ASSESSING THE FEASIBILITY OF FERTIGATION ON COTTON

by

SHELBY SANGSTER

(Under the Direction of George Vellidis)

ABSTRACT

The goal of this work was to evaluate the response of cotton to fertigation in southern Georgia, USA. Specific objectives were to conduct a replicated plot field study that evaluated fertigation as an in-season nitrogen application strategy for cotton and to use the DSSAT CSM CROPGRO-Cotton model to evaluate the response of cotton to several combinations of the timing and the amount of nitrogen in fertigation applications. The field study was conducted near Camilla, Georgia between 2018-2021 and found that fertigation resulted in numerically higher yields that were not significantly different from the yields of other in-season fertilization treatments. Simulation results confirmed field study findings that using fertigation to apply in-season nitrogen to cotton results in higher yields than the conventional approach of one liquid side-dress application commonly used in Georgia regardless of the total nitrogen applied. Fertigation also resulted in higher nitrogen use efficiency (NUE) than the conventional approach.

INDEX WORDS: crop simulation model, DSSAT, field study, irrigation scheduling, nitrogen management

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1.Introduction

Cotton (*Gossypium hirsutum*) is an economically important crop in the United States (Chastain et al., 2014) and especially in Georgia where it is grown on average on 566,000 ha over the past five years. It contributes $120 billion to the U.S. and $2.5 billion to the Georgia economies, respectively. Across the world, cotton is cultivated under a variety of different climate regimes including the humid Southeast of the U.S. (Hearn, 1979; Turner et al., 1986). In Georgia, cotton is grown primarily in the southern half of the state where average annual precipitation is approximately 1270 mm. Although this is enough water to supply crop water requirements (Bednarz et al., 2002), the distribution of rainfall does not always coincide with peak crop water requirements. Short episodes of drought at a critical stage of crop development can limit fiber yield and quality (Bednarz et al., 2002, Chastain et al., 2014).

Proper fertilization is also key to cotton production. One of the most important, and challenging to manage, plant nutrients is nitrogen (N). N fertilizers are applied as complex dry or liquid compounds. The United Nations Food and Agricultural Organization (FAO) estimates that N fertilizer use exceeded 100 million tons in 2018 – an increase of 25% over the past 10 years (FAO, 2019; Udvardi et al., 2015). Under-application of N results in uncaptured yield potential. However, over-application also has adverse consequences and results in rank growth which negatively impacts yield (Guthrie et al., 1994).

1.2. Literature Review

1.2.1. Irrigation

In Georgia, cotton growers are increasingly using center pivot irrigation systems to ensure yield stability. In general, irrigation increases crop yield and crop quality that in turn increases the profitability of the farm operation (Hajin et al., 2002). Excessive irrigation can have a severe impact on water resources. California's Central Valley and the Southern Great Plains are examples of agricultural areas where crop production is threatened by decreasing availability of irrigation water. Over-irrigation can also result in low irrigation efficiency and suppressed yields (Yazar et al., 2002). The extent to which improper timing of irrigation can result in yield losses has been documented for many crops. For example, Voreis et al. (2006) found that improper timing of irrigation on cotton resulted in yield losses of between $370/ha to $1850/ha. Yet relatively few growers use science-based irrigation scheduling methods. Data from the most recent USDA NASS Farm and Ranch Irrigation Survey (NASS, 2019) indicate that fewer than 20% of U.S. growers use science-based irrigation scheduling tools. Growers will typically apply a standard amount (for example 25 mm) at each irrigation event. As a result, both the timing and amounts of irrigation may be inappropriate and may lead to yield, nutrient, and soil losses.

1.2.1.1. Irrigation scheduling

In order to make the best decision when scheduling an irrigation event there are many factors that need to be considered. The goal is to prevent over or under watering by understanding the timing of a crop's water requirement. Three science-based irrigation scheduling methods currently being used on crops in Georgia are the UGA Extension calendar method which is described in the University of Georgia's Cotton Production Guide (Hand et al., 2022), the

SmartIrrigation Cotton App (Vellidis et al., 2016), and University of Georgia Smart Sensor Array (UGA SSA) (Vellidis et al., 2013).

The UGA Extension calendar method (Calendar) recommends weekly irrigation application amounts based on a combination of weeks after planting and phenological stage (Table 1.1.). According to the UGA Cotton Handbook, cotton reaches peak water requirement at 4th week of bloom (Hand et al., 2022). The weekly estimates were determined by using historical meteorological data to calculate weekly evapotranspiration (ET). Weekly crop water use was then estimated using a crop coefficient curve. The weekly irrigation needed is calculated by subtracting precipitation received from weekly demand. The weakness of the Calendar method is that it does not account for current environmental conditions, and it is left to the user to estimate how current conditions may affect the crop's water needs.

The SmartIrrigation Cotton App (SI Cotton) is a FAO-56 (Allen et al., 1998) evapotranspiration (ET) -based irrigation scheduling tool that calculates percent remaining plant available water in the root zone on a daily basis. The app requires daily weather data input from a nearby weather station to determine daily max/min temperatures and rainfall. The crop's evapotranspiration is used to make irrigation recommendations using real time weather data and the crop's estimated evapotranspiration. Using the crop coefficient (Kc) and a reference evapotranspiration (ETo), an estimated evapotranspiration value is calculated and can then be used to make irrigation recommendations (Vellidis et al, 2016). The equation used is:

$$ETc = ETo * Kc \quad (1)$$

Growing degree days are the driver of crop growth as the crop advances from one stage to the next (Ritchie et al., 2007). Calculating the growing degree days uses the daily maximum and minimum temperatures, which are collected from the weather station. Growing degree days and crop coefficient data are both needed to aid in understanding the stage of growth and the crop's water requirements. This data is then used to make an estimate of the available soil moisture in the soil profile. Keeping track of ETc, precipitation, and irrigation amounts allow the application to estimate the available soil water for differing soil types (Vellidis et al, 2016). A threshold value is determined, and an irrigation event is scheduled once the threshold has been met. Available soil water is reported in a range of percentages, 100% meaning no deficit of water and 0% meaning no available soil water. The default threshold set for the SI Cotton app is a 50% deficit prior to first bloom and a 40% deficit thereafter. Just as with the Calendar method, the information you receive from the application is provided without knowing the specific field conditions, so it is important to keep an eye on the field and its condition.

The University of Georgia Smart Sensor Array (UGA SSA) is an inexpensive wireless soil moisture sensing system to monitor field conditions (Vellidis et al., 2013). It consists of smart sensor nodes and a base station. The term sensor node refers to the combination of electronics and sensor probes installed within a field at one location (Figure 1.1.). The electronics include a circuit board for data acquisition and processing and a radio frequency (RF) transmitter. In the current design, the UGA SSA supports Watermark® (Irrometer, Riverside California, USA) sensors at various depths depending on crop. Each soil moisture probe integrates up to three Watermark® sensors as shown in Figure 1.1. In addition, each node supports two thermocouples for measuring soil and/or canopy temperature. For field crops like cotton, the sensors on the probe are arranged so that when installed they are at 0.1 m (4 in.), 0.2 m. (8 in.), and 0.4 m. (16 in.) below the soil surface although any combination of depths is possible. The RF transmitter is responsible for transmitting sensor data. The transmitter is an intelligent, inexpensive, and low-power 2.4 GHz radio module. The transmitters of individual nodes develop a wireless mesh network that is used to communicate between nodes. Data is passed from one node to the other through the RF transmitter that also plays the role of a repeater. If any of the nodes stop transmitting or receiving, or if signal pathways become blocked, the operating software reconfigures signal routes to maintain data acquisition from the network. The range of the RF transmitter exceeds 750 m under field conditions. To overcome the attenuating effect of the plant canopy, the RF transmitter antenna is mounted on spring-loaded telescoping fiberglass rod (Figure 1.1). Variable antenna heights are used to ensure that the antenna is always above the crop canopy. For example, a height of 2.5 m is adequate for low-growing crops like cotton, soybeans, and peanuts while a height of 4.5 m is used for tall crops such as corn. This design allows field equipment such as sprayers and tractors to pass directly over the sensors without damaging them. This is a feature that is typically not found on other wireless soil moisture sensors as most of those require a solar panel to power the sensor and telemetry. The UGA SSA nodes are powered by two 1.5 V alkaline batteries which have a life of more than 150 days. This typically spans an entire growing season. To optimize battery life, the nodes are programmed to be in a low-current sleep mode when not transmitting. The UGA SSA is described in detail by Vellidis et al. (2013) and has been used to monitor soil moisture and schedule irrigation in corn, cotton, peanuts, soybean, vegetables (eggplant, pepper, tomato, watermelon), and blueberry.

The Watermark sensors used in the UGA SSA probe report the soil moisture as soil water tension (SWT) in units of kPa (Vellidis et al., 2013). SWT is the force necessary for plant roots to extract water from the soil (Shock, Wang 2011). Measuring SWT is directly related to crop performance helping researchers understand crop stress. Since the UGA SSA sensors are measuring soil water tension, it is important that the nodes are placed in the crop rooting zone away from weeds near healthy, actively growing plants. The SWT threshold for an irrigation event using the UGA SSA irrigation scheduling method for cotton is set at 70 kPa until first flower and 40 kPa after first flower.

1.2.2. Fertilization

Fertilizers are applied to soils to provide nutrients that are essential for plant growth. One of the most important, and challenging to manage, plant nutrients is nitrogen (N). N fertilizers are applied as complex dry or liquid compounds. The United Nations Food and Agricultural Organization (FAO) estimates that N fertilizer use exceeded 100 million tons in 2018 – an increase of 25% over the past 10 years (FAO, 2019; Udvardi et al., 2015). Through biological and chemical processes in the soil, these compounds are eventually transformed to nitrate (NO_3^-) – an ionic form of N that is biologically available to plants. For plants to absorb nitrate, it must be available in the soil solution – the water found in the pores or the soil matrix.

Nitrogen use efficiency (NUE) is the fraction of applied N fertilizer that is utilized by the plant. Under field conditions, NUE is at best around 50%. This means that up to 50% of the N applied to soil as fertilizer may be unavailable for use by the crop (Udvardi et al., 2015). The N that is unavailable may be lost to volatilization, leaching, or other biogeochemical processes. The process of leaching occurs because nitrate is highly soluble in water and easily transported below the crop root zone by rain or excess irrigation. Nitrate that leaches below the root zone contaminates ground and surface waters causing environmental concern and health problems (Gerik et al., 1998). Improving NUE means more crop per unit input leading to increased profit, the main goal of all producers (Good et al, 2004).

In Georgia, up to a third of the N required by cotton is applied prior to planting (Hand et al., 2022). The remaining N is typically applied with one in-season (also referred to as side-dress or top-dress) application 6-8 weeks after planting. Under these practices, more fertilizer than the crop needs is applied to ensure that nutrients are available throughout the growing season. Under good management, the amount of fertilizer applied is based on soil samples collected prior to planting and/or the farmer's yield goals. However, in areas with sandy soils such as southern Georgia, soil samples are not routinely tested for N because it is assumed that the soils retain little N due of leaching. As a result, the amount of N fertilizer applied is based only on the farmer's yield goal. The University of Georgia's Cotton Production Guide states that nitrogen applied after the third week of bloom would be ineffective (Hand et al., 2022). In-season N should be applied between first square and first bloom to be effective.

N fertilizer is applied as ammonium, nitrate, or urea. The timing and form of N fertilizer used is important to increasing NUE (Snyder et al., 2009). Ammonium-based N fertilizers are best applied on fields with younger plants because ammonium's leachability is less than nitrate since ammonium is a cation and nitrate is an anion (Verbree et al., 2013). While ammonium will be converted into nitrate through microbial soil processes, very little nitrogen is used in the seedling stage, so it is important that N in the soils does not leach so that it remains available for plant uptake. As the growing season progresses, the plants take up nitrate more rapidly as the demand for N increases with plant growth.

1.2.2.1. Fertilizer requirements of cotton during its life cycle

The mechanism of nitrogen uptake is mass flow, which is movement of solutes with the water flow (Hake et al., 1991). Cotton absorbs more nitrogen than immediately required and the plant stores the nitrogen as nitrate, free amino acids, proteins (Rubisco), and chlorophylls (Guilherme et al., 2019). Rubisco's role in photosynthesis is to incorporate carbon dioxide into plants. Rubisco makes up 30% of total proteins in a plant leaf and is the most abundant protein of earth. Rubisco is a major nitrogen sink in plants as plants require major rubisco levels to carry out photosynthesis.

Nitrogen fertilization management in cotton can be difficult. Over-fertilization causes rank growth and delayed maturity which leads to boll rot or delayed boll opening (Hand et al., 2022). Larger leaves create more shading which in turn creates an unfavorable environment for proper boll maturity. Under-fertilization results in lower photosynthetic activity that leads to a decrease in energy production and a decrease in production of economically important plant component, cotton bolls. Adequate soil moisture is critical to nitrogen uptake not only because the nitrogen ions are dissolved in the soil solution but also because adequate water is needed within the plant to maintain photosynthetic activity and crop growth (Gerik et al., 1998).

Cotton leaves contain 60 – 85% of the total nitrogen prior to flowering. After flowering, the concentration of nitrogen in the leaves declines and begins to accumulate in the developing bolls (Rochester et al., 2012). Just as Figure 1.2 shows that the cotton's demand for nitrogen reaches its peak after first bloom, Figure 1.3 shows the cumulative uptake of nitrogen in a growing season between vegetative and reproductive structures.

When soil nitrogen levels are insufficient to meet the plant's demand, the plant uses the nitrogen reserves (Rochester et al., 2012). As the reserved nitrogen is used, nitrogen deficiency becomes a concern. Since nitrogen is mobile within the plants, the visible deficiency symptoms will show on the older leaves of the plant. However, the not so visible symptoms of deficiency include altered photosynthetic rate and leaf expansion (Gerik et al, 1998). Figure 1.2 shows the timeline of cotton growth and development on the x-axis while the y-axis shows the increasing demand of the plants. N demand is highest from mid-bloom through boll set. Blooming begins approximately 60 days after planting (DAP) with peak bloom occurring around 80 DAP. Peak bloom is when the demand for N is highest (Reiter, 2008) and it begins decreasing as the plants begin to set bolls. Once the bolls are set, the demand decreases steadily until it is time to harvest.

1.2.2.2. Fertigation

Fertigation is the application of fertilizers through an irrigation system. The original idea for fertigation was loosely based on hydroponics where all essential plant nutrients were provided in the water, which served as the growing medium. Fertigation can be applied through a pressurized irrigation system or surface irrigation. Liquid fertilizer is injected into the irrigation system and applied to the crops with the irrigation water. Fertigation has potential for improving NUE because the fertilizer can be applied in small doses throughout the growing season (Bronson et al., 2019). This increases the potential that fertilizer is used by the crop and not lost to the environment. Fertigation is used extensively with drip irrigation systems for the production of vegetable and fruit crops. Top-dressing N through overhead sprinkler systems such as center pivots is commonly used with maize in the USA (Gascho and Hook, 1991) and is being adopted in other regions of the world (Asadi et al., 2002; Yolcu and Cetin, 2015, He et al., 2012, Schepers et al., 1995). Georgia growers are currently using fertigation to apply top-dress nitrogen to corn.

Applying multiple rather than a single in-season N application has the potential for improving NUE because the fertilizer can be applied in small doses at frequent intervals which increases the likelihood that N is used by the crop. To document the NUE gains of using fertigation in corn, Toffanin et al. (2019) conducted a replicated plot study at UGA’s Stripling Irrigation Research Park (SIRP) between 2018 and 2020. They evaluated the effect of fertigation with four scheduled side-dress applications on corn as a best management practice in a study funded by USDA-NIFA. Results showed an average *17% gain in NUE* in corn with the same yield when compared to traditional fertilizer application methods.

Although fertigation is used by some growers on corn in Georgia, it is not widely adopted because it requires more intensive management and additional investment in equipment including fertilizer injection pumps and mixing tanks (Biswas, 2010). In addition, *we currently do not have the knowledge to inform Georgia growers on how to schedule fertigation for optimum NUE*. Those who use the technique generally split the top-dress applications into two or more events and apply at regular intervals. In Georgia, fertigation is not commonly used as a fertilization technique, but some growers do utilize it on their acres under center pivot irrigation.

In contrast to maize, the use of fertigation on cotton has not been extensively researched. Hou et al. (2007) conducted a greenhouse study to determine the effect of different fertigation schemes on N uptake and NUE in cotton plants. The study focused primarily on the timing of fertigation during an irrigation cycle. In a similar study conducted in the field using drip irrigation, Hou et al. (2009) found that that N applied at the beginning of an irrigation cycle resulted in the highest seed cotton yield but showed higher potential loss of N from leaching. Nitrogen applied at the end of an irrigation cycle had potential to lessen the amount of N loss from leaching but reported lower yields and NUE. Several studies have been conducted assessing the benefits of fertigation with drip irrigated cotton and results indicate that this approach shows promise for improving yields and NUE. Bronson et al. (2019) conducted a study on cotton irrigated with subsurface drip irrigation in an arid environment and found that high frequency of N fertigation events resulted in providing the crop with adequate in-season N, reducing N losses to the environment, and improving NUE. A study conducted in China compiled previous studies of drip fertigation and resource use efficiency for multiple crops, including cotton, compared to traditional management practices. The information provided from the previous studies and the researcher's analysis showed that drip fertigation increased yield by 11.6% and NUE by 16.5% as compared to traditional farmer's practices (Li et al., 2020).

Few studies have been conducted on evaluating fertigation with overhead sprinkler irrigation on cotton. Antille (2018) evaluated fertigation applied to both furrow and sprinkler-irrigated cotton in Australia. The study found that application of N through fertigation was economical for both furrow and sprinkler irrigation under fertilizer pricing at the time of the study, but relative agronomic efficiencies and economic return from the applied N were higher for fertigation with overhead sprinklers ($p<0.05$). In addition, fertigation with sprinklers resulted in reduced potential for N_2O emissions.

Recent fertigation research has focused on combining experimental and modeling approaches to evaluate the timing and amounts of fertigation. Chauhdary et al. (2019) and Toffanin et al. (2019) conducted these types of studies on maize. This combined approach allows researchers to collect data to calibrate and evaluate crop growth models such as the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2021) which are then used for the simulation of a wide variety of potential management scenarios.

With fertigation on agronomic crops, N is applied as ammonium, nitrate, or urea through the irrigation system using pumps. When utilizing fertigation, it is important for the applied nutrients to reach the root uptake sites. A fertigation event should be applied with minimal water and followed by a 7.6 mm (0.3 in.) irrigation event to ensure the nitrogen has entered the soil profile (Hou et al., 2009). This method will also prevent foliar burning that could be caused by not washing off the nitrogen solution. The primary site of nutrient uptake is the root zone. Figure 1.4 illustrates the early-season progression of cotton's root zone during the growing season. To maximize N uptake, there must be enough water applied with the fertigation event to ensure that the N moves into the soil profile deep enough for root uptake while ensuring that it does not leach below the root zone (Verbree et al., 2013). The amount of water varies based on soil types and the rooting depth of crops. The sandy soils of the southeastern Coastal Plain pose a serious challenge in achieving this balance.

The timing of a fertigation event should respond both to the N status of the soil and the plant's demand for N. The Tennessee Extension service provides growers with a cotton fertigation recommendation of applying 20% of total N requirement at pre-plant, fertigate 50% through squaring, and fertigate the remaining 30% no later than early bloom (Verbree et al., 2013). The N must be in the soil and available for uptake during bloom, the peak N demand period. Applying N too late is noted to be ineffective and will most likely cause rank growth in the plant (Hand et al., 2022, Lemon et al., 2009). Rank growth is the tall, vegetative growth that occurs late season and makes the plant more susceptible to boll rot and more difficult to defoliate (Lemon et al., 2009).

1.2.2.3. Other cotton side-dress fertilization strategies

Another method that has been evaluated as a tool for improving NUE in cotton is using the Normalized Difference Vegetative Index (NDVI) to estimate the amount of side-dress N needed (Porter et al., 2010). This technique uses NDVI to estimate the available cotton biomass at the time of side-dress applications and through a production function, estimates the yield potential and the amount of additional N needed to meet that yield potential (Kim, 2019). NDVI can be measured using ground vehicle or UAV –based optical sensors or images from satellite platforms. Its big advantage is that georeferenced NDVI data can be used to create spatially explicit N application maps that can be used for variable rate application of side-dress N.

NDVI uses the red and near infrared spectral bands captured by an optical sensor/multispectral camera to measure light reflected in those wavebands by the crop canopy. Light reflected is inversely proportional to light absorbed which is directly proportional to the concentration of chlorophyll in plant leaves and the total amount of leaf mass. Chlorophyll content is strongly correlated to N content (Kim, 2019). NDVI is also used to monitor crop nutrient deficiency, long-term water stress, and evapotranspiration.

The Clemson algorithm for determining nitrogen rates using NDVI values was developed for Coastal Plain soils and is based on the algorithm used for cotton in Oklahoma developed by Oklahoma State University (OSU) (Porter et al., 2010). The goal of the algorithm is to reduce the amount of nitrogen applied without negatively affecting the crop. Simply put, the algorithm uses the NDVI value to determine the nitrogen rate that should be applied to the field. Figure 1.5 shows the formula for the Clemson algorithm compared to the Oklahoma algorithm.

Using nitrogen rich strips gives an in-field comparison value of NDVI response to cotton growing in the field without N limitations. An N-Rich strip requires a season's worth of nitrogen fertilizer be applied at pre-plant to ensure nitrogen is not a growth-limiting factor when deciding how much N should be applied at side dressing (Taylor & Fulton, 2010). The nitrogen-rich NDVI is used as benchmark by the algorithm to determine the optimal amount of side-dress needed.

In Georgia, growers typically add 28.0 – 33.6 kg/ha (25 - 30 lb./ac) of preplant nitrogen to cotton. Vellidis et al. (2011) found that in southern Georgia, there is little difference between NDVI of nitrogen rich strips and the remainder of the field at 6-8 weeks after planting with that rate of pre-plant nitrogen. Instead of using N-Rich strips, they recommended using a standard NDVI reference of 0.85 (Vellidis et al., 2011). Other factors included are %N which is the percentage of N concentration of the seeds at harvest and an estimate of nitrogen use efficiency (NUE). Typically, 50% is used (Porter et al., 2010). Figure 1.6 is a graphical representation of the Clemson algorithm showing the relationship between NDVI and recommended nitrogen side-dress application rates. The arrows indicate examples of recommended application rates for two different NDVI values. The relationship has lower (0.3) and upper (0.8) NDVI limits below and above which no nitrogen is added. The lower limit indicates that cotton biomass is so low at this stage of the season that additional nitrogen will not contribute to meeting the crops yield potential. The upper limit indicates that cotton biomass is so large that additional nitrogen will result in rank growth. While many factors are used when determining how much N to apply, this graph can be used to help make the decision simpler.

1.2.3. Crop Simulation Modelling

Crop simulation models are mathematical tools that simultaneously integrate the interacting soil, plant, and weather factors important in determining soil-N availability and crop demand for estimating current and future N needs (Gerik et al., 1998). Crop growth models simulate growth, development, and yield for varying weather, soil conditions, and management practices. Leaf, stem, root, shell, and seed mass are computed on a daily basis, as well as growth stages, leaf area index (LAI), root length density and depth, soil water availability, and soil water content for different soil layers (Ortiz et al, 2009).

The Decision Support System for Agrotechnology Transfer (DSSAT) is a universally used decision support tool that includes dynamic crop growth simulation models for over 42 crops (Boote, 2019). DSSAT was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT, 1993; Tsuji et al., 1994; Uehara, 1989; Jones et al., 1998), to facilitate the application of crop models in a systems approach to agronomic research (Jones et. al, 2003). In the past, there were separate crop models available for different crops such as the CERES models for maize (Jones and Kiniry, 1986) and wheat (Ritchie and Otter, 1985), SOYGRO for soybean (Wilkerson et al., 1983) and PNUTGRO for peanut (Boote et al., 1986) but these models worked individually with different data input structures, different code, and operations. DSSAT was created to provide a common modeling framework for different types of crops where all the models read the same weather, soil, and management input files and use the same modules for soil water balance and soil N balance. The decision to create DSSAT ultimately led to the development of compatible models for additional crops, such as potato, rice, dry beans, sunflower, and sugarcane (Hoogenboom et al., 1994a; Jones et al., 1998; Hoogenboom et al. 1999). DSSAT provides a framework to conduct research for understanding the effect of various management practices and changes in environmental conditions on the growth and yield of crops by evaluating the relative response of different scenarios. The latest version of DSSAT which was released in May 2021 includes models of 40+ crops including the DSSAT CROPGRO-Cotton model (Hoogenboom et al., 2021).

The DSSAT Crop Simulation Model for cotton (DSSAT CSM CROPGRO–Cotton) simulates different crop growth stages of cotton including emergence, first leaf, first flower, first seed, first cracked boll, and 90% open boll and requires data input for soil, management, environment, and cultivar parameters. (Modala et al, 2015). Genetic information of the simulated cultivar is needed including specific timing between crop growth stages, leaf area, and long vs. short season plant to ensure the best simulation results (Thorp et al, 2014).

In a study conducted in the Texas High Plains where water resources are limited, DSSAT was used to evaluate irrigation treatments (Garibay et al., 2019). In-season data were collected to calibrate and evaluate the CSM CROPGRO – Cotton model to develop efficient irrigation practices for the growers across the region. The model showed potential to simulate yields and growth variables under various irrigation practices using a Mean Absolute Percentage Error (MAPE) less than 20% to estimate model performance. Thorp et al. (2014) evaluated CSM-CROPGRO-Cotton for arid environments and the management practices used in that region. Five prior cotton experiments from a span of nearly three decades provided data on management, growth and development, and observed field data. The model was found to respond well, after some adjustment for arid regions, to the various irrigation and nitrogen rates as well as the climate change factors that were studied in the field. In a follow-up study, Thorp et al. (2017) evaluated using CSM-CROPGRO-Cotton for in-season irrigation scheduling decisions on cotton in Arizona. They compared scheduling irrigation with the CSM-CROPGRO-Cotton model to scheduling with a standalone FAO-56 method and a crop growth model. Total seasonal irrigation amounts were similar with both methods but CSM-CROPGRO-Cotton recommended more water during anthesis and less during the early season, which led to higher cotton fiber yield in both seasons ($p < 0.05$).

CSM-CROPGRO-Cotton has also been used to evaluate the relative response to different fertilization strategies. A study conducted by Pal (2020) in the Punjab region of India assessed two different planting dates (May 1 and May 25) with three levels of N application (25% greater than the recommended rate, recommended rate, 25% less than the recommended rate). The crop model underestimated yield in 2014 and overestimated yield in 2015 (Pal, 2020). Whitefly infestation was likely responsible for lower yields in 2015. There was also a significant difference in yields between the normal and late planting date. The results from this project reported a close proximity between observed and simulated seed cotton yield. A study conducted in Pakistan used the model to evaluate the combination of sowing dates, cultivars, and nitrogen levels. The model was calibrated using phenology, biomass, leaf area index, and yield to simulate the phenological development timeline, growth, and seed cotton yield (Wajid et al., 2014). While the model overestimated leaf area index and total dry matter, it was still within a reasonable range, but the development timeline was considered reliable. Another application for the CSM-CROPGRO-Cotton model was the evaluation of the effects of a cover crop on the following cotton crop yield. In Texas, a research group used the model to evaluate the long-term effects of a winter wheat cover crop upon cotton yield and soil water (Adhikari, P. et al., 2017). After successfully calibrating the model using observed soil water and crop yield data, it was found that the cover crop did not affect the following cotton crop's yield nor the availability of soil water under irrigated and dryland management.

1.3. Goals and Objectives

The overall goal of this work was to evaluate the response of cotton to fertigation in southern Georgia. The specific objectives used to achieve this goal were to:

1. Conduct a replicated plot field study that evaluated fertigation as an in-season N application strategy for cotton and compared fertigation to other in-season N application strategies;
2. Use the DSSAT CSM CROPGRO-Cotton model to evaluate the response of cotton to several combinations of the timing and the amount of N in fertigation applications.

This thesis is organized in journal article format. Chapter 2 addresses objective 1 and Chapter 3 addresses objective 2. Chapter 4 provides general conclusions from both the field and modeling components of the study.

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TABLES AND FIGURES

Table 1.1. UGA Extension Calendar method for irrigation scheduling as described in Hand et al. (2022).

Cotton Irrigation Schedule				
Growth Stage	**Days after Planting**	**Weeks after Planting**	**Millimeters/ Week**	**Millimeters/ Day**
Emergence	1 - 7	1	1.02	0.25
Emergence to First Square	8 - 14	2	4.57	0.76
	15 - 21	3	7.37	1.02
	22 - 28	4	10.41	1.52
	29 - 35	5	14.22	2.03
First Square to First Flower	36 - 42	6	18.03	2.54
	43 - 49	7	21.59	3.05
	50 - 56	8	27.43	3.81
First Flower to First Open Boll	57 -63	9	32.51	4.57
	64 - 70	10	37.34	5.33
	71 - 77	11	38.61	5.59
	78 - 84	12	37.6	5.08
	85 - 91	13	36.07	5.08
	92 - 98	14	33.02	4.83
	99 - 105	15	29.46	4.32
	106 - 112	16	22.35	3.3
	113 - 119	17	17.53	2.54
First Open Boll to >60% Open Bolls	120 - 126	18	12.95	1.78
	127 - 133	19	8.89	1.27
	134 - 140	20	5.59	0.76
	141 - 147	21	3.05	0.51
	148 - 154	22	1.27	0.25
	155 - 161	23	0.51	0
Harvest	162 - 168	24	0	0
	169 - 175	25	0	0

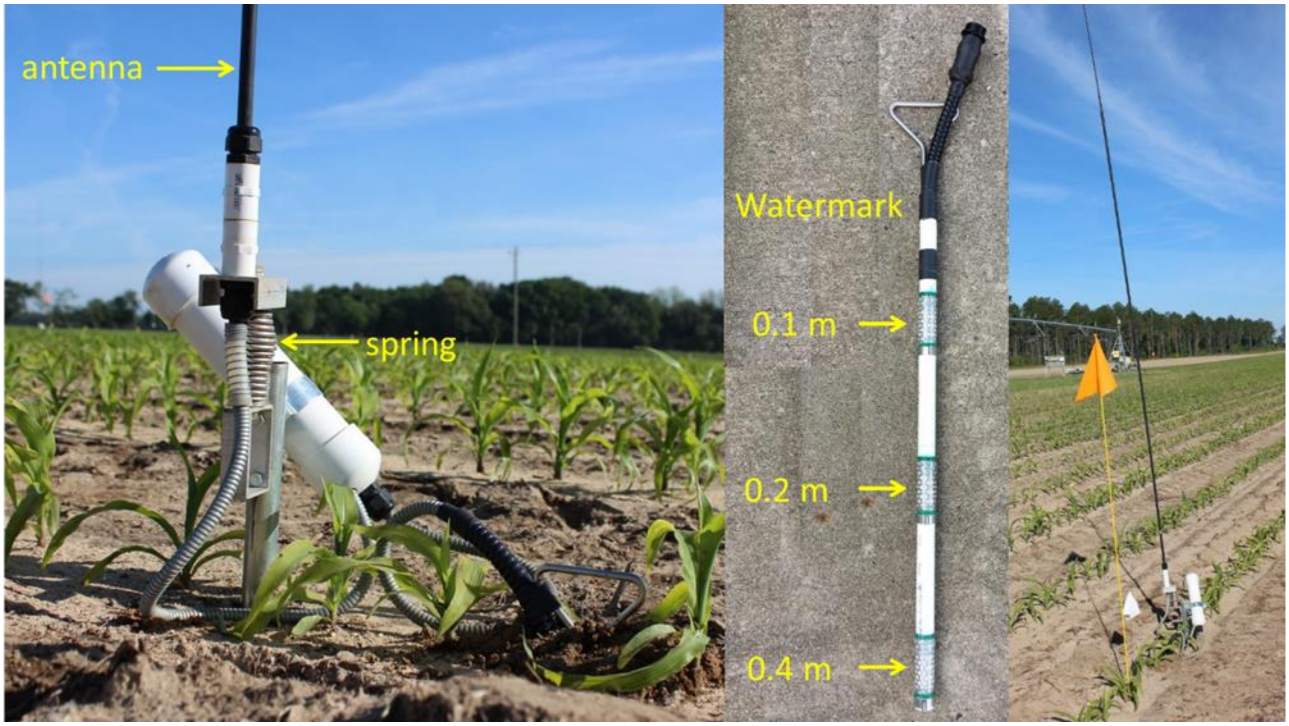

Figure 1.1. University of Georgia Smart Sensor Array (UGA SSA) installation and hardware as described in Vellidis et al. (2013).

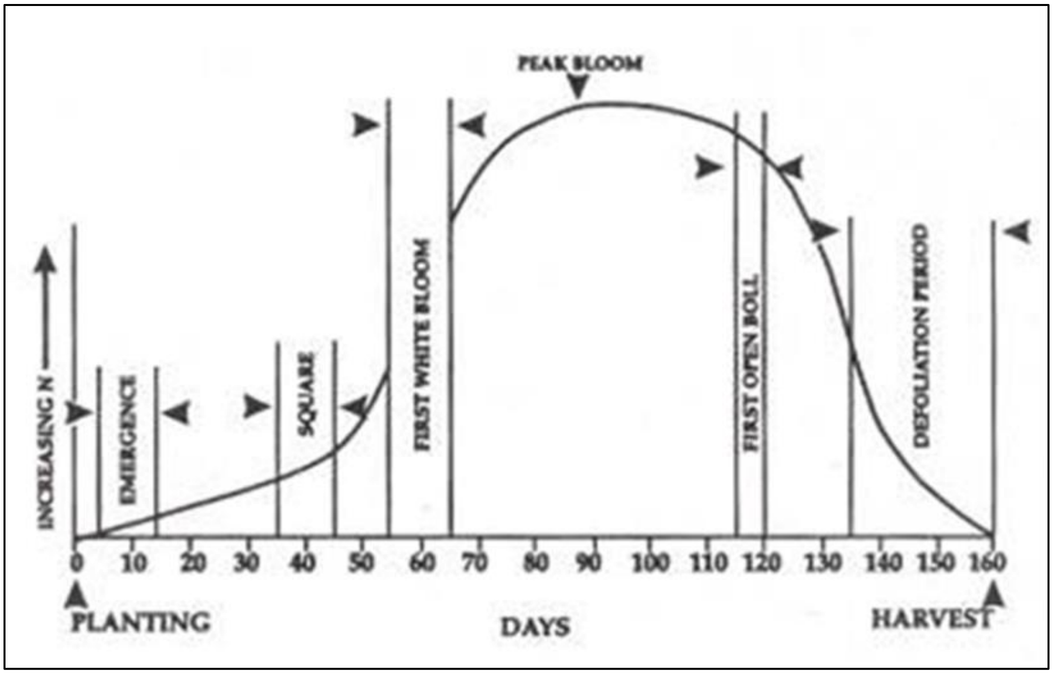

Figure 1.2. Increasing demand of nutrients and water of cotton as season progresses towards harvest (NCC, 1996).

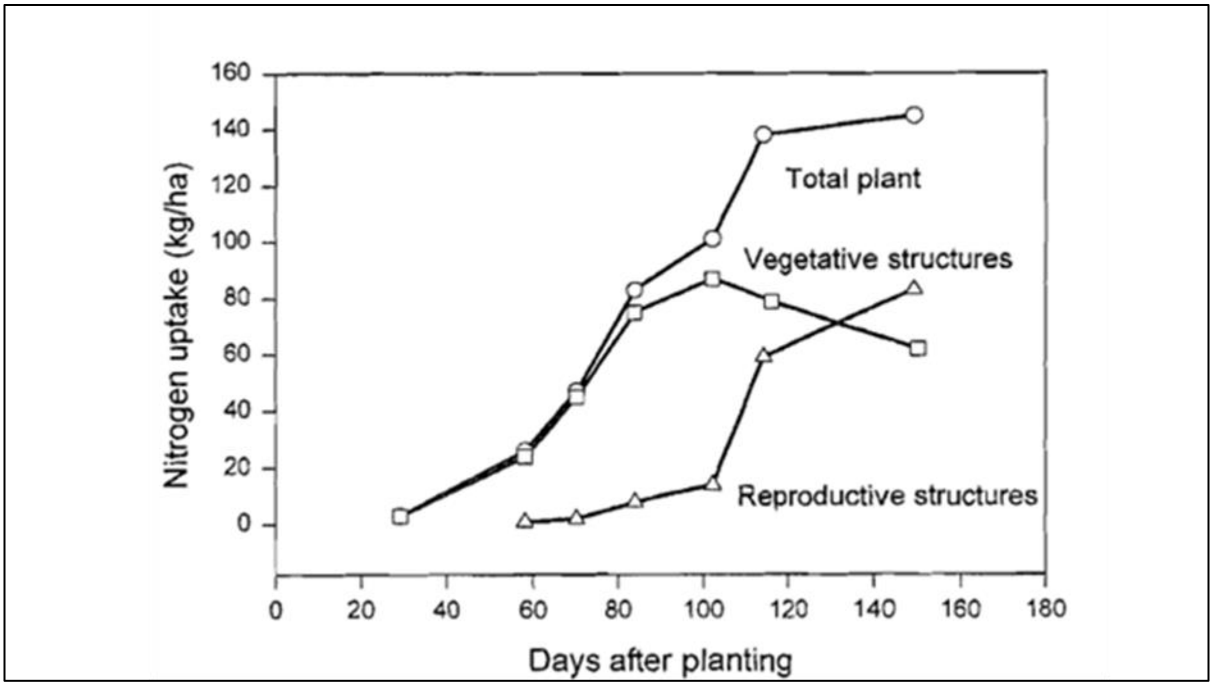

Figure 1.3. Cumulative nitrogen uptake in cotton vegetative and reproductive structure (Gerik et al., 1998).

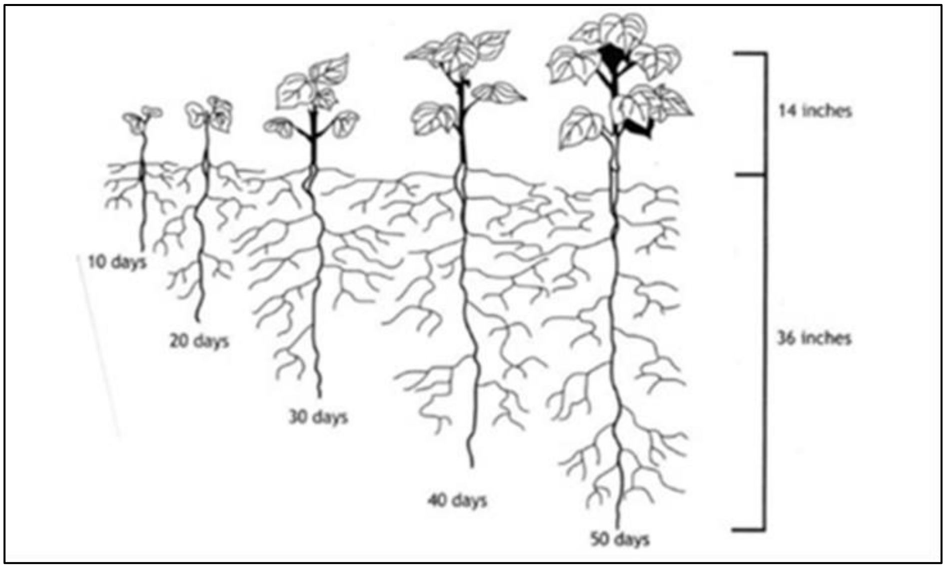

Figure 1.4. Cotton root development at the beginning of the growing season (Gerik et al., 1998).

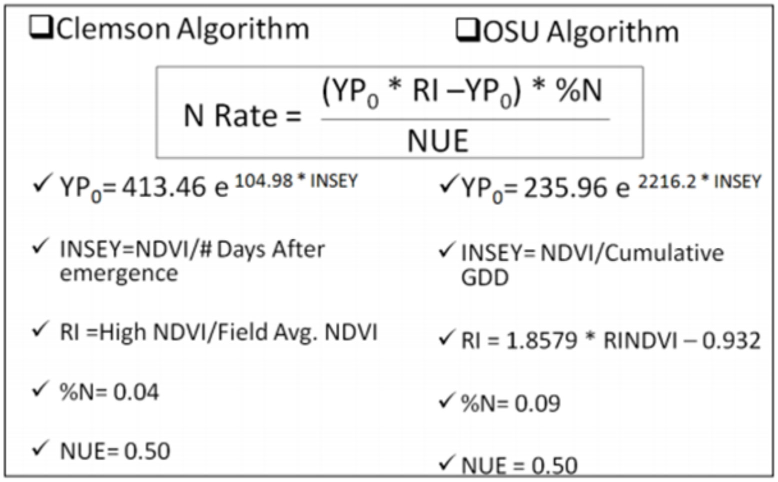

Figure 1.5. Comparison of the Clemson and Oklahoma State University algorithms for determining N rates (Porter et al., 2010)

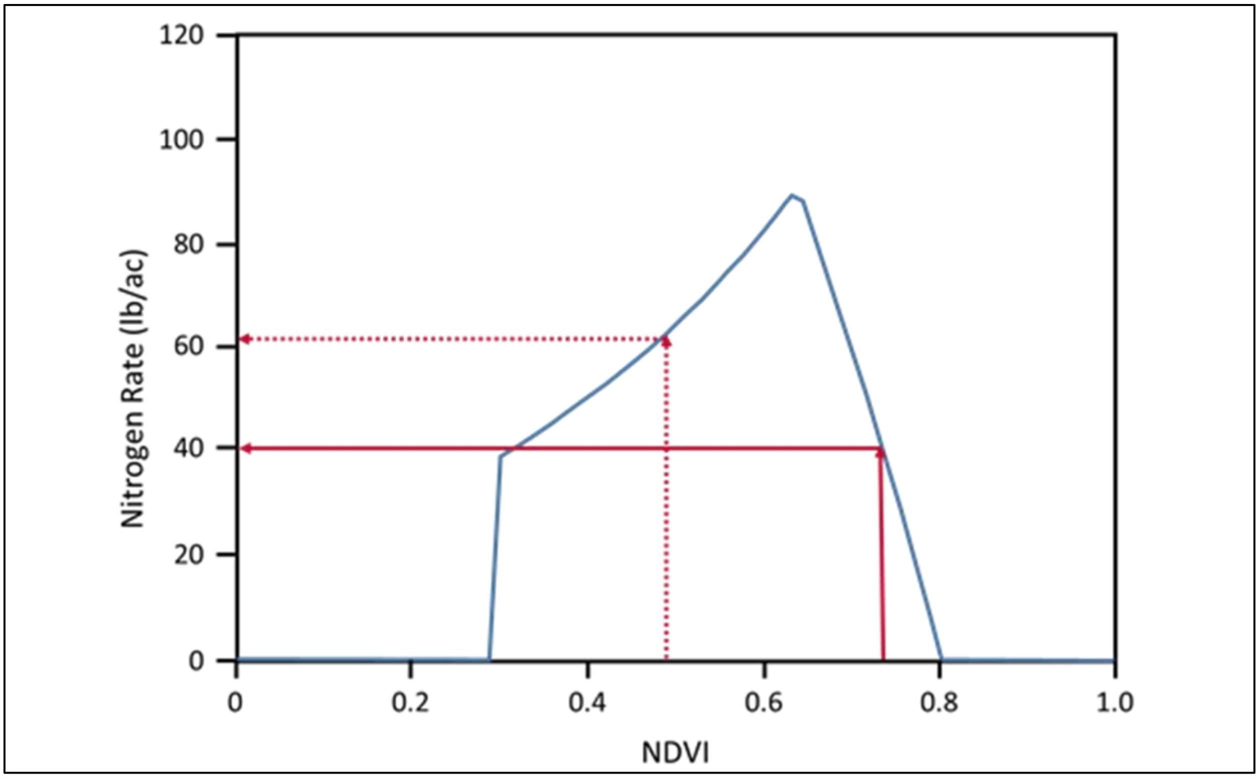

Figure 1.6. Graph of the Clemson algorithm showing the relationship between NDVI and recommended nitrogen side-dress application rates. The arrows indicate examples of recommended application rates for two different NDVI values (Taylor and Fulton, 2010).

CHAPTER 2

EVALUATION OF FERTIGATION AS AN IN-SEASON COTTON NITROGEN MANAGEMENT STRATEGY IN SOUTHERN GEORGIA, USA [1]

[1] Sangster, S., Toffanin, A., Snider, J., Hand, L. C., Gruver, M., Perry, C., Washington, C., and Vellidis, G. To be submitted to the *Field Crops Research* Journal

Abstract

Nitrogen (N) management for cotton production in Georgia, USA is typically split between pre-plant and one in-season N application between first square and first bloom. The work reported here explored the potential of using fertigation as an in-season N application method to improve nitrogen use efficiency (NUE). The field study was conducted near Camilla, Georgia between 2018-2021 using a randomized complete block design with three in-season N treatments (conventional, NDVI, Fertigation) and three irrigation scheduling treatments (calendar, SmartIrrigation Cotton, and UGA Smart Sensor Array (UGA SSA)). Soil and tissue samples were taken during the growing season and yield was measured at harvest. Fertigation resulted in numerically higher yields that were not significantly different from the yields of other in-season fertilization treatments. The UGA SSA irrigation treatment resulted in the highest yields and highest irrigation water use efficiency (IWUE).

2.1. Introduction

Cotton (*Gossypium hirsutum* L.) is an economically important crop in the United States (Chastain et al., 2014) and especially in Georgia where it has been grown on 566,000 ha per year over the past five years. It contributes $120 billion to the U.S. and $2.5 billion to the Georgia economies, respectively. Across the world, cotton is cultivated in multiple climates including the humid Southeast of the U.S. (Hearn, 1979; Turner et al., 1986). In Georgia, cotton is grown primarily in the southern half of the state where average annual precipitation is approximately 1,270 mm. Although this is enough water to supply crop water requirements (Bednarz et al., 2002), the distribution of rainfall does not always coincide with peak crop water requirements. Short episodes of drought at a critical stage of crop development can limit fiber yield and quality (Bednarz et al., 2002, Chastain et al., 2014).

Proper fertilization is also key to cotton production. One of the most important and challenging to manage, plant nutrients is nitrogen (N). N fertilizers are applied as dry or liquid compounds. The United Nations Food and Agricultural Organization (FAO) estimates that N fertilizer use exceeded 100 million tons in 2018 – an increase of 25% over the past 10 years (FAO, 2019; Udvardi et al., 2015). Under-application of N results in uncaptured yield potential. However, over-application in cotton also has adverse consequences and results in rank growth which negatively impacts yield (Guthrie et al., 1994).

The University of Georgia's Cotton Production Guide (Hand et al., 2022) provides N recommendations for different yield goals. The recommendation for a high yield goal of 1681 kg ha^{-1} of cotton fiber is 118 kg N ha^{-1}. In areas with sandy soils such as the Coastal Plain of southern Georgia, soil samples are not routinely tested for N because it is assumed that the soils retain little N due to leaching. As a result, the amount of N fertilizer applied is based on the farmer's yield goal. In Georgia, typically, between 20 and 30% of the N required by cotton is applied prior to planting. The remaining N is usually applied with one in-season application between first square and first bloom. The application is usually made either by broadcasting granular fertilizer (top-dressing) or by applying liquid fertilizer next to the plant rows (side-dressing). The Cotton Production Guide recommends that in-season N be applied between first square and first bloom but no later than the third week of bloom because N applied before or after that period is not used as effectively by the crop (Hand et al., 2022).

A variety of precision agriculture techniques have been used to estimate the amount of in-season N needed by the growing crop to maximize its yield potential. These approaches have revolved around using remote or proximal optical sensors to capture light reflected from the crop canopy and calculating vegetation indices such as the Normalized Difference Vegetative Index (NDVI). NDVI serves as a surrogate for estimating cotton biomass. Algorithms have been developed that estimate in-season N needed from measured NDVI (Kim, 2019; Taylor and Fulton, 2010; Porter et al., 2010a; 2010b). Porter et al. (2010a, 2010b) showed that the use of NDVI as a tool for in-season site-specific N recommendations resulted in less applied N while not negatively impacting yields when compared to the grower standard. In studies conducted in southern Georgia, Liakos et al. (2013) used a Trimble GreenSeeker RT200 system (Trimble, Westminster, Colorado, USA) to measure NDVI and the algorithm proposed by Porter et al. (2010a; 2010b) to variably apply in-season N on cotton in commercial fields. They found that that this approach resulted in yield increases, less N applied, and higher profitability. However, this approach has not been widely adopted in the Southeast because of the relatively high cost of the equipment needed (Liakos et al., 2013).

2.1.1. Increasing Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) is the fraction of applied N fertilizer that is utilized by the plant. Under field conditions, NUE is approximately 50%. This means that up to 50% of the N applied to soil as fertilizer may be unavailable for use by the crop (Udvardi et al., 2015). The N that is unavailable may be lost to volatilization, leaching, or other biogeochemical processes. Improving NUE means more crop per unit input, leading to increased profit, the main goal of all producers (Good et al, 2004). Applying multiple versus a single in-season N application has the potential for improving NUE because the fertilizer can be applied in small doses at frequent intervals which increases the likelihood that N is used by the crop.

McClanahan et al. (2020) conducted a study in Virginia and North Carolina to understand the effects of four total N application rates (45, 90, 135,180 kg N ha^{-1}) and three methods of in-season N applications (broadcast, surface banded, injected) on cotton fiber yield and quality and petiole nitrate concentrations. They demonstrated that N rate and placement affected fiber yield with yield increasing as N rate increased. Petiole nitrate concentrations followed a similar trend.

The effects of rate, source, application method, and timing of N applications on cotton were studied by Reiter et al. (2008) in a high residue conservation tillage program. When total season N was applied at-planting yields were higher; however, when total season N was split between planting and an in-season N application, NUE was improved. With the goal of improving NUE and profit, they suggested broadcasting 126 kg N ha^{-1} applied as ammonium nitrate using a split application between planting and an in-season application for a high residue rye cropping system. NUE and Irrigation Water Use Efficiency (IWUE) can be improved by understanding crop demand based on growth stage. With ever increasing input prices and difficulties with input availability, resource use efficiency has become an important consideration for all producers.

2.1.2.Fertigation

Fertigation is the application of liquid fertilizers through an irrigation system. It has potential for improving NUE because the fertilizer can be applied in small doses at frequent intervals which increases the likelihood that N is used by the crop and not lost to leaching. Top-dressing N through overhead sprinkler systems such as center pivots is commonly used with maize in the USA (Gascho and Hook, 1991) and is being adopted in other regions of the world (Asadi et al., 2002; Yolcu and Cetin, 2015, He et al., 2012, Schepers et al., 1995). Fertigation with center pivots provides many logistical advantages including ensuring that the farmer can apply at the time of peak N demand (Biwas, 2010). Toffanin et al. (2019) conducted a three-year replicated plot study in southern Georgia, USA where they evaluated the effect of fertigation on maize production. Four top-dress N applications were applied using overhead sprinklers. Fertigation was applied separately from regular irrigation events to reduce the potential for leaching. When compared to a single liquid N side-dress application, fertigation resulted in the same yields but with lower amounts of N used and an average 17% gain in NUE over the study period.

In contrast to maize, the use of fertigation on cotton has not been extensively researched. Hou et al. (2007) conducted a greenhouse study to determine the effect of different fertigation schemes on N uptake and NUE in cotton plants. The study focused primarily on the timing of fertigation during an irrigation cycle and found N applied at the beginning of an irrigation cycle showed higher NUE and dry matter measurements. In a similar study conducted in the field using drip irrigation, Hou et al. (2009) found that that N applied at the beginning of an irrigation cycle resulted in the highest seed cotton yield but showed higher potential loss of N from leaching. Nitrogen applied at the end of an irrigation cycle had potential to lessen the amount of N loss from leaching but reported lower yields and NUE. Several studies have been conducted assessing the benefits of fertigation with drip irrigated cotton and results indicate that this approach shows promise for improving yields and NUE.

Bronson et al. (2019) conducted a study on cotton irrigated with subsurface drip irrigation in an arid environment and found that high frequency N fertigation events provided the crop with adequate in-season N, reducing N losses to the environment and improving NUE. Li et al. (2020) compiled previous studies of drip fertigation and resource use efficiency for multiple crops, including cotton, compared to traditional management practices. The analysis showed that drip fertigation increased yield by 11.6% and NUE by 16.5% as compared to traditional farmer practices.

Few studies have been conducted on evaluating fertigation on cotton with overhead sprinkler irrigation. Antille (2018) evaluated fertigation applied to both furrow and sprinkler-irrigated cotton in Australia. The study found that application of N through fertigation was economical for both furrow and sprinkler irrigation under fertilizer pricing at the time of the study, but relative agronomic efficiencies and economic return from the N applied were higher for fertigation with overhead sprinklers ($p<0.05$). In addition, fertigation with sprinklers resulted in reduced potential for N_2O emissions.

2.1.3. Goals and Objectives

The overall goal of the work described in this paper was to evaluate the response of cotton to fertigation in southern Georgia. The specific objective was to conduct a replicated plot field study that evaluated fertigation as an in-season N application strategy for cotton and compared fertigation to other in-season N application strategies.

2.2. Materials and Methods

2.2.1. Study site and management practices

A 4-year study was conducted at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) located near Camilla, Georgia from 2018 – 2021 in a 4 ha research field (31°16'46.24"N, 84°17'59.59"W). The field is divided into three blocks [North (NLN), Middle (NLM), South (NLS)] with each block containing 27 plots (Figure 2.1). The plots were each 14.5 × 14. 5 m (14. 5 m long × 16 rows wide). The eight middle rows in each plot were used for data collection and the four rows on either side of the middle eight served as buffers (Figure 2.2). The soil in the Newton Lateral field is classified as a Lucy Loamy Sand with available water holding capacity of 0.08 cm cm^{-1} with 0 to 5% slope. Soil texture varies slightly across the field with 83% Sand, 10% Silt and 7% Clay in the South block to 86% Sand, 8% Silt, and 6% Clay in the North block.

The experimental design utilized a randomized complete block design. The 27 plots in each block were divided into nine treatments with three replicates each (Figure 2.1). A cotton-peanut-maize rotation was maintained with crops rotating from north to south each year. All crops were planted into a rye cover crop residue using strip tillage following termination with glyphosate.

Cotton was planted in late April or early May (10-May-2018, 3-May-2019, 6-May-2020, and 29-April-2021). The PHY 300 cotton cultivar (PhytoGen, Corteva Agriscience. Indianapolis, Indiana, USA) was used in 2018 and 2019. The PHY 350 cultivar was used beginning in 2020 and 2021 because PHY 300 seed was no longer available. The cultivars have similar traits and growth habits. Both were early-mid maturing cultivars with WideStrike® 3 Insect Protection and the Enlist® (W3FE) cotton trait in-plant protection and bacterial blight and root-knot nematode resistance.

Three irrigation scheduling × three in-season N fertilization treatments were evaluated in the cotton plots. Other than N in-season applications and irrigation applications, all plots were managed uniformly. Table 2.1 summarizes some of the crop production management practices used during this study.

2.2.2. Irrigation Treatments

The Newton Lateral field was irrigated with a variable rate-enabled lateral irrigation system which could apply a unique water application rate to each of the 81 plots. The amount of water applied with each irrigation event was 19 mm. The three irrigation scheduling treatments included in this study were the UGA Extension calendar method which is described in the University of Georgia's Cotton Production Guide (Hand et al., 2022), the SmartIrrigation Cotton App (Vellidis et al., 2016), and University of Georgia Smart Sensor Array (UGA SSA) (Vellidis et al., 2013).

The UGA Extension calendar method (Calendar) recommends weekly irrigation application amounts based on a combination of weeks after planting and phenological stage. Depending on the amount of irrigation recommended, this method was applied with one or more weekly irrigation events. The amount applied was the recommended weekly amount minus precipitation received over the past week. Precipitation was measured by the University of Georgia Weather Network Camilla weather station (31°16'48.3"N 84°17'29.8"W) which is located on the SIRP grounds.

The SmartIrrigation Cotton App (SI Cotton) is a FAO-56 (Allen et al., 1998) evapotranspiration (ET) -based irrigation scheduling tool that calculates percent remaining plant available water in the root zone on a daily basis. In this study, the SI Cotton App used meteorological data from the Camilla weather station. The irrigation triggering threshold was set to 50% of plant available water used from emergence to first flower and 40% of plant available water used from first flower to first open boll. A 19 mm irrigation event was applied whenever the threshold was reached.

The UGA SSA is an automated wireless soil moisture sensing system that measures soil moisture in terms of soil water tension (the absolute value of matric potential) in units of kPa. Each plot was equipped with a UGA SSA node that consisted of a probe with Watermark (Irrometer, Riverside California, USA) sensors at depths of 0.15, 0.30, and 0.45 m (Figure 2.3). Although UGA SSA nodes were installed in all the plots for monitoring purposes, only those installed in the UGA SSA treatment plots were used for scheduling irrigation. These plots were irrigated individually.

Soil water tension (SWT) data from each sensor were recorded hourly. The data collected at 07:00 each morning from the node in each plot were used in Eq. 1 to calculate a weighted average SWT for that plot which was then used to make irrigation scheduling decisions. A weighting factor (α, β and γ) was applied to sensor readings based on sensor depth to represent the distribution of the rooting system of the cotton crop at that phenological stage. The largest weight was given to the shallowest sensor. Initial weighting factors were $\alpha = 0.8$, $\beta = 0.2$, and $\gamma = 0$. The final weighting factors used during the crop's reproductive stage were $\alpha = 0.5$, $\beta = 0.3$, and $\gamma = 2$.

$$Weighted\ Average\ SWT = \alpha * SWT_{0.15\mathrm{m}} + \beta * SWT_{0.30\mathrm{m}} + \gamma * SWT_{0.45\ m} \qquad \text{Eq. 1}$$

2.2.3. In-Season Fertilization Treatments

For the 2018, 2019, and 2020 growing seasons, the in-season fertilization treatments included using a three-event fertigation treatment (Fertigation A) to apply top-dress N, an unmanned aerial vehicle (UAV)-derived NDVI treatment (NDVI) to apply side-dress N once, and the farmer-standard treatment (Conventional) which was also a single side-dress event. Because consistently cloudy conditions prior to and during the period when in-season N was to be applied during the 2021 growing season prevented the acquisition of useable UAV data, the NDVI treatment in 2021 was replaced by a second fertigation treatment (Fertigation B) in which the in-season N was applied with four fertigation events.

A urea-based granular fertilizer was applied uniformly to all plots prior to planting. The total amount of N applied to the Conventional and Fertigation treatments was approximately the amount recommended by the Georgia production guide for a 1681 kg ha^{-1} cotton fiber yield. Table 2.2 presents the pre-plant, in-season, and total N applied to each fertilization treatment during each growing season. The conventional treatment was one urea-based (28-0-0-5) liquid side-dress application shortly after first square. The liquid was dribbled between cotton rows.

Fertigation events were applied between first square and the third week of bloom. For the 3-event fertigation treatment (Fertigation A), this resulted in applications at seven-to-ten-day intervals. For the 4-event fertigation treatment used in 2021 (Fertigation B), this resulted in more frequent applications. Fertigation was accomplished by injecting urea based (28-0-0-5) liquid into the irrigation system's water supply stream using a Marksman Precision Irrigation Injection system (SureFire Ag, Atwood, KS). The liquid N injection point on the lateral's main line was approximately 5 m from the first sprinkler. The N was applied with approximately 3 mm of irrigation water followed by approximately 8 mm of irrigation water to ensure that all the applied fertilizer entered the soil profile.

Liakos et al. (2013) showed that using NDVI to estimate the amount of in-season N was effective at increasing NUE in southern Georgia but difficult to implement because of the cost of equipment. Because the advent and use of UAVs equipped with optical reflectance sensors offered the potential to collect NDVI data at lower costs, a UAV-derived NDVI treatment using the Porter et al. (2010a, 2010b) algorithm to determine the amount of side-dress N was implemented in the study. The in-season N was applied as one liquid N side-dress application at the same time as the conventional treatment. A mean NDVI was calculated for each plot within an NDVI treatment. The means of the three plots in each NDVI treatment were then averaged to produce a treatment mean NDVI which was then applied to the algorithm. Each year, the amounts of N calculated from the algorithm for each of the three NDVI treatments were within 2 kg ha^{-1} of each other so the same rate was applied to all the NDVI treatments.

2.2.4. Field Data Collection

As described earlier, the middle eight rows of each plot were data rows, with four border rows on each side (Figure 2.2). The middle two rows were reserved for mechanical harvest. Two rows on either side of the middle two rows were used for sampling. Soil cores were collected in 0.15-m increments to 0.91 m prior to planting, four times during the cotton growing season, and after harvest to quantify soil N. The soil samples were separated in bags by plot and depth. A subsample from each bag was used for nutrient analysis and another subsample was used to measure volumetric water content. Soil samples were analyzed for NH_4-N (ammonium) and NO_3-N (nitrate) by Waters Agricultural Laboratories (Camilla, Georgia). Volumetric water content was calculated using the gravimetric method by the authors. Soil cores for soil texture, pH, and cation exchange capacity (CEC), organic matter (OM) analyses were collected in 0.15-m increments to 0.91 m from the plots three times during 2018. The analyses were performed by Waters Agricultural Laboratories.

Depending on the year, whole plant samples were collected from the cotton crop three or four times during the cotton growing season. During 2019, plant samples were collected only from the fertigation treatment due to funding constraints. Samples consisted of all the plants within 1 m length of one of the sampling rows. Whole cotton plants were cut at the soil surface and segmented into leaves, petioles, bolls, flowers, and stems. Leaf area index (LAI) was measured using a bench top LI-COR (LI-COR Biosciences, Lincoln, NE.) leaf area meter. The tissue samples were dried at 60 °C for 48 h, weighed to measure dry biomass, and then analyzed for Total Kjeldahl Nitrogen (TKN) by Waters Agricultural Laboratories. Canopy height was measured four times during the growing season in 2021 only. Plant height measurements were made on the same plants within a designated 1 m of row in each of the 27 plots on the same dates as the tissue sampling. Height was measured from the soil surface to the growing point.

Immediately prior to mechanical harvest, 2 m of a sampling row was hand-harvested. Then the middle two rows were mechanically harvested using a spindle picker with a bagging attachment. The bags were weighed immediately after harvest and ginned at the UGA Microgin. The hand-harvested samples were hand-ginned using a small saw gin. Seed cotton yields were calculated by dividing harvested mass by harvest area. Fiber yields were calculated by multiplying seed cotton yields by gin turnout. Annual average gin turnout was 37%, 39%, and 42% for 2019, 2020, and 2021, respectively. The 3-year average was approximately 40%. The hand-harvested samples were used to confirm the results from the mechanical harvest.

2.2.5. Data and Statistical Analyses

The experiment was arranged as a randomized complete block design (RCBD) with three irrigation scheduling treatments and three in-season N treatments. A two-way ANOVA using standard least squares was used for analysis of effects using JMP Pro 16 (SAS Institute, 2021). The comparison of means was done by using Fisher's protected LSD test with a 0.05 significance level. NUE was calculated by dividing fiber yield by total N applied and reported in units of kg-fiber kg-N^{-1}. IWUE was calculated by dividing fiber yield by irrigation water applied and reported in units of kg-fiber mm^{-1}. All data collected in this study are archived in the United States Department of Agriculture's Ag Data Commons (Vellidis and Sangster, 2022).

2.3. Results and Discussion

2.3.1. Precipitation and Irrigation

Cotton grown in Georgia requires approximately 460 mm of water during the growing season (Bednarz et al. 2002; Ritchie et al. 2009). Total precipitation exceeded the amount needed in each of the study's four growing seasons. However, the distribution of precipitation was uneven, thus requiring irrigation. Figure 2.4 shows meteorological data for the 2018 through 2021 growing seasons as reported by the Camilla weather station. The 2019 growing season received the least amount of rainfall (513 mm) while the 2018 growing season received the highest amount with much rainfall occurring from Hurricane Michael at the end of the season. Total precipitation received and the irrigation amounts applied to each irrigation treatment during the four growing seasons are shown in Figure 2.5. The UGA SSA treatment consistently required the lowest amount of irrigation water while the Calendar method required the most.

2.3.2. Yield

Yield data are not available for 2018 as the cotton crop was destroyed by Hurricane Michael a few days before scheduled harvest. Cotton fiber yields (Table 2.3) were lower than what was previously reported by Vellidis et al. (2016) for the Newton Lateral field for all treatments including Conventional fertilization and Calendar irrigation and fiber yields for 2020 and 2021, in which the PHY 350 cultivar was used, were less than 60% of the Cotton Production Guide's yield goal for the N applied. Throughout the study, all plots received an adequate amount of N, and water stress was not a limiting factor. The lower yields were attributed primarily to boll rot at the end of those two growing seasons and may have been exacerbated by the cotton cultivar used in the study.

Overall, yield was not affected by fertilization treatment as there were no significant differences between the means of the treatment yields. Lack of significant differences may be a function of high variability in yield between replicates of the same treatment (Figure 2.6). However, yield was affected by irrigation treatment in 2019 and 2020. The NDVI treatments in 2019 and 2020 received smaller amounts of N during the growing season without significant yield penalties which may indicate that the N rates recommend by the UGA Production Guide may be higher than necessary in this given situation.

In 2019, fiber yields of individual treatments ranged from 1089 kg ha $^{-1}$ (SI Cotton × Fertigation A) to 1493 kg ha $^{-1}$ (UGA SSA × Conventional) and were significantly different (Figure 2.6). The means of all the fertilization treatments were not significantly different (Table 2.3) although Conventional resulted in the highest yield (1335 kg ha $^{-1}$) and Fertigation A in the lowest yield (1174 kg ha $^{-1}$). Because of a mechanical failure with the injection system, the third fertigation event was applied approximately a week after the third week of bloom and this may have adversely affected yield. Yield was affected by irrigation treatment with UGA SSA and SI Cotton treatment yields being significantly higher than the Calendar method treatment (Table 2.3).

In 2020 treatment fiber yields ranged from 778 kg ha^{-1} (Calendar × Fertigation A) to 1101 kg ha^{-1} (UGA SSA × Fertigation A) (Figure 2.6). There were significant differences between the highest and lowest yield treatments. The Calendar × Fertigation A treatment received 267 mm of irrigation while the UGA SSA × Fertigation received 122 mm of irrigation – less than half. It is plausible that the difference in yield may be the result of N loss through leaching which is discussed below. The means of all the fertilization treatments were not significantly different (Table 2.3) although Fertigation A resulted in the highest yield (938 kg ha $^{-1}$) and Conventional in the lowest yield (873 kg ha $^{-1}$) – the opposite of 2019. Yield was affected by irrigation treatment with UGA SSA treatment being significantly higher than the Calendar method treatment (Table 2.3).

In 2021, the six individual Fertigation A and Fertigation B treatments resulted in the highest numerical yields while the three conventional treatments resulted in the lowest numerical yields (Figure 2.6). There were no significant differences in yield in 2021 (Table 2.3). The two fertigation treatments had the highest numerical yields but differences were not significant (Table 2.3). Similarly, yield was not affected by irrigation treatment but unlike the previous years, the Calendar method treatment resulted in the highest yield (Table 2.3).

A higher frequency of in-season N applications should reduce N loss to the environment due to a smaller amount being applied at a given time (Uzen and Centin, 2016). The split in-season N applications provide N as the demand for it ramps up when compared to a single N application which applies the in-season N ahead of peak plant N demand. The combination of N applications and irrigation management can affect plant growth and final yield. A poor combination of nitrogen applied and irrigation can affect the yield potential of a crop and while also promoting unfavorable growth habits and susceptibility to pests (Snider et al, 2021 and Perry et al., 2012)

2.3.3. Nitrogen Use Efficiency (NUE)

The individual treatments with the highest numerical NUE were SI Cotton × NDVI in 2019 (12.4 kg-fiber kg-N^{-1}), UGA SSA × Fertigation in 2020 (8.2 kg-fiber kg-N^{-1}), and Calendar × Fertigation B in 2019 (8.0 kg-fiber kg-N^{-1}). In 2021, the six fertigation treatments resulted in the highest numerical NUEs although there were no significant differences (Table 2.3). Because

NDVI treatments received lower amounts of in-season N with yields in the mid-to-high range of the observed yields, NUE of NDVI treatment means were the numerically highest in 2019 and 2020. Because the NDVI treatment was replaced in 2021, Fertigation A resulted in the highest NUE (Table 2.3). The finding that the NDVI treatment resulted in the highest NUE in 2019 supports findings of Porter et al. (2010) that yield was not negatively impacted even though the applied N rate was reduced. The following two years (2020 and 2021) demonstrated that multiple fertigation treatments improved NUE as compared to single in-season applications. The use of irrigation water following a fertigation event is supported by Bronson et al. (2019) and Hou et al. (2009) to ensure the N is washed off the canopy and into the soil profile for uptake while limiting N loss to the environment.

2.3.4. Irrigation Water Use Efficiency (IWUE)

The UGA SSA treatment consistently used the lowest amount of irrigation water and in 2019 and 2020 resulted in the highest irrigation treatment yields. Consequently, it was also the treatment with the highest numerical IWUE every year. In 2019 and 2020, the treatment's IWUE was 2 to 3 times higher than those of the other treatments (Table 2.3). Because the Calendar irrigation treatment was the most liberal of the three used, it applied much more water than the other treatments during every year of the study. In 2021, for example, it used 111 mm more than SI Cotton and 130 mm more than UGA SSA. Only in 2021 did the Calendar method result in higher yields than the other two treatments but the differences were not significantly different. These results confirm those by Vellidis et al. (2016), Migliaccio et al. (2016), and Zamora-Re et al. (2020) among others which showed that sensor-based or ET model-based irrigation scheduling methods outperform calendar methods. These approaches result in higher IWUE and are suitable irrigation scheduling methods for use by cotton producers.

2.3.5. Tissue Sampling Results

The results of the tissue sampling were used to determine if the fertilization and irrigation treatments affected crop development during the growing season and ultimately fiber yield. Appendix Tables A1-A8 compare mass (kg[dw] ha^{-1}) and %N for each plant component by treatment during each sampling event while Figure 2.7 shows %N of each plant component by sampling date for each treatment during the growing season. In general, treatments did not affect the concentration of N of plant components or the mass of those components although there were sampling dates during which results were significantly different. Because the Conventional and Fertigation A and Fertigation B treatments received the same amount of total N, these findings are expected. But as indicated earlier, the NDVI treatments received smaller amounts of N during the growing season without significant differences in plant biomass and N concentrations which may indicate that the N rates recommend by the UGA Production Guide may be higher than needed in this situation.

As expected, the aboveground biomass increased as the season progressed and plant components, such as stem and boll biomass steadily increased until harvest. Leaf biomass reached a high point during mid-season and began to decrease due to senescence as the plant progresses towards defoliation. This was observed across all fertilization and irrigation treatments for each of the four growing seasons.

Table 2.4 shows tissue biomass by irrigation treatment for the four growing seasons. In 2019, the Calendar irrigation treatment was significantly more than the other two treatments for leaf biomass, petiole biomass, and LAI for the 130 DAP sampling event. 2020 biomass results showed the Calendar treatment to be significantly higher for the third sampling date for leaf biomass, stem biomass, and LAI. The second sampling date saw a similar result for stem and petiole biomass. The Calendar treatment was significantly higher than the UGA SSA treatment for stem biomass on the fourth sampling date. On the first and only sampling date for square biomass, the SI Cotton treatment was significantly higher than the UGA SSA treatment. Leaf biomass was affected by irrigation treatment in 2021 on the first sampling date, where the Calendar treatment was significantly higher than the SI Cotton treatment. Otherwise, biomass distribution of plant segments was not affected by irrigation treatment in 2021.

Table 2.5 shows the tissue biomass by fertilization treatment for the four growing seasons. Leaf biomass, petiole biomass, and LAI were affected by fertilization treatment with Conventional being significantly higher than NDVI on the final sampling date of 2018. In 2020, only the first sample date found boll weight for the Fertigation A treatment to be significantly higher than the NDVI treatment. Fertilization treatments did not affect biomass for any sample date in 2021.

2.3.6. Soil Sampling Results

Soil core segments were analyzed by soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) for NO_3-N (Figure 2.8) and NH_4-N (Figure 2.9). Overall, there were no significant differences between the irrigation treatments or the fertilization treatments for any of the four years of the study. However, there were occasionally differences on specific sampling dates. The results for NO^3-N are reported in Table 2.6 and for NH^4-N in Table 2.7.

In contrast, there were significant differences in NO_3-N (Table 2.8) and NH_4-N (Table 2.9) concentrations by depth at individual sampling dates. In general, concentrations were consistently higher in soil layers A and B and lowest in soil layer D (Figures 2.10 and 2.11). The magnitude of the concentrations in the top two layers was a function of how closely soil sampling followed an in-season N application (Figure 2.12).

Soil N concentrations fluctuate depending on crop growth stage due to N uptake, environmental losses, and fertilization events for both NO_3-N and NH_4-N according to Pengcheng et al. (2017) who studied N rate and split applications on soil N for cotton. The soil N concentrations varied based on fertilization amounts and how the applications were split between pre-plant and in-season N events, as well as the growth stage at the time of the sample. Soil NO_3-N concentrations were noted to be greater at lower soil depths at the end of the growing season showing movement through the soil. Zamora et al (2020) also observed an increase in soil N concentrations after a fertilization event.

2.4 Conclusions

The results from this study confirm the results from many other studies that advanced irrigation scheduling tools such as soil moisture sensors and ET-based models consistently outperform calendar scheduling methods in both yields and IWUE. These are tools that cotton growers can adopt at relatively low cost and little risk of yield loss.

For two of the three years for which yield results were available, fertigation resulted in numerically higher yields that were not significantly different from the yields of the other in-season fertilization treatments. Because the NDVI treatment used less in-season N, it resulted in consistently high NUE. However, using a UAV to collect optical reflectance data from which to calculate NDVI in the 2-5 days prior to scheduled application of in-season N proved frustrating as it was difficult to acquire shadow-free images even over a small area. The increasing availability of for-pay satellite platforms with temporal resolutions of less than 1 day may provide a better solution to developing NDVI maps for regions like the humid Southeast where clouds are present on most days during the growing season.

The problems with collecting reflectance data provided the opportunity to evaluate a second fertigation treatment with 4 in-season events in 2021. The 4-event fertigation treatment did not provide additional benefits – perhaps because the period over which the in-season N was applied was the same as the 3-event fertigation treatment and the time difference between the application events of the two treatments was a few days.

The unusually low yields across all treatments in 2020 in 2021 may have dampened the effect of the treatments so additional research with other cultivars at the plot and farm -scale should be conducted to confirm the findings of this work before fertigation can be recommended as a management strategy to growers. In a parallel study, Sangster et al. (2023) used the Decision Support System for Agrotechnology Transfer (DSSAT) CSM CROPGRO-Cotton model to evaluate the response of cotton to conventional and fertigation in-season N applications. They found that a 3-event fertigation treatment out-performed a single-event conventional treatment in fiber yield by between 50 and 90 kg ha^{-1} depending on how much total N was applied. This is approximately the same range of fiber yield by which Fertigation A exceeded Conventional (65-90 kg ha^{-1}) in this study in 2020 and 2021.

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TABLES AND FIGURES

Table 2.1. Management practices for cotton crop grown at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA for the 2018 through 2021 growing seasons.

	2018	2019	2020	2021
Initial Soil Sampling				
Date	22-Feb-18	15-Apr-19	09-Apr-20	14-Apr-21
Tillage				
Method	Conservation	Conservation	Conservation	Conservation
Planting				
Variety	PHY 300	PHY 350	PHY 350	PHY 350
Plant Date	10-May	03-May	06-May	29-Apr
Planting Population (plants m-2)	14	14	14	14
Depth (cm)	2.5	2.5	2.5	2.5
Row Spacing (cm)	90	90	90	90
Planting Method	Dry Seed	Dry Seed	Dry Seed	Dry Seed
Irrigation (Average Total Amount (mm))				
Calendar	142	221	226	222
SI Cotton	89	152	224	111
UGA SSA *	51	102	122	92
Total Rainfall (mm)	996	513	599	748
Harvest				
Date	24-Oct	27-Sep	02-Nov	21-Oct

*70 kPa up to first flower /40 kPa after first flower through irrigation termination

Table 2.2. In-season fertilization treatments, total in-season N events, and N applied during each cotton growing season (2018-2021) at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

Year	Treatment	Number of In-Season Events	Preplant N (kg ha^{-1})	In-Season N (kg ha^{-1})	Total N (kg ha^{-1})
2018	Conventional	1	22	95	117
	NDVI	1	22	84	106
	Fertigation	3	22	96	118
2019	Conventional	1	34	95	129
	NDVI	1	34	84	118
	Fertigation	3	34	96	130
2020	Conventional	1	34	90	124
	NDVI	1	34	73	107
	Fertigation	3	34	101	135
2021	Conventional	1	22	101	123
	Fertigation A	3	22	101	123
	Fertigation B	4	22	101	123

Table 2.3a. Cotton fiber yield (kg ha^{-1}), total N applied (kg ha^{-1}), Nitrogen Use Efficiency (NUE), total season irrigation applied (mm), and Irrigation Water Use Efficiency (IWUE) of individual treatments where yield data is available. A Fisher's protected LSD test was used for comparison of means by treatment (α = 0.05).

Treatments	Fiber Yield (kg ha^{-1})	N Applied (kg ha^{-1})	NUE (kg-fiber kg-N^{-1})	Irrigation (mm)	IWUE (kg-fiber mm^{-1})
2019					
SI Cotton x Fertigation A	1089 b	130	8.4 b	152	7.2 bcd
UGA SSA x Fertigation A	1335 ab	130	10.3 ab	102	13.1 a
Calendar x Fertigation A	1098 b	130	8.5 b	221	5.0 d
SI Cotton x NDVI	1190 ab	118	10.1 ab	152	7.8 bc
UGA SSA x NDVI	1463 a	118	12.4 a	102	14.3 a
Calendar x NDVI	1218 ab	118	10.3 ab	221	5.5 cd
SI Cotton x Conventional	1266 ab	129	9.8 ab	152	8.3 b
UGA SSA x Conventional	1493 a	129	11.6 a	102	14.6 a
Calendar x Conventional	1248 ab	129	9.7 ab	221	5.7 cd
2020					
SI Cotton x Fertigation A	936 ab	135	7.0 ab	224	4.0 c
UGA SSA x Fertigation A	1101 a	135	8.2 a	122	7.8 b
Calendar x Fertigation A	778 b	135	5.8 b	267	2.8 c
SI Cotton x NDVI	813 b	107	7.6 a	224	3.7 c
UGA SSA x NDVI	865 b	107	8.1 a	122	7.1 b
Calendar x NDVI	875 b	107	8.2 a	267	3.4 c
SI Cotton x Conventional	860 b	124	7.0 ab	224	3.9 c
UGA SSA x Conventional	937 ab	124	7.6 a	122	9.1 a
Calendar x Conventional	821 b	124	6.7 ab	267	3.2 c
2021					
SI Cotton x Fertigation B	956 a	110	7.7 a	111	7.5 c
UGA SSA x Fertigation B	953 a	110	7.8 a	92	8.2 bc
Calendar x Fertigation B	955 a	110	7.8 a	222	10.3 ab
SI Cotton x Fertigation A	970 a	110	7.9 a	111	10.8 a
UGA SSA x Fertigation A	935 a	110	7.6 a	92	9.4 abc
Calendar x Fertigation A	983 a	110	8.0 a	222	8.9 abc
SI Cotton x Conventional	912 a	110	7.4 a	111	4.0 d
UGA SSA x Conventional	794 a	110	6.4 a	92	4.4 d
Calendar x Conventional	914 a	110	7.4 a	222	4.4 d

Table 2.3b. Cotton fiber yield (kg ha^{-1}), total N applied (kg ha^{-1}) and Nitrogen Use Efficiency (NUE) of Fertilization treatments for 2019 – 2021 growing seasons. A Fisher's protected LSD test was used for comparison of means (α = 0.05).

Treatments	Fiber Yield (kg ha^{-1})	N Applied (kg ha^{-1})	NUE (kg-fiber kg-N^{-1})
2019			
Conventional	1335 a	126	10.4 ab
NDVI	1290 a	118	10.9 a
Fertigation A	1174 a	130	9.0 b
2020			
Conventional	873 a	124	7.1 ab
NDVI	851 a	107	8.0 a
Fertigation A	938 a	135	7.0 b
2021			
Conventional	873 a	110	7.1 a
Fertigation A	963 a	110	7.8 a
Fertigation B	955 a	110	7.6 a

Table 2.3c. Cotton fiber yield (kg ha^{-1}), total season irrigation applied (mm), and Irrigation Water Use Efficiency (IWUE) of Irrigation treatments for 2019 – 2021 growing seasons. A Fisher's protected LSD test was used for comparison of means (α = 0.05).

Treatments	**Fiber Yield (kg ha^{-1})**	**Irrigation (mm)**	**IWUE (kg-fiber mm^{-1})**
		2019	
SI Cotton	1182 a	152	7.8 b
Calendar	1188 b	221	5.4 c
UGA SSA	1430 a	102	14.0 a
		2020	
SI Cotton	869 ab	224	3.9 b
Calendar	825 b	267	3.1 c
UGA SSA	968 a	122	8.0 a
		2021	
SI Cotton	946 a	111	8.7 a
Calendar	951 a	222	4.3 b
UGA SSA	894 a	92	9.7 a

Table 2.4. Cotton plant component biomass (kg ha^{-1}) by irrigation treatment for the 2018 – 2021 growing seasons. A Fisher's protected LSD test was used for comparison of means across treatments by sampling date (DAP) (α = 0.05).

Plant Comp-onent	2018				2019				2020				2021			
	DAP	Mass (kg ha $^{-1}$) [1]			DAP	Mass (kg ha $^{-1}$) [1]			DAP	Mass (kg ha $^{-1}$) [1]			DAP	Mass (kg ha $^{-1}$) [1]		
		UGA SSA	SI Cotton	Calendar		UGA SSA	SI Cotton	Calendar		UGA SSA	SI Cotton	Calendar		UGA SSA	SI Cotton	Calendar
Leaf	41	130 a	158 a	134 a	75	4332 a	33263 a	3347 a	75	3269 a	3888 a	3675 a	60	663 ab	580 b	701 a
	82	1157 a	1235 a	1083 a	109	2292 a	2252 a	2209 a	111	2378 a	2500 a	2427 a	75	1174 a	959 a	1016 a
	118	694 a	816 a	789 a	130	1251 b	1217 b	1695 a	132	1314 b	1306 b	1627 a	111	1488 a	1476 a	1514 a
	137	957 a	890 a	851 a					139	1141 a	1240 a	1417 a	137	894 a	656 a	843 a
	146	558 a	667 a	748 a												
Stem	41	51 a	65 a	54 a	75	2914 a	2378 a	2441 a	75	2558 b	3291 a	3061 ab	60	713 a	557 a	725 a
	82	1468 a	1621 a	1342 a	109	3234 a	3538 a	3307 a	111	2520 b	2707 b	3528 a	75	1194 a	976 a	1053 a
	118	1724 a	2048 a	2064 a	130	4032 a	4178 a	5296 a	132	2851 b	2982 b	3713 a	111	4051 a	3921 a	4182 a
	137	2124 a	2006 a	2047 a					139	2836 b	3231 ab	3752 a	137	4483 a	3754 a	4319 a
	146	1683 b	1943 ab	2553 a												
Petiole	41	17 a	24 a	19 a	75	447 a	390 a	362 a	75	412 a	486 a	479 a	60	144 a	134 a	166 a
	82	268 a	261 a	262 a	109	283 a	293 a	320 a	111	473 b	526 ab	609 a	75	209 a	172 a	188 a
	118	156 a	174 a	183 a	130	413 b	418 b	522 a	132	410 a	438 a	475 a	111	411 a	378 a	423 a
	137	121 a	120 a	116 a					139	195 a	244 a	255 a	137	137 a	107 a	151 a
	146	65 a	71 a	89 a												
Square	41	5.8 a	6.5 a	5.2 a	75	280 a	277 a	203 a	75	550 b	754 a	674 ab	60	60 a	55 a	53 a
	82	183 a	156 a	172 a	109	40 a	45 a	74 a								
Boll	82	592 a	891 a	541 a	75	342 a	140 a	172 a	111	8488 a	7520 a	7221 a	75	559 a	599 a	776 a
	118	2614 a	2905 a	2782 a	109	7646 a	6827 a	5176 a	132	6229 a	5567 a	6119 a	111	3665 a	3627 a	3837 a
	137	3545 a	3195 a	3178 a	130	4623 a	4746 a	5054 a	139	6068 a	5915 a	6133 a	137	6013 a	5365 a	5643 a
	146	3275 a	3746 a	4255 a												
LAI	41	2.01 a	2.22 a	1.96 a	75	3.26 a	2.82 a	2.61 a	75	2.09 a	2.28 a	2.28 a	60	1.22 a	1.05 a	1.22 a
	82	1.42 a	1.66 a	1.60 a	109	2.28 a	2.25 a	2.42 a	111	2.05 a	1.77 a	1.88 a	75	1.35 a	1.14 a	1.28 a
	118	1.17 a	1.10 a	0.97 a	130	1.03 b	0.93 b	1.66 a	132	1.23 b	1.25 b	1.66 a	111	2.16 a	2.01 a	2.24 a
	137	0.68 a	0.79 a	0.86 a					139	0.83 a	0.94 a	1.15 a	137	1.16 a	0.90 a	116 a

[1] Except for LAI (Leaf Area Index) which is unitless

Table 2.5. Cotton plant component biomass (kg ha^{-1}) by fertilization treatment for the 2018 – 2021 growing seasons. A Fisher's protected LSD test was used for comparison of means across treatments by sampling date (DAP) (α = 0.05).

Plant Component	2018				2019		2020				2021			
	DAP	Mass (kg ha^{-1}) [1]			DAP	Mass (kg ha^{-1}) [1]	DAP	Mass (kg ha^{-1}) [1]			DAP	Mass (kg ha^{-1}) [1]		
		Conventional	Fertigation A	NDVI		Fertigation A		Conventional	Fertigation A	NDVI		Conventional	Fertigation A	Fertigation B
Leaf	41	135 a	146 a	140 a	75	3647	75	3485 a	3911 a	3436 a	60	632 a	658 a	655 a
	82	1262 a	1277 a	935 a	109	2251	111	2214 a	2451 a	2641 a	75	1110 a	1005 a	1035 a
	118	810 a	775 a	714 a	130	1388	132	1393 a	1407 a	1447 a	111	1546 a	1668 a	1265 a
	137	987 a	1044 a	667 a			139	1346 a	1234 a	1217 a	137	851 a	703 a	867 a
	146	793 a	694 ab	487 b										
Stem	41	53 a	61 a	57 a	75	2578	75	3147 a	3025 a	2737 a	60	606 a	685 a	704 a
	82	1603 a	1641 a	1188 a	109	3360	111	2840 a	3098 a	2816 a	75	1141 a	976 a	1106 a
	118	2036 a	2036 a	1764 a	130	4502	132	2973 a	3515 a	3059 a	111	3881 a	4489 a	3787 a
	137	2254 ab	2508 a	1414 b			139	3557 a	3240 a	3023 a	137	3697 a	4229 a	4630 a
	146	2286 a	1337 a	1555 a										
Petiole	41	19 a	22 a	19 a	75	400	75	442 a	505 a	430 a	60	156 a	147 a	142 a
	82	286 a	271 a	234 a	109	299	111	585 a	500 a	522 a	75	188 a	194 a	186 a
	118	190 a	178 a	145 a	130	451	132	435 a	440 a	447 a	111	417 a	454 a	342 a
	137	133 a	136 a	89 a			139	260 a	205 a	229 a	137	134 a	118 a	143 a
	146	93 a	80 ab	51 b										
Square	41	5.3 a	6.0 a	6.1 a	75	253	75	625 a	739 a	615 a	60	49 a	61 a	57 a
	82	214 a	189 ab	108 b	109	53								
Boll	82	710 a	741 a	573 a	75	218	111	8404 ab	8571 a	6254 b	75	541 a	575 a	818 a
	118	2852 a	2435 a	3014 a	109	6550	132	5502 a	6490 a	5923 a	111	3982 a	3504 a	3644 a
	137	3463 a	3747 a	2707 a	130	4808	139	6776 a	5528 a	5812 a	137	5405 a	4965 a	6551 a
	146	4059 a	4012 a	3205 a										
LAI	41	2.34 a	2.27 a	1.57 a	75	2.89	75	2.21 a	2.25 a	2.18 a	60	1.14 a	1.18 a	1.17 a
	82	1.81 a	1.51 a	1.35 a	109	2.32	111	1.81 a	1.94 a	1.95 a	75	1.21 a	1.25 a	1.31 a
	118	1.19 a	1.23 a	0.82 a	130	1.21	132	1.34 a	1.36 a	1.44 a	111	2.32 a	2.21 a	1.89 a
	137	0.92 a	0.81 ab	0.61 b			139	1.04 a	0.95 a	0.93 a	137	1.12 a	0.99 a	1.11 a

[1] Except for LAI (Leaf Area Index) which is unitless

Table 2.6. Soil NO3-N concentrations (mg kg^{-1}) for irrigation and fertilization treatments for 2018 – 2021 cotton growing seasons. A Fisher's protected LSD test was used for comparison of means across treatments for individual sampling dates (DAP) (α = 0.05).

Soil Layer	2018				2019			
	DAP	NO3-N (mg kg^{-1})			DAP	NO3-N (mg kg^{-1})		
		UGA SSA	SI Cotton	Calendar		UGA SSA	SI Cotton	Calendar
A	50	0.84 a	0.60 a	0.50 a	75	1.10 a	2.27 a	1.48 a
	131	2.66 a	2.19 a	2.02 a	109	1.37 a	0.94 a	0.84 a
(0-0.15	145	3.40 a	3.76 a	2.24 b	130	0.24 a	0.13 a	0.76 a
m)								
B	50	1.64 a	0.51 a	0.42 a	75	4.85 a	2.41 a	2.06 a
	131	1.83 a	2.79 a	2.11 a	109	0.22 a	0.64 a	0.23 a
(0.15-	145	2.17 a	2.62 a	1.95 a	130	0.22 a	3.34 a	0.26 a
0.30 m)								
C	50	0.54 a	0.44 a	0.41 a	75	3.70 a	4.81 a	5.21 a
	131	2.01 a	1.56 a	1.95 a	109	0.01 a	0.37 a	1.98 a
(0.30-	145	0.64 a	0.69 a	0.69 a	130	0.17 a	0.22 a	0.16 a
0.45m)								
D	50	0.41 a	0.84 a	0.66 a	75	1.36 b	5.79 a	4.95 a
	131	2.11 a	2.85 a	2.61 a	109	0.01 a	0.14 a	0.54 a
(0.45-	145	0.67 a	0.46 a	0.80 a	130	0.21 a	0.10 a	0.18 a
0.60 m)								
Soil Layer	2020				2021			
	DAP	NO3-N (mg kg^{-1})			DAP	NO3-N (mg kg^{-1})		
		UGA SSA	SI Cotton	Calendar		UGA SSA	SI Cotton	Calendar
A	82	4.03 a	4.10 a	3.05 a	60	2.84 a	2.43 a	2.81 a
	152	1.98 a	2.18 a	2.12 a	75	6.48 a	4.60 a	4.31 a
(0-0.15					116	0.99 a	0.94 a	0.87 a
m)					147	1.25 a	1.37 a	1.68 a
B	82	8.20 a	5.73 a	4.45 a	60	2.36 a	2.58 a	2.38 a
	152	1.63 a	1.94 a	1.85 a	75	5.79 a	4.67 a	7.13 a
(0.15-					116	0.49 a	0.49 a	0.66 a
0.30 m)					147	1.52 a	1.68 a	1.17 a
C	82	5.89 a	11.06 a	4.08 a	60	1.17 a	1.79 a	1.13 a
	152	0.99 a	1.16 a	1.00 a	75	1.26 a	1.63 a	2.12 a
(0.30-					116	0.87 a	0.29 a	0.37 a
0.45m)					147	0.69 a	0.90 a	0.53 a
D	82	4.84 a	9.99 a	4.84 a	60	2.05 a	2.53 a	1.74 a
	152	1.01 a	1.13 a	0.96 a	75	1.65 a	1.23 a	1.66 a
(0.45-					116	0.26 a	0.27 a	0.44 a
0.60 m)					147	1.09 a	0.99 a	0.79 a

Table 2.6. continued

Soil Layer	2018				2019			
	DAP	NO3-N (mg kg^{-1})			DAP	NO3-N (mg kg^{-1})		
		Conventional	Fertigation A	NDVI		Fertigation A		
A	50	0.62 a	0.72 a	0.60 a	75	1.61		
	131	2.00 ab	3.42 a	1.44 b	109	1.05		
(0-0.15 m)	145	3.68 a	2.46 b	3.27 ab	130	0.38		
B	50	0.46 a	0.49 a	1.62 a	75	3.11		
	131	3.52 a	2.14 ab	1.08 b	109	0.36		
(0.15-0.30 m)	145	2.42 ab	1.64 b	2.67 a	130	1.27		
C	50	0.52 a	0.49 a	0.43 a	75	4.57		
	131	1.74 a	2.06 a	1.71 a	109	0.79		
(0.30-0.45m)	145	0.76 a	0.62 a	0.65 a	130	0.18		
D	50	0.83 a	0.50 a	0.57 a	75	4.03		
	131	2.75 a	2.53 a	2.29 a	109	0.23		
(0.45-0.60 m)	145	0.63 a	0.61 a	0.69 a	130	0.16		

Soil Layer	2020				2021			
	DAP	NO3-N (mg kg^{-1})			DAP	NO3-N (mg kg^{-1})		
		Conventional	Fertigation A	NDVI		Conventional	Fertigation A	Fertigation B
A	82	3.91 a	3.04 a	4.22 a	60	2.63 a	2.73 a	2.72 a
	152	2.14 a	2.03 a	2.12 a	75	5.81 a	4.16 a	5.42 a
(0-0.15 m)					116	0.74 a	1.15 a	0.91 a
					147	1.46 a	1.42 a	1.42 a
B	82	6.70 a	4.52 a	7.17 a	60	2.62 a	2.34 a	2.36 a
	152	1.72 a	1.64 a	2.05 a	75	7.34 a	4.23 a	6.02 a
(0.15-0.30 m)					116	0.47 a	0.66 a	0.48 a
					147	1.02 a	1.58 a	1.77 a
C	82	8.16 a	6.13 a	6.74 a	60	1.50 a	1.25 a	1.34 a
	152	1.04 a	1.08 a	1.03 a	75	1.85 a	1.66 a	1.49 a
(0.30-0.45m)					116	0.29 a	0.33 a	0.90 a
					147	0.33 b	0.72 ab	1.08 a
D	82	6.41 a	5.15 a	8.11 a	60	2.78 a	1.45 a	2.08 a
	152	0.93 a	0.97 a	1.21 a	75	2.10 a	1.14 b	1.30 ab
(0.45-0.60 m)					116	0.51 a	0.17 a	0.28 a
					147	1.07 a	0.82 a	0.96 a

Table 2.7. Soil NH4-N concentrations (mg kg^{-1}) for a) irrigation and b) fertilization treatments for 2018 – 2021 cotton growing seasons. A Fisher's protected LSD test was used for comparison of means across treatments for individual sampling dates (DAP) (α = 0.05)

Soil Layer	2018				2019			
	DAP	NH4-N (mg kg^{-1})			DAP	NH4-N (mg kg^{-1})		
		UGA SSA	SI Cotton	Calendar		UGA SSA	SI Cotton	Calendar
A (0-0.15 m)	50	0.86 a	0.86 a	0.93 a	75	0.67 a	0.33 a	0.22 a
	131	1.05 a	1.07 a	1.59 a	109	0.46 a	0.63 a	0.35 a
	145	0.84 a	0.93 a	0.95 a	130	1.78 a	3.02 a	4.03 a
B (0.15-0.30 m)	50	0.71 a	0.81 a	0.81 a	75	0.31 a	0.77 a	0.04
	131	1.83 a	1.39 a	1.80 a	109	0.37 a	0.26 a	0.33 a
	145	1.20 a	1.03 a	1.25 a	130	0.71 a	2.61 a	2.98 a
C (0.30-0.45m)	50	0.52 a	0.62 a	0.69 a	75	0.73 a	1.12 a	0.17 a
	131	1.65 a	1.26 ab	0.94 b	109	0.63 a	0.43 a	0.42 a
	145	1.47 a	1.56 a	1.13 a	130	0.01 a	0.52 a	0.11 a
D (0.45-0.60 m)	50	0.60 a	0.43 a	0.47 a	75	0.19 a	1.19 a	0.33 a
	131	1.72 a	1.47 a	1.12 a	109	0.43 a	0.59 a	0.85 a
	145	1.55 a	1.34 a	1.00 a	130	0.23 a	0.11 a	0.55 a

Soil Layer	2020				2021			
	DAP	NH4-N (mg kg^{-1})			DAP	NH4-N (mg kg^{-1})		
		UGA SSA	SI Cotton	Calendar		UGA SSA	SI Cotton	Calendar
A (0-0.15 m)	82	0.43 a	0.37 a	0.55 a	60	0.73 a	1.27 a	0.79 a
	152	0.70 a	0.70 a	0.68 a	75	2.68 a	3.20 a	4.66 a
					116	2.41 a	2.55 a	2.44 a
					147	0.34 a	0.59 a	0.57 a
B (0.15-0.30 m)	82	0.28 a	0.38 a	0.31 a	60	0.72 a	1.25 a	0.84 a
	152	0.56 a	0.56 a	0.72 a	75	3.09 a	3.11 a	2.51 a
					116	1.76 a	1.60 a	1.69 a
					147	1.62 a	0.36 a	0.32 a
C (0.30-0.45m)	82	0.22 a	0.26 a	0.29 a	60	0.44 a	0.57 a	0.64 a
	152	0.47 a	0.63 a	0.47 a	75	0.50 a	0.59 a	0.54 a
					116	1.09 a	1.36 a	1.02 a
					147	0.26 a	0.26 a	0.33 a
D (0.45-0.60 m)	82	0.32 a	0.18 a	0.24 a	60	0.51 a	0.42 a	0.62 a
	152	0.64 a	0.55 a	0.52 a	75	0.29 a	0.28 a	0.24 a
					116	1.59 a	1.30 a	1.04 a
					147	0.32 a	0.35 a	0.23 a

Table 2.7. continued

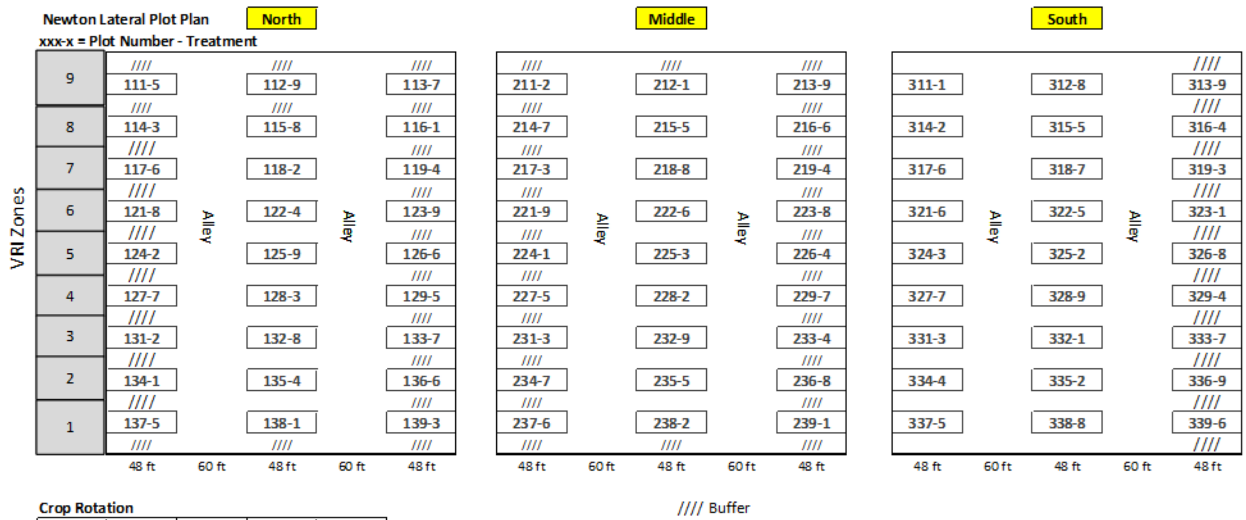
Soil Layer	2018				2019			
	DAP	NH4-N (mg kg⁻¹)			DAP	NH4-N (mg kg⁻¹)		
		Conventional	Fertigation A	NDVI		Fertigation A		
A	50	0.96 a	0.83 a	0.87 a	75	0.41		
	131	1.30 a	1.28 a	1.13 a	109	0.48		
(0-0.15	145	0.87 a	0.88 a	0.97 a	130	2.94		
m)								
B	50	0.85 a	0.71 a	0.77 a	75	0.38		
	131	1.19 a	1.03 a	2.80 a	109	0.32		
(0.15-	145	1.20 a	0.93 a	1.34 a	130	2.10		
0.30 m)								
C	50	0.76 a	0.60 ab	0.48 b	75	0.67		
	131	1.43 a	1.26 a	1.17 a	109	0.49		
(0.30-	145	1.32 a	1.63 a	1.22 a	130	0.21		
0.45m)								
D	50	0.51 a	0.49 a	0.50 a	75	0.57		
	131	1.56 a	1.49 a	1.26 a	109	0.62		
(0.45-	145	1.16 a	1.50 a	1.23 a	130	0.3		
0.60 m)								
Soil Layer	2020				2021			
	DAP	NH4-N (mg kg⁻¹)			DAP	NH4-N (mg kg⁻¹)		
		Conventional	Fertigation A	NDVI		Conventional	Fertigation A	Fertigation B
A	82	0.47 a	0.38 a	0.49 a	60	0.64 a	0.91 a	1.24 a
	152	0.71 a	0.70 a	0.67 a	75	4.84 a	3.23 a	2.46 a
(0-0.15					116	2.38 a	2.35 a	2.68 a
m)					147	0.33 a	0.54 a	0.63 a
B	82	0.28 a	0.35 a	0.34 a	60	0.93 a	0.95 a	0.93 a
	152	0.58 a	0.54 a	0.71 a	75	2.99 a	3.07 a	2.66 a
(0.15-					116	1.61 a	1.81 a	1.63 a
0.30 m)					147	0.36 a	1.56 a	0.38 a
C	82	0.29 a	0.24 a	0.24 a	60	0.67 a	0.50 a	0.50 a
	152	0.54 a	0.53 a	0.51 a	75	0.53 a	0.51 a	0.59 a
(0.30-					116	1.20 a	1.13 a	1.13 a
0.45m)					147	0.25 a	0.25 a	0.34 a
D	82	0.17 a	0.27 a	0.29 a	60	0.82 a	0.37 a	0.36 a
	152	0.56 ab	0.43 b	0.72 a	75	0.42 a	0.17 b	0.22 b
(0.45-					116	1.54 a	1.19 a	1.20 a
0.60 m)					147	0.40 a	0.21 a	0.28 a

Table 2.8. Soil NO3-N concentrations (mg kg^{-1}) for individual soil depths by sampling date (DAP). A Fisher's protected LSD test was used for comparison of means across soil layers for individual sampling dates (DAP) (α = 0.05).

Soil Layer	2018			
	NO3-N (mg kg^{-1})			
	50	131	145	
A	0.65 a	2.29 a	3.14 a	
B	0.85	2.24 a	2.24 b	
C	0.47 a	1.84 a	0.68 c	
D	0.63 a	2.52 a	0.65 c	
Soil Layer	2019			
	NO3-N (mg kg^{-1})			
	75	109	130	
A	1.61 b	1.05 a	0.38 a	
B	3.11 ab	0.36 ab	1.27 a	
C	4.57 a	0.79 ab	0.18 a	
D	4.03 a	0.23 b	0.16 a	
Soil Layer	2020			
	NO3-N (mg kg^{-1})			
	82	152		
A	3.72 b	2.10 a		
B	5.35 ab	1.80 a		
C	5.77 a	1.05 b		
D	5.84 a	1.03 b		
Soil Layer	2021			
	NO3-N (mg kg^{-1})			
	60	75	116	147
A	2.69a	5.10 a	0.95 a	1.43 a
B	2.44 a	5.86 a	0.53 b	1.46 a
C	1.36 b	1.67 b	0.51 b	0.71 b
D	2.10 a	1.51 b	0.32 b	0.95 b

Table 2.9. Soil NH4-N concentrations (mg kg^{-1}) for individual soil depths by sampling date (DAP). A Fisher's protected LSD test was used for comparison of means across soil layers for individual sampling dates (DAP) (α = 0.05).

Soil Layer	2018			
	NH4-N (mg kg^{-1})			
	50	131	145	
A	0.88 a	1.24 a	0.90 b	
B	0.77 a	1.67 a	1.16 ab	
C	0.61 b	1.28 a	1.39 a	
D	0.51 b	1.44 a	1.30 a	
Soil Layer	2019			
	NO3-N (mg kg^{-1})			
	75	109	130	
A	0.41 a	0.48 ab	2.94 a	
B	0.38 a	0.32 b	2.10 a	
C	0.67 a	0.49 ab	0.21 b	
D	0.57 a	0.62 a	0.30 b	
Soil Layer	2020			
	NO3-N (mg kg^{-1})			
	82	152		
A	0.45 a	0.69 a		
B	0.33 ab	0.61 ab		
C	0.26 b	0.52 b		
D	0.25 b	0.57 ab		
Soil Layer	2021			
	NO3-N (mg kg^{-1})			
	60	75	116	147
A	0.93 a	3.51 a	2.47 a	0.50 a
B	0.94 a	2.90 a	1.68 b	0.77 a
C	0.55 b	0.54 b	1.15 c	0.28 a
D	0.52 b	0.27 b	1.31 c	0.30 a



Crop Rotation

Plots	2018	2019	2020	2021
111-139	corn	cotton	peanut	corn
211-239	peanut	corn	cotton	peanut
311-339	cotton	peanut	corn	cotton

Figure 2.1. Experimental design used in the Newton Lateral field at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) with crop rotation.

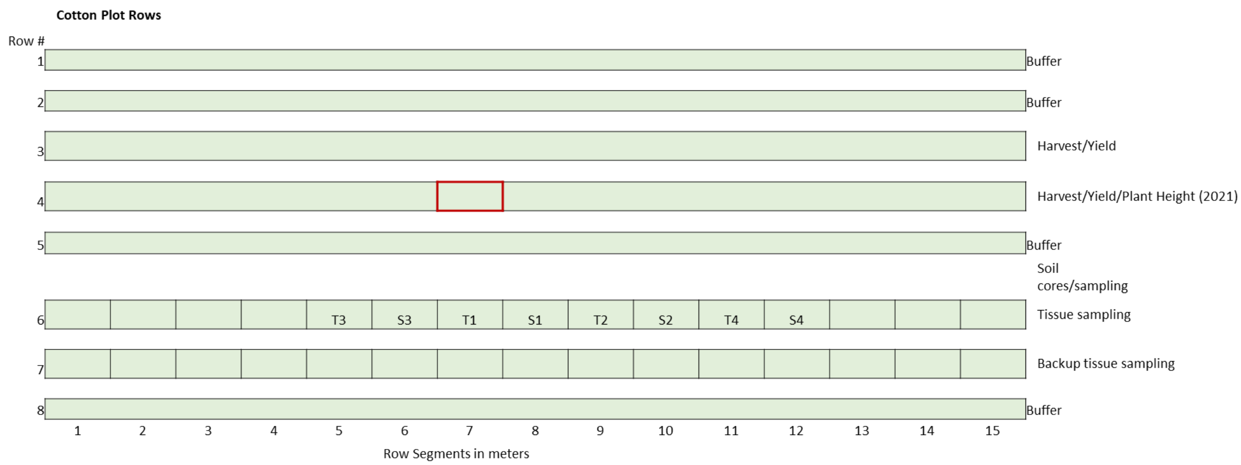


Figure 2.2. Plot design and description of sampling/harvested plot rows and locations used at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

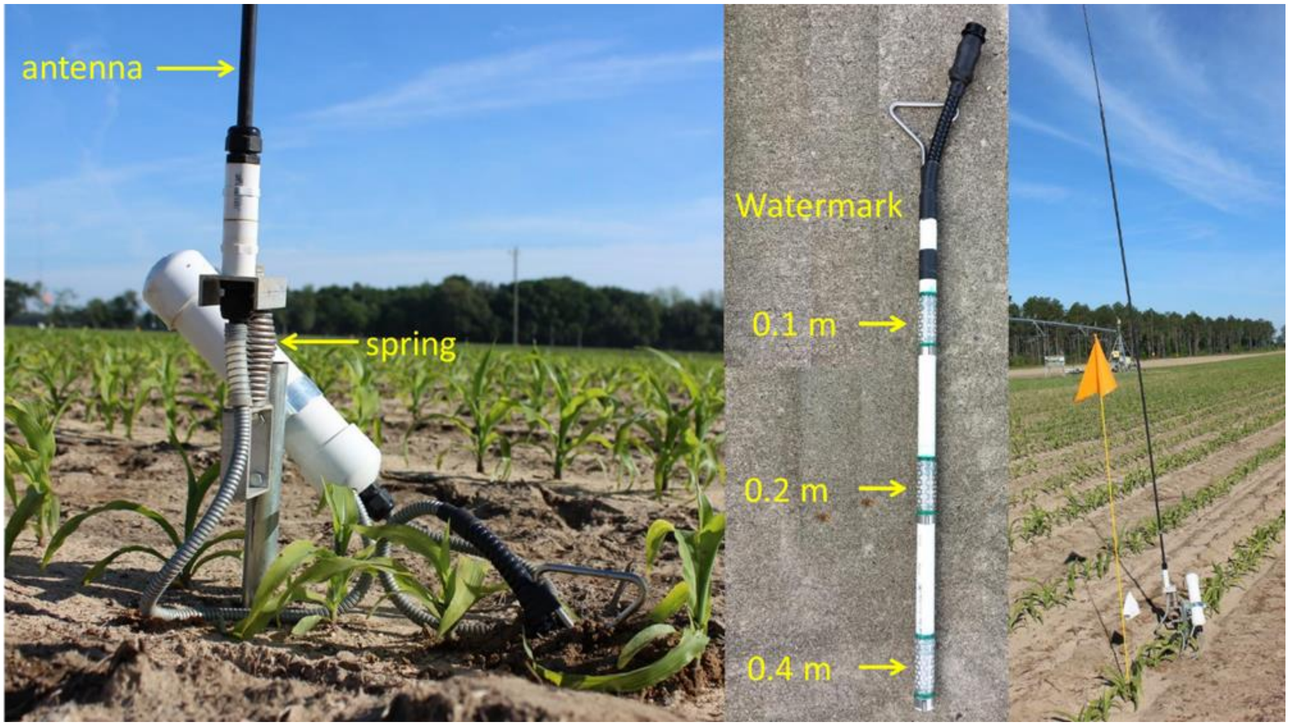


Figure 2.3. University of Georgia Smart Sensor Array (UGA SSA) installation and hardware as described in Vellidis et al. (2013).

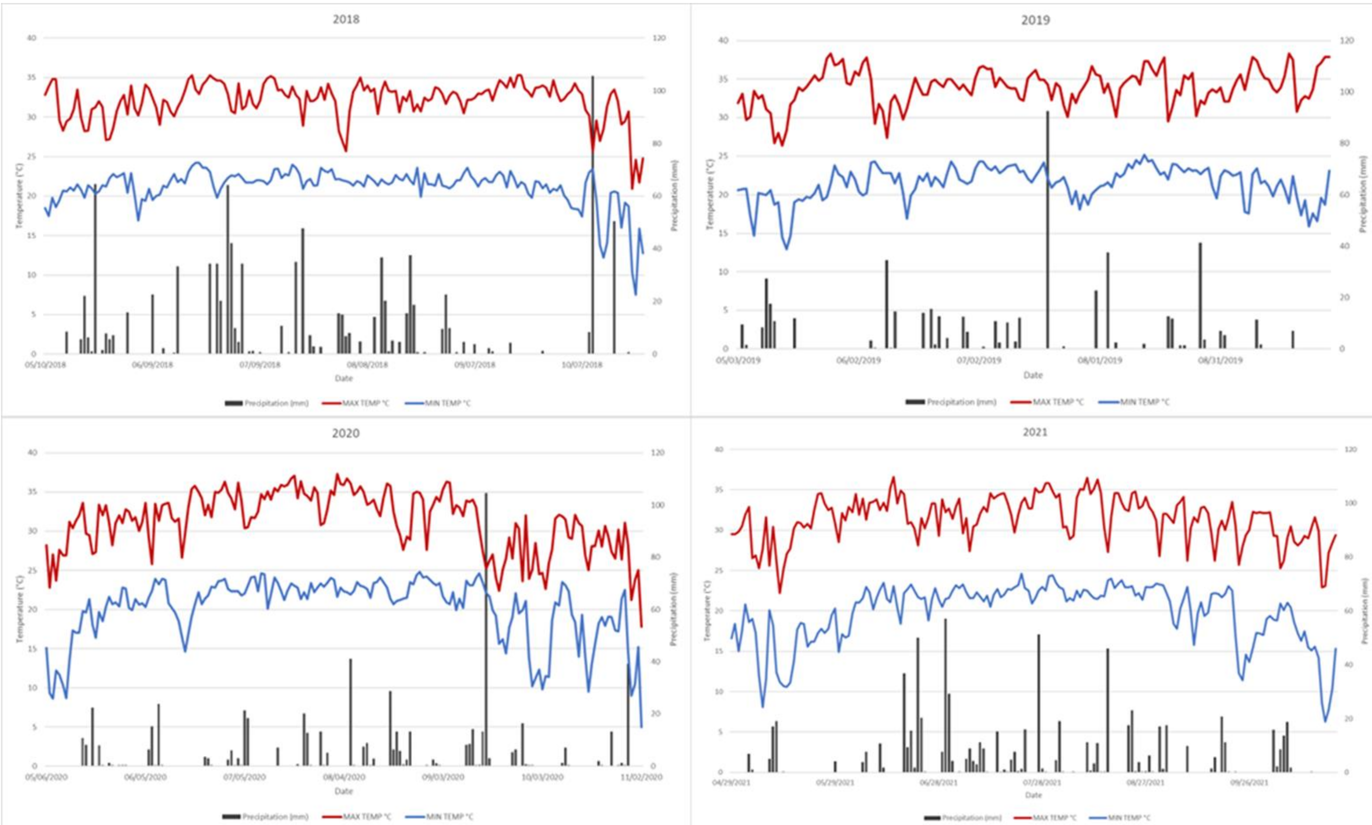


Figure 2.4. Maximum and minimum temperatures (°C) plus rainfall received during the a) 2018, b) 2019, c) 2020, and d) 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA. Reported by the UGA Weather Net station on SIRP grounds.

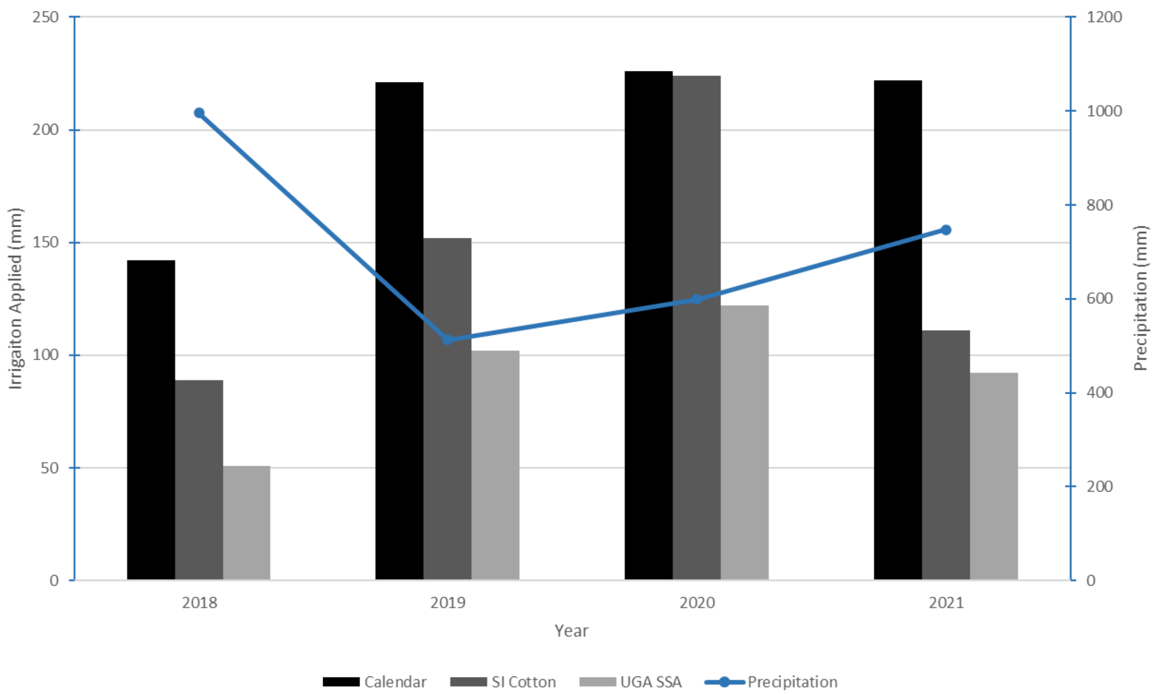


Figure 2.5. Average amounts of irrigation applied for each treatment during the cotton growing seasons (2018 – 2021) as well as the amount of precipitation received as reported by the University of Georgia Weather Net station located on SIRP grounds near Camilla, GA.

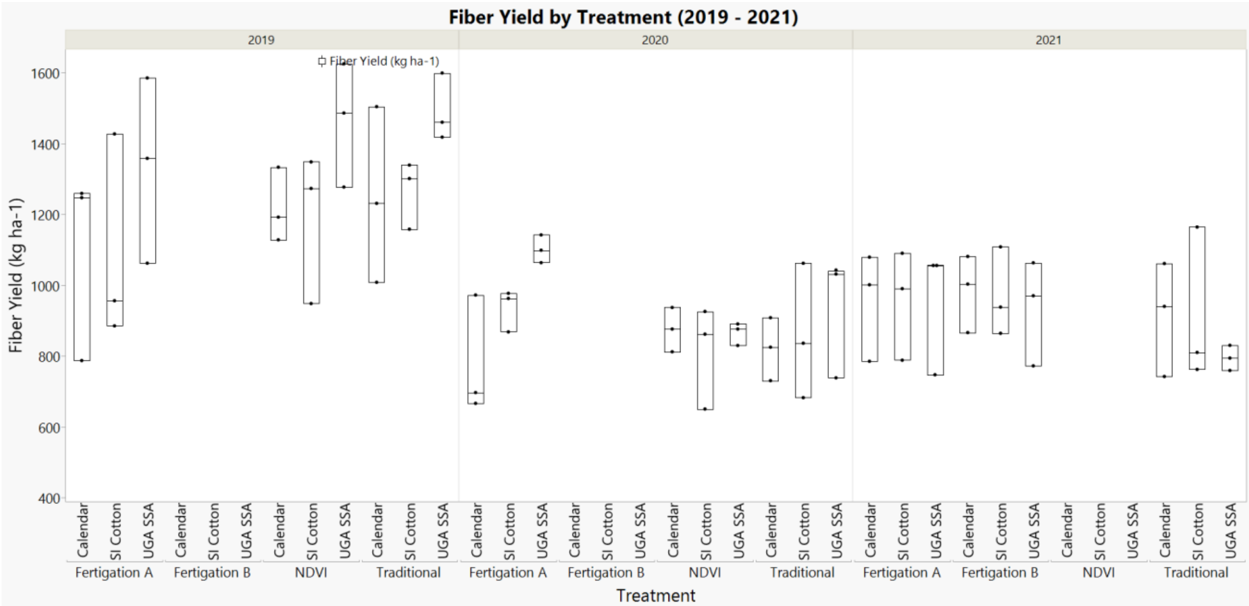


Figure 2.6. Fiber yield (kg ha^{-1}) of individual treatments for the 2019 through 2021 growing seasons at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

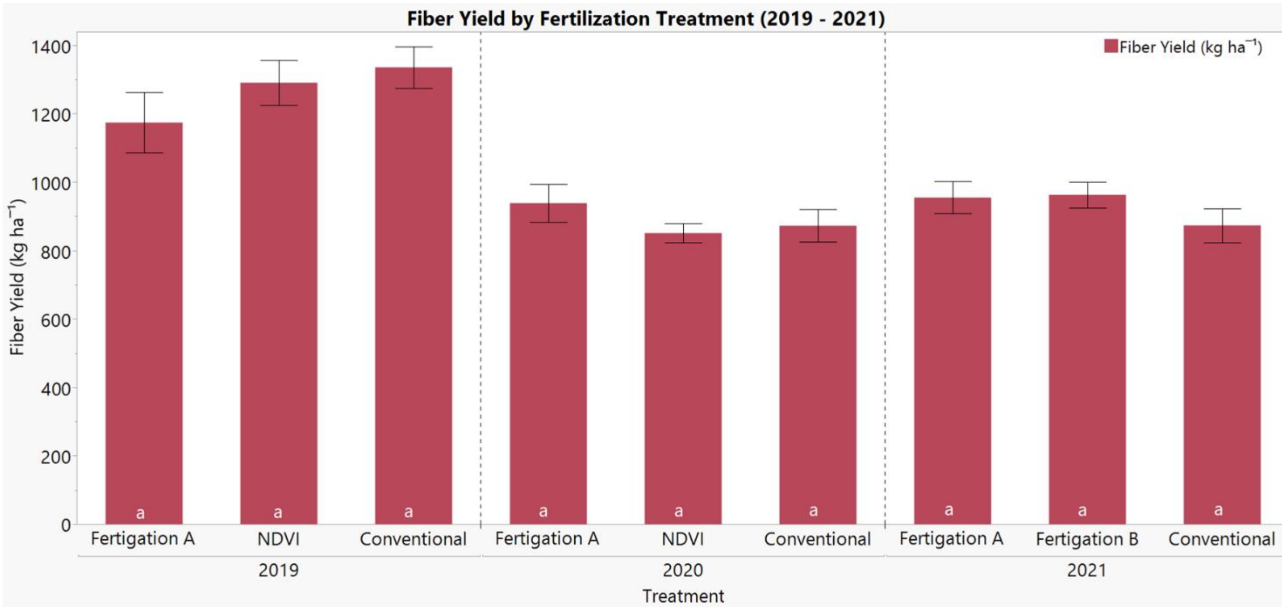


Figure 2.6 continued. Fiber yield (kg ha^{-1}) separated by fertilization treatment for the 2019 through 2021 growing seasons at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

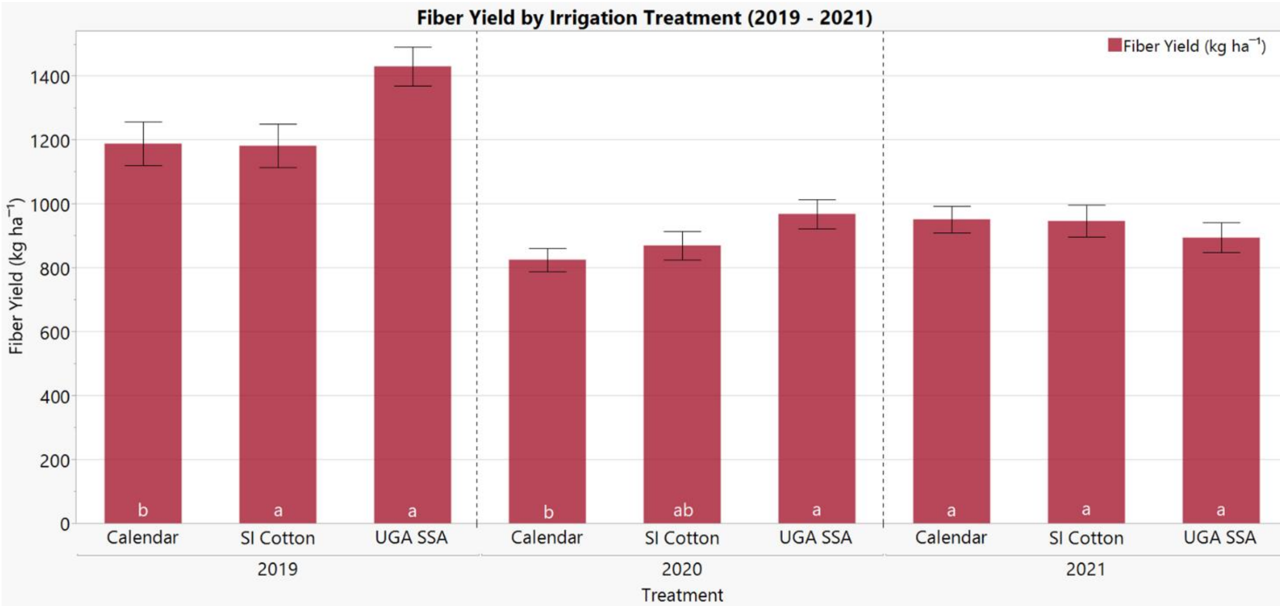


Figure 2.6 continued. Fiber yield (kg ha^{-1}) separated by irrigation treatment for the 2019 through 2021 growing seasons at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

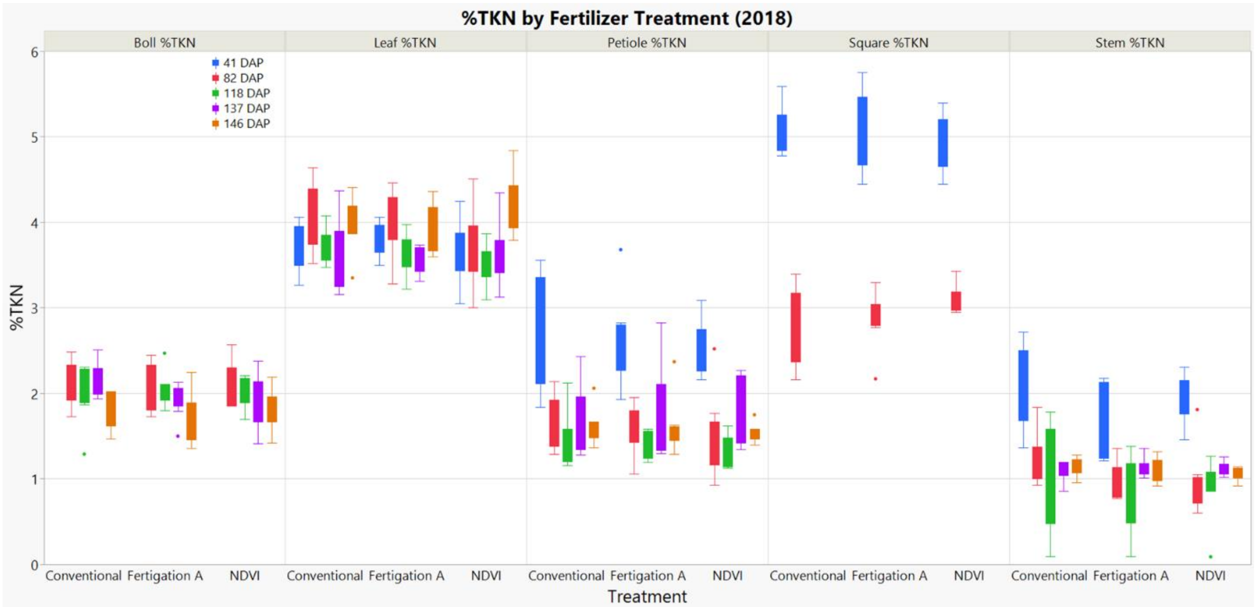


Figure 2.7. %TKN of each plant component by fertilizer treatment for the 2018 growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

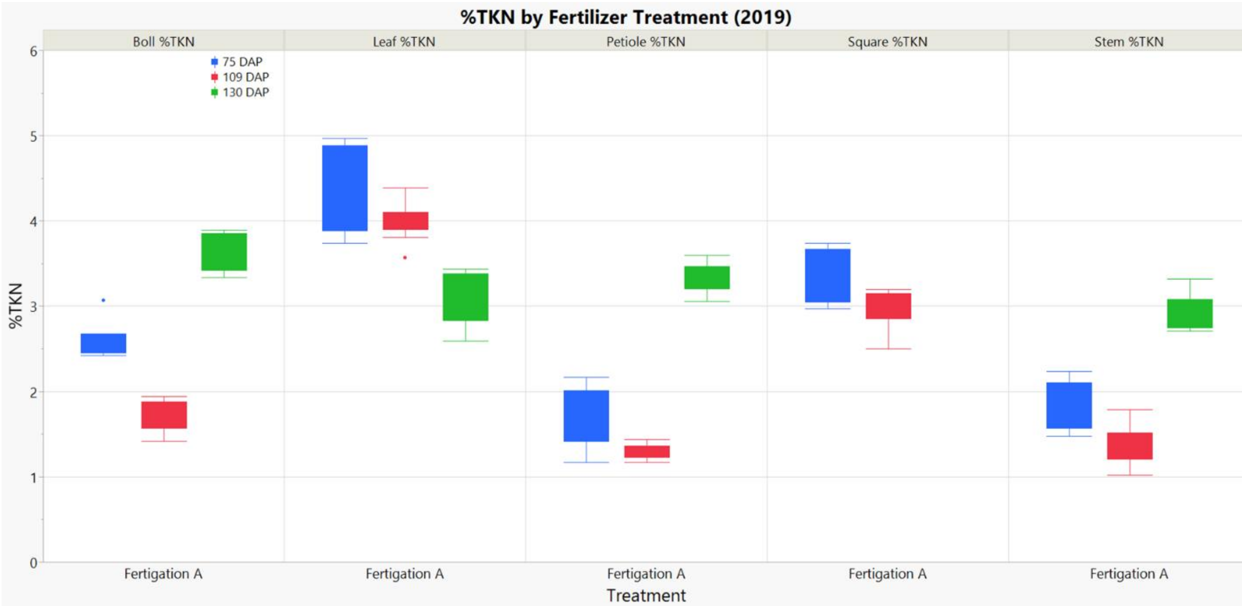


Figure 2.7 continued. %TKN of each plant component by fertilizer treatment for the 2019 growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

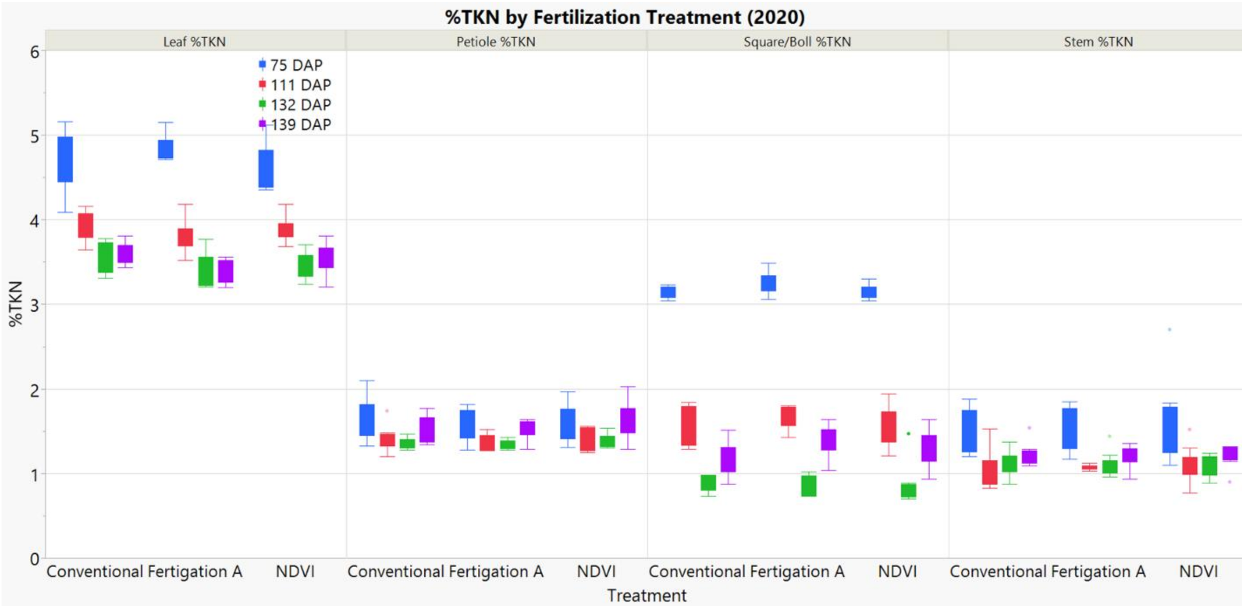


Figure 2.7 continued. %TKN of each plant component by fertilizer treatment for the 2020 growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

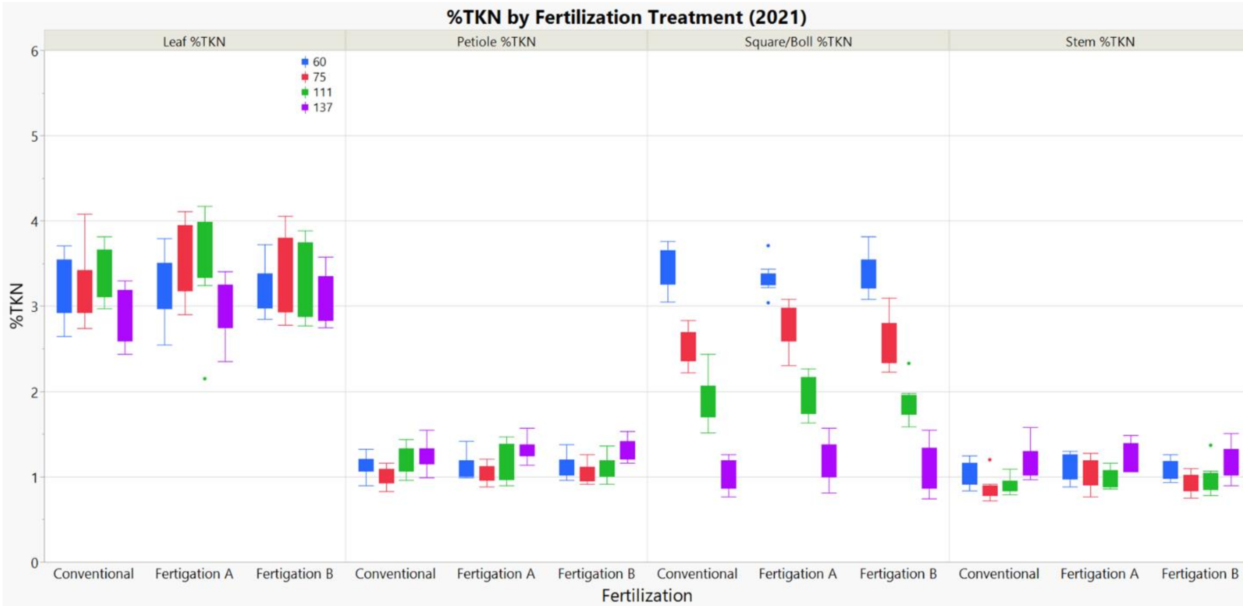


Figure 2.7 continued. %TKN of each plant component by fertilizer treatment for the 2021 growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

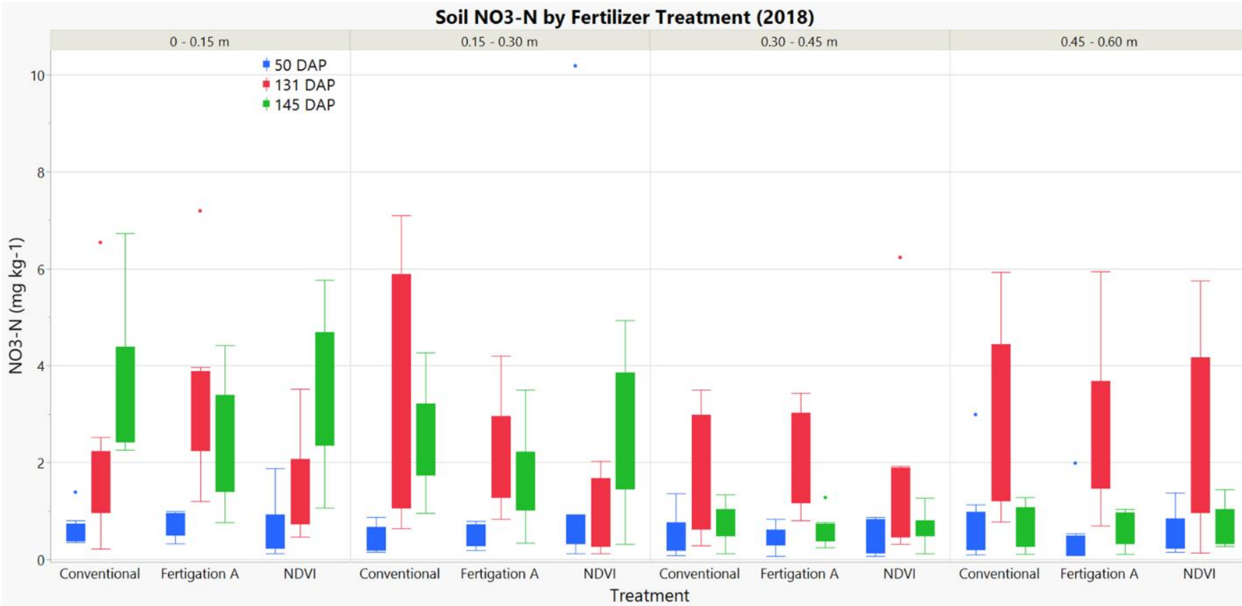


Figure 2.8. Soil NO_3-N for each fertilizer treatment separated by soil layer depth for each soil sampling date from the 2018 – 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

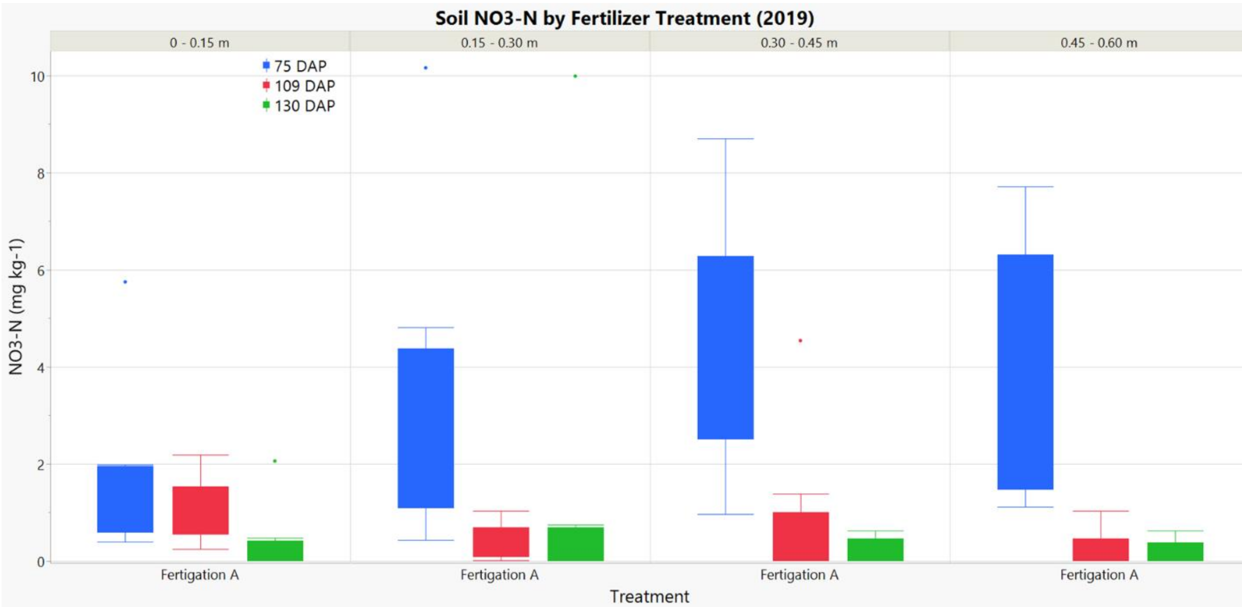


Figure 2.8 continued. Soil NO_3-N for each fertilizer treatment separated by soil layer depth for each soil sampling date from the 2018 – 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

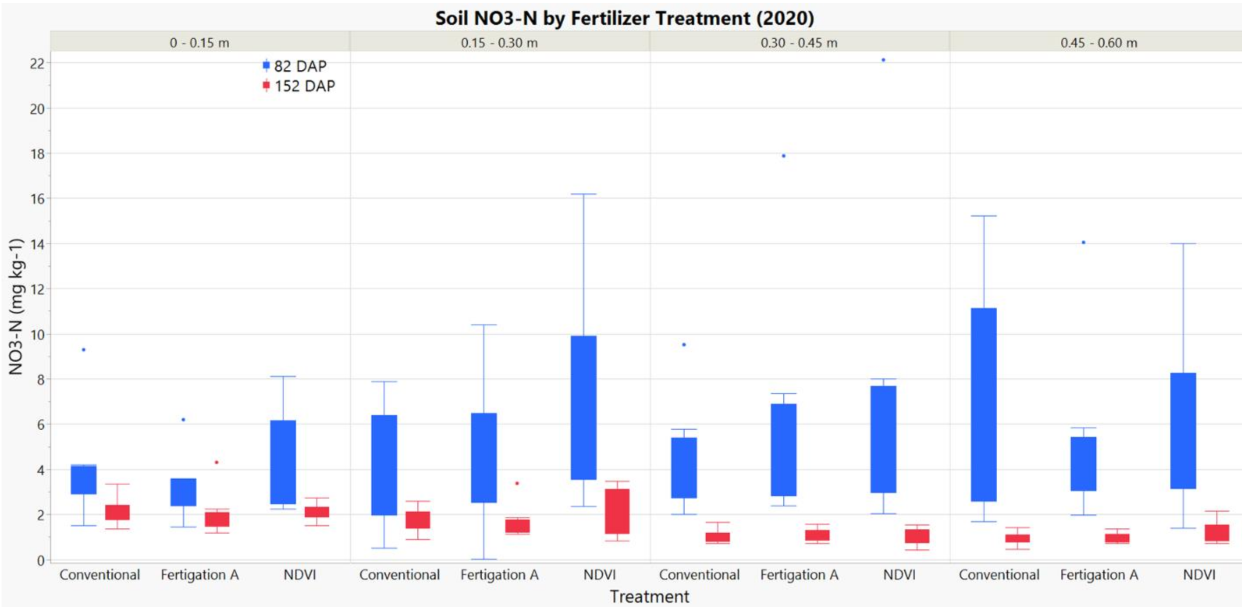


Figure 2.8 continued. Soil NO_3-N for each fertilizer treatment separated by soil layer depth for each soil sampling date from the 2018 – 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

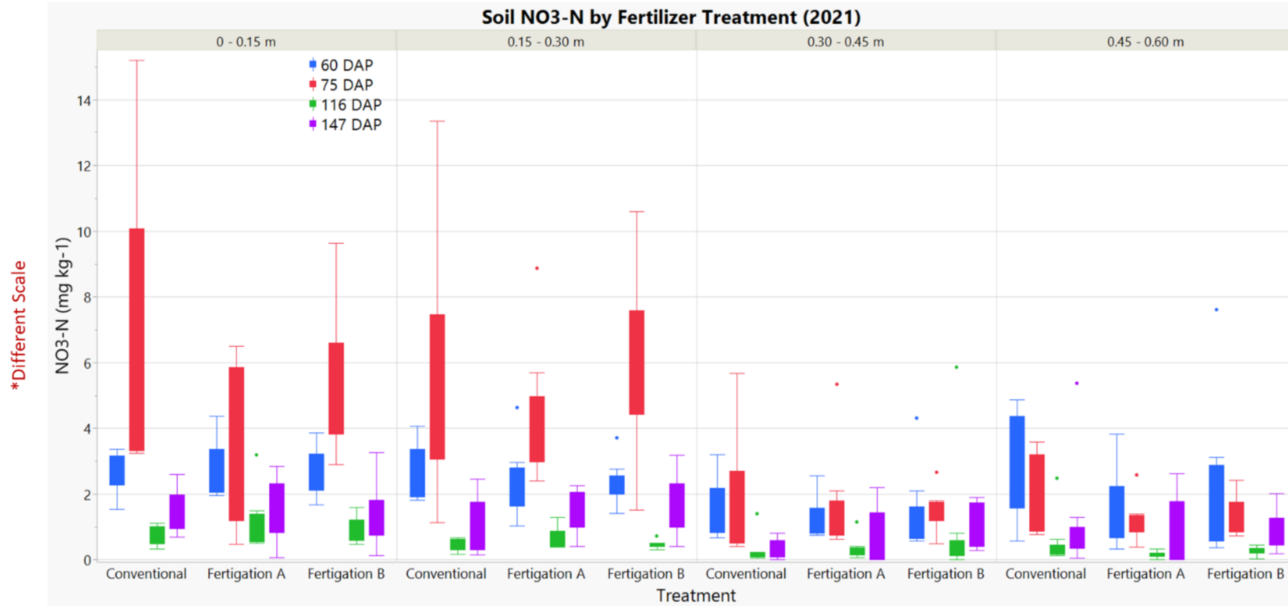


Figure 2.8 continued. Soil NO_3-N for each fertilizer treatment separated by soil layer depth for each soil sampling date from the 2018 – 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

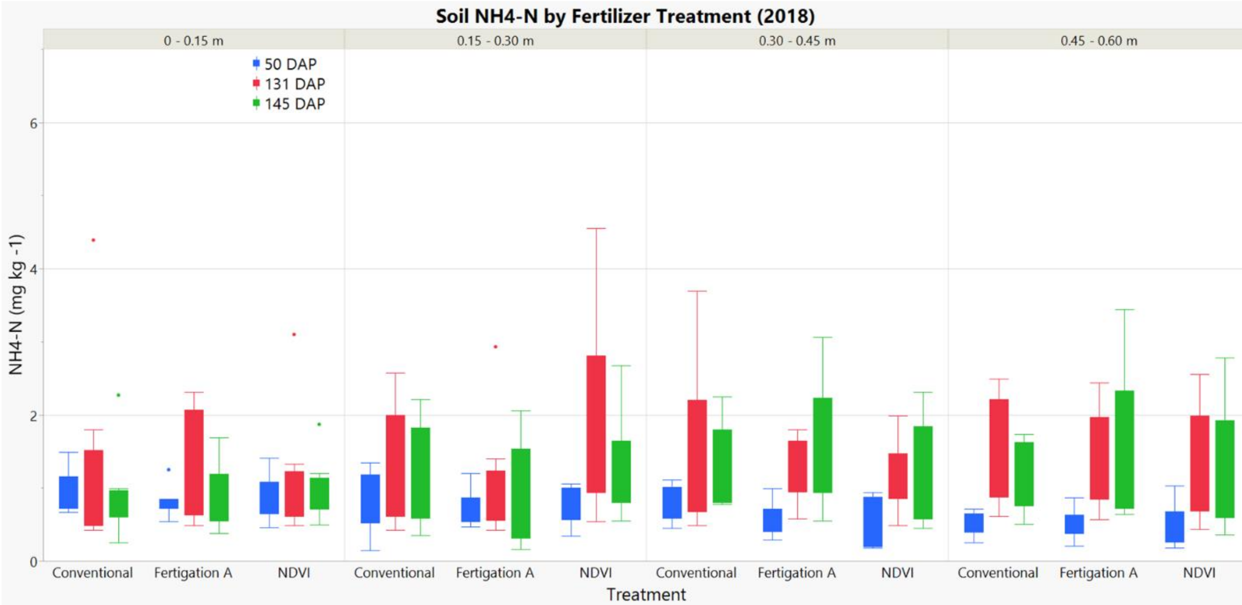


Figure 2.9. Soil NH_4-N for each fertilizer treatment separated by soil layer depth for each soil sampling date from the 2018 – 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

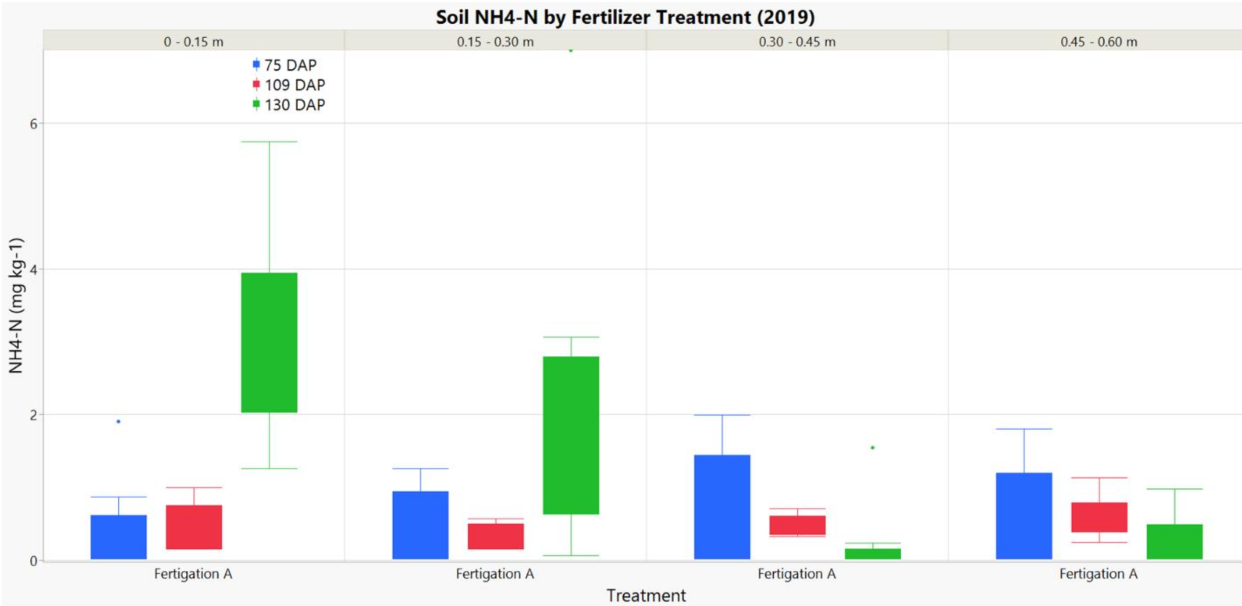


Figure 2.9 continued. Soil NH_4-N for each fertilizer treatment separated by soil layer depth for each soil sampling date from the 2018 – 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

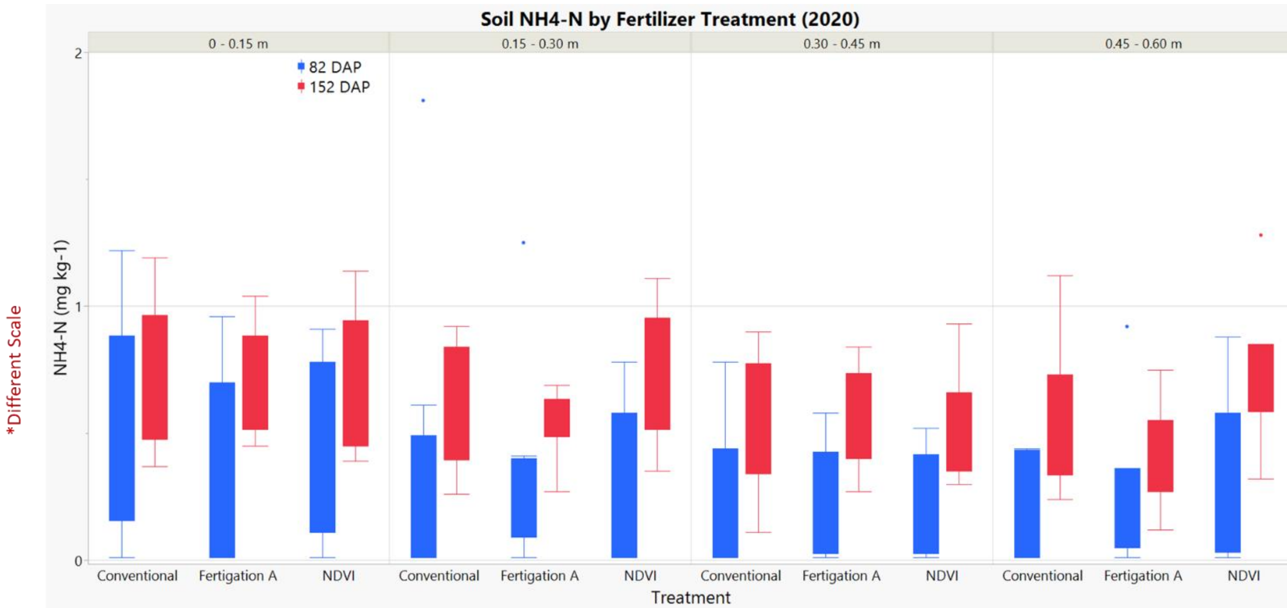


Figure 2.9 continued. Soil NH_4-N for each fertilizer treatment separated by soil layer depth for each soil sampling date from the 2018 – 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

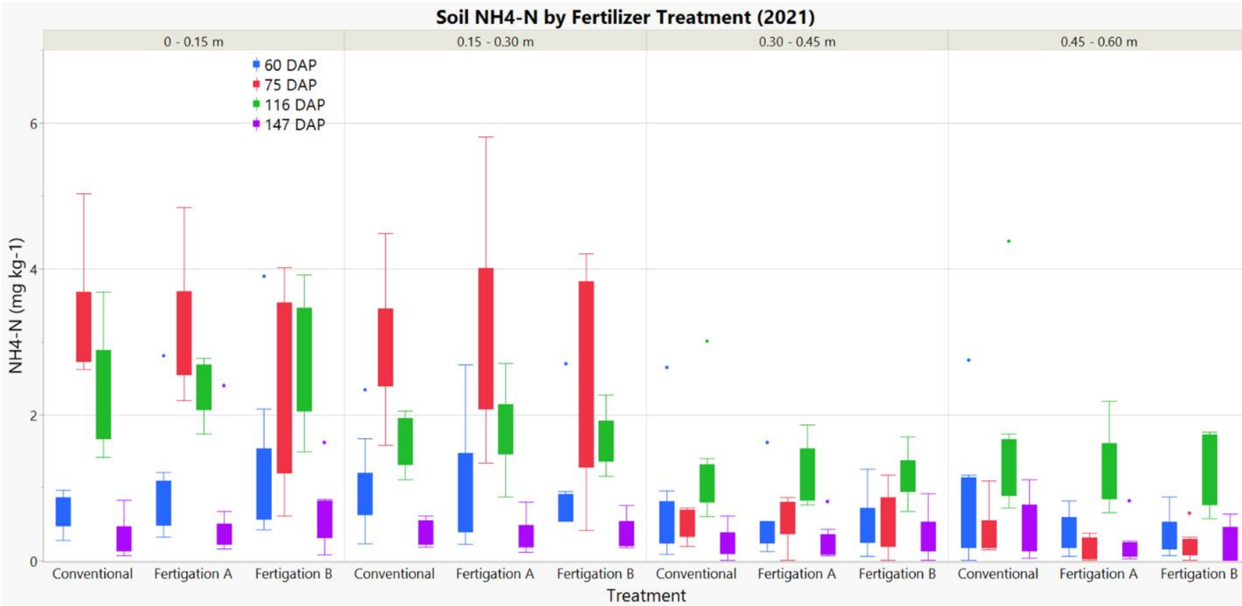


Figure 2.9 continued. Soil NH_4-N for each fertilizer treatment separated by soil layer depth for each soil sampling date from the 2018 – 2021 cotton growing season at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

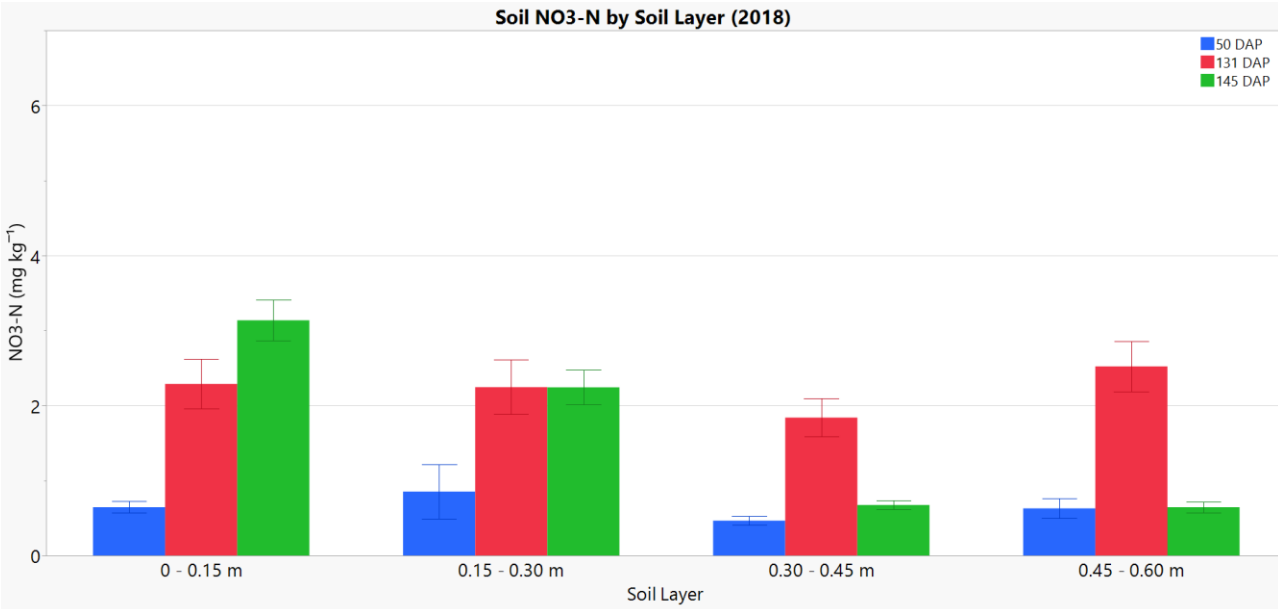


Figure 2.10. Soil NO3-N concentration (mg kg^{-1}) of each soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) on individual sampling dates (DAP) for 2018 – 2021 cotton growing seasons. Error bar is 1 standard error from mean.

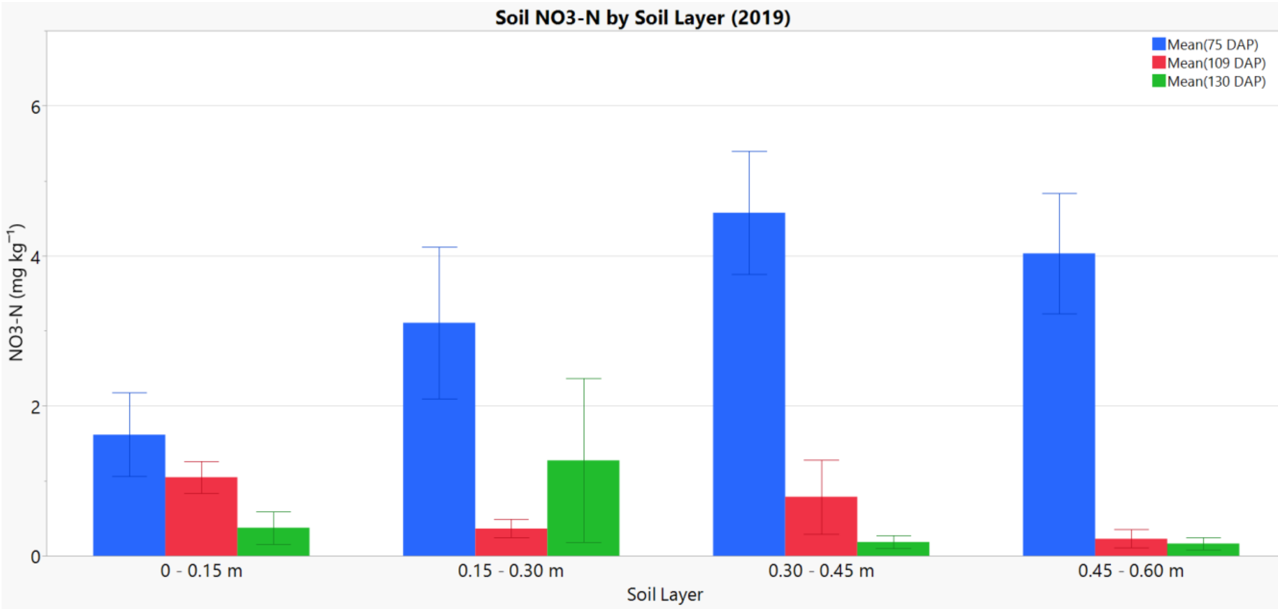


Figure 2.10 continued. Soil NO3-N concentration (mg kg^{-1}) of each soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) on individual sampling dates (DAP) for 2018 – 2021 cotton growing seasons. Error bar is 1 standard error from mean.

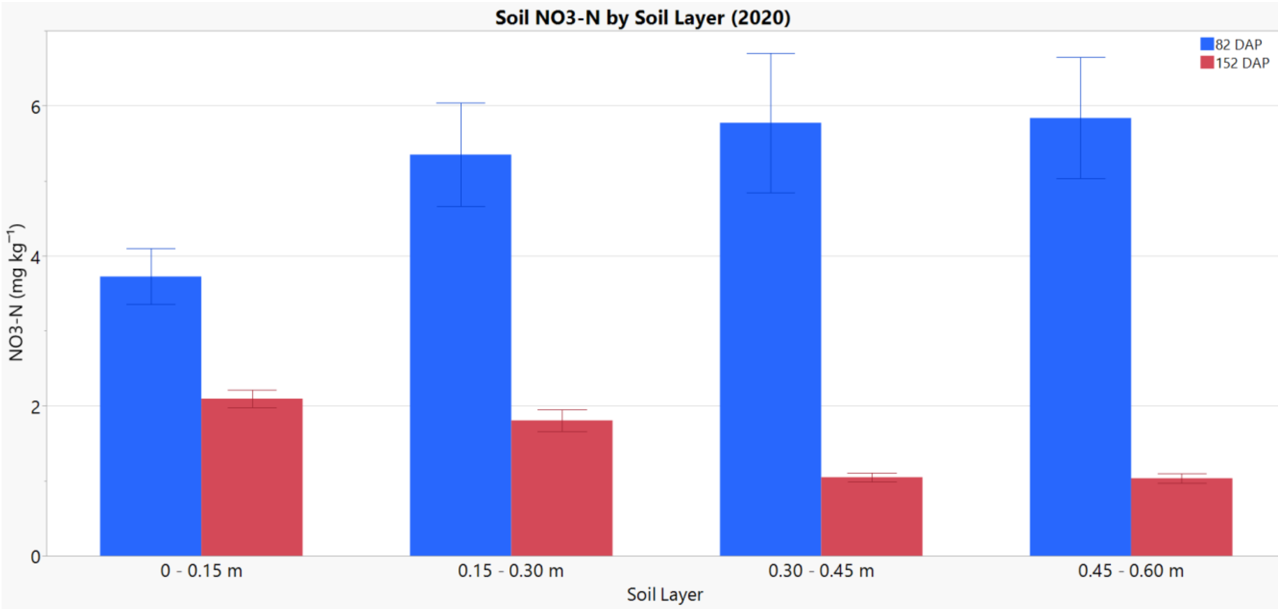


Figure 2.10 continued. Soil NO3-N concentration (mg kg^{-1}) of each soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) on individual sampling dates (DAP) for 2018 – 2021 cotton growing seasons. Error bar is 1 standard error from mean.

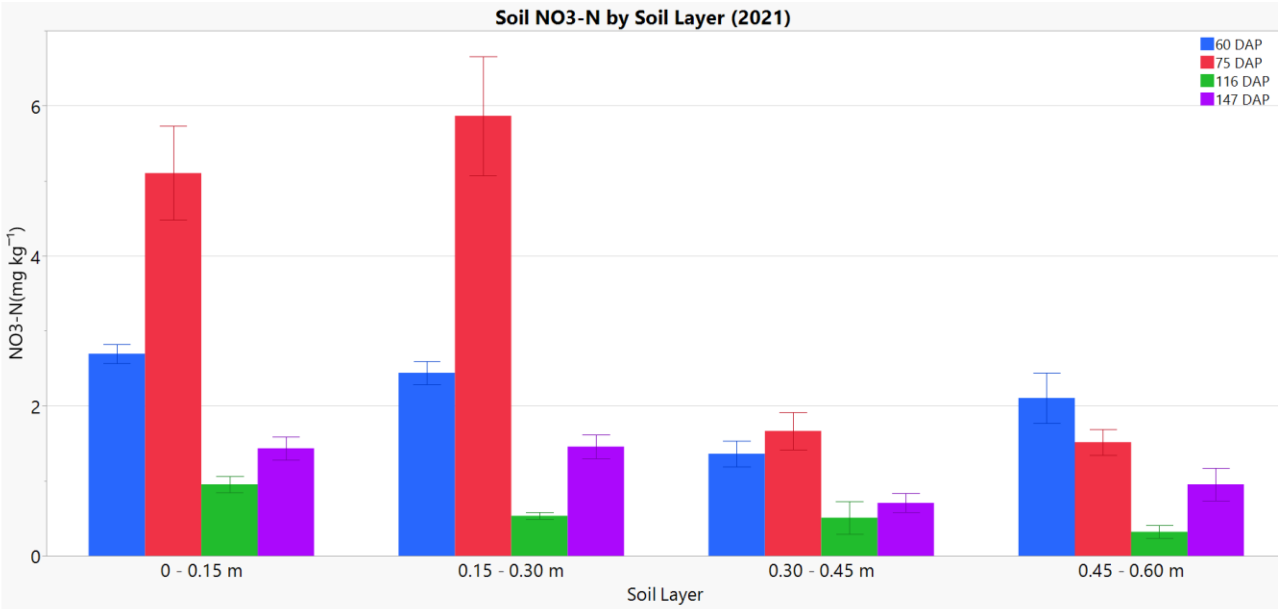


Figure 2.10 continued. Soil NO3-N concentration (mg kg^{-1}) of each soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) on individual sampling dates (DAP) for 2018 – 2021 cotton growing seasons. Error bar is 1 standard error from mean.

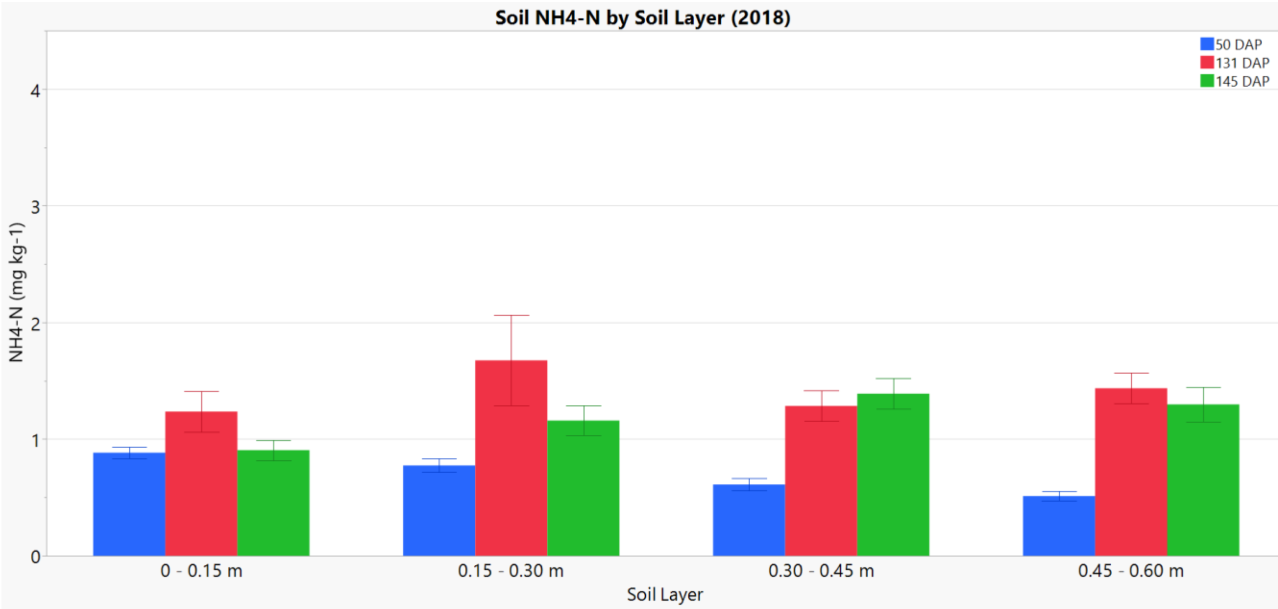


Figure 2.11. Soil NH4-N concentration (mg kg^{-1}) of each soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) on individual sampling dates (DAP) for 2018 – 2021 cotton growing seasons. Error bar is 1 standard error from mean.

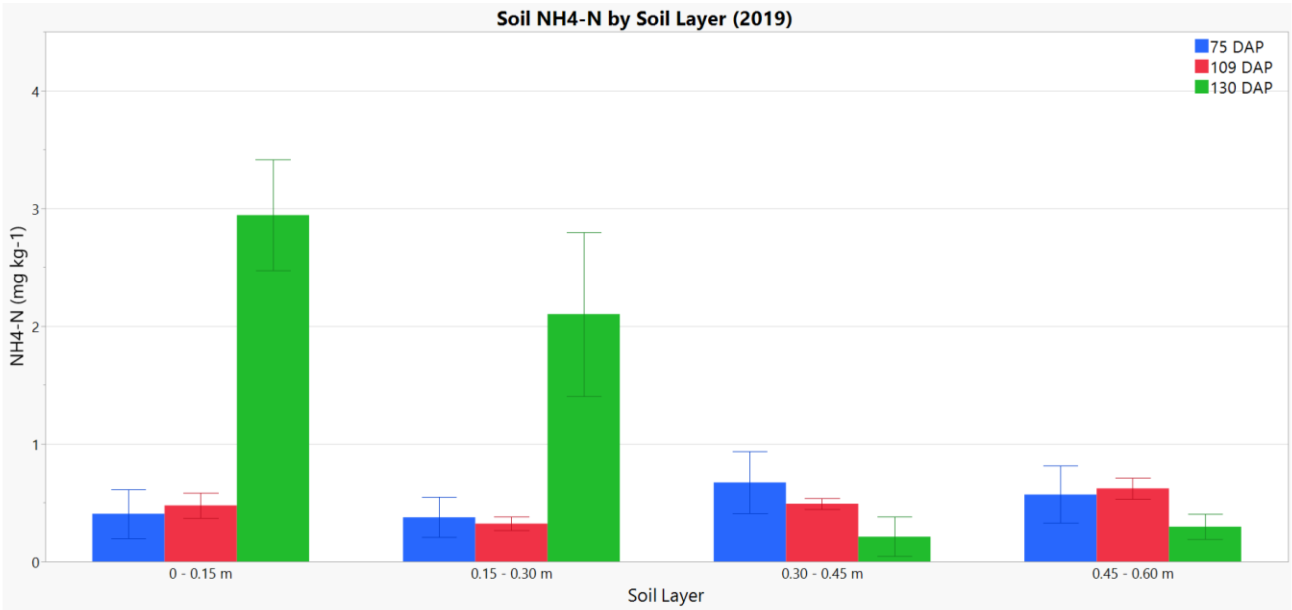


Figure 2.11 continued. Soil NH4-N concentration (mg kg^{-1}) of each soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) on individual sampling dates (DAP) for 2018 – 2021 cotton growing seasons. Error bar is 1 standard error from mean.

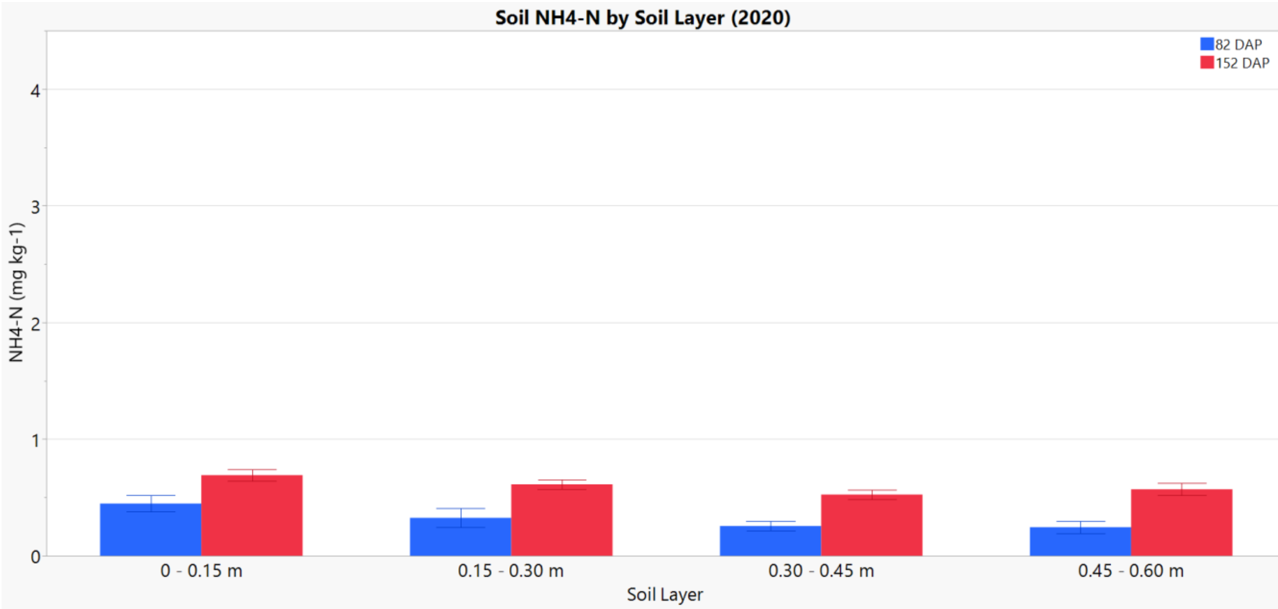


Figure 2.11 continued. Soil NH4-N concentration (mg kg^{-1}) of each soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) on individual sampling dates (DAP) for 2018 – 2021 cotton growing seasons. Error bar is 1 standard error from mean.

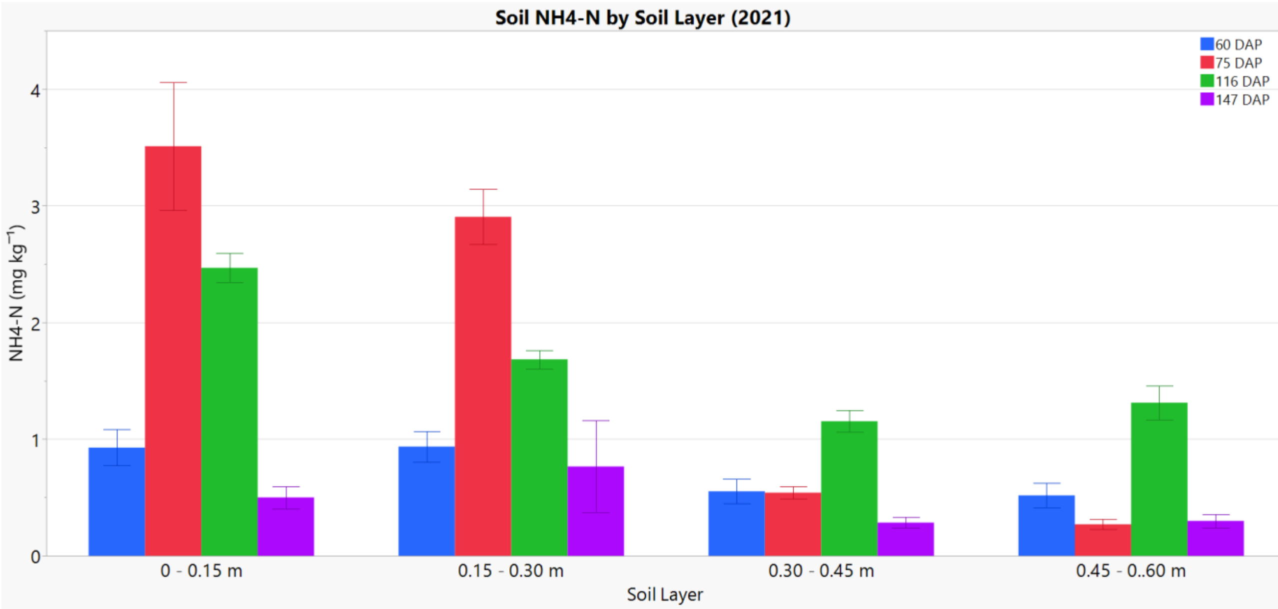


Figure 2.11 continued. Soil NH4-N concentration (mg kg^{-1}) of each soil layer (A = 0 – 0.15 m, B = 0.15 – 0.30 m, C = 0.30 – 0.45 m, D = 0.45 – 0.60 m) on individual sampling dates (DAP) for 2018 – 2021 cotton growing seasons. Error bar is 1 standard error from mean.

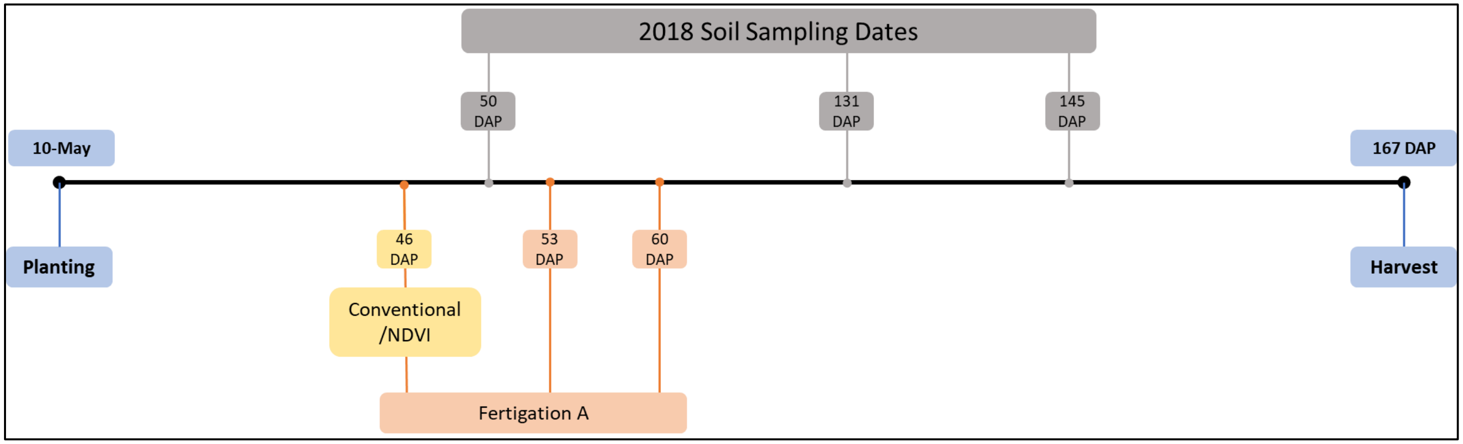


Figure 2.12. Timeline of soil sampling dates and in-season N applications for the 2018 cotton growing seasons at the University of Georgia (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

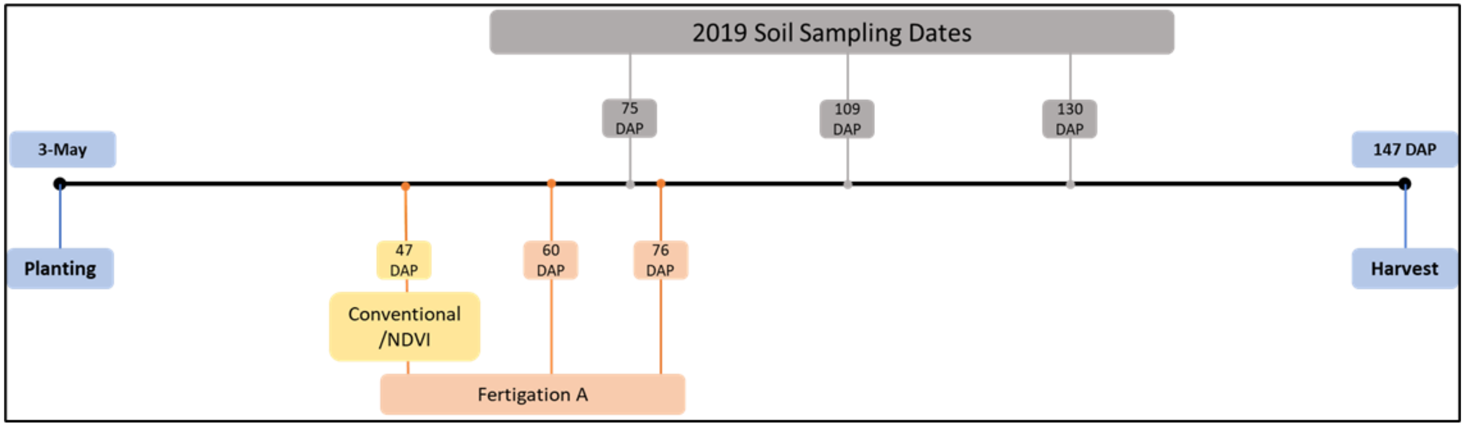


Figure 2.12 continued. Timeline of soil sampling dates and in-season N applications for the 2019 cotton growing seasons at the University of Georgia (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

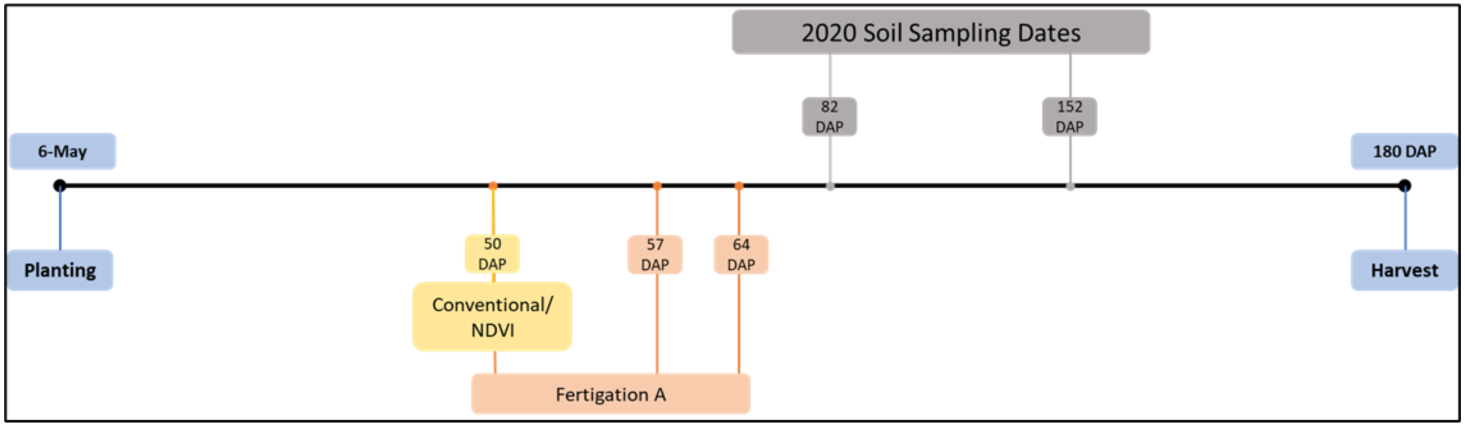


Figure 2.12 continued. Timeline of soil sampling dates and in-season N applications for the 2020 cotton growing seasons at the University of Georgia (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

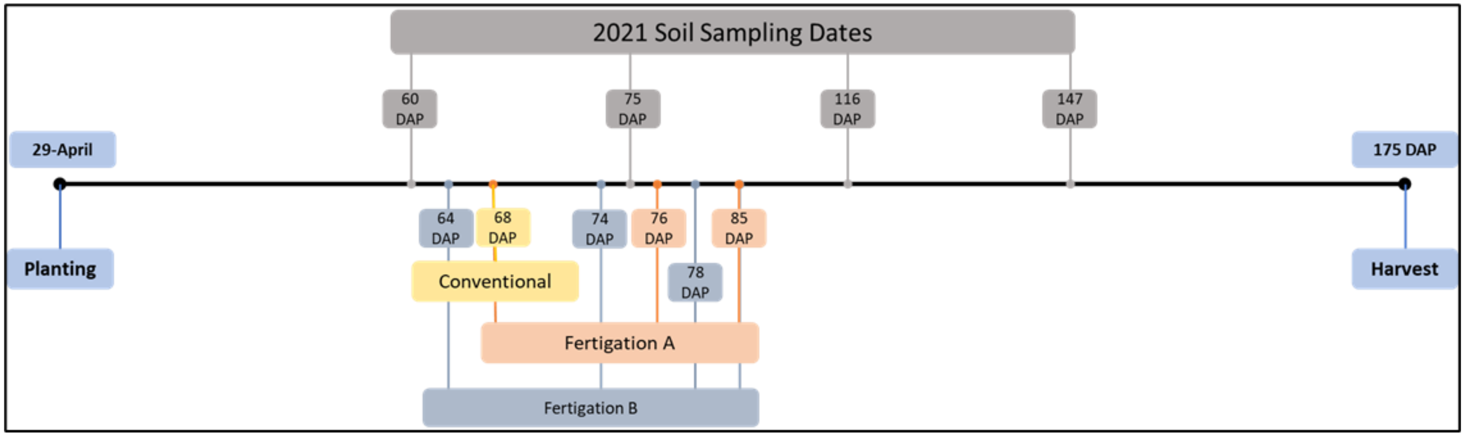


Figure 2.12 continued. Timeline of soil sampling dates and in-season N applications for the 202021 cotton growing seasons at the University of Georgia (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

CHAPTER 3

EVALUATION OF IN-SEASON COTTON NITROGEN MANAGEMENT STRATEGIES WITH THE DSSAT CSM CROPGRO-COTTON MODEL[2]

[2] Sangster, S., Toffanin, A., Boote, K. J., Gruver, M., Perry, C., Washington, B. J., and Vellidis, G. To be submitted to the *Smart Agricultural Technology* Journal

Abstract

The Decision Support System for Agrotechnology Transfer (DSSAT) CSM-CROPGRO-Cotton model was used to evaluate various nitrogen management scenarios for cotton including timing and High (148 kg N ha^{-1}), Baseline (118 kg N ha^{-1}) and Low (101 kg N ha^{-1}) nitrogen (N) rates, which were guided by the University of Georgia Cotton Production Guide. Soil and tissue samples were collected to perform calibration of the model from the 2021 growing season while the 2020 growing season was used for evaluation. The Seasonal Analysis tool was used to evaluate various in-season N scenarios on cotton using historical weather data and found that more in-season N events applied using fertigation resulted in higher yields and improved nitrogen use efficiency (NUE) when compared to the conventional, one in-season N application, approach regardless of total N applied. The model appears to be an effective way to evaluate management strategies for applying N on cotton.

3.1 Introduction

Cotton (*Gossypium hirsutum*) is an economically important crop in the United States (Chastain et al., 2014) and especially in the state of Georgia where it is grown on approximately 566,000 ha over the past 5 years. It contributes $120 billion to the U.S. and $2.5 billion to the Georgia economies, respectively.

Across the world, cotton is cultivated under a variety of different climate regimes including the humid Southeast of the U.S. (Hearn, 1979; Turner et al., 1986). In Georgia, cotton is grown primarily in the southern half of the state where mean annual precipitation is approximately 1270 mm with an average maximum air temperature of 26°C and average minimum air temperature of 12°C. Proper fertilization is key to cotton production. One of the most important, and challenging plant nutrients to manage is nitrogen (N). N fertilizers are applied as complex dry or liquid compounds. The United Nations Food and Agricultural Organization (FAO) estimates that N fertilizer use exceeded 100 million tons in 2018 – an increase of 25% over the past 10 years (FAO, 2019; Udvardi et al., 2015).

Nitrogen use efficiency (NUE) is the fraction of applied N fertilizer that is absorbed and used by the plant. Under field conditions, NUE is at best around 50%. This means that up to 50% of the N applied to soil as fertilizer may be unavailable for use by the crop (Udvardi et al., 2015). Leaching occurs because nitrate is highly soluble in water and is easily transported below the crop root zone by rain or excess irrigation. Nitrate that leaches below the root zone contaminates ground and surface waters causing environmental concerns and health problems.

In Georgia, typically, between 20 and 30% of the N required by cotton is applied prior to planting. The remaining N is usually applied with one in-season application 6-8 weeks after planting. The application is usually made either by broadcasting granular fertilizer (top-dressing) or by applying liquid fertilizer in the furrow next to the plant rows (side-dressing). Under these practices, more fertilizer than the crop requirement is applied to ensure that nutrients are available throughout the growing season. In some cotton growing regions, the amount of fertilizer applied is based on soil samples collected prior to planting and/or the farmer’s yield goals; however, in areas with sandy soils such as southern Georgia, soil samples are not routinely tested for N because it is assumed that the soils retain little N due to leaching. As a result, the amount of N fertilizer applied is based on the farmer’s yield goal. The University of Georgia’s Cotton Production Guide (Hand et al., 2022) provides N recommendations for different yield goals. The Guide also recommends that the in-season N be applied between first square and first bloom but no later than the third week of bloom because N applied before or after that period is not used as effectively by the crop (Hand et al., 2022).

3.1.1. Fertigation

Fertigation is the application of liquid fertilizers through an irrigation system. It has potential for improving NUE because the fertilizer can be applied in small doses at frequent intervals which increases the likelihood that N is used by the crop and not lost to leaching. Top-dressing N through overhead sprinkler systems such as center pivots is commonly used with maize in the USA (Gascho and Hook, 1991) and is being adopted in other regions of the world (Asadi et al., 2002; Yolcu and Cetin, 2015, He et al., 2012, Schepers et al., 1995). Fertigation with center pivots provides many logistical advantages including ensuring that the farmer can apply at the peak N demand (Biwas, 2010). Toffanin et al. (2019) conducted a three-year replicated plot study in southern Georgia, USA where they evaluated the effect of fertigation on maize production. Four top-dress N applications were applied using overhead sprinklers. Fertigation was applied separately from regular irrigation events to reduce the potential for leaching. When compared to a single liquid N side-dress application, fertigation resulted in the same yields but with lower amounts of N used and an average 17% gain in NUE over the study period.

In contrast to maize, the use of fertigation on cotton has not been extensively researched. Hou et al. (2007) conducted a greenhouse study to determine the effect of different fertigation schemes on N uptake and NUE in cotton plants. The study focused primarily on the timing of fertigation during an irrigation cycle. In a similar study conducted in the field using drip irrigation, Hou et al. (2009) found that that N applied at the beginning of an irrigation cycle resulted in the highest seed cotton yield but showed higher potential loss of N from leaching. Nitrogen applied at the end of an irrigation cycle had potential to lessen the amount of N loss from leaching but reported lower yields and NUE. Several studies have been conducted assessing the benefits of fertigation with drip irrigated cotton and results indicate that this approach shows promise for improving yields and NUE. Bronson et al. (2019) conducted a study on cotton irrigated with subsurface drip irrigation in an arid environment and found that high frequency of N fertigation events resulted in providing the crop with adequate in-season N, reducing N losses to the environment, and improving NUE. A study conducted in China compiled previous studies of drip fertigation and resource use efficiency for multiple crops, including cotton, compared to traditional management practices. The information provided from the previous studies and the researcher’s analysis showed that drip fertigation increased yield by 11.6% and NUE by 16.5% as compared to traditional farmer’s practices (Li et al., 2020).

Few studies have been conducted on evaluating fertigation with overhead sprinkler irrigation on cotton. Antille (2018) evaluated fertigation applied to both furrow and sprinkler-irrigated cotton in Australia. The study found that application of N through fertigation was economical for both furrow and sprinkler irrigation under fertilizer pricing at the time of the study, but relative agronomic efficiencies and economic return from the applied N were higher for fertigation with overhead sprinklers ($p<0.05$). In addition, fertigation with sprinklers resulted in reduced potential for N_2O emissions.

Recent fertigation research has focused on combining experimental and modeling approaches to evaluate the timing and amounts of fertigation. Chauhdary et al. (2019) and Toffanin et al. (2019) conducted these types of studies on maize. This combined approach allows researchers to collect data to calibrate and evaluate crop growth models such as the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2021) which are then used for the simulation of a wide variety of potential management scenarios.

3.1.2 Decision Support System for Agrotechnology Transfer (DSSAT)

DSSAT is a universally used decision support tool that includes dynamic crop growth simulation models for over 42 crops (Boote, 2019). DSSAT was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT, 1993; Tsuji, 1998; Uehara, 1998; Jones et al., 1998), to facilitate the application of crop models in a systems approach to agronomic research (Jones et. al, 2003). In the past, there were separate crop models available for different crops such as the CERES models for maize (Jones and Kiniry, 1986) and wheat (Ritchie and Otter, 1985), SOYGRO for soybean (Wilkerson et al., 1983) and PNUTGRO for peanut (Boote et al., 1986) but these models worked individually with different data input structures, different code, and operations. DSSAT was created to provide a common modeling framework for different types of crops where all the models read the same weather, soil, and management input files and use the same modules for soil water balance and soil N balance. The decision to create DSSAT ultimately led to the development of compatible models for additional crops, such as potato, rice, dry beans, sunflower, and sugarcane (Hoogenboom et al., 1994a; Jones et al., 1998; Hoogenboom et al. 1999). DSSAT provides a framework to conduct research for understanding the effect of various management practices and changes in environmental conditions on the growth and yield of crops by evaluating the relative response of different scenarios. The latest version of DSSAT which was released in May 2021 includes models of 40+ crops including the DSSAT CROPGRO-Cotton model (Hoogenboom et al., 2021.

In a study conducted in the Texas High Plains where water resources are limited, DSSAT was used to evaluate irrigation treatments (Garibay et al., 2019). In-season data were collected to calibrate and evaluate the DSSAT CSM CROPGRO – Cotton model to develop efficient irrigation practices for the growers across the region. The model showed potential to simulate yields and growth variables under various irrigation practices using a Mean Absolute Percentage Error (MAPE) less than 20% to estimate model performance. Thorp et al. (2014) evaluated CSM-CROPGRO-Cotton for arid environments and the management practices used in that region. Five prior cotton experiments from a span of nearly three decades provided data on management, growth and development, and observed field data. The model was found to respond well, after some adjustment for arid regions, to the various irrigation and nitrogen rates as well as the climate change factors that were studied in the field. In a follow-up study, Thorp et al. (2017) evaluated using CSM-CROPGRO-Cotton for in-season irrigation scheduling decisions on cotton in Arizona. They compared scheduling irrigation with the CSM-CROPGRO-Cotton model to scheduling with a standalone FAO-56. Total seasonal irrigation amounts were similar with both methods but CSM-CROPGRO-Cotton recommended more water during anthesis and less during the early season, which led to higher cotton fiber yield in both seasons ($p < 0.05$).

CSM-CROPGRO-Cotton has also been used to evaluate the relative response to different fertilization strategies. A study conducted by Pal (2020) in the Punjab region of India assessed two different planting dates (May 1 and May 25) with three levels of N application (25% greater than the recommended rate, recommended rate, 25% less than the recommended rate). The crop model underestimated yield in 2014 and overestimated yield in 2015 (Pal, 2020). Whitefly infestation was likely responsible for lower yields in 2015. There was also a significant difference in yields between the normal and late planting date. The results from this project reported a close proximity between observed and simulated seed cotton yield. A study conducted in Pakistan used the model to evaluate the combination of sowing dates, cultivars, and nitrogen levels. The model was calibrated using phenology, biomass, leaf area index, and yield to simulate the phenological development timeline, growth, and seed cotton yield (Wajid et al., 2014). While the model overestimated leaf area index and total dry matter, it was still within a reasonable range, but the development timeline was considered reliable. Another application for the CSM-CROPGRO-Cotton model was the evaluation of the effects of a cover crop on the following cotton crop yield. In Texas, a research group used the model to evaluate the long-term effects of a winter wheat cover crop upon cotton yield and soil water (Adhikari, P. et al., 2017). After successfully calibrating the model using observed soil water and crop yield data, it was found that the cover crop did not affect the following cotton crop's yield nor the availability of soil water under irrigated and dryland management.

3.1.3 Goal and Objectives

The overall goal of the work described in this paper was to evaluate the response of cotton to fertigation in southern Georgia. Specific objectives were to conduct a replicated plot field study that evaluated the response of cotton to fertigation and to use the DSSAT CSM CROPGRO-

Cotton model to evaluate the response of cotton to several combinations of the timing and the amount of N in fertigation applications. This paper presents the results of the modeling component of the study.

3.2 Materials and Methods

3.2.1 Study site and management practices

The four-year field study was described in detail by Sangster et al. (2022) and is briefly summarized here. The study was conducted at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) located near Camilla, Georgia in a 4 ha field known as the Newton Lateral (NL) (31°16'46.24"N, 84°17'59.59"W). The field is divided into three blocks [North (NLN), Middle (NLM), South (NLS)] with each block containing 27 plots. The plots were each 14.5 × 14. 5 m (14. 5 m long × 16 rows wide). The eight middle rows in each plot were used for data collection and the four rows on either side of the middle eight served as buffers. The soil in the Newton Lateral field is classified as a Lucy Loamy Sand with available water holding capacity of 0.08 cm/cm with 0 to 5% slope. Soil texture varied slightly across the field with 83% Sand, 10% Silt and 7% Clay in the South block to 86% Sand, 8% Silt, and 6% Clay in the North block. The field was irrigated with a variable rate-enabled lateral irrigation system which can apply a unique water application rate to each of the 81 plots. A portable liquid fertilizer injection system allowed for application of unique fertigation rates to each of the 81 plots through the irrigation system.

The experimental design utilized a randomized complete block design. The 27 plots in each block were divided into nine treatments with three replicates each. A cotton-peanut-maize rotation was maintained with crops rotating from north to south each year. All crops were planted into a rye cover crop using strip tillage following burndown with glyphosate. Three irrigation × three in-season N fertilization treatments were evaluated in the cotton plots. These consisted of two irrigation and two fertilization management treatments compared to farmer-standard (conventional) irrigation and fertilization practices. Irrigation scheduling treatments included using soil moisture sensors (SMS) and ET-based scheduling tools. The conventional treatment used the UGA Extension calendar method (Hand et al., 2022).

3.2.2. In-Season Fertilization Treatments

For the 2018, 2019, and 2020 growing seasons, the fertilization treatments included using a fertigation treatment to apply top-dress N, a UAV-derived NDVI treatment to apply side-dress N once, and the farmer-standard (conventional) treatment. Fertigation events were applied three times between first square and the third week of bloom. The conventional treatment was one liquid N side-dress application shortly after first square. The UAV-derived NDVI treatment used a production function to determine the amount of side-dress N needed to optimize NUE and maximize yield (Porter et al., 2010a, b) which was applied as one liquid N side-dress application at the same time as the conventional. Because consistently cloudy conditions prior to and during the period when in-season N was to be applied during the 2021 growing season prevented the acquisition of useable UAV data, the NDVI treatment was replaced by a second fertigation treatment in which the in-season N was applied with four fertigation events. Table 3.1 presents the in-season fertilization treatments and the amounts of N applied during each growing season.

3.2.3. Field data collection

As described earlier, the middle eight rows of each plot were considered data rows while the outer four on either side, were considered buffer rows. The middle two rows were reserved for mechanical harvest. Two rows on either side of the middle two rows were used for sampling. Soil cores were collected in 0.15-m increments to 0.91 m prior to planting in the rye cover crop, four times during the cotton growing season, and after harvest to quantify soil N. The soil samples were separated in bags by plot and depth. A subsample from each bag was used for nutrient analysis and another subsample was used to measure volumetric water content. Soil samples were analyzed for NH_4-N (ammonium) and NO_3-N (nitrate) by Waters Agricultural Laboratories (Camilla, Georgia). Volumetric water content was calculated using the gravimetric method by the authors. Soil cores for soil texture, pH, and cation exchange capacity (CEC), organic matter (OM) analyses were collected in 0.15-m increments to 0.91 m from the plots three times during 2018. The analyses were performed by Waters Agricultural Laboratories.

Whole samples were collected from the rye cover crop once prior to burndown. Rye plant samples consisted of all the plants within a 1 m^2 area cut at the soil surface. Whole plant samples were collected from the cotton crop four times during the cotton growing season. Cotton samples consisted of all the plants within 1 m length of one of the sampling rows. Whole plants were cut at the soil surface. Cotton plants were segmented into leaves, petioles, bolls, flowers, and stems. Cotton leaf area index (LAI) was measured using a bench top LI-COR (LI-COR Biosciences, Lincoln, NE.) leaf area meter. The tissue samples were dried at 60 °C for 48 h, weighed to measure dry biomass, and then analyzed for Total Kjeldahl Nitrogen (TKN) by Waters Agricultural Laboratories.

Immediately prior to mechanical harvest, 2 m of a sampling row was hand-harvested. Then the middle two rows were mechanically harvested using a spindle picker with a bagging attachment. The bags were weighed immediately after harvest and ginned at the UGA Microgin. The hand-harvested samples were hand-ginned. Seed cotton yields were calculated by dividing harvested mass by harvest area. Fiber yields were calculated by multiplying seed cotton yields by gin turnout. Annual average gin turnout was 37%, 39%, and 42% for 2019, 2020, and 2021, respectively. The 3-year average was approximately 40%.

3.2.4. CSM CROPGRO-Cotton

Observed data from the field experiments were used to calibrate and evaluate the CSM CROPGRO-Cotton model. The model was then used to evaluate fertigation management scenarios. Meteorological data required by the model were retrieved from the University of Georgia Weather Network Camilla weather station (31°16'48.3" N 84°17'29.8" W) which is located on the SIRP grounds. The weather station became operational on 25-April-1997 (97115). Daily data were retrieved from this date through 1-December-2021 (21335) and included solar radiation (SRAD) (MJ/m^2-day), maximum and minimum daily air temperature (°C), and precipitation (mm).

Soils data were extracted from the NRCS SSURGO Web Soil Survey (classification, slope, color, permeability, and drainage classification) and from soil sampling results (texture, CEC, organic carbon, pH, initial N concentrations). Field and crop management data included planting date, planting method (dry seed), planting distribution (rows), plant population at seeding (14 m^{-2}), row spacing (90 cm), and planting depth (2.5 cm), crop variety, irrigation and fertilization management.

Because the cotton crop rotated between other crops grown on the three blocks of the Newton Lateral field during the course of the study, soil profiles were created for each of the three Newton Lateral field blocks (NLN, NLM, NLS) using averages for soil texture analysis, CEC, and organic carbon (estimated from OM) from the sampling events conducted in 2018. Seasonal initial conditions were developed from the tissue and soil sampling that occurred in the rye cover crop 2-3 weeks before the cotton was planted. Initial conditions for crop residue were as follows: rye aboveground dry tissue mass for each treatment (the average of the 3 plots per treatment), rye root mass estimated as 10% of dry tissue mass, %TKN for aboveground crop residue, and initial conditions for soil including NH_4-N and NO_3-N.

In-season soil and tissue sample observations and plant height measurements were used to calibrate and evaluate the model. Data derived from the tissue samples included leaf weight, stem weight, tops weight (above-ground biomass including boll), leaf area index (LAI), pod (boll) weight, specific leaf area, and pod harvest index for each sampling date. Weight was reported in units of mass per unit area (kg ha^{-1}). Data derived from the soil samples included NH_4-N and NO_3-N concentrations (mg kg^{-1}) for each soil sample depth for each sampling date. Simulated yield was compared to measured seed cotton yield (kg ha^{-1}).

Observed data from six 2021 treatments (the three irrigation treatments × 2 fertigation treatments) were used to calibrate the model and are summarized in Table 3.2. The observed data and the DSSAT Generalized Likelihood Estimator (GLUE) were used to develop the DSSAT genetic coefficients for the cotton cultivar and additional adjustments were made to the cultivar coefficients based on the performance metrics (RMSE and d-statistic) using the time series data as a guide. Calibration of the model focused on five genetic coefficients: EM-FL, SD-PM, XFRT, THRSH, and SLAVR which along with other coefficients are described in Table 3.3. The model includes defined minima and maxima values for the cultivar coefficients and these values are used as a guide during cultivar calibration.

Observed cotton yields for most of the study period were lower than what was previously reported by Vellidis et al. (2016) for the Newton Lateral field for all treatments including conventional treatments. All plots received an adequate amount of N, and water stress was not a limiting factor. The low yields were attributed primarily to boll rot at the end of the growing season that may have been exacerbated by the cotton cultivar used in the study. The lower-than-expected measured yields proved a significant challenge during calibration as simulated yields were consistently higher than measured yields.

The calibrated model was compared to in-season data from the 2018, 2019, and 2020 growing seasons and yield data from the 2019 and 2020 growing seasons. Model performance was assessed using the index of agreement (D-statistic), root mean square error (RMSE), normalized RMSE (NRMSE), and the observed and simulated means provided by the model.

3.2.5. Simulation of Fertigation Management Scenarios

To assess the relative difference in yield response from different cotton N fertilization strategies, DSSAT's Seasonal Analysis tool was used to run the model for the entire meteorological period for which data were available (1997-2021) using the 2021 initial conditions. Irrigation was set to "automatic when required" to ensure that water stress was not a factor, preplant and in-season N fertilization events were a function of each scenario. Pre-plant fertilizer applications were simulated using the "Broadcast Incorporated" application option. Fertigation events were simulated using the "Applied in Irrigation Water" fertilizer application option. Conventional liquid side-dress was simulated using the "Banded on Surface" option on the DSSAT fertilizers tab. Yield was reported "at maturity". Reported yields are the means of the 24 growing seasons simulated for each scenario.

The UGA Cotton Production Guide (Hand et al., 2022) recommendations for high yield (101 kg N ha^{-1} to achieve 1401 kg fiber ha^{-1}) was used to benchmark total N applied and the period during which in-season N was applied (between first square and first bloom and no later than third week of bloom). This is hereafter referred to as the Baseline N rate. Fertilization scenarios evaluated ranged from 0 N applied to 125% of the Baseline N rate with several combinations of preplant vs in-season applications.

3.3 Results and Discussions

Observed soil and tissue sampling and yield data collected between 2018 and 2021 were described in detail by Sangster et al. (2022). Yield data from 2018 were not available as the cotton in the plots was destroyed by Hurricane Michael's passage over SIRP a few days before the scheduled harvest. In summary, the three-event fertigation treatment resulted in the highest observed yields in 2020 and 2021 with a mean increase in yield of 9.1% when compared to conventional. The NDVI treatment resulted in the highest yield during 2019 (Sangster et al., 2022).

3.3.1 CSM CROPGRO-Cotton Calibration and Evaluation

Tops weight (kg ha^{-1}) which represents dry above-ground biomass, dry stem weight (kg ha^{-1}), pod weight (kg ha^{-1}) which represents the mass of dried cotton bolls, dry leaf weight (kg ha^{-1}), leaf area index (LAI), leaf N (%), and canopy height (m) (available only for 2021) were the model variables used for comparison to observed data during model calibration and evaluation. The D-statistic, RMSE, and normalized RMSE (NRMSE) and the observed and simulated means of the model output variables were the metrics used for evaluating model performance (Table 3.4). Figure 3.1 shows the fit between simulated and observed data for tops weight after calibration with the 2021 data. Model performance metrics for the simulation of the 2018-2021 SMS × Fertigation and SMS × Conventional treatments are summarized in Table 3.4. The soil moisture sensor (SMS) treatments were selected for calibration because they consistently resulted in the highest observed yields across growing seasons (Sangster et al., 2022)

The D-statistic is a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 0 indicates no agreement between simulated results and observed data while a value of 1 indicates total agreement (Willmott, 1981). In general, the D-statistic indicated good agreement between simulated results and observed data of the three conventional treatments of 2021 and the SMS × Fertigation and the SMS × Conventional treatments in 2018 for most variables. The worst agreement was observed for 2019 and 2020. The best agreement for individual variables was for Tops Weight, Stem Weight, Pod Weight and the worst for LAI and Leaf N.

RMSE measures the quality of fit of a model with a value of zero meaning a perfect fit. Normalized RMSE can be used for comparison of different variables. NRMSE allows for comparison between variables that could otherwise not be compared due to differences in scale (Otto et al., 2018) and is reported in Table 3.4. LAI and Leaf Weight resulted in values indicating very poor quality of fit (using a > 0.4 standard from Otto et al., 2018). Yield for 2021 and 2020 also fell in this category. The model overpredicted these variables. All other variables for the four-year study fell in the ≤ 0.4 NRMSE range, including 2019 yield which resulted in the best fit.

Observed and Simulated means are also provided for all available variables. These are the means of all observed measurements for a given variable during the growing season and the means of all simulated values for those variables during the growing season. In general, agreement between observed and simulated means was good (Table 3.4).

Overall, the model predicted critical growth outputs such as above-ground biomass and boll mass relatively well across several treatments even if not for all of the growing seasons. This provided confidence that the model, as calibrated, could be used effectively to evaluate the relative differences between additional management scenarios.

3.3.2 Simulation of Fertigation Management Scenarios

As stated previously, the UGA Cotton Production Guide was used to establish the N rates that were used for the management simulation scenarios. The baseline N rate used (118 kg N ha $^{-1}$) was that recommended for high yield (1681 kg fiber ha $^{-1}$) under irrigated conditions. This matched the N rate used in the field study. Two additional N rates were used – a high rate (148 kg N ha $^{-1}$) which was 25% higher than the baseline rate and a low rate (102 kg N ha $^{-1}$) which was the rate recommended by the UGA Cotton Production Guide for a 1401 kg fiber ha $^{-1}$ yield goal.

Table 3.5 shows the simulation results for these N rates applied using the conventional (grower standard) treatment compared to the UGA Cotton Production Guide yield goals. For the conventional treatment, the N application was split into 22 kg N ha $^{-1}$ applied as preplant and the remainder applied as a single liquid N side-dress event between first square and first flower. Production Guide yield goals are generic across all soil types in Georgia and do not account for the yield potential of individual fields. Overall, the simulated yield results were lower than the Production Guide yield goals and lower than the cotton fiber yields observed at the Newton Lateral field from 2013-2017 in studies using the recommended N rates with one liquid N side-dress event and SMS-based irrigation scheduling (Vellidis et al., 2016). It is likely that the simulation results are lower because the observed time-series growth and final yields during the current field study were lower than in the past for the reasons described earlier and this affected the model's yield calibration.

The primary purpose of the DSSAT simulations was to evaluate the response of different fertigation N management strategies and compare them to conventional in-season N application practices. Table 3.6 presents the simulation results of these scenarios. Results are grouped by total N applied (High – 148 kg ha^{-1}, Baseline – 118 kg ha^{-1}, Low – 101 kg ha^{-1}). Within those groups are several in-season application strategies. In addition to simulated yield results, Table 3.6 includes N Uptake, N Leached, and NUE – all important parameters when evaluating different management strategies. Fiber yield was calculated using the 3-year average 40% lint turnout since DSSAT reports harvested yield as seed cotton.

Overall, higher N application rates resulted in higher simulated yields. However, the highest NUE resulted from the Low application rates with fertigation. Within every grouping of total applied N (Low, Baseline, High), either the 3-event or 4-event fertigation in-season applications with a broadcast preplant application resulted in the highest fiber yields and highest NUEs (Table 6). Applying all the N with 3 or 4 in-season fertigation applications without pre-plant fertilizer resulted in simulated yields as high or nearly as high as the combination of pre-plant and fertigation.

Based on DSSAT's Godwin-Singh soil carbon module, the N mineralization resulting from the rye cover crop and existing native soil organic matter was between 75 – 80 kg N ha^{-1} (Table 6) and provided 35-45% of total N uptake. Because of N mineralization, even the Zero N simulation resulted in fiber yield of 516 kg N ha^{-1}.

Leaching of N below the root zone was very low and ranged from 1 – 1.5 kg N ha^{-1}. The low leaching rate may be a function of using the "automatic when required" irrigation option in DSSAT which optimized irrigation applications but also because of the increasing clay content of the subsoil at the Newton Lateral field which may have limited vertical movement of soil water beyond the root zone. Small amounts of leaching may also be a function of the cotton taking up about 50% more total N than the amount applied through inorganic fertilizers.

These findings match findings reported by Bronson et al. (2019) who found that high frequency of N fertigation events provided cotton with adequate in-season N, reduced N losses to the environment, and improved NUE. Similarly, Li et al. (2020) found that fertigation on cotton increased yield by 11.6% and NUE by 16.5% as compared to traditional farmer's practices in a study conducted in China. Both of these studies were conducted with drip irrigation. In a study that included overhead sprinkler irrigation, Antille (2018) found that application of N through fertigation was economical for both furrow and sprinkler irrigation under fertilizer pricing at the time of the study, but relative agronomic efficiencies and economic return from the N applied were higher for fertigation with overhead and that fertigation with sprinklers resulted in reduced potential for N_2O emissions.

3.4 Conclusions

The simulation results confirm the field study findings that using fertigation to apply in-season N to cotton results in higher yields than the conventional approach of one liquid side-dress application that is commonly used in Georgia regardless of the total N applied. Fertigation also resulted in higher NUE than the conventional approach. Although some problems were encountered when calibrating DSSAT to a single 2021 season because of the low observed yields in that season, the model appears to be an effective way to evaluate management strategies for applying N on cotton.

Additional plot-scale research with other cultivars and on-farm field-scale research should be conducted to confirm the findings of this work before fertigation can be recommended as a management strategy to growers. However, it appears that fertigation provides both yield and NUE advantages when compared to conventional approaches of applying in-season N.

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TABLES AND FIGURES

Table 3.1. In-season fertilization treatments, total in-season N events, and N applied during each cotton growing season (2018-2021) at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) near Camilla, GA.

Year	Treatment	Number of In-Season Events	Preplant N (kg ha^{-1})	In-Season N (kg ha^{-1})	Total N (kg ha^{-1})
2018	Conventional	1	22	95	117
	NDVI	1	22	84	106
	Fertigation	3	22	96	118
2019	Conventional	1	34	95	129
	NDVI	1	34	84	118
	Fertigation	3	34	96	130
2020	Conventional	1	34	90	124
	NDVI	1	34	73	107
	Fertigation	3	34	101	135
2021	Conventional	1	22	101	123
	Fertigation A	4	22	101	123
	Fertigation B	3	22	101	123

Table 3.2. Cotton growth data from the six 2021 soil moisture sensor (SMS) × Fertigation treatments that were used to calibrate the CSM CROPGRO-Cotton model.

Treatment	Date (YrDoY) [1]	Leaf Weight (kg ha⁻¹)	Stem Weight (kg ha⁻¹)	Tops Weight (kg ha⁻¹)	Pod (Boll) Weight (kg ha⁻¹)	LAI [2]	Leaf N (%)	Canopy Height (m)
App × **Fertigation** (4 events)	21167	-	-	-	-	-	-	0.47
	21179	571	534	1309	-	1.04	3.19	-
	21194	1044	992	2782	736	1.25	3.42	0.75
	21230	1954	5097	11213	3630	2.29	3.33	0.94
	21256	650	4361	9769	4645	0.92	3.11	-
App × **Fertigation** (3 events)	21167	-	-	-	-	-	-	0.41
	21179	542	534	1240	-	0.96	3.02	-
	21194	914	807	2271	400	1.02	3.43	0.63
	21230	1302	3771	9377	3931	1.93	3.55	0.89
	21256	670	3927	10991	6294	0.83	3.16	-
SMS × **Fertigation** (4 events)	21167	-	-	-	-	-	-	0.4
	21179	731	828	1797	-	1.38	3.6	-
	21194	1071	1026	2782	471	1.32	3.66	0.67
	21230	1672	4008	9775	3653	2.09	3.63	0.96
	21256	713	4150	9920	4928	1.03	2.87	-
SMS × **Fertigation** (3 events)	21167	-	-	-	-	-	-	0.43
	21179	641	721	1564	-	1.17	3.34	-
	21194	917	1177	2983	702	1.3	3.32	0.68
	21230	1236	4040	8702	3132	1.78	3.29	0.96
	21256	975	5261	13710	7323	1.25	3.22	-
Checkbook × **Fertigation** (4 events)	21167	-	-	-	-	-	-	0.46
	21179	671	691	1545	-	1.11	2.95	-
	21194	900	908	2508	517	1.19	3.49	0.72
	21230	1377	4356	9351	3228	2.26	3.62	1.02
	21256	746	4174	10356	5321	1.04	3.01	-
Checkbook × **Fertigation** (3 events)	21167	-	-	-	-	-	-	0.48
	21179	780	855	1870	-	1.37	3.32	-
	21194	1273	1334	4180	1352	1.62	3.32	0.75
	21230	1255	3548	9031	3867	1.95	3.07	0.97
	21256	956	4700	12169	6334	1.24	2.93	-

[1] Two-digit year followed by three-digit day of the year, e.g, 21167 = 167th day of 2021
[2] Leaf area index

Table 3.3. CSM CROPGRO-Cotton cultivar coefficients with descriptions and value used for each variable.

Coefficient	Genetic Coefficient Description	Cultivar
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)	37.00
FL-SH	Time between first flower and first pod (R3) (photothermal days)	11.21
FL-SD	Time between first flower and first seed (R5) (photothermal days)	15.06
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)	40.00
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)	72.89
LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light (mg CO2/m2-s) -- from Reddy Adv. Agron. 1997?	1.100
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm2/g)	170.0
SIZLF	Maximum size of full leaf (three leaflets) (cm2)	273.3
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.630
WTPSD	Maximum weight per seed (g)	0.180
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	28.00
SDPDV	Average seed per pod under standard growing conditions (#/pod)	26.08
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	13.91
THRSH	Threshing percentage. The maximum ratio of (seed/(seed+shell)) increases until the shells are filled in a cohort	70.00
SDPRO	Fraction protein in seeds (g(protein)/g(seed))	0.153
SDLIP	Fraction oil in seeds (g(oil)/g(seed))	0.120

Table 3.4. Summary of the performance metrics resulting from the calibration and evaluation of the CSM CROPGRO-Cotton model (*Calibrated only to 2021 season).

Variable	Mean of All Observed Values and Simulated Results[1]							
	2018		2019		2020		2021*	
	Obs.[1]	Sim.[2]	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
LAI	1.37	1.90	2.14	2.49	1.61	3.46	1.41	2.28
Leaf wt (kg ha^{-1})	724	998	2429	1395	2180	1890	1000	1234
Stem wt (kg ha^{-1})	1519	1860	3479	2511	3095	3096	2494	1968
Tops wt (kg ha^{-1})	4512	5364	10260	6886	10511	8634	6228	5471
Pod wt (kg ha^{-1})	2625	3133	3961	2980	6591	4769	3342	3026
Pod Index	0.44	0.46	0.33	0.37	0.55	0.47	0.38	0.35
Canopy Height (m)	-	-	-	-	-	-	0.7	0.77
Leaf N%	3.78	2.11	3.82	2.4	3.89	2.84	3.26	2.91
Stem N%	1.22	0.87	2.06	0.89	1.24	1.12	1.04	1.00
Yield (kg ha^{-1})	-	-	3319	3241	2423	3645	2034	3689

Variable	D-statistic				NRMSE[3]			
	2018	2019	2020	2021*	2018	2019	2020	2021*
LAI	0.13	0.71	0.34	0.50	0.99	0.30	1.19	0.70
Leaf wt (kg ha^{-1})	0.82	0.54	0.35	0.74	0.48	0.53	0.49	0.35
Stem wt (kg ha^{-1})	0.88	0.58	0.42	0.86	0.39	0.33	0.26	0.38
Tops wt (kg ha^{-1})	0.92	0.68	0.64	0.97	0.31	0.34	0.33	0.20
Pod wt (kg ha^{-1})	0.90	0.88	0.33	0.98	0.3	0.38	0.35	0.18
Pod Index	0.96	0.96	0.31	0.89	0.13	0.24	0.16	0.29
Canopy Height (m)	-	-	-	0.94	-	-	-	0.18
Leaf N%	0.18	0.49	0.60	0.36	0.48	0.40	0.30	0.26
Stem N%	0.61	0.41	0.76	0.16	0.35	0.69	0.22	0.35
Yield (kg ha^{-1})	-	0.13	0.20	0.08	-	0.13	0.53	0.82

[1] Mean of all observed measurements for a given time-series variable during the growing season.
[2] Mean of all simulated values for a given time-series variable during the growing season.
[3] Normalized Root Mean Square Error (RMSE)

Table 3.5. Comparison of simulated fiber yields to Georgia Cotton Production Guide yield goals using recommended N application rates and one liquid N side-dress application. Fiber yield was calculated using a 40% of simulated harvested (seed cotton) yield.

Simulation N Rate	UGA Cotton Production Guide		Simulated Fiber Yield (kg ha^{-1})	Fiber Yield from Vellidis et al. (2016) (kg ha^{-1})
	Recommended N Rate (kg ha^{-1})	Fiber Yield Goal (kg ha^{-1})		
High	N/A (148)[1]	N/A	1466	N/A
Baseline	118	1681	1352	1665
Low	101	1401	1272	N/A

[1] The highest N rate recommended by the UGA Cotton Production Guide is 118 kg ha^{-1} and is referred to here as the Baseline. 148 kg ha^{-1} is the N rate used in DSSAT for simulating the High rate.

Table 3.6. CSM-CROPGRO-Cotton N management scenario results showing simulated outputs. Scenarios compare conventional to fertigation in-season N application at different total N rates.

N Rate Scenario	In-Season Application		N Applied (kg ha^{-1})			Fiber Yield (kg ha^{-1})	N Uptake (kg ha^{-1})	Net N Mineralization (kg ha^{-1})	N Leached (kg ha $^{-1}$)	NUE (kg-fiber kg-N^{-1})
	Method	Eve nts	Total	Pre-plant	In-Season					
High	Conventional	1	148	22	126	1466	213.1	79.3	1.2	9.9
	Fertigation	3	148	22	126	1532	224.1	79.8	1.2	10.3
	Fertigation	4	148	22	126	1538	224.1	80.0	1.2	10.4
	Fertigation	3	148	0	148	1431	224.3	79.9	1.1	9.7
	Fertigation	4	148	0	148	1466	224.6	80.2	1.1	9.9
	None	0	148	148	0	1441	215.1	77.5	2.3	9.7
Baseline	Conventional	1	118	22	96	1352	186.7	78.8	1.2	11.5
	Fertigation	3	118	22	96	1443	193.2	78.9	1.2	12.2
	Fertigation	4	118	22	96	1424	193.0	78.8	1.2	12.1
	Fertigation	3	118	0	118	1404	194.3	79.6	1.1	11.9
	Fertigation	4	118	0	118	1423	194.3	79.8	1.1	12.1
	None	0	118	118	0	1322	186.5	77.0	2.0	11.2
Low	Conventional	1	101	22	79	1272	171.3	78.5	1.2	12.6
	Fertigation	3	101	22	79	1327	175.3	77.9	1.2	13.1
	Fertigation	4	101	22	79	1325	175.7	78,3	1.2	13.1
	Fertigation	3	101	0	101	1354	176.8	79.0	1.1	13.4
	Fertigation	4	101	0	101	1340	177.3	79.4	1.1	13.3
	None	0	101	101	0	1233	170.4	76.5	1.9	13.2
Zero	None	–	0	–	–	516	71.4	74.2	1.0	–

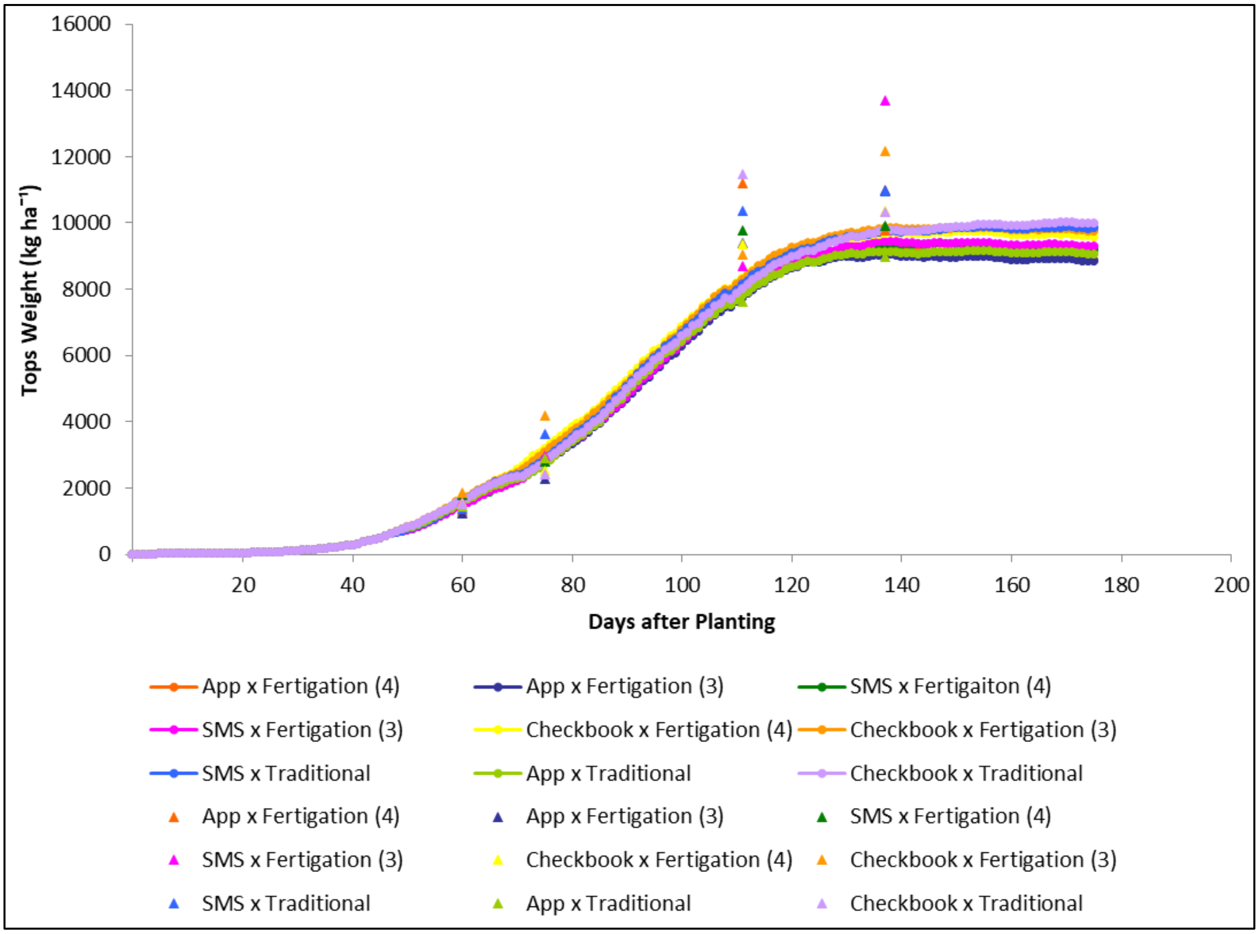

Figure 3.1. Comparison of observed and simulated Tops Weight (above-ground biomass) (kg ha $^{-1}$) following calibration for the 2021 irrigation × fertilization treatments used to calibrate the CSM-CROPGRO-Cotton model.

CHAPTER 4

CONCLUSIONS

The field study conducted at the University of Georgia's (UGA) Stripling Irrigation Research Park (SIRP) during the 2018, 2019, 2020, and 2021 growing seasons explored the combination of in-season N and irrigation scheduling treatments and the effect they had on cotton fiber yield, NUE, and IWUE. Comparing in-season N applications with fertigation to other in-season management practices and measuring how they affected soil and tissue N concentrations, fiber yield, and NUE provided valuable data that were later used for mathematical simulations. For two of the three years for which yield results were available, fertigation resulted in numerically higher yields that were not significantly different from the yields of the other in-season fertilization treatments. Because the NDVI treatment used less in-season N, it resulted in consistently high NUE. The 4-event fertigation treatment, from the 2021 growing season, did not provide additional benefits – perhaps because the period over which the in-season N was applied was the same as the 3-event fertigation treatment and the time difference between the application events of the two treatments was a few days. The unusually low yields across all treatments in 2020 in 2021 may have dampened the effect of the treatments so additional research with other cultivars at the plot and farm -scale should be conducted to confirm the findings of this work before fertigation can be recommended as a management strategy to growers.

The results from the 2018 – 2021 cotton study also confirm the results from many other studies that advanced irrigation scheduling tools like soil moisture sensors and ET-based models consistently outperform calendar scheduling methods in both yields and IWUE. These are tools that cotton growers can adopt at relatively low cost and little risk of yield loss.

The data collected in the 2018 – 2021 field study were used to calibrate and evaluate the DSSAT CSM-CROPGRO-Cotton model which was then used to evaluate a variety of in-season N management strategies. The simulation results confirm the field study findings that using fertigation to apply in-season N to cotton results in higher yields than the conventional approach of one liquid side-dress application that is commonly used in Georgia regardless of the total N applied. Fertigation also resulted in higher NUE than the conventional approach. Although some problems were encountered when calibrating the model to a single 2021 season because of the low observed yields in that season, the model appears to be an effective way to evaluate management strategies for applying N on cotton.

Additional plot-scale research with other cultivars and on-farm field-scale research must be conducted to confirm the findings of this work before fertigation can be recommended as a management strategy to growers. However, it appears that fertigation provides both yield and NUE advantages when compared to conventional approaches of applying in-season N.

APPENDIX A

Appendix Table A1. 2018 plant component biomass (kg ha^{-1}) by individual treatment. A Fisher's protected LSD test was used for comparison of means for each plant component by treatment for a specific sampling date (DAP) (α = 0.05).

2018						
Treatment	**Plant Comp-onent**	**Tissue Biomass (kg ha⁻¹)**				
		DAP				
		41	82	118	137	146
SI Cotton x Fertigation	Leaf	167 ab	1421 a	907 a	1214 a	740 ab
	Stem	78 a	1897 a	2261 a	2837 a	2220 abc
	Petiole	28 a	299 a	202 a	174 a	76 ab
	Square	6.8 a	252 abc	-	-	-
	Boll	-	1098 a	2531 a	4064 a	3982 a
	LAI	2.49 a	1.80 a	1.49 a	0.87 ab	-
SI Cotton x NDVI	Leaf	179 a	890 a	613 a	580 a	532 ab
	Stem	73 ab	1231 a	1504 a	1167 b	1240 c
	Petiole	28 a	205 a	105 a	72 a	56 ab
	Square	7.4 a	82 c	-	-	-
	Boll	-	656 a	2674 a	2766 a	2807 a
	LAI	1.49 a	1.09 a	0.68 b	0.66 ab	-
SI Cotton x Conventional	Leaf	127 ab	1393 a	928 a	877 a	730 ab
	Stem	46 b	1737 a	2380 a	2013 ab	2368 abc
	Petiole	15 bc	280 a	215 a	113 a	82 ab
	Square	5.4 a	235 ab	-	-	-
	Boll	-	920 a	3509 a	2754 a	4449 a
	LAI	2.67 a	2.10 a	1.14 ab	0.85 ab	
UGA SSA x Fertigation	Leaf	134 ab	1269 a	721 a	1113 a	575 ab
	Stem	53 ab	1499 a	1836 a	2598 ab	1786 abc
	Petiole	17 abc	263 a	167 a	132 a	68 ab
	Square	6.0 a	198 abc	-	-	-

	Boll	-	642 a	2480 a	4527 a	3486 a
	LAI	2.13 a	1.43 a	1.28 ab	0.74 ab	-
UGA SSA x NDVI	Leaf	133 ab	849 a	805 a	636 a	399 b
	Stem	53 ab	1121 a	2030 a	1284 ab	1500 bc
	Petiole	18 abc	209 a	173 a	74 a	43 b
	Square	5.9 a	85 bc	-	-	-
	Boll	-	530 a	3304 a	2541 a	3000 a
	LAI	1.46 a	1.54 a	0.84 ab	0.46 b	
UGA SSA x Conventional	Leaf	123 ab	1351 a	556 a	1122 a	701 ab
	Stem	48 ab	1748 a	1307 a	2489 ab	1763 abc
	Petiole	17 abc	332 a	127 a	158 a	83 ab
	Square	5.3 a	267 a	-	-	-
	Boll	-	604 a	2057 a	3567 a	3339 a
	LAI	2.45 a	1.27 a	1.40 ab	0.86 ab	-
Calendar x Fertigation	Leaf	137 ab	1142 a	697 a	804 a	767 ab
	Stem	52 ab	1528 a	2012 a	2091 ab	3006 a
	Petiole	21 abc	252 a	164 a	103 a	97 ab
	Square	5.2 a	217 abc	-	-	-
	Boll	-	485 a	2294 a	2650 a	4569 a
	LAI	2.18 a	1.31 a	0.94 ab	0.81 ab	
Calendar x NDVI	Leaf	109 b	1142 a	723 a	786 a	531 ab
	Stem	44 b	1213 a	1757 a	1791 ab	1925 abc
	Petiole	11 c	288 a	156 a	120 a	54 ab
	Square	5.1 a	157 abc	-	-	-
	Boll	-	533 a	3064 a	2815.0	3809 a
	LAI	1.77 a	1.43 a	0.95 ab	0.72 ab	
Calendar x Conventional	Leaf	155 ab	1041 a	947 a	963 a	947 a

	Stem	66 ab	1286 a	2421 a	2258 ab	2727 ab
	Petiole	24 ab	246 a	228 a	127 a	115 a
	Square	5.3 a	141 abc	-	-	-
	Boll	-	606 a	2989 a	4068 a	4388 a
	LAI	1.91 a	2.06 a	1.03 ab	1.04 a	-

Appendix Table A2. 2019 plant component biomass (kg ha^{-1}) by individual treatment. A Fisher's protected LSD test was used for comparison of means for each plant component by treatment for a specific sampling date (DAP) ($\alpha = 0.05$).

2019				
Treatment	**Plant Comp-onent**	**Tissue Biomass (kg ha^{-1})**		
		DAP		
		75	109	130
SI Cotton x Fertigation	Leaf	3263 a	2252 a	1217 b
	Stem	2379 a	3538 a	4178 a
	Petiole	390 a	293 a	418 b
	Square	277 a	45 a	-
	Boll	140 a	6827 a	4746 a
	LAI	2.82 a	2.25 a	0.93 b
UGA SSA x Fertigation	Leaf	4332 a	2292 a	1251 b
	Stem	2914 a	3234 a	4033 a
	Petiole	447 a	283 a	413 b
	Square	280 a	40 a	-
	Boll	342 a	7646 a	4623 a
	LAI	3.26 a	2.28 a	1.03 b
Calendar x Fertigation	Leaf	3347 a	2209 a	1696 a
	Stem	2441 a	3307 a	5296 a
	Petiole	362 a	320 a	522 a
	Square	203 a	74 a	-
	Boll	172 a	5176 a	5054 a
	LAI	2.61 a	2.42 a	1.67 a

Appendix Table A3. 2020 plant component biomass (kg ha^{-1}) by individual treatment. A Fisher's protected LSD test was used for comparison of means for each plant component by treatment for a specific sampling date (DAP) (α = 0.05).

2020					
Treatment	**Plant Comp-onent**	**Tissue Biomass (kg ha^{-1})**			
		DAP			
		75	111	132	139
SI Cotton x Fertigation	Leaf	3696 ab	2534 a	1284 ab	1309 a
	Stem	3161 abc	2958 abc	3346 ab	3400 ab
	Petiole	524 a	530 b	409 a	215 a
	Square	713 ab	---	---	---
	Boll	---	7354 abc	6501 a	5406 a
	LAI	2.27 a	1.69 a	1.21 ab	1.06 a
SI Cotton x NDVI	Leaf	3525 ab	2450 a	1271 b	1180 a
	Stem	2878 abc	2864 abc	2666 b	2977 ab
	Petiole	426 a	535 b	430 a	275 a
	Square	695 ab	---	---	---
	Boll	---	5833 bc	4725 a	6036 a
	LAI	2.07 ab	1.74 a	1.22 ab	0.89 a
SI Cotton x Conventional	Leaf	4231 a	2849 a	1370 ab	1161 a
	Stem	3787 a	2584 bc	3001 ab	3341 ab
	Petiole	507 a	541 b	451 a	253 a
	Square	857 a	---	---	---
	Boll	---	9586 ab	5478 a	6278 a
	LAI	2.37 a	2.10 a	1.33 ab	0.86 a
UGA SSA x Fertigation	Leaf	3620 ab	2680 a	1328 ab	1007 a
	Stem	3167 abc	2672 bc	3124 ab	2590 b
	Petiole	456 a	470 b	415 a	154 a
	Square	653 ab	---	---	---
	Boll	---	10244 a	6788 a	5447 a
	LAI	2.23 ab	2.26 a	1.25 ab	0.68 ab
UGA SSA x NDVI	Leaf	3515 ab	2737 a	1342 ab	1074 a
	Stem	2243 c	2721 bc	2898 b	2731 b
	Petiole	470 a	467 b	423 a	170 a

	Square	553 ab	---	---	---
	Boll	---	7663 abc	5984 a	5680 a
	LAI	2.37 a	2.14 a	1.29 ab	0.69 a
UGA SSA x Conventional	Leaf	2671 b	1718 a	1272 b	1341 a
	Stem	2264 c	2167 c	2530 b	3187 ab
	Petiole	309 a	481 b	391 a	261 a
	Square	443 b	---	---	---
	Boll	---	7556 abc	5916 a	7079 a
	LAI	1.66 b	1.75 a	1.15 b	1.13 a
Calendar x Fertigation	Leaf	4416 a	2138 a	1610 ab	1387 a
	Stem	2748 bc	3666 ab	4073 a	3730 ab
	Petiole	535 a	500 b	497 a	247 a
	Square	850 a	---	---	---
	Boll	---	8115 abc	6181 a	5731 a
	LAI	2.25 a	1.85 a	1.63 ab	1.10 a
Calendar x NDVI	Leaf	3267 ab	2738 a	1728 a	1398 a
	Stem	3090 abc	2861 abc	3613 ab	3359 ab
	Petiole	394.1	565 b	488 a	242 a
	Square	595 ab	---	---	---
	Boll	---	5266 c	7061 a	5721 a
	LAI	2.10 ab	1.96 a	1.83 a	1.20 a
Calendar x Conventional	Leaf	3342 ab	2406 a	1544 ab	1467 a
	Stem	3344 ab	4056 a	3453 ab	4168 a
	Petiole	509 a	763 a	438 a	276 a
	Square	578 ab	---	---	---
	Boll	---	8281 abc	5115 a	6946 a
	LAI	2.48 a	1.82 a	1.54 ab	1.14 a

Appendix Table A4. 2021 plant component biomass (kg ha^{-1}) by individual treatment. A Fisher's protected LSD test was used for comparison of means for each plant component by treatment for a specific sampling date (DAP) (α = 0.05).

2021					
Treatment	**Plant Comp-onent**	**Tissue Biomass (kg ha⁻¹)**			
		DAP			
		60	75	111	137
SI Cotton x Fertigation	Leaf	571 b	1044 ab	1955 a	650 a
	Stem	535 b	993 abc	5098 a	4361 a
	Petiole	149 ab	187 a	530 a	112 a
	Square	55 ab	---	---	---
	Boll	---	736 ab	3630 a	4646 a
	LAI	1.04 ab	1.25 ab	2.29 a	0.92 a
SI Cotton x Fert #2	Leaf	543 b	914 b	1302 a	670 a
	Stem	535 b	807 c	3772 a	3927 a
	Petiole	117 b	150 a	372 a	100 a
	Square	45 ab	---	---	---
	Boll	---	401 b	3932 a	6294 a
	LAI	0.96 b	1.02 b	1.93 a	0.83 a
SI Cotton x Conventional	Leaf	627 ab	919 b	1173 a	736 a
	Stem	601 ab	1128 abc	2896 a	2973 a
	Petiole	137 ab	178 a	233 a	109 a
	Square	64 ab	---	---	---
	Boll	---	661 b	3318 a	5156 a
	LAI	1.15ab	1.16 b	1.83 a	0.95 a
UGA SSA x Fertigation	Leaf	731 ab	1071 ab	1673 a	713 a
	Stem	828 ab	1027 abc	4009 a	4150 a
	Petiole	160 ab	213 a	441 a	129 a
	Square	78 a	---	---	---
	Boll	---	471 b	3653 a	4928 a
	LAI	1.38 a	1.32 ab	2.09 a	1.03 a

UGA SSA x Fert #2	Leaf	641 ab	917 b	1236 a	976 a
	Stem	721 ab	1177 abc	4040 a	5261 a
	Petiole	137 ab	187 a	294 a	150 a
	Square	64 ab	---	---	---
	Boll	---	702 ab	3133 a	7324 a
	LAI	1.18 ab	1.30 ab	1.78 a	1.25 a
UGA SSA x Conventional	Leaf	617 ab	1534 a	1556 a	993 a
	Stem	588 ab	1378 a	4105 a	4036 a
	Petiole	135 ab	226 a	498 a	133 a
	Square	36 b	---	---	---
	Boll	---	504 b	4210 a	5785.9
	LAI	1.09 ab	1.43 ab	2.61 a	1.19 a
Calendar x Fertigation	Leaf	672 ab	900 b	1378 a	747 a
	Stem	692 ab	909 c	4356 a	4174 a
	Petiole	131 ab	182 a	390 a	114 a
	Square	51 ab	---	---	---
	Boll	---	517 b	3228 a	5321 a
	LAI	1.11 ab	1.19 ab	2.26 a	1.04 a
Calendar x Fert #2	Leaf	780 a	1273 ab	1256 a	956.3
	Stem	855 a	1334 ab	3548 a	4700.7
	Petiole	172 ab	220 a	361 a	178 a
	Square	63 ab	---	---	---
	Boll	---	1353 a	3867 a	6334 a
	LAI	1.37 a	1.62 a	1.95 a	1.24 a
Calendar x Conventional	Leaf	652 ab	876 b	1909 a	825 a
	Stem	628 ab	916 bc	4641 a	4081 a
	Petiole	196 a	161 a	520 a	161 a

	Square	46 ab	---	---	---
	Boll	---	458 b	4416 a	5273 a
	LAI	1.18 ab	1.04 b	2.52 a	1.20 a

Appendix Table A5. 2018 plant component nitrogen concentration (%TKN) by individual treatment. A Fisher's protected LSD test was used for comparison of means for each plant component by treatment for a specific sampling date (DAP) (α = 0.05).

2018						
Treatment	Plant Component	Tissue N (%)				
		DAP				
		41	82	118	137	146
SI Cotton x Fertigation	Leaf	3.83 a	3.95 a	3.72 a	3.66 a	3.88 ab
	Stem	1.59 c	1.05 b	1.15 a	1.19 a	1.20 a
	Petiole	2.78 ab	1.59 a	1.33 a	1.57 ab	1.84 a
	Square	4.96 a	2.97 a	-	-	-
	Boll	-	2.01 ab	1.96 a	1.99 ab	1.89 ab
SI Cotton x NDVI	Leaf	3.71 a	3.56 a	3.28 b	3.73 a	4.36 a
	Stem	1.89 abc	0.89 b	1.00 a	1.12 a	1.12 abcd
	Petiole	2.56 ab	1.38 a	1.31 a	1.65 ab	1.61 ab
	Square	4.85 a	3.10 a			
	Boll		2.44 a	2.03 a	2.16 ab	1.87 ab
SI Cotton x Conventional	Leaf	3.94 a	4.08 a	3.68 a	3.41 a	4.20 ab
	Stem	2.29 ab	1.17 ab	1.35 a	1.07 a	1.09 abcd
	Petiole	3.08 a	1.51 a	1.32 a	1.98 a	1.50 b
	Square	5.27 a	3.02 a	-	-	-
	Boll	-	1.98 ab	2.14 a	2.18 a	2.02 a
UGA SSA x Fertigation	Leaf	3.71 a	4.10 a	3.50 ab	3.57 a	4.01 ab
	Stem	1.78 abc	0.89 b	0.62 a	1.09 a	1.01 d
	Petiole	2.22 ab	1.61 a	1.43 a	1.67 ab	1.52 b
	Square	5.10 a	3.0	-	-	-
	Boll	-	2.15 ab	2.16 a	2.08 ab	1.67 ab
UGA SSA x NDVI	Leaf	3.78 a	3.93 a	3.59 ab	3.51 a	4.19 ab
	Stem	2.21 abc	0.89 b	0.93 a	1.13 a	1.06 bcd
	Petiole	2.60 ab	1.37 a	1.21 a	2.19 a	1.56 ab
	Square	5.13 a	3.00 a	-	-	-

	Boll	-	2.09 a	2.02 a	1.86 b	1.86 ab
UGA SSA x Conventional	Leaf	3.80 a	4.08 a	3.73 a	3.51 a	3.70 b
	Stem	2.32 a	1.53 a	1.00 a	1.12 a	1.16 abc
	Petiole	2.81 ab	1.59 a	1.66 a	1.64 ab	1.73 ab
	Square	5.07 a	2.86 a	-	-	-
	Boll	-	2.09 a	2.12 a	2.08 ab	1.94 a
Calendar x Fertigation	Leaf	3.86 a	4.09 a	3.74 a	3.49 a	3.86 ab
	Stem	1.85 abc	1.03 b	0.79 a	1.12 a	1.13 abcd
	Petiole	2.64 ab	1.49 a	1.44 a	2.09 ab	1.48 b
	Square	5.05 a	2.61 a	-	-	-
	Boll	-	2.08 ab	1.97 a	1.77 b	1.67 ab
Calendar x NDVI	Leaf	3.47 a	3.77 a	3.65 a	3.65 a	4.10 ab
	Stem	1.69 bc	1.05 b	0.74 a	1.07 a	1.03 cd
	Petiole	2.23 ab	1.77 a	1.36 a	1.66 ab	1.47 b
	Square	4.78 a	3.19 a	-	-	-
	Boll	-	1.87 b	2.06 a	1.86 ab	1.69 ab
Calendar x Conventional	Leaf	3.49 a	4.05 a	3.74 a	3.90 a	4.01 ab
	Stem	1.62 c	1.02 b	0.70 a	1.08 a	1.17 ab
	Petiole	2.12 b	1.85 a	1.38 a	1.40 b	1.51 b
	Square	4.85 a	2.65 a	-	-	-
	Boll	-	2.32 a	1.91 a	2.15 ab	1.57 b

Appendix Table A6. 2019 plant component nitrogen concentration (%TKN) by individual treatment. A Fisher's protected LSD test was used for comparison of means for each plant component by treatment for a specific sampling date (DAP) (α = 0.05).

2019				
Treatment	**Plant Comp-onent**	**Tissue N (%)**		
		DAP		
		75	109	130
SI Cotton x Fertigation	Leaf	4.49 a	4.12 a	2.84 a
	Stem	1.81 a	1.31 a	3.00 a
	Petiole	1.75 a	1.34 a	3.23 ab
	Square	3.40 a	3.18 a	-
	Boll	2.48 a	1.81 a	3.66 a
UGA SSA x Fertigation	Leaf	4.47 a	3.89 a	3.16 a
	Stem	1.77 a	1.55 a	2.79 a
	Petiole	1.63 a	1.25 a	3.19 b
	Square	3.66 a	2.95 a	-
	Boll	2.71 a	1.62 a	3.75 a
Calendar x Fertigation	Leaf	4.27 a	4.00 a	3.17 a
	Stem	1.97 a	1.30 a	3.04 a
	Petiole	1.73 a	1.28 a	3.53 a
	Square	3.23 a	2.83 a	-
	Boll	2.68 a	1.73 a	3.51 a

Appendix Table A7. 2020 plant component nitrogen concentration (%TKN) by individual treatment. A Fisher's protected LSD test was used for comparison of means for each plant component by treatment for a specific sampling date (DAP) (α = 0.05).

2020					
Treatment	**Plant Comp-onent**	**Tissue N (%)**			
		DAP			
		75	111	132	139
SI Cotton x Fertigation	Leaf	4.81 ab	3.74 a	3.43 ab	3.49 ab
	Stem	1.54 ab	1.06 a	1.02 a	1.17 ab
	Petiole	1.58 ab	1.42 a	1.33 b	1.46 b
	Square	3.22 abc	-	-	-
	Boll	2.45 a	1.55 abc	0.92 a	1.33 ab
SI Cotton x NDVI	Leaf	4.51 bc	3.98 a	3.51 a	3.52 ab
	Stem	1.93 a	1.19 a	1.04 a	1.12 b
	Petiole	1.38 b	1.37 a	1.33 b	1.54 ab
	Square	3.09 bc	-	-	-
	Boll	2.34 a	1.60 abc	0.97 a	1.37 a
SI Cotton x Conventional	Leaf	4.93 a	3.92 a	3.44 ab	3.64 a
	Stem	1.56 ab	0.90 a	1.20 a	1.18 ab
	Petiole	1.59 ab	1.37 a	1.36 b	1.52 ab
	Square	3.08 c	-	-	-
	Boll	2.51 a	1.57 abc	0.79 a	1.32 ab
UGA SSA x Fertigation	Leaf	4.84 ab	3.75 a	3.28 b	3.28 b
	Stem	1.53 ab	1.08 a	1.12 a	1.26 ab
	Petiole	1.57 ab	1.39 a	1.36 b	1.57 ab
	Square	3.26 a	-	-	-
	Boll	2.33 a	1.42 bc	0.86 a	1.51 a
UGA SSA x NDVI	Leaf	4.92 a	3.87 a	3.44 ab	3.61 a
	Stem	1.59 ab	1.04 a	1.14 a	1.24 ab
	Petiole	1.83 a	1.38 a	1.47 a	1.54 ab
	Square	3.14 abc	-	-	-
	Boll	2.61 a	1.42 c	0.80 a	1.10 c
UGA SSA x Conventional	Leaf	4.47 bc	3.77 a	3.61 a	3.62 a
	Stem	1.61 ab	1.06 a	1.11 a	1.33 a
	Petiole	1.70 ab	1.38 a	1.34 b	1.59 ab
	Square	3.14 abc	-	-	-
	Boll	2.55 a	1.45 c	0.94 a	1.11 c

Calendar x Fertigation	Leaf	4.92 a	3.87 a	3.52 a	3.40 ab
	Stem	1.55 ab	1.07 a	1.17 a	1.22 ab
	Petiole	1.62 ab	1.36 a	1.33 b	1.53 ab
	Square	3.23 ab	-	-	-
	Boll	2.58 a	1.75 a	0.83 a	1.30 abc
Calendar x NDVI	Leaf	4.38 c	3.81 a	3.43 ab	3.46 ab
	Stem	1.25 b	1.03 a	1.11 a	1.29 ab
	Petiole	1.63 ab	1.43 a	1.34 b	1.76 a
	Square	3.17 abc	-	-	-
	Boll	2.53 a	1.59 abc	0.83 a	1.42 a
Calendar x Conventional	Leaf	4.77 ab	4.03 a	3.60 a	3.57 a
	Stem	1.49 ab	1.19 a	1.10 a	1.18 ab
	Petiole	1.72 a	1.51 a	1.39 ab	1.47 b
	Square	3.17 abc	-	-	-
	Boll	2.56 a	1.68 ab	0.95 a	1.13 bc

Appendix Table A8. 2021 plant component nitrogen concentration (%TKN) by individual treatment. A Fisher's protected LSD test was used for comparison of means for each plant component by treatment for a specific sampling date (DAP) (α = 0.05).

2021					
Treatment	**Plant Comp-onent**	**Tissue N (%)**			
		DAP			
		60	75	111	137
SI Cotton x Fertigation	Leaf	3.19 ab	3.42 a	3.33 a	3.11 a
	Stem	1.00 a	1.06 a	1.00 a	1.28 abc
	Petiole	1.18 ab	1.00 a	1.22 a	1.41 a
	Square	3.41 ab	-	-	-
	Boll	-	2.65 ab	1.96 a	1.28 ab
SI Cotton x Fert #2	Leaf	3.02 b	3.43 a	3.55 a	3.16 a
	Stem	1.11 a	0.95 ab	0.95 a	1.27 abc
	Petiole	1.03 ab	1.05 a	1.10 a	1.41 a
	Square	3.25 ab	-	-	-
	Boll	-	2.75 ab	1.91 a	1.23 ab
SI Cotton x Conventional	Leaf	3.10 ab	2.93 a	3.42 a	2.94 a
	Stem	1.06 a	0.77 b	0.87 a	1.39 a
	Petiole	1.17 ab	0.95 ab	1.30 a	1.38 ab
	Square	3.41 ab	-	-	-
	Boll	-	2.31 b	2.05 a	1.08 ab
UGA SSA x Fertigation	Leaf	3.60 a	3.66 a	3.63 a	2.87 a
	Stem	1.21 a	1.08 a	1.00 a	1.31 ab
	Petiole	1.22 a	1.09 a	1.20 a	1.26 abc
	Square	3.35 ab	-	-	-
	Boll	-	2.85 a	1.86 a	0.97 b
UGA SSA x Fert #2	Leaf	3.34 ab	3.32 a	3.29 a	3.22 a
	Stem	1.03 a	0.94 ab	1.04 a	1.23 abc
	Petiole	1.20 a	1.04 a	1.13 a	1.38 ab
	Square	3.47 ab	-	-	-
	Boll	-	2.61 ab	1.92 a	1.05 ab
UGA SSA x Conventional	Leaf	3.40 ab	3.23 a	3.44 a	3.11 a
	Stem	1.12 a	0.82 ab	0.99 a	1.14 abc
	Petiole	1.19 ab	1.03 a	1.12 a	1.26 abc
	Square	3.55 a	-	-	-
	Boll	-	2.59 ab	1.86 a	1.10 ab

Calendar x Fertigation	Leaf	2.95 b	3.49 a	3.62 a	3.01 a
	Stem	1.13 a	1.00 ab	0.99 a	1.14 abc
	Petiole	1.00 b	1.04 a	1.04 a	1.33 abc
	Square	3.22 b	-	-	-
	Boll	-	2.87 a	1.95 a	1.35 a
Calendar x Fert #2	Leaf	3.32 ab	3.32 a	3.07 a	2.93 a
	Stem	1.10 a	0.89 ab	0.97 a	1.04 c
	Petiole	1.12 ab	1.04 a	1.04 a	1.19 bc
	Square	3.45 ab	-	-	-
	Boll	-	2.53 ab	1.78 a	1.02 ab
Calendar x Conventional	Leaf	3.25 ab	3.50 a	3.41 a	2.72 a
	Stem	0.96 a	1.00 ab	0.87 a	1.04 bc
	Petiole	1.04 ab	1.07 a	1.12 a	1.13 c
	Square	3.32 ab	-	-	-
	Boll	-	2.68 ab	1.77 a	0.95 b