 5. The main effects of irrigation scheduling and fertilizer application regimes significantly affected IWUE; however, the interaction between irrigation and nutrient scheduling was not significant ($P < 0.05$). Specifically, irrigating the corn plants at 50%

field capacity (FC-50) had IWUE averaging (3.80 Mg ha^{-1} mm^{-1}), making it 25% more efficient than corn plants under FC-80 with an average IWUE of (2.80 Mg ha^{-1} mm^{-1}). Under the different fertilizer application regimes, the highest IWUE of 3.80 Mg ha^{-1} mm^{-1} was recorded for NA-R2, and this was statistically similar to the IWUE of 3.60 Mg ha^{-1} mm^{-1} for NA-VT. The least IWUE among the nutrient scheduling was 2.50 Mg ha^{-1} mm^{-1}, which was observed under ES-VT. The IWUE for ES-VT was about 30% less than the IWUE of the other nutrient treatments.

Effective water delivery to the root zone of plants can significantly reduce water requirements for crop production and improve irrigation water use efficiency (Demie et al., 2010). The IWUE of this study was estimated by dividing grain yield by the total amount of irrigation water supplied for each treatment. In the experiment, the grain yield obtained was similar between the two irrigation regimes; however, the total amount of irrigation water given (490 mm) for FC-80 was significantly higher than the amount of irrigation water (325 mm) provided for FC-50. The increased amount of water used in FC-80 could partially account for the lower IWUE observed because more irrigation water did not correspond to an increased corn yield. Observations in this study agree with the results of other studies (Chaichi et al., 2015; Djaman and Irmak, 2012; Irmak et al., 2016).

Plant nutrients play a crucial role in improving water use efficiency under limited water conditions; therefore, ensuring adequate nutrient supply throughout the growing season is an important strategy to enhance water use efficiency (Waraich et al., 2011). The IWUE of the well-fertilized plots (NA-VT and NA-R2) were high because nutrients were adequately supplied. Research has shown that an adequate amount of N and Mg facilitates light interception by chlorophyll. P is essential in accumulating energy for carbohydrate build-up, while K helps regulate the stomata. Therefore, well-fertilized corn plants are expected to produce more biomass and grain for every unit of irrigation water used than a nutrient-deficient corn plant (Waraich et al., 2011). IWUE of the ES-VT nutrient treatment was low because biomass and grain production was reduced due to the early-season nutrient stress. Moreover, studies have found that N and P stress causes a reduction in the hydraulic conductivity of the roots cell, leading to lower water absorption and a subsequent decrease in water use efficiency (Radin and Matthews, 1989)

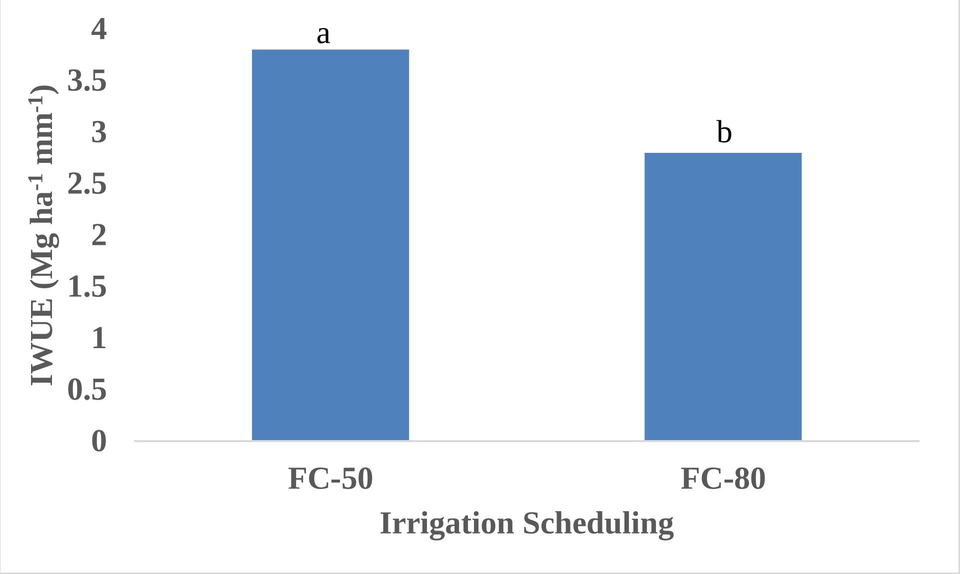

Figure 6. Effects of irrigation scheduling on irrigation water use efficiency (IWUE) in corn. Within irrigation scheduling, means not sharing any letter are significantly different ($P < 0.05$).

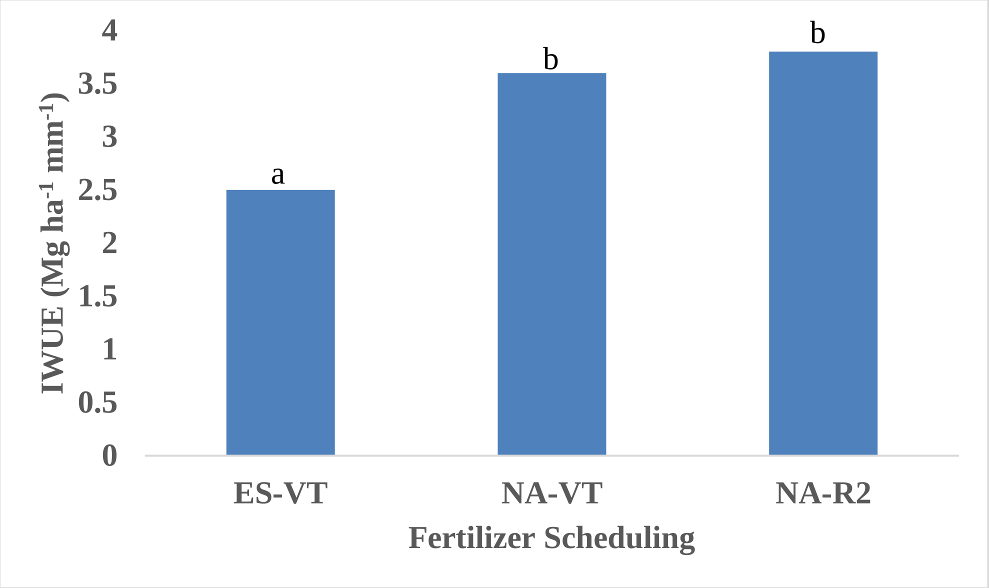

Figure 7. Effects of Nutrient scheduling on irrigation water use efficiency (IWUE) in corn. Within fertilizer scheduling, means not sharing any letter are significantly different ($P < 0.05$).

Table 9. Irrigation scheduling effects on nutrient uptake in corn grain and stover

Treatment	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	←		kg ha^{-1}			→	←		g ha^{-1}		→
						Nutrient uptake in the corn grain					
FC-50	122a	30.3a	38.7a	8.8a	0.9a	9.7a	30.0a	190a	60a	140a	20a
FC-80	140a	33.9a	42.3a	9.7a	1.0a	10.3a	30.0a	210a	60a	150a	30a
						Nutrient uptake in the corn stover					
FC-50	73.3a	11.3a	102a	8.16a	10.2a	5.9a	50.0a	180a	230a	230a	40a
FC-80	73.1a	12.9a	113a	8.96a	10.4a	6.0a	50.0a	200a	240a	230a	40a

Within nutrient element and corn tissue component, means not sharing any letter are significantly different ($P < 0.05$) according to Tukey’s test

Table 10. Nutrient scheduling effects on nutrient uptake in corn grain and stover

Treatment	N	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
	←		kg ha^{-1}			→	←		g ha^{-1}		→
						Nutrient uptake in the corn grain					
ES-VT	98a	22.2a	29.0a	6.1a	0.6a	6.5a	30.0a	150a	40a	110a	20a
NA-VT	149b	39.2b	49.1b	11.7b	1.1b	11.8b	40.0b	240b	80b	170b	30b
NA-R2	146b	35.0b	43.2b	10.1b	1.1b	11.7b	40.0b	210b	60b	150b	30b
						Nutrient uptake in the corn stover					
ES-VT	34.5a	5.8a	56.8a	3.9a	5.2a	2.9a	20.0a	110a	110a	90a	20a
NA-VT	86.9b	14.3b	130b	10.9b	13.2b	7.3b	60.0b	230b	320b	290b	50b
NA-R2	98.2b	16.4b	137b	10.9b	12.4b	7.7b	60.0b	240b	270b	310b	50b

Within nutrient element and corn tissue component, means not sharing any letter are significantly different ($P < 0.05$) according to Tukey's test

CONCLUSION

This study evaluated different irrigation and nutrient management regimes and how it affects nutrient uptake and water use efficiency in corn under a subsurface drip irrigation system. The two irrigation treatments (FC-80 and FC-80) evaluated did not significantly impact nutrient uptake as the uptake of all applied nutrients was similar. The total amount of water used in FC-50 was substantially lower than the amount of water applied in FC-80, resulting in a significantly higher IWUE for FC-50. The nutrient management regimes had a significant impact on nutrient uptake and irrigation water use efficiency. Delaying nutrient application up to V6 significantly reduced the uptake of the applied nutrients and also decreased IWUE. No significant difference in nutrient uptake and irrigation water use efficiency were detected under NA-VT and NA-R2. The observations in this study suggest that, under a subsurface drip irrigation, nutrient uptake and water use efficiency under limited water conditions can be very high when corn is well nourished. However, the subsurface drip irrigation system could induce moisture stress in the topsoil profile in course-textured soil conditions due to limited capillary rise of soil moisture.

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CHAPTER 4

SUMMARY AND CONCLUSIONS

The current research was established to evaluate the effect of partial nutrient and water stress on corn yield and biomass production and estimate nutrient uptake and Irrigation Water Use Efficiency (IWUE) under a subsurface drip irrigation system.

In the first study, where we analyzed the effect of partial water and partial nutrient stress on corn yield and biomass production, we found that decreasing the amount of irrigation water applied did not significantly impact corn yield and biomass production. The effect of partial nutrient stress was more pronounced, especially during the early growth stage. In a treatment where the nutrient application was delayed until V6, corn yield and biomass production were significantly reduced. It was revealing that corn could not recover from an early nutrient shock even though all the nutrient needed was provided from V6 up to VT. This observation shows that early stage (pre-plant, planting, and early vegetative stage) fertilization in corn is critical. Corn yield and biomass production between treatments where the nutrient application was terminated at either VT or R2 were not statistically different. The additional fertilizer applied after VT did not enhance yield and biomass production. This observation shows that adopting a fertilizer application regime where an adequate amount of nutrient is provided from pre-plant up to VT can result in optimum yield and biomass without additional fertilizer at post tasseling.

In the second study, we sought to investigate how nutrient is taken up by corn under varying moisture and nutrient management strategies using a subsurface drip irrigation system. The results show that supplying fertilizers to corn using a subsurface drip delivers nutrients close to plant roots, and this facilitates nutrient uptake even when water is limited. Nutrient uptake in both grains and stover was not affected by irrigation amount. Irrigation water use efficiency (IWUE) was considerably higher for irrigated plots at 50% field capacity than plots that received irrigation at 80% field capacity. Nutrient uptake was higher for the well-fertilized plots (plots that received fertilization from pre-plant up to either VT or R2) than plots that received nutrients from V6. Irrigation water use efficiency (IWUE) was higher for the well-nourished plots than the plots with nutrient application delayed until V6. This observation shows that well-fed corn plants can use irrigation water better than poorly fertilized corn plants.