EVALUATING COTTON IRRIGATION SCHEDULING STRATEGIES AND POPULATION EFFECTS ON IRRIGATION TIMING

by

MILLER WIRT HAYES

(Under the Direction of Wesley M. Porter)

ABSTRACT

Irrigation has become a key management practice in cotton production throughout the southeast. However, in the past 10 years, many scheduling tools have been developed to better improve irrigation efficiency and reduce input costs. The main objective of this study is to evaluate various commercially available irrigation scheduling techniques for cotton. Then, assess the effects of population density on irrigation frequency and efficiency to maintain profitability through seed and irrigation inputs. The results of this study show that many sensor-based scheduling tools and the SmartIrrigation Cropfit app can all perform well when used properly. They also showed that lower final plant stands required higher irrigation volumes than denser populations. Because of this, there was no difference in profitability between any of the irrigated treatments in both 2023 and 2024.

INDEX WORDS: Soil moisture sensor, Cotton, Irrigation scheduling, Population density, SmartIrrigation App

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DEDICATION

In recognition of the generations of agronomists who have come before me. Their work is marked by a passion for agriculture and dedication to helping others as much as possible. Dad, Bumpa, Buster, and Andy, without y’all pouring countless hours instilling your passion, teaching, and always encouraging me to strive for more, there is no way that any of this would be possible. I am eternally grateful for the sacrifices you have made and the unwavering support you have shown me since I was born. Without y’all taking me under your wings and giving me some of my favorite memories from the field, whether it is crawling under the rows of cotton looking for stinkbugs, riding a tractor picking peanuts, or counting and chasing cows, without your guidance, I would not be the man I am today.

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CHAPTER I

INTRODUCTION

Cotton is one of the most economically significant crops in the U.S. with a production value of around $7 billion annually (Meyer, 2022). This comes as the U.S. is the leading global exporter of cotton providing approximately 35% of all exports in recent years (Meyer, 2022). There are two main species of cotton produced in America, Upland cotton (*Gossypium hirsutum* L.) and Pima cotton (*Gossypium bardadense* L.). Upland cotton accounts for approximately 97% of all cotton production while Pima cotton makes up the other approximately 3% of cotton production (Meyer, 2022). As a state, Georgia ranks second in the nation, with an overall cotton production of 2.21 million bales of lint and 555,000 tonnes of cotton seed for oil or feed in 2021 (*USDA/NASS 2022 State Agriculture Overview for Georgia*, 2023). The production value of this one crop alone totaled over $1.13 billion in Georgia. To produce this amount of cotton, farmers planted 473,000 hectares and harvested an average of 1024 kg per hectare (*USDA/NASS 2022 State Agriculture Overview for Georgia*, 2023). In 2017 approximately 30% of all croplands in Georgia were irrigated mainly via center pivot systems spread across the coastal plain region of the state (USDA NASS, 2017). This has allowed for yield increases of up to 968kg per hectare in drought-stricken growing seasons (Hand et al., 2024). However, this has not always equaled higher profit margins for cotton farmers as the cost of irrigation has increased in recent years to $1.33 per ha-mm of irrigation water used when using a diesel-powered system. Seed costs have also become a sizable expense for cotton producers across the state leading many of them to adjust management practices to accommodate lower planting populations. Therefore, this project aimed at identifying the irrigation scheduling techniques needed to maximize productivity in four critical parameters. Based on the top-performing techniques it also explores the effects of lowering planting populations on the efficiency and profitability of cotton production in Georgia.

Hypothesis

- Selection of the appropriate irrigation scheduling method for cotton production is critical for maximizing yield and irrigation water use efficiency.
- Cotton planting density affects the rate of soil water use in Georgia cotton production systems.
- Reducing the planting population of cotton can help reduce the overall irrigation frequency required to maintain irrigation water use efficiency.
- Increasing irrigation water use efficiency could help to maintain the profitability of cotton production in fields with lower populations.

Project Objectives

To thoroughly test the above hypothesis, the following objectives must be met.

- Compare commonly used irrigation scheduling techniques to identify optimum irrigation

  scheduling tools based on water use, maximum yield, and profitability.
- Determine if irrigation frequency be reduced at lower populations to help maintain profitability.
- Identify water use differences in cotton plant densities.
- Validate the optimum cotton irrigation scheduling strategies.

CHAPTER II

REVIEW OF LITERATURE

Introduction to Cotton Production

Cotton Production

Cotton is one of the most economically significant crops in the U.S., with a production value of around $7 billion annually (Meyer, 2022). This comes as the U.S. is the leading global exporter of cotton, providing approximately 35% of all exports in recent years (Meyer, 2022). There are two main species of cotton produced in America, Upland cotton (*Gossypium hirsutum* L.) and Pima cotton (*Gossypium bardadense* L.). Upland cotton accounts for approximately 97% of all cotton production, while Pima cotton makes up the other approximately 3% of cotton production (Meyer, 2022). This Pima-type cotton is mainly grown in the central valley of California and the western regions of the Cotton Belt. As a state, Georgia ranks second in the nation, with an overall cotton production of 2.21 million bales of lint and 555,000 tonnes of cottonseed for oil or feed in 2021 (*USDA/NASS 2022 State Agriculture Overview for Georgia*, 2023). The production value of this one crop alone totaled over $1.13 billion in Georgia. To produce this amount of cotton, farmers planted 473,000 hectares and harvested an average of 1024 kg per hectare (*USDA/NASS 2022 State Agriculture Overview for Georgia*, 2023).

Georgia Cotton Production

The vast majority of cotton grown in Georgia is spread across the coastal plain region of the state which is known for its sandy loam and loamy sand soils that are inherently well-drained. This region is home to the Tifton soil series, which covers more than 75% of the southern coastal plain soil province (Hancock et al., 2014), (*Official Series Description - TIFTON Series*, n.d.). These soil types, paired with the long, warm growing season and consistent high humidity found in the southeast, create an ideal environment for cotton production (Sawan, 2017). The growing season in Georgia begins in late April to early June after soil temperatures have reached a minimum temperature of 18˚C (Hand et al., 2021).

Stand Establishment

The foundation of growing any type of crop profitably begins with getting a proper stand and plant density. The most critical time for this is at the very beginning when a seed is planted. One of the biggest factors for the early growth and development of cotton is planting depth. This has one of the most significant effects on crop emergence and initial stand establishment. New developments in planter technology, particularly downforce systems being utilized, have been shown to help with the emergence and early season plant development by placing the seed as close to the soil moisture front as possible (Virk et al., 2021). Planting in high downforce situations such as a no-till or conservation tillage situation requires the seed to have a higher seedling vigor. This can be achieved by using a hill-drop planting configuration, where multiple seeds are placed in one hill so that they have a higher combined seedling emergence. However, this can be an impedance in cases where seedling diseases, particularly Rhizoctonia, can infect all the plants in that hill space and lead to a large skip in the final crop stand (Hake, Burch, et al., 1991). In areas where planting conditions are optimal, lower downforce can be used, and singulated uniform plant spacing creates a more uniform stand than a hill-dropped planting configuration (Virk et al., 2018).

The effects of plant density in cotton include alterations in humidity, wind movement, and soil moisture extraction. Crop factors like plant height, branch development, fruit location, size, light interception, and crop maturity can all be affected by plant density. Intra-plant competition drives early-season growth, leading to a taller crop canopy. However, as the plants develop and begin competing with each other, the scarcity of resources begins to limit the amount of total crop growth possible (*History of the Boll Weevil Eradication Program*, n.d.).

Much research has been done to determine the optimum planting population for cotton; however, many of the studies have reported mixed results. It has been noted that lower populations resulted in greater fruiting site production and increased fruit retention and boll weights per plant (Bednarz et al., 2000; Baker, 1976). Yields are highest in populations up to 152,880 plants per hectare in a three-plant hill drop arrangement. However, yields did not begin to reduce significantly until populations were reduced to 83,918 plants per hectare (30.5-cm plant spacing) in a singulated situation and 50,956 plants per hectare in a hill drop situation with three plants per hill (60cm hill spacing) (Siebert et al., 2006a). This data was confirmed by Wrather et al. (2008), whose data from Missouri in the northern part of the mid-south cotton belt showed comparable results. This study found that seed cotton yields were similar for populations from 33,976 to 135,904 plants per hectare and significantly lower at 23,782 plants per hectare.

Early research conducted at the University of Georgia Coastal Plain Experiment Station in Tifton, GA, found that there was no significant difference in yields between plant populations of 214,977, 286,636, and 358,295 plants per hectare when planted in various row arrangements. This included a 25-cm twin row and a 38-cm narrow row configuration, as well as a 107,489 plant per hectare check, planted on 91.4-cm standard single rows. However, based on bloom counts conducted on the 21st day after the first bloom that study found that the traditional 91-cm rows planted at 214,890 plants per hectare had the lowest bloom counts, with the narrow rows having the higher bloom counts. The plant population did not have a significant effect on the total number of blooms per plot, which was affected the most by row configuration. Yield potential followed the trends seen with bloom counts; however, the highest percentage of blooms harvested came from the 91.4 cm wide row plots. This was due to an inverse relationship found between the row spacing and the percentage of harvested bolls. This was found to be due to boll shedding caused by environmental factors related to the crowding of the plants (Baker, 1976).

Canopy Effects

Cotton canopy architecture, which is the above-ground three-dimensional organization of plant parts, plays a key role in many physiological processes, such as photosynthetic efficiency (Reinhardt & Kuhlemeier, 2002). Because cotton is an indeterminate perennial plant that is managed as an annual crop, factors such as height and branching must be managed properly to preserve yield. The two types of cotton canopy are columnar and bush varieties. The taller more cylindrical columnar varieties tend to be more competitive with weeds and are, therefore, better suited for mechanical cultivation.

However, bush types are better at accumulating more nutrients in their branches and leaves than columnar plants. Bush-type varieties are more likely to compensate for lower planting populations with no significant yield response being seen between populations of 23,198 and 51,295 plants per acre in a study conducted in Maricopa, Arizona. This same study showed that the bush variety began reproductive growth earlier, allowing it to partition more resources to boll development; however, at higher populations, higher yields were attained with columnar-type plants (Kaggwa-Asiimwe et al., 2013).

Cotton Growth, Development, and Production Practices

After planting, cotton grows through five main growth stages, which include germination and emergence, seedling establishment, leaf area and canopy development, flowering and boll development, and maturation (Oosterhuis et al., 2008). The first square, called the pinhead square, typically appears between the fifth and seventh mainstem node; this is the squaring structure that will develop the plant's first flower if not aborted. After this, the same fruiting position on the next sequential mainstem branch up the plant will open about three days later. The next successive fruit on the same branch will develop after about six days from the first bloom opening. This pattern continues in a spiral pattern up the plant until frost or the plant goes into cutout, which is the end of the effective fruiting period (Oosterhuis et al., 2008).

Many things can affect cotton growth and development rates and patterns which is measured as the height-to-node ratio (HNR). HNR is an indicator of plant stress or can be a sign that an application of a plant growth regulator, most commonly mepiquat chloride (MC), is needed. Mepiquat chloride inhibits the production of the plant growth hormone gibberellic acid which is critical to cell and node elongation (P. Jost et al., 2006). A secondary effect of MC application is a small, 5-10% decrease in leaf area index as well as thicker leaves, making them appear to be greener as a result of extra layers of chloroplast cells (Hake et al., 1991). Temperature has an impact on growth rate as seen by a study conducted by Reddy et al., (1996), which concluded cotton grown with a daytime temperature of 35˚C and a nighttime temperature of 27˚C was taller and developed fruit sooner than its counterparts grown in warmer and cooler environments.

Plant height is a critical factor in production because a more compact plant typically is easier to harvest as the plants are able to move through the cotton picker head more freely. A study found a yield response to the cotton height that up to 5.53kg/cm/ha could be lost due to rank growth (Mahaffey, 2022). Smaller plants allow for pesticides to be more evenly distributed throughout the plant canopy. The droplet can penetrate the sides of the canopy allowing deeper penetration into the canopy cover.

After cotton has developed and matured, bolls begin opening to expose the lint and seeds that have formed inside. Cotton in the mid-south on average requires about 2600 growing degree days (DD-60) to complete its growth cycle from planting to harvest. The growing degree day concept uses heat accumulation rather than days to describe cotton development and is used as a general physiological time scale for crop development (Oosterhuis, 1990; Raper et al., 2023).

Defoliation is the final step in the cotton production process before it is finally harvested, using a mechanical cotton harvester. Studies have shown that full-season cultivars see maximum yields when defoliation occurs at ten mature fruiting branches and

42-64% open bolls (Siebert & Stewart, 2006). There are a variety of ways that this can occur, and they are all utilized differently based on the situation. However, all methods include the broadcast application of a defoliant over the crop. All defoliant applications include some sort of a combination of an herbicidal or hormonal chemical application made in either one or two applications. These chemicals will have an herbicide that will damage the leaf to the point where the plant is forced to abort and abscise it at the base of the petiole causing it to fall off. If they do not utilize an herbicide, there are other chemicals which contain hormones that suppress the auxin in the plant allowing the natural ethylene and abscisic acid to mature the leaf causing it to abscise and fall off in the same manner (Cothren et al., 2001). This process is necessary to prevent the leaf from crushing and contaminating the lint and prevents staining of the lint as it is harvested. After the crop is harvested, it is transported to a gin where the seeds are separated from the lint, and it is cleaned and prepared for use by a textile mill.

Cotton pest control

Various types of pests cause crop stress and damage to cotton which ultimately leads to yield loss. Historically, the most detrimental pest to cotton production in Georgia was the boll weevil (*Anthonomus grandis*, Boheman, 1843) (*History of the Boll Weevil Eradication Program*, n.d.). The boll weevil spread rapidly up across the entire Cotton Belt from Mexico costing over $100 million to control from 1985-1995 (Haney et al., 2009). The total cost of the program in Georgia was around 99.3 million with 69.1% of the funds raised coming from growers as a per acre fee for cotton production (Haney et al., 2009). The Boll Weevil Eradication Program has been one of the most successful programs in agricultural history as, the final and ongoing results have completely eradicated boll weevils from all parts of the U.S. Cotton Belt, except for a small area in south Texas. This is because natural events such as hurricanes keep reintroducing them to areas that are nearly eradicated (*History of the Boll Weevil Eradication Program*, n.d.). Other major insect pests include aphids (*Aphis gossypii*), thrips (*Frankliniella fusca,* Hinds), plant bugs *(lygus lineolaris*, Palisot de Beauvois), and the bollworm complex which all attack the plant at various stages of growth and development (Hand et al., 2023).

Aphids tend to attack the soft developing tissue near the terminal or bud of the plant through many stages of growth. They feed by piercing and sucking the sap out of the plant while secreting a sticky substance called honeydew that creates favorable conditions for other fungal pests such as sooty mold to grow on the leaves after aphid's feed. They also serve as a vector for cotton leafroll dwarf virus (CLDRV), which is a potentially major yield-limiting plant virus that can have vastly differing effects and symptoms on the plant (Mahas et al., 2022). Thankfully, there is a fungal species, *Neozygites fresenii*, which is pathogenic to aphids, and naturally regulates the populations in cotton (O'Brien et al., 1993).

Thrips attack cotton as it begins to develop its first few leaves and as they unfurl out of the terminal. This causes the leaves to come out wrinkled and impaired which can delay the maturity of the crop and reduce crop yield (Leigh, 1995). Several strategies for controlling thrips include the use of insecticides applied either via broadcast, banded, as a seed treatment, or systemically in the planter furrow. Once a cotton plant grows to the four-leaf stage it will become increasingly tolerant to thrips feeding (Hand et al., 2023).

Plant bugs begin to feed on small pinhead squares as soon as they begin to develop in the terminal by using their needle-like mouthparts to suck the sap and nutrients out of the squares causing them to abort and fall off. They can also feed on larger blooms right before they open causing darkened and damaged pollen anthers which are known as dirty blooms and can cause pollination issues within that particular fruiting position. Plant bugs have also been known to feed on smaller bolls causing wart calluses inside, causing the internal lint to begin rotting. The main method of plant bug control is through the use of a variety of broadcast applications of insecticides applied as economic thresholds are met (Reisig & Huseth, 2023).

The cotton bollworm complex refers to both tobacco budworms (*Heliothis virescens,* F.) and the corn earworm (*Helicoverpa zea*, Boddie) as they are both anatomically identical to the naked eye as larvae and are therefore indistinguishable from each other based on infield observations. Both species have similar feeding processes and similar control regimes, therefore, they are both referred to as the bollworm complex. (Roehrdanz, 1997). Bollworms feed on the top or sides of maturing bolls by feeding off the contents, typically under bloom tags or hidden within the bracts. Insecticide applications have been used as a control method for bollworms but are limited due to resistance management and toxicity concerns with the chemicals used (Musser & Catchot, 2022).

In 1995 the Environmental Protection Agency (EPA) approved the use of a genetically modified cotton variety. It contained a foreign gene from the bacteria, *Bacillus thuringiensis* (BT), creating the first commercially available transgenic cotton. This gene causes the plant to produce a protein known as Cry1Ac, which is crucial to the management of many lepidopteran pests (Hardee et al., 2001). In recent years, new variants of this same technology have been commercialized to stack up to three BT traits into modern germplasms. As of 2023, new approval for a similar trait, called Thryvon, has been granted for use in Bayer cotton varieties with strong activity against thrips and lygus species (Graham & Smith, 2023).

Similar technology has been used to create cotton varieties that are now herbicide tolerant (HTC), to allow widespread use of nonselective herbicides for weed control that previously had not been available for use in this way. While other traits for more herbicides are still in development, currently, the only four herbicides that have a trait designated for resistance to them in cotton are glyphosate, glufosinate, dicamba, isoxaflutole, and 2,4-D choline (Dodson et al., 2021). While this has helped growers in numerous ways, it has also caused issues such as herbicide resistance and an increase in off-target applications, particularly related to dicamba's volatilization and drift (Vieira et al., 2020). Herbicide resistance has been a widespread issue in cotton production. In a study conducted by Culpepper et al. (2006), 3260 palmer amaranth plants ha^{-1} reduced cotton lint yield by 22%. Since the release of HTC, there has been a shift in the weed spectrum to species that are resistant to herbicides with an associated tolerance trait. This makes stewardship and the development of a well-balanced weed management program one of the most critical components of our pest management system (Webster & Sosnoskie, 2010).

Row Crop Irrigation

Irrigation History

One of the most crucial drivers of societal and agricultural advancement throughout history has been the development and ability to implement irrigation devices or structures to nourish crops across the globe. Artifacts dating back nearly 5,000 years ago have been found in Egypt, where embankments and channels were constructed to capture and retain the annual flood waters of the Nile (Gulhati & Smith, 1967). By the 8th century, 607,000 hectares across the globe were under annual irrigation using similar structures. Similar canals and diversion structures have been found across southern and eastern Asia that date back prior to 600 B.C. Canal irrigation has been continuously used in most natively settled areas along rivers or major sources of water across all continents since then. However, many of these systems had shortcomings and design flaws due to the lack of understanding of river hydraulics at the time of construction. In the late 19th century, several large canal and river control structures turned out to be largely successful in India. Shortly after, more large advancements came with the advancement of the steam and gasoline motors, which could be attached to submersion pumps and used to make groundwater readily accessible for irrigation use independent of river levels (Gulhati & Smith, 1967).

The Reclamation Act of 1902 provided federal funds to areas of the American West and High Plains to construct major water control structures. Large-scale adoption of irrigation practices occurred in the middle of the 20th century due to this new infrastructure that gave steady access to water in areas such as the Imperial Valley that were previously arid or drought-stricken (Gulhati & Smith, 1967). In 1948, Frank Zybach invented the center pivot sprinkler irrigation system, which has quickly become the most popular irrigation method in America because of its potential for automated use, low labor requirements, and minimal annual setup after initial installation (Eisenhauer et al., 2021). Areas in the southeast, like Georgia, were some of the last areas to adopt irrigation practices. Much of the water used in Georgia comes from groundwater wells rather than rivers or surface canals (Eisenhauer et. al, 2021).

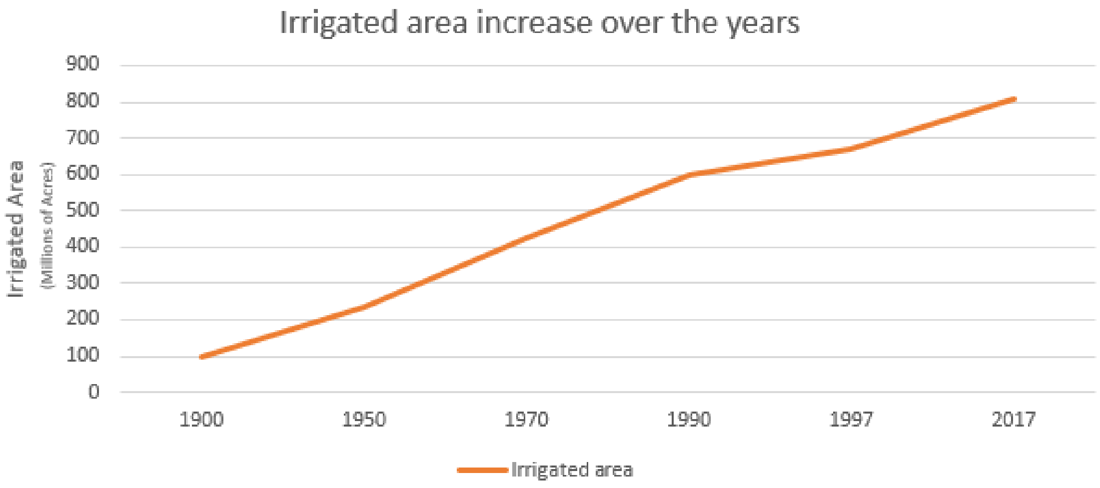

Figure 1: Rate of Irrigation adoption since 1900 (Eisenhauer et al., 2021)

Irrigation Design

Three main types of irrigation systems are widely used in modern agriculture: sprinkler irrigation, micro irrigation systems, and gravity flow irrigation systems. While there are several different sub-designs of each of these main system types.

Sprinkler irrigation systems can be described as solid-set sprinklers, traveling guns, center pivot, or lateral move systems. A solid set is a system in which large sprinkler guns are permanently installed in a field at a distance that optimizes irrigation uniformity (Smajstrla et al., 2018). These systems tend to be costly to install in large areas and create obstacles in fields that could potentially become bothersome to work around. Traveling gun systems are a second type of sprinkler irrigation that features a single portable water gun similar to a solid set gun that is pulled across the field slowly by a hose reel or cable tow, which allows it to water a small area. The most common type of sprinkler system is a center pivot and lateral move system. These are self-propelled systems that are designed for use in a particular field or location. They work using an overhead pipe to feed sprinklers that are located along the length of its spans. Center pivots are fixed on one end of the system in the middle of the field, and the other parts of it move in a circle around it, covering a large area. Lateral movement systems move in a straight line, being guided by either a trench, GPS, or tight cable. They typically drag a large hose or pump out of a ditch that is parallel to them (Smajstrla et al., 2018).

Micro irrigation systems are low-pressure systems that use low-flow rate emitters positioned near the root zone (Evans et al., 2007). This type of irrigation is known for its high irrigation efficiencies and wide use in plasticulture and orchard production systems. The first type is known as dripline systems, which use a small tape that is placed near the row on top or below the soil surface to apply water continuously along the length of the line. The next type of micro irrigation is the spray systems, which use a small mister to spread water over a small area within a few feet of the emitter. This type of system is the most common in orchards or crops with a large rooting zone. These systems can also provide limited freeze protection because they have a larger application area than other micro-irrigation systems. The final type of micro irrigation system is bubbler systems, which use a low-pressure emitter to trickle water into individual containers or basins.

Bubblers are normally only used in nurseries due to complexity and design limitations (Evans et al., 2007; Smajstrla et al., 2018).

The final type of irrigation is gravity flow irrigation systems. Gravity systems are highly dependent on topographic and hydraulic properties. Most fields that utilize gravity systems are leveled or graded using advanced surveying equipment and can only be utilized in readily suited soil types. The two types of gravity flow systems are sub-irrigation systems and surface flooding systems. Sub-irrigation or seepage systems work by filling ditches above field level or underground conduits to create a water table above the natural one that is shallow enough for the crop can reach. Surface flood irrigation is the practice of releasing water in large quantities to flow down the row and then letting it slowly infiltrate into the soil. This system is not used in Georgia because it requires soil with high clay content and a slow infiltration rate (Smajstrla et al., 2018).

Irrigation Efficacy

A long-term systems comparison study conducted in Shellman, Georgia, found that using a sprinkler or shallow subsurface drip (S3DI) system resulted in higher lint yields than a normal subsurface drip line system (SSDI) when based on irrigation recommendations using the USDA-ARS Irrigator Pro irrigation scheduling app (Sorensen et al., 2021). Additionally, this study found an increase in irrigation water use efficiency (IWUE), kg cm^{-1}, and value water use efficiency (VWUE, \$ cm^{-1}) of a sprinkler system compared to the SSDI (Sorensen et al., 2021). It has been noted that when using sprinkler systems, the water took longer to recharge further into the root zone than it did when using drip irrigation. This requires either a large rain or an excessive or sequential irrigation event to allow water penetration deep into the root zone (Whitaker et al., 2008). Some of this reduced infiltration can be caused by crusting of the soil surface, which is exacerbated by water droplets force when contacting the soil surface. AL-Kayssi & Mustafa, (2016) found that this phenomenon got progressively worse with repeated rain and irrigation events.

Reduced infiltration rates can be correlated with reduced irrigation efficiency. When irrigation is supplied at a rate higher than the infiltration rate, then the water will leave the field as runoff, carrying nutrients, soil, and chemicals with it (Alhammadi et al., 2013). It has been shown that irrigation runoff can contain significant levels of not only sediment but also the nitrogen, phosphorus, and potassium that is held onto it. This is, of course, influenced by furrow length, runoff velocity, and fertilization timing and type (Lentz & Lehrsch, 2010). Erosion is the main means of transport for nutrients in the water as they were found to be directly related. This erosion starts when soil particles are detached and carried by the water to other areas (Bjorneberg et al., 2006). This is less of a factor to consider when irrigating cotton in Georgia, as center pivot systems are by far the most widely used irrigation system on Georgia farms (Porter et al., 2022). However, the slope and topography of much of Georgia was classified by the USDA as being either moderately or severely at risk for sheet and gully erosion (Trimble, 1985). This can lead to ecological issues as well since the nutrients in the water often flow into larger aquatic basins that can suffer from algal blooms because of the influx of fresh nutrients (Bjorneberg et al., 2006).

Reducing irrigation water loss should be of utmost priority for growers and producers as every acre-inch of water that is pumped and lost reduces the overall profitability of the grower’s operation. The expense of irrigation varies year to year depending on the well type, fuel prices, and pivot length per area watered. In 2021, the University of Georgia's irrigation budget estimated an approximate cost of \$0.60 ha mm^{-1} of water applied using an electric well system. If a grower is using a diesel well, the cost per hectare millimeter of water in that same spreadsheet was estimated to cost approximately \$1.33 (Liu et al., 2024). While it is hard to quantify and varies vastly on a case-to-case basis, these numbers do not account for depleted or leached fertilizer and pesticides or the loss of soil via erosion and crop yield.

Cotton Irrigation

Crop Water Use

The yield benefits of irrigation on cotton have been widely documented by scientists for many years. These include everything from aiding in stand establishment to herbicide activation and pest management. It also aids in helping the plant avoid water stress throughout the normally hot reproductive periods when the plant is the most active. However, issues can also arise from over-irrigating, like rank growth patterns or the creation of an excessively humid environment as bolls begin to open, which can lead to boll rot (Perry et al., 2017). Water is arguably the most important molecule in plant function as it combines with CO_2 during photosynthesis to form glucose, which is the main source of energy for the plant. Proper hydration is also tightly coupled with a plant's ability to maintain proper turgor pressure (Wrona et al., 1999).

Cotton extracts its water from the soil, acting as a straw between the soil and the atmosphere, using its stomates to regulate the process. The atmospheric draw for water is a key factor in determining how much water needs to be supplied to the plant, either as rain or irrigation. If this requirement is not met, then the plant will undergo stress from heat and dehydration, referred to as crop evapotranspiration (ET_C). The actual rate of ET_C is affected by climatic conditions, crop size, and soil moisture content. This flow of water through a plant can also be used to determine plant health as the evaporative cooling from the water helps to cool the plant (Hake et al., 1992). This can be measured with infrared reflectance sensors to calculate crop vegetation indices such as the normalized difference vegetative index (NDVI). A significant connection between soil water content and plant water content has been found to influence nitrogen uptake through the plant. This has led to a decrease in near-infrared light reflectance, which is a key component in NDVI calculations, reflecting a healthier plant when plant water demand is met (Li et al., 2001).

The basis for all healthy plant development begins with a strong, healthy root system. Roots are the primary vessel for nutrient and water uptake for the plant and can significantly affect plant development. Taylor & Klepper (1974) found that plants with smaller root systems were much more susceptible to drought stress than plants with a larger root system; they also found that drought stress begins to become a self-propagating issue. They also found that root growth ceased to increase when soil moisture dropped below 0.06-0.07cm^3/cm^3. A limited period of drought stress in cotton, however, can help to drive cotton roots deeper into the soil profile in search of available water (Taylor & Klepper, 1974). However, this does not equate to a larger root system as the roots that developed in drought conditions tend to have a thinner, longer tap root with the same biomass as a well-watered plant (Pace et al., 1999). The source-sink relationship between the plant’s roots and shoots has an interdependent relationship with the carbohydrate production of the plants, so if damage or stress, including drought, is applied to one system, then growth is lowered, and yield potential is lost (Ritchie et al., 2007).

Irrigation Scheduling

Soil is made up of three parts: ~35-55% solid soil and ~45-65% pore space, which is made up of either water or air in varying ratios. These ratios change based on factors such as soil texture, rainfall/irrigation, and structure (Easton & Bock, 2016). Soil water content (SWC) is the amount of water held within the soil profile at any time. SWC can be measured in several different ways: volumetrically, gravimetrically, or Matric potential. Volumetric measurement is measuring the volume of water per unit volume of dry soil expressed as percent moisture. Gravimetric content is the mass of water compared to the unit mass of dry soil measured as (cm^3/g) * (g/cm) (Peterson, 1999). Lastly, the matric potential is the measure of the force that it takes the plant to exert to remove the water from the soil particles measured as kilopascals (kPa).

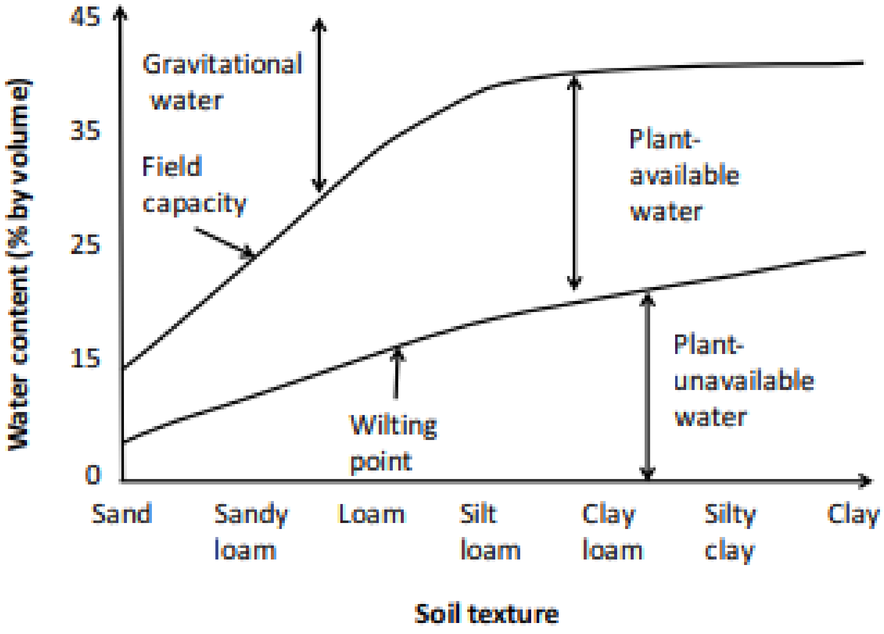

Figure 2: Plant available Soil water content as a percentage of soil content based on various soil textures (Eason and Bock, 2016).

It is important to know that not all SWC is completely plant-available water for plant use or uptake. Different soil textures have different holding capacities based on particle size. Sandy soils have smaller pores for water to be held in and have more macro pores and infiltration because there is less surface area to hold the water on the surface of the soil particle as compared to clay soils. Heavier clay soils have more surface area on them, so they have a stronger adhesion force holding the water molecules to the soil particles. This, combined with clay's increased pore space, allows it to hold a significantly higher volume of water compared to sand particles. This is one of the reasons for the higher infiltration rates of sandy soils which are found in the Coastal Plains of Georgia. These adhesive forces are what prevent a plant from completely absorbing all of the SWC. Plants can break many of the chains of molecular cohesive forces that attach water molecules to each other which is what is known as plant-available water, this volume of SWC changes based on soil texture as described in Figure 2 The matric potential measures the forces needed to overcome the adhesive and cohesive forces exerted on the SWC. When water is bound tightly to the soil, the roots of cotton struggle to absorb it into the plant, which leads to drought stress. Soil matric potential is never a positive value and starts at zero at complete saturation and only goes down from there in most cases (Alhammadi et al., 2013; Easton & Bock, 2016).

There are several methods and devices for determining soil moisture based on the various properties and characteristics of SWC. The weight method is a method that requires sampling and physically drying soil to obtain a measurement of moisture at one point and time. This is a very time-consuming and laborious process that is not well suited for production agriculture in America. The use of a tensiometer allows for the estimation of the binding forces in the soil metrics. This process is commonly used and involves using a gauge like a mechanical tensiometer or an electronic sensor such as a Watermark Irrometer sensor (Irrometer Company, Inc. Riverside, CA.). These are relatively inexpensive and can be monitored remotely. However, they require some calibration and can be less accurate or slow to respond in sandy soils. Volumetric probes measure several factors, including the capacitance of the soil by emitting an electromagnetic field in the soil, which is influenced by SWC. This can be a very accurate way to measure soil moisture. However, one sensor can only measure a small area of the field. Time domain reflectometry measures the dielectric constant of the soil between two probes using an oscilloscope to measure the time it takes the pulse to travel, thus relating it to SWC. Neuron probes are the final method of collecting volumetric SWC data using a device that emits radiation and measures its rate of attenuation, which is slowed by an increase in hydrogen in the water, allowing for a calculation of water content. This process is extremely expensive and requires licensing and special training due to its use of radioactive properties (Sharma, 2019).

Evapotranspiration

Cotton water use changes throughout the growing season based on both crop growth stage and relative humidity. This can be described by the crop coefficient (K_C) value, which is equal to the evapotranspiration (ET) of the crop (ET_c) divided by the local reference ET (ET_0), which is known as the Penman-Monteith equation. The K_c curve developed by many scientists across many cotton-growing regions of the world and adopted by the FAO, known as FAO 56, is shown in Figure 3 (Allen et al., 1998; Kumar et al., 2015). This can be an important model for irrigation scheduling as the crop water use changes throughout the season.

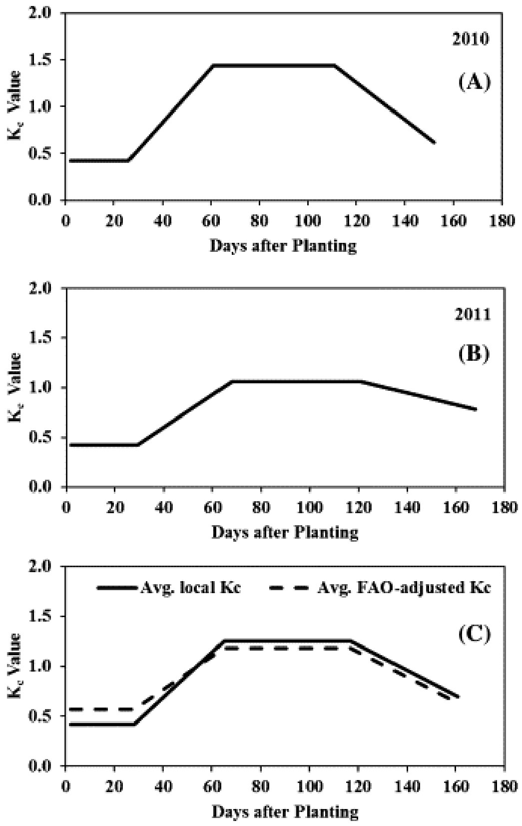

Figure 3: Kc curves from a model developed for humid climates in Louisiana based on the FAO 56 formula developed by Allen et al. (1998) (Kumar et al., 2015).

One issue with irrigating based on this model is that it needs to be calibrated for site or region-specific conditions to accurately calculate data from in-field conditions. This model serves well as the basis of a checkbook-type irrigation scheduling tool. However, a report by Thorp et al. (2017) listed databases on real-time soil moisture and climactic sensors as an avenue for potential future irrigation scheduling optimization. Vellidis et al., (2016) were able to integrate these data together to make a successful smartphone app that not only uses the FAO-56 curve but also integrates local weather and an estimate of a soil water balance to determine an estimated water requirement. Soil moisture data is estimated by using the University of Georgia weather network or a local weather station hardware to input data into the app. The app then uses climate data and the local K_c curve created by Vellidis et al. (2016) to estimate the ET_c and volumetric water content of the soil.

Other methods integrate one or more soil moisture sensors into an algorithm that schedules irrigation based on measured soil moisture measurements. One example of this is the UGA smart sensor array (UGA SSA) that uses a threshold of 40 -50 kPa (Vellidis et al., 2008). Various studies have found variable results for what is the best SWT to schedule irrigation. Typically, they range from -30 kPa to -70 kPa depending on the production region (Flynn & Barnes, 1998; Leib et al., 2015; Porter et al., 2023). There are several other commercially available systems that many irrigation companies have created using their own proprietary version of this same concept. Some of these systems integrate multiple sensors into one platform and dashboard, such as the Valley 365 (Valmont Industries, Valley, NE) or Crop Metric CropX system. Some researchers have tried to incorporate these into variable-rate equipped center pivot systems to apply irrigation only in areas that need it (Vellidis et al., 2013). This is a way that growers and researchers are addressing the issue of spatial variability of slope texture and water holding capacity as well as nonfarmed areas, however, adoption of such practices is still low. (Vellidis et al., 2013).

CHAPTER III

COTTON IRRIGATION SCHEDULING: WHICH APPROACH IS THE BEST FIT FOR GEORGIA?[1]

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[1] Hayes, M. W., Porter W. M., Snider, J. L., Reagin, K. G., Perry, C. M., 2024. *Journal of Cotton Science* 28 (3) Reprinted here with permission of the publisher

Abstract

Cotton (*Gossypium hirsutum*) is one of the most difficult crops to properly manage irrigation due to the crop's perennial physiology. In recent years, many new technologies have been developed to help improve irrigation management. The main objective of this study was to evaluate various irrigation management tools and to assist farmers in determining which method is the best for their operation. The sub-objectives of this study included monitoring soil moisture and determining the optimal irrigation application point of each method by logging the total rainfall and irrigation distribution throughout the growing season. A three-year study was conducted at the University of Georgia Stripling Irrigation Research Park near Camilla, GA, where cotton was grown on loamy sand soil. A lateral-move overhead sprinkler system, equipped with a variable rate system, allowed plots to be irrigated independently based on treatment. Irrigation treatments included a range of weighted average soil water tension (SWT) thresholds, measured using three Watermark SWT sensors placed into two of the three replicates. The UGA SmartIrrigation Cotton app (SI App), the UGA Checkbook method (checkbook), three commercially available tools, and a rainfed check were included in the trial. Each irrigation method was evaluated based on crop yield, irrigation water use efficiency (IWUE), and profitability. The analysis revealed significant variations in several metrics between treatments and validates a 45 kPa SWT threshold, and the SI App are top-performing advanced irrigation scheduling tools on an annual basis. This indicates the importance of advanced irrigation scheduling and highlights the strengths and weaknesses of each method.

Introduction

The use of irrigation systems has increased significantly over the last two decades across the southern region of the cotton belt (Perry et al., 2017). Since 1900, irrigated land area has increased from 40.5 to 326.1 million hectares in 2017, with an increase of 55.4 million hectares since 1997 (Eisenhauer et al., 2021). This drastic increase has led irrigated agriculture to become the largest user of freshwater resources (Berthold et al., 2021). Reports from Dieter et al. (2018) have shown that irrigation accounts for 42% of all freshwater withdrawals, adding up to 277 million cubic meters of water per day in 2015. Southeastern states account for approximately 18.4% of all irrigation water consumption and is primarily in Arkansas, Florida, and Georgia (Hrozencik, 2023).

With this increase in water usage has come a rise in the number of systems and tools designed to optimize irrigation scheduling practices. Many of these tools are marketed commercially by private companies or are the results of public research developments from land grant universities or the United States Department of Agriculture (USDA). Several factors, such as initial investment price, time requirements, and performance, influence the adoption of these methods (Porter et al., 2023a). A few of these scheduling methods include the UGA Checkbook method (Checkbook) or the SmartIrrigation smartphone app (SI App), which are free to use but may require a daily time investment to track local rainfall to calculate irrigation requirements (Bhattarai et al., 2020; Vellidis et al., 2016).

Many of the systems require the use of a weather station or Soil Moisture Sensor System (SMSS) to quantify Soil Water Content (SWC). The most common SMSSs measure soil moisture based on either soil water capacitance or Soil Water Tension (SWT).

Soil water capacitance is a measurement of the dielectric properties of the soil based mainly on SWC to quantify its Volumetric Water Content (VWC) (Francesca et al., 2010; Gardner et al., 1998; Moncks et al., 2022). SWT is the other commonly utilized method for measuring SWC. It is based on electrical resistance inside a granular matrix moisture sensor such as a Watermark sensor (Irrometer Co. Riverside, Ca.) (El-Marazky et al., 2011; Rix et al., 2021). Research has shown that the optimum irrigation threshold for SWT sensors can vary substantially, with various studies finding optimum results to be anywhere from 40-60 kPa for field-grown cotton (Flynn & Barnes, 1998; Grant et al., 2017; Porter et al., 2023b; Vellidis et al., 2008)

Over the past couple of decades, numerous studies have shown yield and profit reductions caused by both under and over-irrigation in Georgia cotton crops. Drought stress or under-irrigating can limit cotton growth and development, especially leaf area development, mainstem elongation, and reduced number of fruiting sites (Chastain et al., 2016; Krieg & Sung, 1986; Loka & Oosterhuis, 2012; Pace et al., 1999). In addition, source strength is limited by drought due to reduced leaf area, which reduces the amount of photosynthate available to support a developing boll load by up to 54% (Chastain et al., 2014; Krieg & Sung, 1986; Pace et al., 1999). This reduction in photosynthate can result in a substantial yield decline caused by drought stress-induced fruit shedding leading to a reduction in boll density of 33.7% and a yield decline of up to 58% compared to a well-watered crop (Balkcom et al., 2006; Chastain et al., 2016; Krieg & Sung, 1986; Lee et al., 2023; Loka & Oosterhuis, 2012; Lokhande & Reddy, 2014). However, other studies have shown that excessive irrigation can also be detrimental to cotton yields, profitability, and groundwater resources as well (Ermanis et al., 2021; Geerts & Raes, 2009; Grant et al., 2017; Liu, et al., 2022b). Ermanis et al. (2021) showed reductions in yield as irrigation volume increased from 100% crop evapotranspiration (ET_C) to 125% ET_C, which was calculated using the Penman-Montieth formula as reported by Vellidis et al. (2014) (Equation 1). A Similar study found that yield loss is driven by a reduction in radiation use efficiency by up to 35%, which lowered overall dry matter accumulation, fruiting sites, and yield potential (Bange et al., 2004; Najeeb et al., 2016). Other abiotic problems can arise from over-irrigation, such as nutrient leaching and boll rot development (DeTar, 2008; Perry et al., 2017). Because of this delicate balance, cotton is regarded as one of the most challenging crops to properly irrigate, as over- and under-irrigation can both be detrimental to yield and profitability (Liu et al., 2022b; Porter et al., 2023a).

One of the foundational publications for irrigation scheduling, which most scheduling models are based on, was the FAO Report 56 (Allen et al., 1998). This established guidelines for determining localized crop coefficient (Kc) curves for crops such as cotton, as seen in (Ko et al., 2009; Kumar et al., 2015). This allows for the calculation of crop evapotranspiration (ETc) based on local reference evapotranspiration data (ET_0) using the Penman-Monteith (Equation 1) (Allen et al., 1998; Ko et al., 2009). This model has been widely adapted for use by many of the water balance models, such as the SmartIrrigation app (Vellidis et al., 2016).

$$\mathbf{ETc = Kc\ X\ ETo}$$

Equation 1: Penman-Monteith equation for calculating crop evapotranspiration.

With these new advances in irrigation scheduling technology, many farmers are overwhelmed when determining which scheduling approach best fits their operation. Therefore, the main objective of this multi-year study was to evaluate various irrigation scheduling tools and strategies based on yield, Irrigation Water Use Efficiency (IWUE), and profitability. This is aimed at helping producers determine which irrigation scheduling tools are best for their operation.

Materials & Methods

The field experiment for this study was conducted throughout the 2020, 2021, and 2022 cotton growing seasons on a Lucy loamy sand (Loamy, kaolinitic, thermic Arenic Kandiudult) at UGA's Stripling Irrigation Research Park (SIRP) near Camilla, GA. The plot layouts followed a randomized complete block design under a lateral movement overhead sprinkler irrigation system equipped with a variable rate controller. Nine treatments were replicated three times in the 2020 growing season. Then, for the years 2021 and 2022, because of field constraints, seven and six treatments were replicated four times, respectively. Each plot measured 12.8m long and 7.3m wide, containing eight rows of cotton, with the center six being used for data collection.

Deltapine 1646 B2XF cottonseed was planted on May 7, 2020; May 7, 2021; and April 25, 2022, in a 91.4 cm row spacing configuration. Throughout the three-year duration of the study, ten treatments were used in various combinations, including:

- 75 kPa (Dry, SWT threshold)
- 45 kPa (Optimum, SWT threshold)
- 20 kPa (Wet, SWT threshold)

- UGA SmartIrrigation Cotton (SI app, Soil water balance model)
- UGA Cotton Irrigation Checkbook (Checkbook, Soil water balance model)
- USDA-ARS Irrigator Pro (Irrigator Pro, Soil water balance model)
- Crop Metrics CropX (CropX, Commercialized sensor telemetry)
- Valmont Vally Scheduler (Valley, Commercialized sensor telemetry)
- Limited water (Limited, Experimental concept)
- Rainfed (Control)

The 2020 growing season evaluated all treatments except the limited water treatment. In 2021, the trial contained the 45 kPa, 20 kPa, SI App, Irrigator Pro, Valley, Checkbook, and Rainfed treatments. Finally, in the 2022 growing season, the only treatments included were the 45 kPa, 20 kPa, SI App, Checkbook, limited water, and rainfed treatments.

Irrigation Scheduling Methods

The 45 kPa, 20 kPa, and 75 kPa treatments were a weighted average soil water tension threshold representing an optimal, wet, and dry treatment, respectively. To calculate the SWT in these treatments, a weighted average approach was implemented based on crop age and estimated root depth to determine when the irrigation trigger point was reached, and irrigation was to be applied. Weights changed 30 and 60 days after planting to prioritize areas with estimated maximum root growth throughout the growing season, as shown in Table 1.

Table 1: Weights used for soil water tension irrigation scheduling.

	Sensor Averages by Depth		
DAP	15 cm	25 cm	35 cm
< 30	60%	30%	10%
30 to 60	40%	40%	20%
>60	30%	50%	20%

The SI App is a soil water deficit model that uses local weather, evapotranspiration (ET) data, and the K_c curve to estimate crop water use and irrigation requirements (Vellidis et al., 2016). The Checkbook works as a historical ET calendar-based scheduling method that outlines the weekly crop water requirements and serves as a budget for estimating irrigation needs. Irrigator Pro is a program that estimates plant available water content based on sensor readings and soil type. It also integrates daily crop water use based on crop growth stage to schedule irrigation events and termination timing in cotton.

CropX is a commercially available sensor-based system that connects to a dashboard that can be accessed through a smartphone app. Similarly, the Valley treatment is another commercially available system similar to the CropX. Although it integrates into other Valmont control systems such as pivot control panels allowing irrigation control from a singular user interface.

The limited treatment assumed that only 101.6mm of water was available for irrigation throughout the growing season. Assuming that there is an average of eight weeks of bloom, the goal was to split the total over the eight weeks evenly with a weekly 12.7-mm application throughout bloom. If at least 12.7 mm of rain was received during the week, then the irrigation was withheld to be used later in the season if needed. The final treatment was a rainfed check for baseline comparison and IWUE calculation.

After planting, all plots received 25 mm of irrigation to ensure stand establishment and properly activate herbicide applications at the beginning of the growing season. After full emergence was observed, custom soil water tension probes with three watermark SWT sensors (Irrometer Co. Riverside, Ca.) integrated at depths of 20, 40, and 60 cm were installed into two of the three replications of each treatment (Vellidis et al., 2008). Data were logged and monitored hourly using Realm5 telemetry (Realm5, Lincoln NE.), and the collected data were used daily in the 20, 45, and 75kPa and Irrigator Pro treatments to schedule irrigation events. The SWT probes were used only to monitor irrigation and SWT in all other treatments. Each of the other systems had irrigation trigger recommendations, which were followed as it was reported by each tool. Each irrigation event was a 19-mm irrigation application applied to all three replications on the day that the threshold was reached, continuing through the entire growing season. The only exceptions were the limited water treatment in 2022, where 12.7-mm applications were applied as described above. As well as the Checkbook method where the total weekly water requirement minus rainfall was divided between three days and applied at the resulting rate. An example of this would be from June 26, 2020, through July 2, 2020; the weekly crop water requirement was 27.4 mm per week or 3.8 mm per day, according to the UGA Checkbook (Hand et al., 2023). During this period, a total of 8 mm of rainfall was received in two small rain events, therefore, 19 mm of irrigation was required for this week. Because of this, the Checkbook recommended scheduling two irrigation events, one of 14 mm and the other of 11 mm, to be applied on Monday and Wednesday of that week. Irrigation applications were adjusted based on the local weather forecast and scheduled up to the checkbook-recommended amount as needed. The irrigation volumes were divided and limited by system capabilities to between 10 and 20 mm per event.

Irrigation Termination and Harvest

All irrigation was terminated once 10% of bolls had opened on average across the field according to UGA Extension recommendations; these termination points were reached on September 4, 2020; September 10, 2021; and September 1, 2022 (Porter et al., 2023b). From planting to harvest, plots received 542.5, 753.4, and 541.3 mm of rainfall throughout the 2020, 2021, and 2022 production seasons, respectively. Since the 10-year average rainfall between April 25 and September 10 for this site is 510 mm of rain, all three of these years were above-average rainfall years; therefore, potentially lower amounts of irrigation were required to sustain yields.

The center two rows of each plot were harvested on October 26, 2020; October 20, 2021; and October 24, 2022, using a two-row John Deere 9930 cotton picker with a bagging attachment in the basket. The seed cotton weight for each plot was recorded on site, and then a sub-sample was obtained for processing at the UGA Cotton Microgin in all three years. The lint turnout value was calculated based on the data from the gin processing and was applied to all samples to calculate the total lint yield. These data were then used to calculate the IWUE of each scheduling method. To do this, the mean rainfed yield was subtracted from the plot yield and divided by the irrigation amount, as shown in Equation 2 (Howell, 2001). This allows us to explain the total yield increase per mm of irrigation.

$$IWUE = \frac{Lint\ yield - Mean\ Rainfed\ yield}{Irrigation\ volume}$$

Equation 2: Formula for calculating IWUE.

A profitability analysis was conducted based on each year's cotton market price and UGA enterprise budget estimated cost of pumping irrigation (Liu et al., 2021, 2023). These estimates assume an average cost of \$0.60 per ha-mm^{-1} when using an electric pumping unit to calculate profitability$_{E}$ and \$1.03 per ha-mm^{-1} to calculate Profitability$_{D,}$ which is based on a diesel-powered unit in 2020 and 2021 (Liu et al., 2021). \$1.33 per ha-mm^{-1} was used in 2022 for the diesel pumping system to compensate for the higher fuel prices that year (Liu et al., 2022). The cost of irrigation was calculated by multiplying these values with the total irrigation amount applied, as seen in Equation 3. The lint value was calculated by multiplying the per-hectare yield by the estimated market lint value for that year (Equation 4).

$$Irrigation\ cost = Volume\ irrigated\ x\ Pumping\ cost$$

Equation 3: Formula for calculating the total irrigation cost.

$$Lint\ value = Market\ value\ x\ Lint\ yield$$

Equation 4: Formula used for calculating the lint value of cotton harvested.

These estimates were \$1.74 kg^{-1}, \$2.20 kg^{-1}, and \$1.98 kg^{-1} in 2020, 2021, and 2022, respectively (Liu et al., 2021). Irrigation profitability was measured by subtracting the cost of irrigation from the lint value, this does not give total profitability for all inputs but allows for the calculation of return on investment for each irrigation treatment Equation

5. No other input factors were considered in the profitability calculations because all other inputs were consistent across all treatments within each growing season of the study.

$$\boldsymbol{Irrigation\ profitability = Lint\ value - Irrigation\ cost}$$

Equation 5: Formula used to calculate the total irrigation profitability.

Analysis

Data from all three years were analyzed in JMP Pro 17 (SAS Institute, Cary, NC). Specifically, an initial mixed-effects analysis was conducted where year, treatment, and year x treatment were considered fixed effects, and replication was considered a random effect. Since there was a significant interaction between year and treatment, statistical analysis was conducted separately within each year of the study. A mixed effects ANOVA was utilized within each year, where irrigation treatment was considered a fixed effect and replication was considered a random effect. There were three replicates in 2020 and four replicates in 2021 and 2022. Means separations for yield, IWUE, and profitability were considered significant at an alpha level of 0.05 with a Tukey HSD post hoc test.

Results

2020

Results from the 2020 growing season showed no statistical differences in yields among any of the irrigated treatments. However, the rainfed check yielded less with a mean yield of 936 kg ha^{-1} (p = 0.0221) (Table 2), which was not statistically different from the 20 and 75 kPa SWT thresholds, the Checkbook method, or the CropX. Insignificant variations were observed in IWUE (p = 0.1223), which could be attributed to a consistent pattern of small rain showers throughout the growing season (Figure 3). The Profitability$_E$ of all the irrigation treatments was comparable as well, with the only differing treatment being the rainfed treatment, which was insignificantly different from every treatment except the 45 kPa and the SI app (Table 2). Results were similar for Profitability$_{D,}$ except the 45 kPa threshold was the only treatment that outperformed the rainfed.

Table 2: Means and groupings for Yield, IWUE, and Profitability in 2020.

Treatment	Yield (kg/ha)	IWUE (kg/mm)	Profitability$_E$ ($/ha)	Profitability$_D$ ($/ha)	Irrigation (mm)
75 kPa	1329^{AB}	4.76	2263^{AB}	2228^{AB}	82.5
45 kPa	1535^{A}	4.29	2588^{A}	2528^{A}	139.7
20 kPa	1362^{AB}	2.17	2251^{AB}	2167^{AB}	196.9
SI APP	1495^{A}	3.52	2505^{A}	2437^{AB}	158.8
Irrigator Pro	1465^{A}	3.79	2465^{AB}	2405^{AB}	139.7
Valley Scheduler	1460^{A}	2.43	2411^{AB}	2318^{AB}	214.9
Checkbook	1340^{AB}	1.45	2164^{AB}	2044^{AB}	279.4
CropX	1310^{AB}	3.68	2219^{AB}	2175^{AB}	101.6
Rainfed	936^{B}	-	1613^{B}	1605^{B}	25.4
p-value	0.0252	0.1223	0.0444	0.0607	

Note: Means with different connecting letters indicate statistical differences.

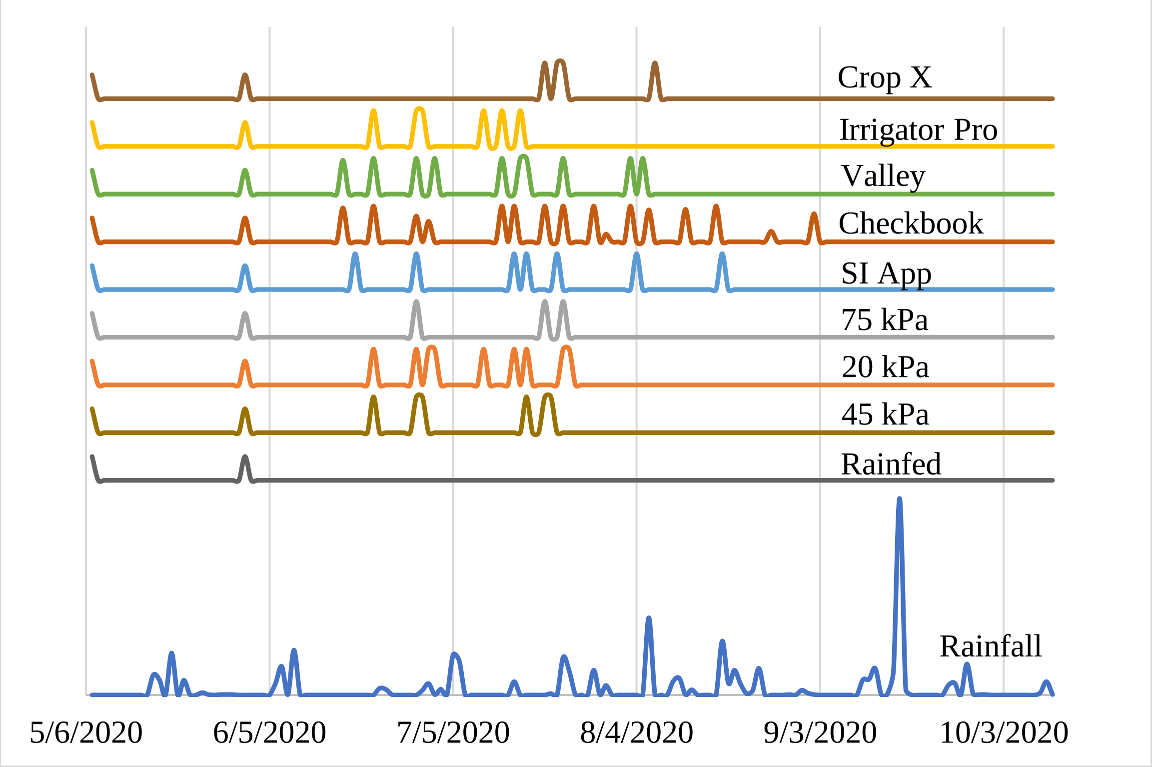

Figure 4: Irrigation and rainfall timing throughout the 2020 growing season.

2021

Minimal significant differences were observed in any of the metrics measured through the 2021 growing season. This is likely caused by consistent and adequate rainfall events from mid-June through late August (Figure 6). These events line up well with the peak water use of the crop, which has been widely reported as being through the blooming stage of development (Allen et al., 1998; Bednarz et al., 2002; Perry et al., 2017; Ritchie et al., 2007; Vellidis et al., 2016). Mean yields for all treatments were 1308 kg ha^{-1} (p = 0.1196) with a mean IWUE of 0.84 kg mm^{-1} (p = 0.7513). Differences in profitability were also insignificant with a mean of \$2818 ha^{-1} (p = 0.2018) and \$2785 ha^{-1} (p = 0.1984) for Profitability$_E$ and Profitability$_D$, respectively.

Table 3: Means and groupings for Yield, IWUE, and profitability in 2021.

Treatment	Yield (kg/ha)	IWUE (kg/mm)	Profitability$_E$ ($/ha)	Profitability$_D$ ($/ha)	Irrigation (mm)
45 kPa	1335	1.34	2900	2875	59.9
20 kPa	1342	0.89	2893	2851	98.0
SI APP	1305	0.85	2835	2810	59.9
Irrigator Pro	1317	1.05	2862	2837	59.9
Valley Scheduler	1287	0.54	2795	2769	59.9
Checkbook	1319	0.35	2792	2713	184.4
Rainfed	1254	-	2648	2637	25.4
p-value	0.1196	0.7513	0.2018	0.1984	

Note: No statistical differences were seen within any metric in 2021.

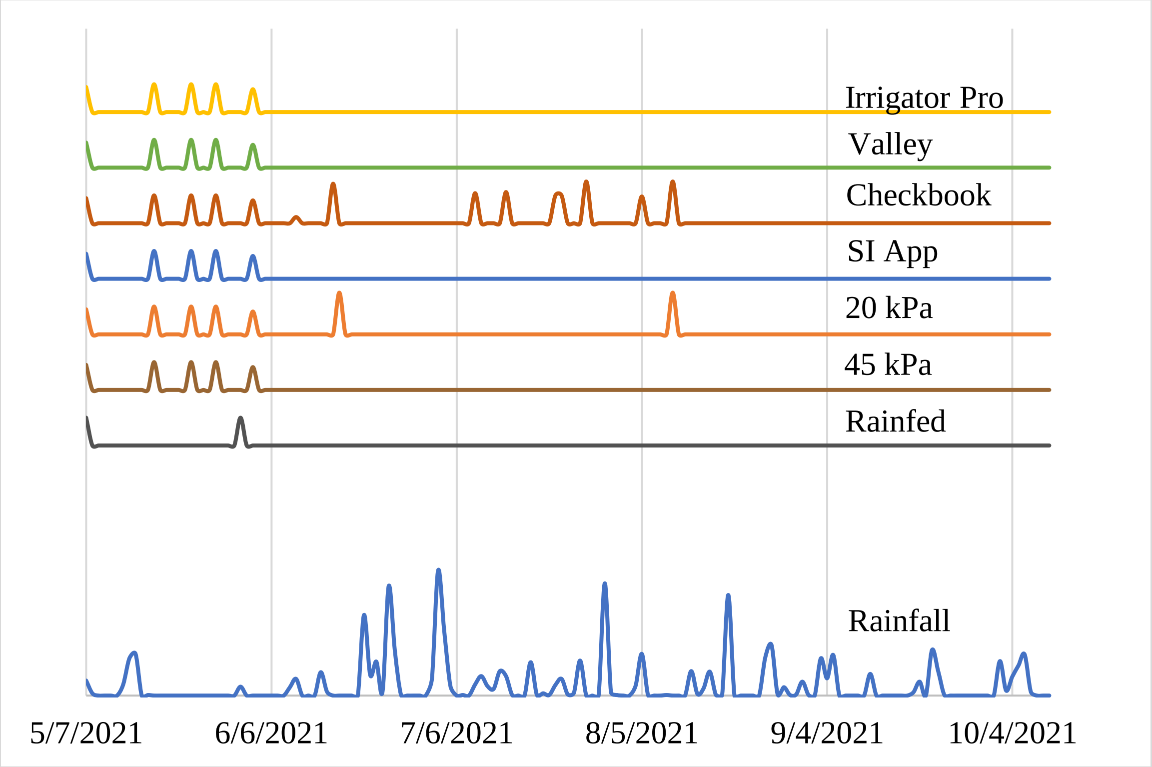

Figure 5: Irrigation and rainfall timing throughout the 2021 growing season.

2022

In the 2022 season, the largest variations among treatments were observed, likely caused by the timing of many rainfall events that were large enough to refill the soil profile

(Figure 7). Because of the constant availability of moisture, all of the irrigation treatments saw numerically negative returns on irrigation inputs. However, when comparing yields, the rainfed treatment was only statistically different from the 20 kPa threshold, which was similar to all other irrigation treatments (*p* = 0.0114) (Table 5). This was likely due to over-irrigation of many of the irrigated treatments which could have led to excessive vegetative growth at the expense of boll production (Ermanis et al., 2021) or reduced radiation use efficiency and nutrient leaching caused by waterlogging (Bange et al., 2004; DeTar, 2008; Najeeb et al., 2016; Perry et al., 2017). Much of this over-irrigation was due to thresholds being reached and irrigation events being initiated in the morning, followed by a scattered pop-up rain event in the evening. Many of these rain events deposited substantive volumes of water, negating the need for irrigation. This occurred four separate times across various treatments and highlights the limitations of implementing in-field irrigation studies.

Table 4: Means and groupings for Yield, IWUE, and profitability in 2022.

Treatment	Yield (kg/ha)	IWUE (kg/mm)	Profitability$_E$ ($/ha)	Profitability$_D$ ($/ha)	Irrigation (mm)
45 kPa	1408^{AB}	-1.24	2692^{B}	2548^{BC}	158.8
20 kPa	1232^{B}	-1.28	2263^{B}	2026^{C}	292.1
SI APP	1346^{AB}	-1.85	2581^{B}	2452^{BC}	139.7
Checkbook	1366^{AB}	-0.88	2543^{B}	2319^{BC}	270.3
Limited water	1418^{AB}	-2.1	2755^{AB}	2661^{AB}	88.9
Rainfed	1604^{A}	-	3248^{A}	3145^{A}	25.4
p-value	0.0114	0.7203	0.0007	0.0002	

Note: Means with different connecting letters indicate statistical differences.

As a result of the numerically higher rainfed yields, IWUE was negative for all irrigation treatments as no yield benefits were observed from irrigation. Because of a lack of variation in yields and constant soil moisture availability, no significant differences in IWUE were observed ($p = 0.7203$). As such, it can be attributed to the timing of irrigation and provides us with a good indication of performance for each scheduling method (Howell, 2001) (Figure 5).

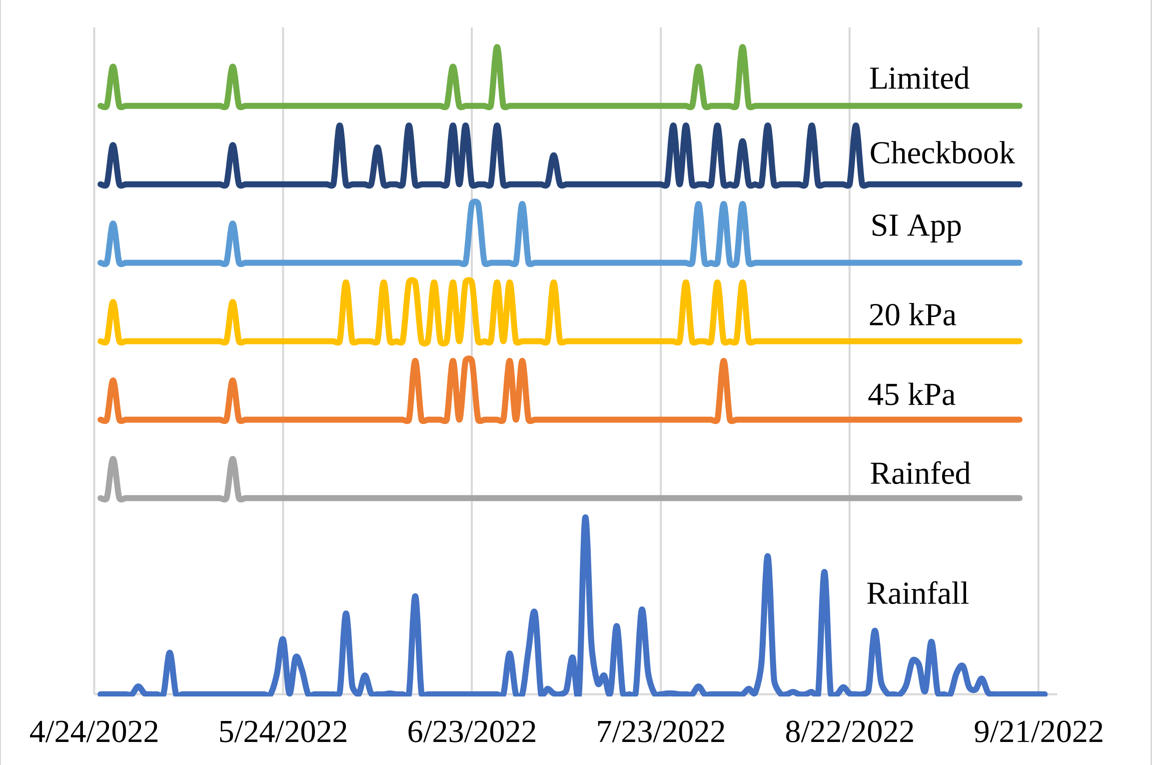

Figure 6: Irrigation and rainfall timing throughout the 2022 growing season.

Because of unnecessary irrigation applications, profitability was generally reduced compared to the rainfed treatment ($p = 0.0007$). This reduction in profitability is due to both lower yield values and increased inputs from all irrigation applications, similar to the findings of Liu et al. (2022b). However, profitability$_E$ was not reduced in the limited water treatment because of limited overall irrigation inputs (Table 4). The profitability$_E$ of the limited water treatment was not considered statistically different compared to all other irrigated treatments. Similar to profitability$_E$ the rainfed and limited water treatments were the most profitable when considering diesel-powered equipment, which resulted in the largest amount of variability ($p = 0.0002$). Similarities were observed between the limited water and all irrigation treatments except for the 20 kPa threshold. However, all other irrigated treatments were considered to be statistically similar to each other. This is likely because, in the development of the SI app, the K_c curve that was modified for use in South Georgia was set so that an estimated root zone soil water deficit of 50% coincides with a 40-50 kPa soil water tension (Vellidis et al., 2016). This is designed to be a similar estimate based on weather and soil type to what is expected from the 45 kPa threshold. However, since the SI app estimates field conditions, it is likely that on rainy years like 2022, it overestimated irrigation requirements, leading to performance similar to the more conservative 20 kPa and Checkbook methods (Table 4).

Further considerations for the adoption of advanced irrigation scheduling tools should be included when deciding which is the best method for a particular producer. Some of these considerations should encompass the number and size of fields and the time required for training and implementation of the tools. This was documented as being one of the largest barriers to adoption in the Rio Grande Valley, with 39% of respondents surveyed affirming that training time was a major reason for slow adoption (Berthold et al., 2021b). It should be noted that the cost of time was not accounted for in this study because it varies based on each producer’s situation. However, in general terms, the sensor-based scheduling tools required a larger time commitment. Comparatively, the SI app is mostly automated when access to a supported weather network is readily available. While many ET models, such as the SI app, are generally free to use, to optimize their performance, they must have real-time access to accurate weather data, which may require the installation of weather stations (Davidson et al., 2022; Vellidis et al., 2016). Not only is a reliable source of current weather important, but reliable short-term forecasts are also an essential requirement. This need for reliable short-term forecast was highlighted in 2022, affecting all treatments due to the large amount of sporadic rainfall, which would have likely led to a reduction in irrigation events across all treatments had more accurate forecasts been available. There are several other concerns about the return on capital investment for adopting sensor-based scheduling (Berthold et al., 2021b). However, the data shown in this study from 2020 shows significant increases in profitability and no reduction in profits in 2021, proving that they can be an effective tool for better irrigation management.

Conclusions

In conclusion, cotton irrigation can be a highly variable and challenging task that can have direct effects on end-of-season profitability. It was shown that over-irrigating cotton could be detrimental to the profitability of cotton production, as observed in 2022. Therefore, it is crucial to select the appropriate tool for making informed decisions about proper irrigation timing. Based on the results of this study, several high-performing tools are available to minimize the risk of reduced yields due to moisture stress. Scheduling based on a sensor-based threshold most consistently provided top-tier yield returns as an advanced irrigation scheduling tool consistent with the findings of (Flynn & Barnes, 1998; Grant et al., 2017; Vellidis et al., 2008, 2016). We can also see that the UGA SmartIrrigation app performed well as a soil water balance estimation model across all three years of the study. In comparison, the Checkbook irrigated the most in 2020 and 2021, which could increase the risk of undesirable agronomic outcomes. Similarly, the 20kPa threshold over-irrigated the crop, reducing yields and, consequently, profitability in 2022. Therefore, it is critically important to educate our growers about the various options that are available to aid in deciding when to irrigate a crop. These options can vary in style, training time, necessary equipment/installation, and cost. These data offer an infield comparison for helping to decide which tool is the best fit for each unique operation and set of challenges.

CHAPTER IV

ASSESSING WATER USE DIFFERENCES ACROSS VARIOUS COTTON CROP DENSITIES

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Abstract

In recent years, the rising cost of crop inputs has driven farmers to find places to reduce costs, one area they have focused on is the seeding rate, in an effort to minimize seed cost. Numerous studies have been completed every few years to evaluate optimum seeding rates across the cotton belt. However, few of these have focused on the effects of plant population on irrigation requirements and water use. To bridge this research gap, a two-year research trial was conducted at the University of Georgia's Stripling Irrigation Research Park near Camilla, Georgia. This trial was implemented using a variable-rate overhead lateral irrigation system to independently irrigate nine different treatments. Deltapine 2038 B3XF was planted on May 5, 2023, and April 29, 2024, and hand-thinned to represent high, moderate, and low populations in Georgia. Each population had a corresponding plot that was irrigated based on the UGA SmartIrrigation Cropfit app, another irrigated using a 45kPa weighted average soil water tension (SWT) threshold, and a rainfed check. Each treatment was replicated three times and had custom-built probes with Watermark tensiometers integrated at 8, 16, and 24 inches (Irrometer Co. Riverside, CA) attached to Realm5 telemetry (Realm, Lincoln, NE) installed randomly into two of the three replicates. SWT was logged hourly for all treatments and used for daily irrigation scheduling of appropriate plots. Notably, as populations increased, sensor-based irrigation requirements were reduced compared to lower plant densities. While there is no statistical correlation between crop density and soil moisture depletion rates were observed.

Introduction

Cotton (*Gossypium hirsutum L.*) is the most planted row crop in Georgia, with over 445,000 ha planted in the state for the 2023 growing season (*USDA/NASS,* 2024). However, the profitability of cotton has dwindled in recent years due to volatile markets and increased production costs; some of the highest of which are seed and irrigation costs (Adams et al., 2019; Larson et al., 2006; Liu, Smith, et al., 2022; Moon & Hand, 2022). Many growers understand the expense that comes with planting seeds with plant-incorporated protectants and herbicide resistance traits. However, the cost of irrigation is not as easy to quantify due to varying input costs such as fuel and maintenance. The University of Georgia Enterprise budget estimates this to be around \$0.68 - 0.88 ha-mm^{-1} with electric pumping units and between \$1.54 - 1.94 ha-mm^{-1} when employing diesel-powered systems (Liu et al., 2022). Current estimates are that approximately 45% of Georgia cotton acreage is irrigated each year, highlighting the importance of effective irrigation management (*USDA/NASS,* n.d.).

Proper irrigation management can have many implications on cotton growth and development, affecting yields and, consequently, profitability. Because of the perennial nature of cotton, both over- and under-irrigation can negatively affect yield components. Drought stress or under-irrigation can significantly reduce the development of fruiting sites, leaf area, and internodal elongation (Chastain et al., 2016; Krieg & Sung, 1986; Loka & Oosterhuis, 2012; Pace et al., 1999). Due to reduced leaf area, source strength can be limited, which is the amount of photosynthate available to support developing bolls (Chastain et al., 2014; Krieg & Sung, 1986; Pace et al., 1999). Reductions in source strength can induce fruit shedding, significantly reducing boll density and yields compared to a properly managed crop (Balkcom et al., 2006; Chastain et al., 2016; Krieg & Sung, 1986; Lee et al., 2023; Loka & Oosterhuis, 2012; Lokhande & Reddy, 2014). Conversely, over-irrigation can have negative effects on yield and the environment (Ermanis et al., 2021; Geerts & Raes, 2009; Grant et al., 2017; Liu, Snider, et al., 2022). Yield reductions have been documented when irrigation applications exceed 125% ET_C, more than the estimated crop water requirement (Ermanis et al., 2021). These yield losses are driven by reductions in radiation use efficiency, lowering overall dry matter accumulation and fruiting sites (Bange et al., 2004; Najeeb et al., 2016). Over-irrigation can also lead to nutrient leaching and boll rot development (DeTar, 2008; Perry et al., 2017).

There has also been an increase in the availability of advanced irrigation scheduling technologies, such as soil moisture sensor systems, soil water deficit models, and variable rate irrigation systems (Davidson et al., 2022; Francesca et al., 2010; Porter et al., 2022, 2023; Vellidis et al., 2008, 2013, 2016). Of these, there are three major types of systems, capacitance, tensiometric, and root zone soil water deficit models. Capacitance systems measure the dielectric properties of the soil, primarily from the SWC, to quantify the volumetric water content of the soil. Tensiometric systems measure Soil Water Tension (SWT) using the electrical resistance across a granular matrix embedded to form a continuum in soil moisture. This measures the pressure required to overcome the cohesive bonds between the soil particles and the water (El-Marazky et al., 2011; Rix et al., 2021). Finally, root zone soil water deficit models, such as the UGA SmartIrrigation Cropfit smartphone application, keep a revolving estimate of soil water depletion. They calculate ETc using the Penman-Montieth equation and subtract that from the estimated root zone soil water holding capacity. Current research shows that the optimum irrigation initiation threshold is around 50% soil water deficit for capacitance or root zone soil water deficit model or 45 kPa SWT (Flynn & Barnes, 1998; Grant et al., 2017; Hayes et al., 2024; Porter et al., 2023; Vellidis et al., 2008)

Recent volatility in the cotton markets has pressured cotton producers to find ways to reduce operating costs without sacrificing yield. Many times, this includes planting at or below recommended planting rates (Adams et al., 2019; Collins & Edmisten, 2015; Hand et al., 2022; Moon & Hand, 2022). One of the most common approaches is reducing seeding rates, which can lead to lower than optimal final stands and increased risk of yield loss throughout the growing season (Adams et al., 2019; Bednarz et al., 2000, 2005; Dai et al., 2015; Feng et al., 2014; Gwathmey et al., 2011; Pettigrew & Johnson, 2005; Wrather et al., 2008; Zhi et al., 2016). Plant population and row spacing can influence boll distribution and density among other yield components, such as boll mass and intra-boll components (Bednarz et al., 2006; Lawton et al., 2024; Roche & Bange, 2008; Zhi et al., 2016). Some of the ways this occurs are through increased boll retention beyond the first position and in nodes above the tenth mainstem node in lower plant densities (Zhi et al., 2016). Another way this occurs is through reductions in seeds per boll, seed mass, and boll mass with increasing populations; conversely, lint per seed increases in lower populations (Bednarz et al., 2006; Lawton et al., 2024; Zhi et al., 2016). Previous research provides ample documentation on the influence of planting density on vegetative growth, interplant competition for light, as well as fruiting and canopy structure (Ethridge et al., 2022; Hake, Burch, et al., 1991; Jones & Wells, 1998; Siebert et al., 2006b). Furthermore, studies have shown density effects on other production factors such as fertility, weed control, and fiber quality (Adams et al., 2019; Dong et al., 2010; Feng et al., 2014; Lawton et al., 2024; K. N. Reddy et al., 2009; Sapkota et al., 2023; Vories et al.,2001; Wrather et al., 2008; Zhi et al., 2016).

Other studies in arid Australian production regions have suggested that using skip-row planting configurations can increase soil water availability per plant but have not shown significant increases in simulated lint yield (Bange et al., 2005; Buehring et al., 2006). Similar lint yield results have been documented in the southeast despite reductions in boll rot and hard lock occurrence using skip-row configurations (Hall et al., 2024) Historically skip-row configurations have been used to reduce seeding rate, therefore, reducing final plant population, and inputs to maintain profitability which can be maintained due to reduced input cost per land hectare in skip-row configurations (Spurlock & Willcutt, 2006; Hall et al., 2024; Hall et al., 2024). However, there is limited research focused specifically on the relationship between final plant population and irrigation requirements and efficiency in the southeast within a standard solid planting configuration. Based on these prior conclusions we have hypothesized that irrigation inputs will be reduced as plant spacing increases with lower plant populations. Because of this, net profit after variable costs can be maintained through input savings rather than yield increases. Therefore, the main objective of this study was to identify differences in irrigation requirements and yield based on cotton plant population and to determine if irrigation frequency could be reduced to maintain profitability at lower planting densities. This should serve as a baseline to guide further research evaluating irrigation scheduling tools and farm scale effects of variable rate seeding of cotton on irrigation management.

Materials and Methods

Field Layout

A randomized complete block design trial was conducted at Stripling Irrigation Research Park near Camilla, Georgia. This study was implemented throughout the 2023, and 2024 cotton growing seasons and contained three replicates of nine treatments. A lateral-move overhead irrigation system equipped with a variable rate controller (Valmont Industries, Valley NE.) allowed for each of the 12.8m x 7.3m plots to be irrigated independently based on treatment requirements. Treatments included three different cotton populations factorially combined with two different irrigation scheduling tools and a rainfed control. The two irrigation scheduling tools were a 45 kPa weighed average threshold representing a sensor-based irrigation scheduling tool as described by (Hayes et al., 2025; Porter et al., 2023). The other was the UGA SmartIrrigation Cropfit smartphone application which has proven to be an outstanding soil water balance estimation model (Porter et al., 2023; Vellidis et al., 2014, 2016). The three populations tested were 67,925, 49,400, and 30,875 plants/ha, this was intended to represent a high population, a moderate population, and a low population respectively (Adams et al., 2019; Hand et al., 2022).

Field implementation

The cotton cultivar Deltapine 2038 B3XF was planted in 8 row-wide plots (91cm spacing) on May 5, 2023, and April 29, 2024, at a density of 93,900 seeds per hectare. After planting a 12.5 mm blanket irrigation event was applied before emergence to ensure uniform stand establishment and early season herbicide activation. After emergence, custom-built soil water tension probes, with Watermark tensiometers (Irrometer Co. Riverside, Ca.) integrated at 20, 40, and 60 cm attached to Realm5 Telemetry (Realm5, Lincoln, Ne.) were installed randomly into two of the three replicates of each treatment in 2023. For the 2024 growing season, three additional probes were installed into the 45 kPa treatments to collect data from all three replicates. Data from all of the soil moisture sensors (SMS) were logged hourly and used to schedule irrigation for appropriate plots daily based on the 6:00 am reading. These readings were averaged together and the appropriate weights were applied to account for rooting depth based on Hayes, et al., (2025) and Porter et al., (2023) as seen in Table 5. Each irrigation event included a 19 mm irrigation application to all three treatment replicates on the same day the thresholds were reached. When cotton reached the 4-leaf growth stage, all plots were hand-thinned to the target population so that every population treatment had a plot represented by each irrigation treatment. Irrigation and rainfall records were recorded and logged daily according to SMS readings and an on-site weather station. Irrigation was terminated according to Extension recommendations when cotton reached 10% open bolls which occurred on August 29, 2023, and August 26, 2024, (Hand et al., 2024).

Table 5: Weights used for soil water tension irrigation scheduling in 2023 and 2024.

	Sensor Averages by Depth		
DAP	20 cm	40 cm	60 cm
< 30	60%	30%	10%
30 to 60	40%	40%	20%
>60	30%	50%	20%

Crop measurements

Throughout both growing seasons ten weekly canopy crop development measurements were taken to record the physical development of the plants. Height and width measurements were collected from three plants in each of the center four rows randomly for a total of 12 measurements. Width measurements were conducted across the widest point of the plant across the apical meristem directly outwards to the middle of the row (Ethridge et al., 2022). These were initiated at first square and continued until crop growth ceased at cutout or 3 nodes above white flower, at which point no more harvestable bolls could be set (Ritchie et al., 2007). Weekly growth stage measurements were noted as a field average and validated according to growing degree day (GDD) (DD-60) accumulation throughout the growing season (Mauney, 1986; Raper et al., 2023). The center four rows were harvested on October 19, 2023, and October 4, 2024, using a two-row John Deere 9930 cotton picker with a bagging attachment (Deere and Co. Moline Ill.). Seed cotton was weighed in the field and then sent to the UGA Cotton Microgin (Li et al., 2011) to be ginned, and then lint turnout percentage and yield were calculated. In 2024 as each sample was ginned, a 100 fuzzy seed sample was collected to determine seed index and investigate variations in lint turnout observed in 2023 (Lawton et al., 2024).

Following defoliation in 2024 and prior to harvest, five consecutive plants from two adjacent rows were collected to evaluate boll density and canopy structure. Boll distribution was evaluated by counting the number of 1st, 2nd, and 3rd position reproductive bolls, vegetative and the 4th+ position bolls, total nodes, and rotten or non-harvestable bolls (Lawton et al., 2024). Based on this data, the boll rot percentage was also calculated for each plot by transforming the number of rotten or non-harvestable bolls into a percentage of total bolls (Hayes et al., 2025).

Irrigation Water Use Efficiency Calculation

Post-harvest computations for irrigation water use efficiency (IWUE) were compiled based on yields and irrigation records for each plot throughout the year. IWUE was calculated by subtracting the rainfed mean yield from the treatment yield, before dividing it by the irrigation volume (Howell, 2001) (Equation 6). IWUE provides a simple metric to quantify the effect of irrigation volume on yield and allows us to compare the negative impacts of over-irrigation

$$IWUE = \frac{Yield - Rainfed\ Mean\ Yield}{Irrigation}$$

Equation 6: Formula used to calculate IWUE in 2023 and 2024 (Howell, 2001).

Profitability Calculation

Profitability data were compiled using estimated costs as reported by the University of Georgia Extension Enterprise budgets for the 2023 and 2024 growing years as appropriate (Liu et al., 2023, 2024). The values used are shown in Table 6, and represent the estimated values and cost of inputs for each growing season. Seed costs were calculated as planted values thus assuming an 80% germination rate as specified on the seed tag (Equation 7). Using these data profitability was calculated for both electric (Profitability_E) and diesel (Profitability_D) pumping systems accounting for both total irrigation amount as well as seed cost using equation 7.

Table 6: Values for cost and profit estimations in 2023 and 2024.

Product	2023 price	2024 price
Lint (kg)	\$1.68	\$1.68
1000 seeds	2.76	2.87
Electric system (ha-mm-1)	0.68	0.88
Diesel system (ha-mm-1)	1.94	1.56

$$Cost = (Populationx\ 1.20\ x\ seed\ price) + (Irrigation\ volume\ x\ Irrigation\ price)$$

$$Profitability = \ (lint\ yield\ x\ lint\ price) - Cost$$

Note: 1.20 is used in the cost equation to adjust for the planting rate which assumes an 80% germination rate as listed on the seed label.

Equation 7: Formulas used to calculate variable treatment cost and net profitability.

Irrigation Effects Analysis

Data from both years were analyzed in JMP Pro 17 (SAS Institute, Cary, NC). An initial mixed effects ANOVA was conducted with year, treatment, and year by treatment as fixed effects and replication as a random effect. The analysis indicated a significant year-by-treatment interaction; therefore, a two-way mixed effects ANOVA was used within each year of the study. This model included the irrigation scheduling tool, population, and their interactions as fixed effects and replication as a random effect. Means separation for lint percentage, yield, IWUE, profitability, and fuzzy 100 seed weight were considered significant with an alpha level of 0.1 based on a Tukey HSD post hoc test. Means separation of IWUE between scheduling tools was considered significant based on a post hoc Students

T-test with an alpha level also set at 0.1. This was done because IWUE was not calculated for the rainfed check; therefore, only one pairwise comparison was evaluated, differing from the other response variables which had multiple comparisons being analyzed.

Canopy size was analyzed with height and width measurements for each date as response variables. As with other whole plot variables, irrigation and population treatments and their interactions as fixed effects with the plant and replicate as random effects. A Tukey HSD post hoc correction was again used to separate means with alpha set at 0.1. A similar model was used to analyze total nodes, boll rot, and boll distribution in 2024. Boll distribution was analysed considering each fruiting position as its own response variable as previously described above with 4th and greater being grouped with the monopodal branches.

Soil Moisture Depletion Analysis

Because data from soil moisture probes were only collected in two of the three replicates in the 45 kPa treatments throughout the 2023 growing season, no statistical analysis was conducted. However, this led to updated protocols for the 2024 growing season to accommodate further statistical analysis. The weighted average soil moisture sensor data that were compiled throughout the growing season were analyzed to determine if differences in soil moisture depletion rate could be observed between population treatments. The data used for analysis were selected based on growth stage, while also being a multiday rain and irrigation-free period for all 45 kPa irrigation treatments. Throughout both growing seasons the three time periods that fit these criteria as being suitable for analysis were 33-37, 73-78, and 98-102 days after planting (DAP). These each represent five days at pinhead square, peak bloom, and cutout respectively for each regresson timeframe. These three timeframes represent a period in the early season, peak water use, and near irrigation termination respectively. Based on the weighted average soil moisture readings used to schedule daily irrigation events a simple slope analysis was conducted in SAS Enterprise Guide 7.1 (SAS Institute, Cary, NC.). A linear mixed model with the population as a fixed effect and days after planting as a continuous covariant was conducted with replication as a random effect. PROC MIXED and PROC PLM were used to compare slopes of soil moisture depletion across time. A Bonferroni correction was used to adjust *p*-values to indicate statistical differences between population treatments. Data for both growing seasons were visualized using linear graphs created by Microsoft Excel 365 (Microsoft Corp., Redmond Wa.).

Results

Irrigation timing

The 2023 growing season was particularly cool and wet until later in the growing season. This resulted in only one irrigation event in the treatments watered according to the SI App until after peak bloom. No irrigation was required for treatments irrigated according to the sensor-based threshold until the month of August. Peak bloom is well correlated with peak water use according to numerous irrigation studies throughout the cotton belt (Hand et al., 2022; Ko et al., 2009; Kumar et al., 2015; Perry et al., 2017; Vellidis et al., 2016) The 2023 irrigation and rainfall timings as shown in Figure 7, reflect the early season rainfall frequency and volume with a total accumulation of 564 mm of rainfall throughout the entire growing season and 2779 GDD. This is 123 GDD below the 10-year average for the 2023 growing dates at this site, indicating a slightly cooler season.

While all of the treatments that were irrigated with the SI App followed the same irrigation schedule within each year, we did see irrigation application frequency differences in the 45 kPa sensor-based treatments (Figure 7). In the 45 kPa sensor-based treatments there was an increase of one irrigation treatment per 18,500 plants/ha increment as the population decreased, reducing total irrigation applications by 36 mm in the high population compared to the low population.

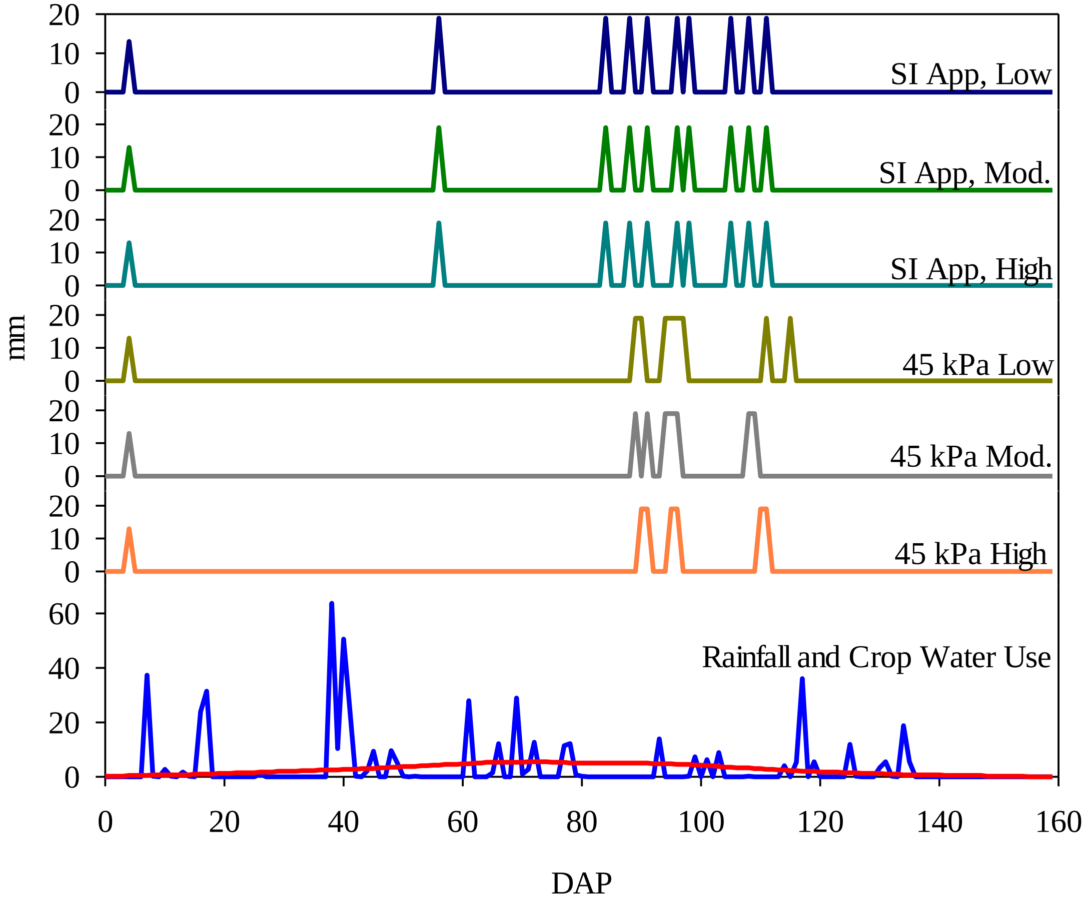

Figure 7: Irrigation treatment timing and rainfall volume and timing throughout the 2023 growing season. Plateau-shaped peaks indicate days with sequential irrigation events.

This trend continued into the 2024 growing season with an increase in irrigation requirements from the High population to the moderate population. However, it did not continue into the low population which required the same irrigation volumes as the moderate population due to a single late-season irrigation event (Figure 8). 2024 differed significantly from the 2023 season with a large amount of rainfall scattered incrementally throughout the later part of the season with seasons-long rainfall accumulations of 766mm. This was well above the 10-year average for the 2024 growing season dates of 620mm. This limited most of the irrigation events to the early part of the growth cycle before peak water use. The heat unit accumulation in 2024 was 2972 GDD, slightly lower than the 10-year average of 3025 GDD for the growing dates.

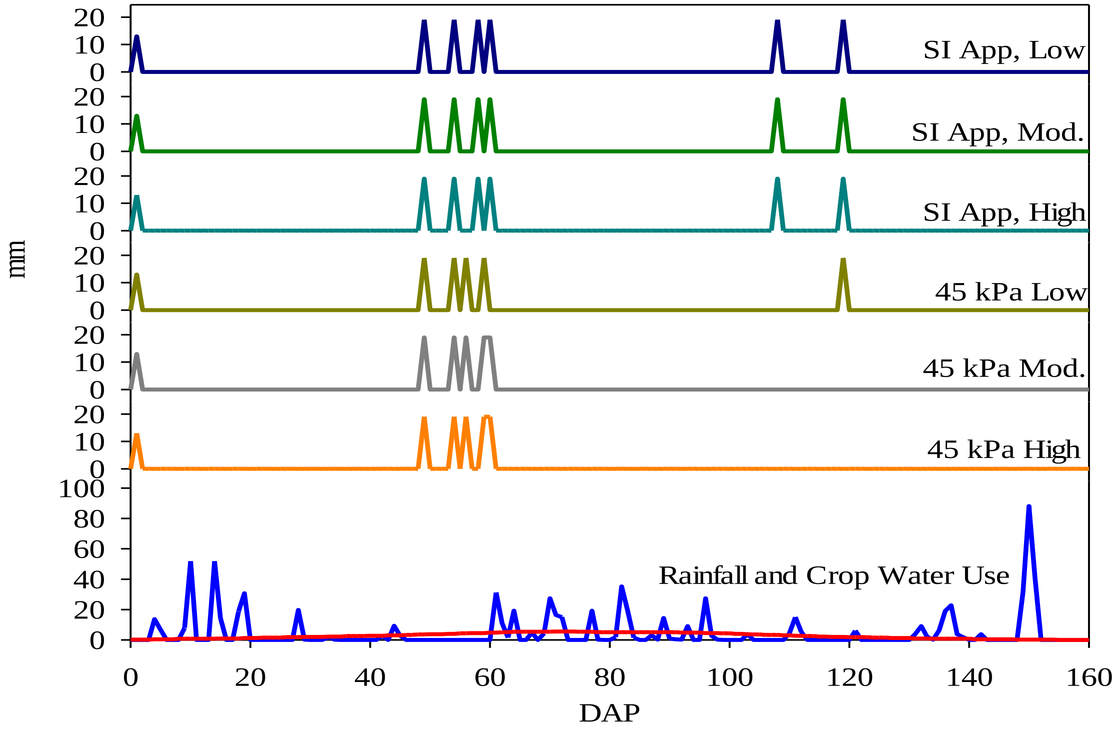

Figure 8: Irrigation treatment timing and rainfall volume and timing throughout the 2024 growing season.

Soil Moisture Trends

2023

Despite the frequent rainfall events throughout the 2023 growing season, several anecdotal trends in soil moisture depletion were observed throughout the growing season, particularly in the 45 kPa irrigation treatments. One of the most notable occurred at approximately 35 DAP as the trial reached the pinhead square growth stage (Figure 9). Throughout this period the low population treatment appeared to deplete soil moisture slower than the other treatments. Fitting a linear trendline across the readings for five consecutive days from both replicates shows that the mean daily depletion in the high and moderate treatments was more than twice that of the low population treatment (Figure 10). As the season progressed the high population appeared to reduce its rate of soil moisture depletion so that all three populations were depleting moisture at approximately the same rate through peak bloom and peak water use. (Figure 11). For the rest of the season, this same trend was observed where all three populations were utilizing similar rates of soil moisture. However, near cutout, approximately 100 DAP, the lower population began using water at a slightly higher rate than the other populations (Figure 12). This potentially explains the increased irrigation volumes since none of the sensor-based treatments required irrigation events till later in the growing season (Figure 7).

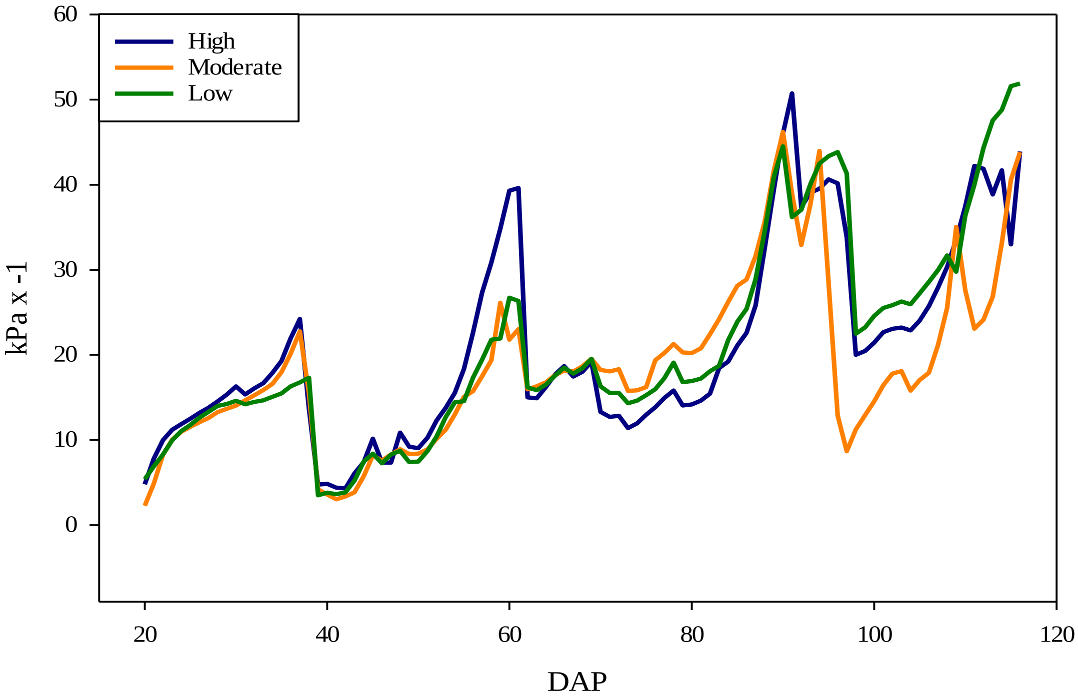

Figure 9: 45 kPa soil moisture sensor readings throughout the 2023 growing season.

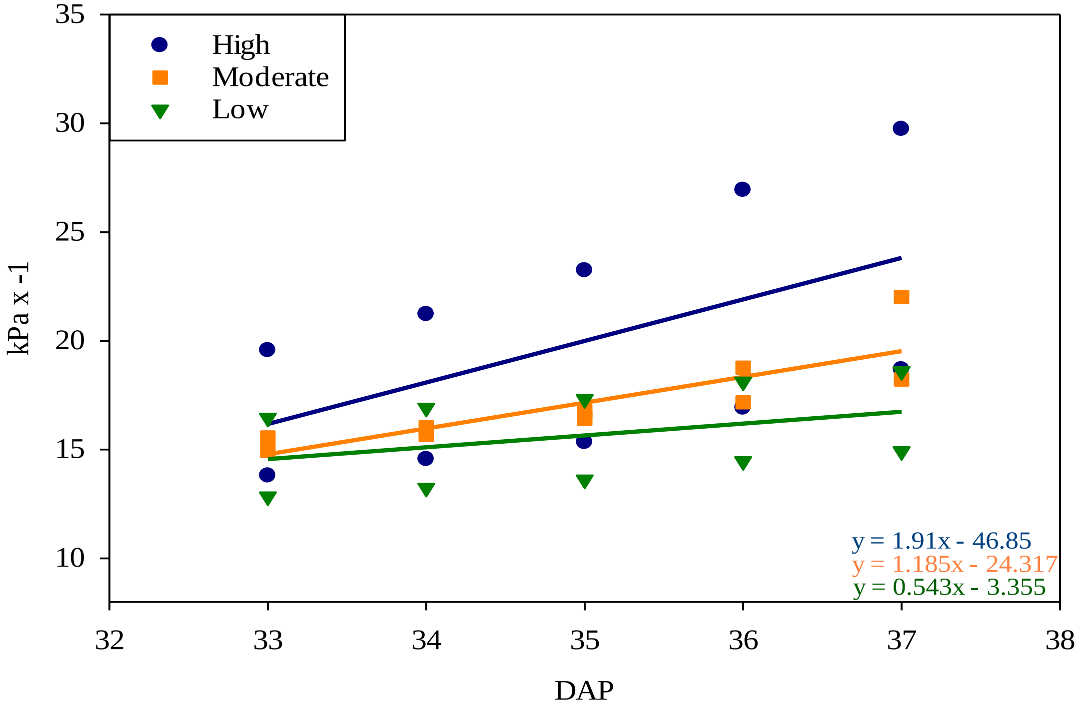

Figure 10: Soil moisture depletion rate of all populations at Pinhead Square in 2023.

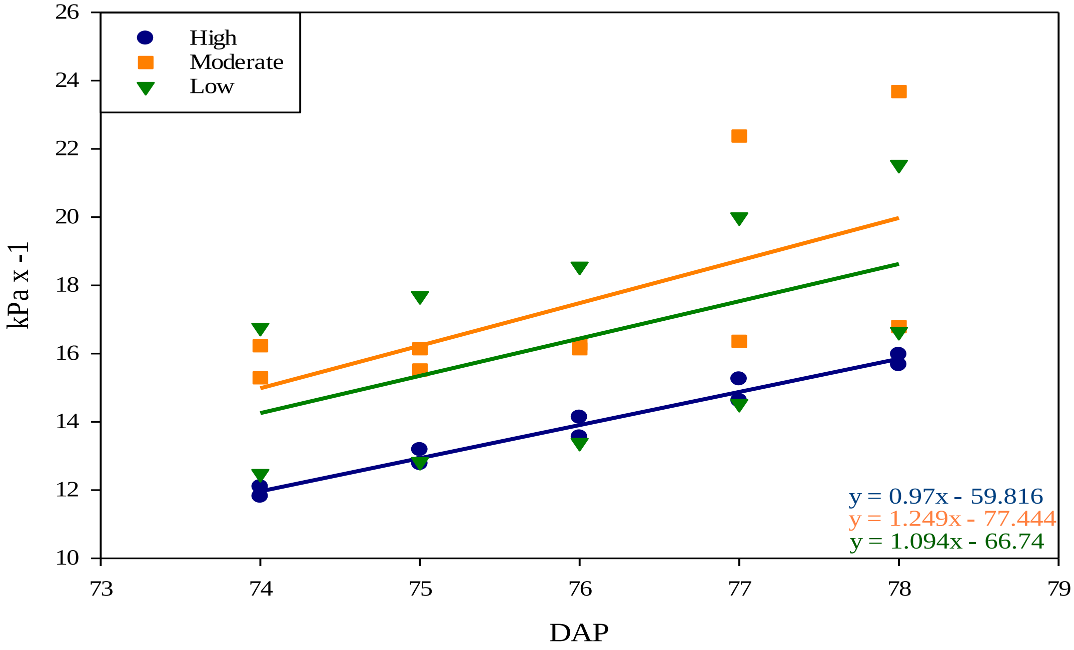

Figure 11: Soil moisture depletion rate of all populations at peak bloom in 2023.

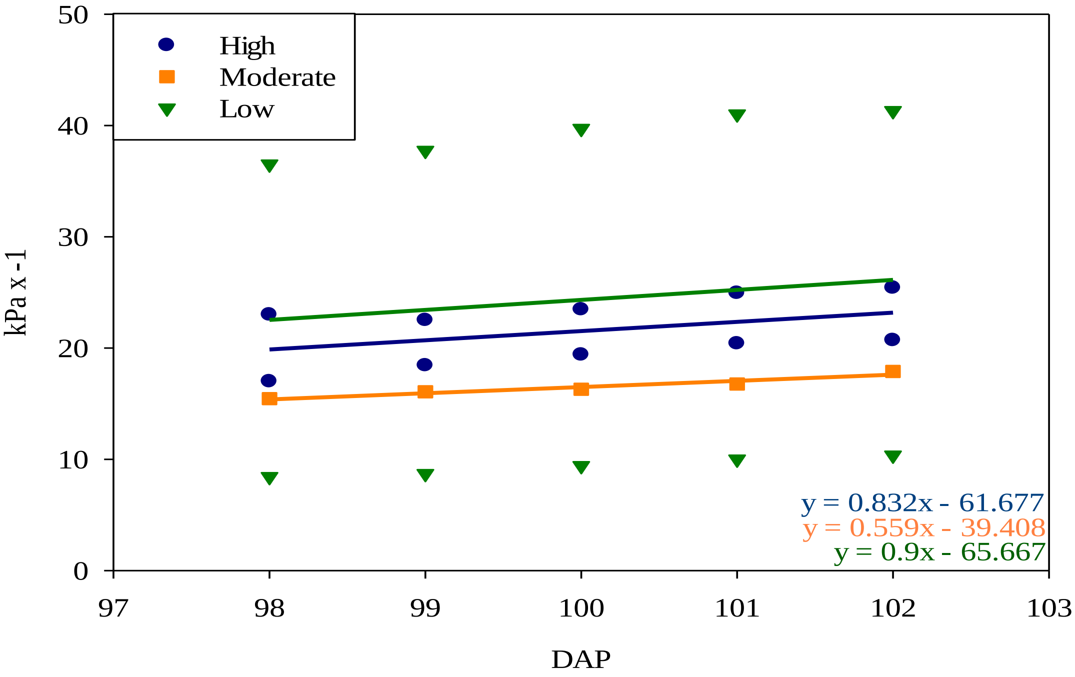

Figure 12: Soil moisture depletion rate of all populations at cutout in 2023.

2024

Following the anecdotal observations in 2023 further investigation into soil moisture depletion was conducted in 2024. To do this a soil moisture sensor was placed in all three replicates of the 45 kPa treatments which are sensor-based so each irrigation event could be influenced by population. Because of the extra sensor in each treatment, enough observations were made to statistically analyze each treatment based on population as a sub-objective within the main study. While the observations seen in 2024 were less drastic than in 2023 as seen in Figure 13, the same three timeframes 33-37, 73-78, and 98-102 DAP met the previously stated criteria for analysis.

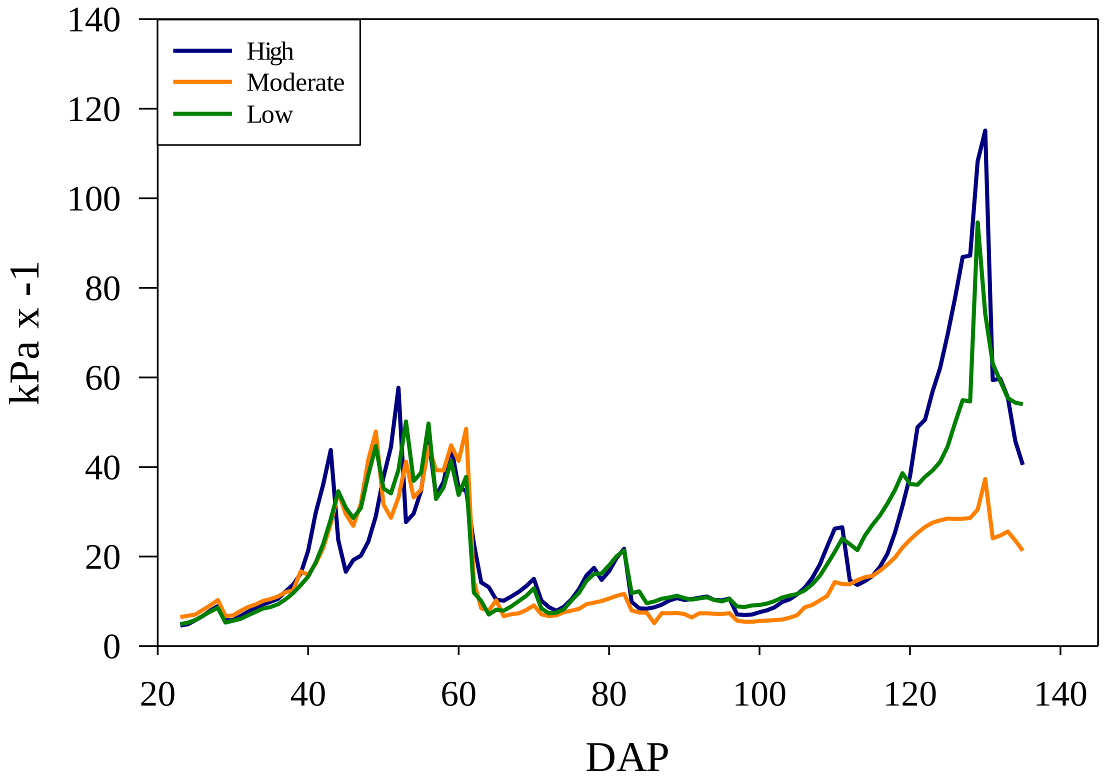

Figure 13: 45 kPa soil moisture sensor readings throughout the 2024 growing season.

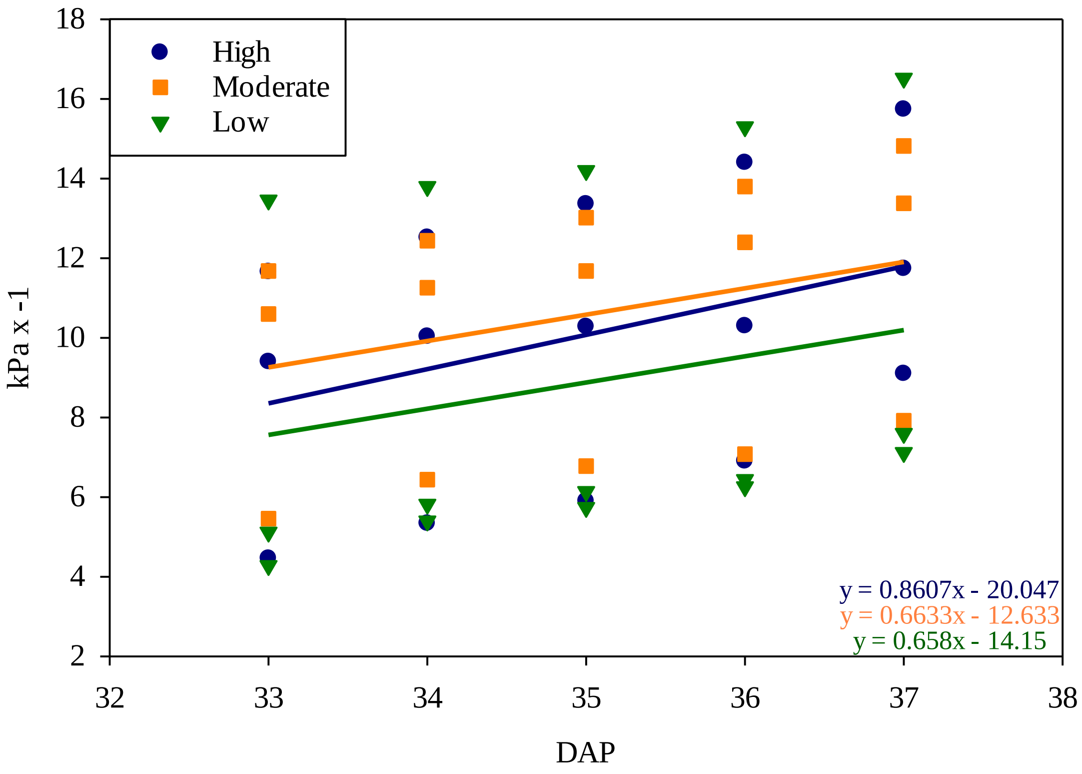

Figure 14: Soil moisture depletion rate of all populations at pinhead square in 2024.

Through the pinhead squaring stage of growth, no statistical differences were observed in soil moisture depletion between any of the populations in 2024 (Figure: 14). The same is true for the late season measurements which showed no difference between the populations, similar to the observations in 2023 (Figure 16). However, in the peak bloom observations, there were substantial but insignificant differences of more than one standard error (SE = 0.839) between the slope of the high and low populations when compared to the moderate population (Table 7). However, the estimated difference between the high and low populations was only 0.185 kPa per day (Figure 15).

Table 7: Bonferroni adjusted *p-values* for the comparisons of slopes of soil moisture depletion rates by observation period.

Treatment	Pinhead square			Peak bloom			Cutout		
	Low	Mod.	High	Low	Mod.	High	Low	Mod.	High
High	1.0000	1.0000	-	1.0000	0.3048	-	1.0000	1.0000	-
Mod.	1.0000	-		0.4595	-		1.0000	-	
Low	-			-			-		

Note: p-values of 1.0000 indicate no evidence of statistical variation between populations

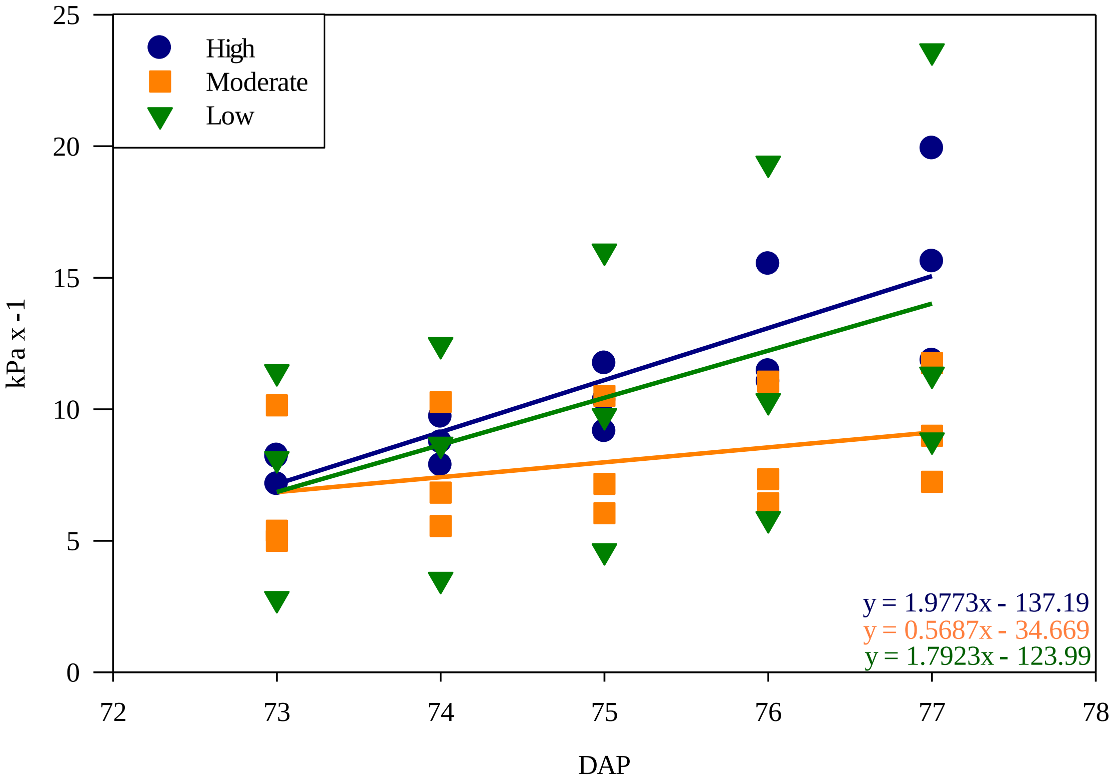

Figure 15: Soil moisture depletion rate of all populations through peak bloom in 2024.

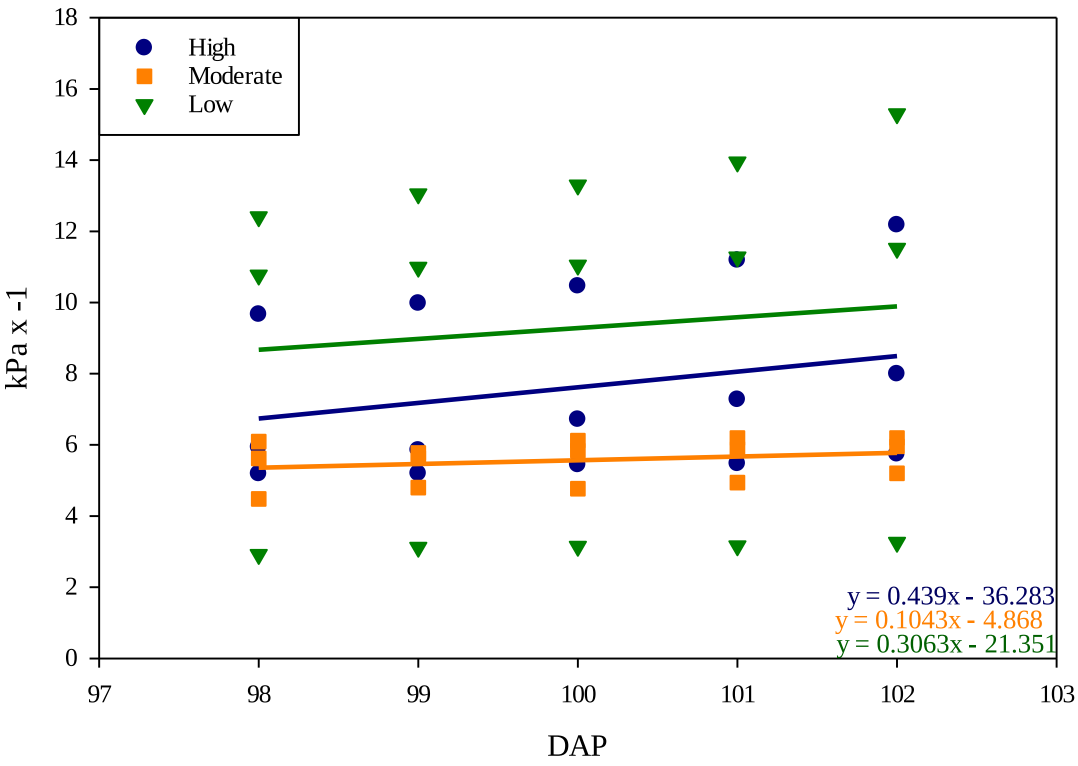

Figure 16: Soil moisture depletion rate of all populations through cutout in 2024.

Yields and Profitability

2023

Overall lint yields for all irrigated treatments were similar; however, there were variations observed between the rainfed treatments. The low population 45 kPa treatment was found to be similar to all other treatments, including the high and low rainfed treatments which were lower than all of the other irrigated treatments ($p = 0.8138$) (Table 8). When each of the main effects was evaluated individually no differences were observed between any of the populations with lint yields averaging 1833 kg/ha ($p = 0.1740$). The rainfed treatment yielded statistically lower than both of the irrigation treatments, but no differences were observed in the scheduling tool ($p = <0.0001$). This is likely due to the early season rains that limited the overall need for irrigation throughout the majority of the growing season restricting potential variability in irrigated treatments. When looking at the interaction between population and irrigation scheduling tool, as well as population as a main effect no differences in lint turnout were observed averaging 43.71% (p = 0.7706) and 43.70% (p = 0.5804) respectively (Table 8). However, variation was noted between irrigation treatments with a higher lint percentage being observed in the SI App than in the other treatments (p = 0.0097). No variations in IWUE between any of the treatments were observed in 2023 with an average efficiency of 3.78 kg/mm across all treatments (p = 0.4819).

Throughout the 2023 growing season, profitability was most affected by irrigation treatment as the rainfed plots yielded significantly less than all of the irrigated treatments (p = <0.0001). Despite increased irrigation volumes in lower-density treatments, no difference in profitability could be attributed to population regardless of drive system (p = 0.2555 & 0.2484). This indicates that the cost of each irrigation application, offset the initial savings from the reduction in seed inputs.

Table 8: Summary of crop yield, irrigation efficiency, profitability, and statistical significance in response to population and irrigation treatments in 2023.

Irrigation	Lint Turnout (%)	Lint Yield (kg/ha)	IWUE (kg/mm)	Profitability$_{E}$ ($/ha)	Profitability$_{D}$ ($/ha)
SI app	44.30^{A}	2117^{A}	3.78	3631^{A}	3398^{A}
45kPa	43.52^{B}	1963^{A}	3.78	3373^{A}	3188^{A}
Rainfed	43.28^{B}	1421^{B}	-	2460^{B}	2444^{B}
p-value	0.0097	<0.0001	0.9947	<0.0001	<0.0001
Population					
High	43.87	1920	4.19	3100	2964
Mod.	43.69	1835	4.03	3314	3159
Low	43.55	1746	3.12	3049	2897
p-value	0.5804	0.1740	0.3706	0.2555	0.2484
Irrigation x Population					
Rainfed, High	43.28	1417^{BC}	-	2391^{B}	2376^{B}
Rainfed, Mod.	43.48	1550^{ABC}	-	2698^{AB}	2683^{AB}
Rainfed, Low	43.09	1296^{C}	-	2290^{B}	2275^{B}
45 kPa, High	43.98	1951^{AB}	4.18	3302^{AB}	3142^{AB}
45 kPa, Mod.	43.17	2091^{A}	4.59	3610^{A}	3425^{A}
45 kPa, Low	43.41	1847^{ABC}	2.58	3205^{AB}	2997^{AB}
SI App, High	44.36	2137^{A}	3.89	3608^{A}	3375^{A}
SI App, Mod.	44.43	2117^{A}	3.78	3633^{A}	3400^{A}
SI App, Low	44.16	2095^{A}	3.66	3652^{A}	3419^{A}
p-value	0.7706	0.8138	0.4819	0.8099	0.7969

Note: letters with the same connecting letter are considered statistically similar at $p \leq 0.1$

2024

Throughout the 2024 growing season, consistent rainfall limited much of the potential variability between any treatment or metrics measured except for lint turnout percentage which was negatively affected in the low population rainfed treatment when compared to the 45 kPa high population treatment and SI App low population which were significantly higher. However, this was the full extent of any treatment variation between the treatment interactions (Table 9). A significant reduction in lint turnout was attributed to the scheduling tool with the rainfed treatments having lower gin turnouts than both irrigation treatments (*p* = 0.0112). No other variations could be observed between irrigation treatments in 2024. Comparatively, no significant differences were observed between populations as a main effect in 2024.

Table 9: Summary of crop yield, irrigation efficiency, profitability, and statistical significance in response to population and irrigation treatments in 2024.

Irrigation	Lint Turnout (%)	Lint Yield (kg/ha)	Seed index (g/100 seeds)	IWUE (kg/mm)	Profitability_{E} ($/ha)	Profitability_{D} ($/ha)
SI App	43.18^{A}	1337	7.76	0.24	1988	1919
45 kPa	43.58^{A}	1331	7.63	0.28	1999	1948
Rainfed	41.92^{B}	1306	7.73	-	2036	2045
p-value	0.0112	0.9205	0.3830	0.9505	0.9317	0.6226
Population						
High	43.21	1354	7.64	0.86	2007	1955
Mod.	42.89	1371	7.81	0.39	2084	2081
Low	42.58	1249	7.66	-0.46	1932	1876
p-value	0.4667	0.2829	0.1668	0.3360	0.5402	0.3306
Irrigation x Population						
Rainfed, High	42.57^{AB}	1270	7.57	-	1923	1914
Rainfed, Mod.	42.35^{AB}	1408	7.82	-	2205	2250
Rainfed, Low	40.83^{B}	1241	7.81	-	1980	1972
45 kPa, High	44.48^{A}	1401	7.57	1.07	2075	2015
45 kPa, Mod.	43.13^{AB}	1342	7.77	0.33	2012	1992
45 kPa, Low	43.13^{AB}	1249	7.56	-0.53	1909	1836
SI App, High	42.58^{AB}	1390	7.78	0.66	2023	1937
SI App, Mod.	43.18^{AB}	1364	7.85	0.46	2033	2000
SI App, Low	43.77^{A}	1258	7.63	-0.38	1907	1821
p-value	0.1285	0.8765	0.5356	0.9351	0.8621	0.8484

Note: letters with the same connecting letter are considered statistically similar at $p \leq 0.1$

2023 Crop canopy effects

One potential physical measurement that could affect the soil evaporation and water use rates of cotton is the canopy size and density. Tighter canopies could restrict airflow increasing humidity around the stomata, reducing the vapor pressure deficit within the canopy microclimate (Marois et al., 2004). Because of this the height and widths of each treatment were analyzed to evaluate the canopy size and coverage across the row. In 2023 high degrees of variation in canopy widths could be observed between irrigation treatments through the later parts of the growing season after 72 DAP (Table 10). Most notably, reduced lateral branching from the rainfed treatment and slower lateral growth in the 45 kPa treatment until approximately 88 DAP was noted. While there is a large degree of variation across measurement points in general, the moderate population tended to branch out more than the other populations. However, as the canopies began to close at 88 DAP both the high and moderate populations became similar in both height and width. When considering the combination of treatments, large degrees of variation were observed throughout the growing season, which was primarily caused by irrigation treatment effects. The only exceptions were at 51 and 65 DAP where population had a greater influence on variation (Table 10).

Table 10: Summary of crop width and statistical significance in response to population and irrigation treatments in 2023.

	DAP									
Irrigation	38	45	51	58	65	72	81	88	95	102
SI App	26.6^{B}	36.2	40.9	42.3	49.3	67.2^{A}	78.2^{A}	79.7^{A}	75.3^{A}	83.1^{A}
45 kPa	26.2^{B}	36.3	40.1	41.1	48.3	64.4^{B}	73.1^{B}	77.7^{AB}	72.7^{AB}	84.9^{A}
Rainfed	27.9^{A}	36.6	40.5	40.7	47.4	63.4^{B}	72.5^{B}	75.2^{B}	71.2^{B}	78.0^{B}
p-value	0.0055	0.7363	0.4349	0.2473	0.2902	0.0071	0.0002	0.0089	0.0279	0.0007
Population										
High	25.6^{C}	36.6	39.7^{B}	40.8	49.8^{A}	64.9	75.2	77.2	74.4^{A}	80.3^{B}
Mod.	27.0^{B}	36.4	41.4^{A}	41.3	46.9^{AB}	65.5	75.1	78.3	73.9^{AB}	85.9^{A}
Low	28.2^{A}	36.2	40.3^{AB}	41.9	48.3^{B}	64.6	73.5	77.1	70.9^{B}	79.8^{B}
p-value	<0.0001	0.7029	0.0326	0.4936	0.0662	0.7490	0.4483	0.6327	0.0510	0.0013
Irrigation x Population										
Rainfed, High	30.4^{A}	36.3	39.8	38.9^{BC}	45.5^{BC}	61.9^{B}	70.9^{B}	73.4	68.9^{CD}	71.0^{D}
Rainfed, Mod.	28.2^{AB}	37.2	41.3	40.1^{ABC}	46.1^{BC}	64.9^{AB}	75.2^{AB}	75.0	77.1^{A}	85.8^{ABC}
Rainfed, Low	27.7^{ABC}	36.4	40.5	43.0^{AB}	50.6^{AB}	63.5^{AB}	71.3^{AB}	77.3	67.6^{D}	77.3^{CD}
45 kPa, High	26.9^{BC}	37.1	40.0	42.3^{ABC}	52.6^{A}	65.7^{AB}	76.1^{AB}	78.3	76.6^{AB}	87.2^{AB}
45 kPa, Mod.	26.3^{BC}	36.8	41.4	43.0^{AB}	48.4^{ABC}	65.3^{AB}	71.8^{AB}	80.2	72.2^{ABCD}	84.0^{ABC}
45 kPa, Low	25.9^{BC}	35.1	38.7	38.0^{C}	44.0^{C}	62.3^{AB}	71.5^{AB}	74.6	69.3^{ABCD}	83.6^{ABC}
SI App, High	25.8^{BC}	36.4	39.4	41.1^{ABC}	51.3^{AB}	67.1^{AB}	78.6^{A}	79.9	77.6^{A}	82.7^{ABC}
SI App, Mod.	25.7^{BC}	35.3	41.3	40.9^{ABC}	46.3^{BC}	66.4^{AB}	78.4^{A}	79.9	72.5^{ABCD}	88.1^{A}
SI App, Low	25.2^{C}	37.0	41.8	44.7^{A}	50.4^{AB}	68.1^{A}	77.7^{AB}	79.3	75.8^{ABC}	78.5^{BCD}
p-value	0.0060	0.0721	0.1646	0.0004	0.0001	0.2770	0.2147	0.1660	0.0006	0.0013

Note: letters with the same connecting letter are considered statistically similar at $p \leq 0.1$

Variability between treatment heights followed a more consistent trend throughout the growing season than the canopy widths. The heights for both irrigated treatments were similar in all but the 51 and 81 DAP measurements, where the 45 kPa treatment was significantly shorter than the SI App (Table 11). Notably, the rainfed treatment was among the tallest groupings until the 65 DAP measurement, after which, the irrigated treatments were as tall or taller. Consistent with the literature, the low population had consistently shorter plants than both of the denser populations throughout the growing season. When considering the interaction of the irrigation and population treatments, variability became much more erratic with lower *p-values* being reported throughout the mid to latter part of the growing season (Table 11). However, the majority of the variation throughout the growing season was driven by the population treatment.

Table 11: Summary of crop height and statistical significance in response to population and irrigation treatments in 2023.

	DAP									
Irrigation	38	45	51	58	65	72	81	88	95	102
SI App	25.5	37.5^{B}	51.4^{A}	60.7	74.1^{A}	87.1^{A}	96.0^{A}	102.9^{A}	103.8^{A}	104.6^{A}
45 kPa	25.1	37.5^{B}	49.2^{B}	60.7	71.5^{AB}	84.7^{AB}	92.9^{B}	100.3^{AB}	104.6^{A}	102.3^{A}
Rainfed	25.5	39.1^{A}	52.1^{A}	60.1	70.6^{B}	82.4^{B}	90.7^{B}	98.4^{B}	96.0^{B}	97.0^{B}
p-value	0.5704	0.0173	0.0006	0.7804	0.0368	0.0025	0.0012	0.0162	<0.0001	<0.0001
Population										
High	25.6^{A}	38.7^{A}	52.5^{A}	61.7^{A}	74.4^{A}	86.7^{A}	96.0^{A}	103.1^{A}	104.3^{A}	103.1^{A}
Mod.	25.8^{A}	39.2^{A}	52.0^{A}	61.5^{A}	72.1^{AB}	85.6^{A}	94.9^{A}	102.7^{A}	105.1^{A}	104.0^{A}
Low	24.8^{B}	36.2^{B}	48.2^{B}	58.2^{B}	69.8^{B}	82.0^{B}	88.8^{B}	95.8^{B}	95.1^{B}	96.7^{B}
p-value	0.0297	<0.0001	<0.0001	0.0003	0.0051	0.0014	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation x Population										
Rainfed, High	25.3	39.4^{AB}	53.2^{A}	61.7^{AB}	70.0^{BC}	82.4^{BCD}	90.7^{BCD}	97.6^{BCD}	94.4^{C}	95.2^{C}
Rainfed, Mod.	25.9	41.3^{A}	54.0^{A}	60.7^{AB}	70.3^{ABC}	81.0^{CD}	93.3^{ABC}	100.6^{ABC}	99.9^{BC}	100.2^{ABC}
Rainfed, Low	25.3	36.5^{BC}	49.2^{A}	57.9^{B}	71.7^{AB}	84.0^{ABC}	88.3^{CD}	96.8^{CD}	93.8^{C}	95.7^{C}
45 kPa, High	25.5	38.5^{ABC}	50.8^{AB}	61.3^{AB}	76.0^{AB}	88.0^{AB}	98.4^{A}	105.2^{AB}	112.0^{A}	107.6^{A}
45 kPa, Mod.	25.2	38.4^{ABC}	50.2^{AB}	63.1^{A}	73.7^{AB}	88.9^{AB}	95.7^{AB}	103.9^{ABC}	107.5^{AB}	104.4^{AB}
45 kPa, Low	24.8	35.7^{C}	46.5^{ABC}	57.5^{B}	64.7^{C}	77.3^{D}	84.7^{D}	91.8^{D}	94.3^{C}	94.8^{C}
SI App, High	26.0	38.2^{ABC}	53.6^{BC}	62.2^{AB}	77.1^{A}	89.6^{A}	98.8^{A}	106.5^{A}	106.3^{AB}	106.6^{AB}
SI App, Mod.	26.2	38.0^{BC}	51.8^{BC}	60.7^{AB}	72.2^{AB}	87.0^{ABC}	95.7^{AB}	103.5^{ABC}	107.8^{AB}	107.5^{A}
SI App, Low	24.3	36.3^{BC}	48.8^{C}	59.3^{AB}	73.0^{AB}	84.7^{ABC}	93.4^{ABC}	98.8^{ABCD}	97.2^{C}	99.7^{BC}
p-value	0.3244	0.3411	0.7847	0.4495	0.0010	0.0001	0.0071	0.0164	0.0023	0.0102

Note: letters with the same connecting letter are considered statistically similar at $p \leq 0.1$

2024 cotton canopy architecture

Canopy measurements from the 2024 growing season showed less variability throughout the growing season than what was observed in 2023. An example of this would be the widths throughout the early part of the growing season indicating significantly wider plants in the 45 kPa treatment than both the SI App and the rainfed treatments until the 78 DAP measurements. After the 85 DAP measurement, there was no variation between the irrigation treatments until the last measurement (106 DAP) where the SI a was narrower than the rainfed treatment but not different than the 45 kPa (Table 12). When considering the population effects the only variation in widths between crop densities occurred at 99DAP. At this measurement, the high population was wider than the average population with the low population being similar to both the other populations (Table 12). However, the interaction between both treatments induced large amounts of statistical variability within the model. Most of the variation observed in 2024 was induced by the irrigation effects and the interaction between the main effects especially throughout the period from 57-85 DAP.

Table 12: Summary of crop width and statistical significance in response to population and irrigation treatments in 2024.

	DAP									
Irrigation	43	50	57	64	71	78	85	92	99	106
SI App	20.9	33.1	35.6^{A}	45.9^{B}	54.0^{B}	57.5^{A}	65.2^{A}	76.5	61.9	77.8^{B}
45 kPa	21.5	32.8	37.2^{B}	49.2^{A}	57.4^{A}	59.5^{A}	67.6^{A}	78.6	61.4	79.2^{AB}
Rainfed	22.4	32.5	33.3^{C}	37.6^{C}	46.5^{C}	51.9^{B}	60.7^{B}	77.7	62.5	79.9^{A}
p-value	0.0817	0.9451	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.1303	0.4476	0.0908
Population										
High	21.0	34.1	35.1	43.8	51.6	56.2	64.9	77.2	62.7^{A}	78.9
Mod.	21.5	32.5	35.5	44.4	53.1	56.9	65.0	78.3	60.8^{B}	79.1
Low	22.3	31.8	35.6	44.5	53.2	55.9	63.5	77.2	62.4^{AB}	79.0
p-value	0.1418	0.3964	0.7166	0.5198	0.1972	0.4810	0.4984	0.4770	0.0622	0.9724
Irrigation x Population										
Rainfed, High	22.4	32.8	32.9^{C}	36.8^{D}	45.4^{E}	52.1^{B}	61.2^{BC}	77.4^{AB}	61.5^{ABC}	78.4^{ABC}
Rainfed, Mod.	21.7	32.2	32.5^{C}	37.7^{D}	47.6^{DE}	52.1^{B}	61.2^{BC}	79.2^{AB}	63.3^{AB}	78.7^{ABC}
Rainfed, Low	23.1	32.7	34.4^{BC}	38.2^{D}	46.5^{E}	51.5^{B}	59.6^{C}	76.4^{AB}	62.9^{AB}	82.7^{A}
45 kPa, High	20.4	32.9	37.7^{A}	47.0^{BC}	53.8^{BC}	57.8^{A}	65.8^{ABC}	74.6^{B}	62.8^{AB}	81.2^{ABC}
45 kPa, Mod.	21.5	32.4	37.8^{A}	49.1^{AB}	57.3^{AB}	60.3^{A}	68.0^{AB}	80.6^{A}	61.6^{ABC}	78.1^{ABC}
45 kPa, Low	22.7	32.9	36.1^{AB}	51.6^{A}	61.0^{A}	60.4^{A}	68.9^{A}	80.6^{A}	59.9^{BC}	78.3^{ABC}
SI App, High	20.3	36.7	34.6^{BC}	47.6^{B}	55.6^{BC}	58.6^{A}	67.7^{AB}	79.6^{AB}	63.9^{AB}	80.1^{ABC}
SI App, Mod.	21.3	30.8	36.1^{AB}	46.5^{BC}	54.4^{BC}	58.3^{A}	65.8^{ABC}	75.2^{B}	57.4^{C}	77.3^{BC}
SI App, Low	21.2	31.9	36.2^{AB}	43.6^{C}	52.1^{CD}	55.8^{AB}	61.9^{ABC}	74.6^{B}	64.5^{A}	76.1^{C}
p-value	0.6065	0.6677	0.0379	<0.0001	0.0004	0.1526	0.1653	0.0001	<0.0001	0.0013

Note: letters with the same connecting letter are considered statistically similar at $p \leq 0$.

Table 13: Summary of crop height and statistical significance in response to population and irrigation treatments in 2024.

	DAP									
Irrigation	43	50	57	64	71	78	85	92	99	106
SI App	30.5^{B}	43.0	46.9	58.0^{B}	75.3^{B}	85.6^{B}	92.8^{B}	100.3^{B}	98.9^{B}	100.2^{A}
45 kPa	32.0^{A}	44.1	49.8	61.8^{A}	81.3^{A}	89.7^{A}	96.8^{A}	105.3^{A}	98.3^{A}	98.4^{A}
Rainfed	32.7^{A}	44.5	47.8	48.2^{C}	61.7^{C}	71.2^{C}	80.6^{C}	93.6^{C}	97.2^{C}	93.0^{B}
p-value	0.0034	0.0660	0.0030	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.4459	0.0038
Population										
High	31.7	44.6	49.2^{A}	56.1	74.1^{A}	$83.^{A}$	92.6^{A}	101.9^{A}	100.0^{A}	99.7^{A}
Mod.	32.0	43.6	48.0^{AB}	56.6	73.4^{A}	81.7^{B}	89.9^{AB}	100.4^{A}	98.6^{AB}	96.8^{B}
Low	31.5	43.4	47.3^{B}	55.3	70.7^{B}	81.0^{B}	87.7^{B}	97.0^{B}	95.9^{B}	95.0^{B}
p-value	0.7270	0.2147	0.1047	0.3444	0.0026	0.0077	0.0011	0.0005	0.0101	<0.0001
Irrigation x Population										
Rainfed, High	33.2	44.7	48.4^{AB}	48.1^{C}	62.7^{C}	71.1^{D}	82.0^{BC}	92.9^{D}	97.5^{BC}	97.1^{BC}
Rainfed, Mod.	32.2	44.0	45.3^{BC}	48.3^{C}	62.3^{C}	71.4^{D}	80.6^{BC}	95.7^{CD}	97.2^{BC}	95.6^{BC}
Rainfed, Low	32.7	44.9	49.6^{A}	48.3^{C}	60.0^{C}	71.0^{D}	79.2^{C}	92.2^{D}	96.9^{BC}	92.4^{C}
45 kPa, High	31.2	45.6	50.4^{A}	60.4^{A}	81.1^{A}	88.3^{AB}	97.1^{A}	105.8^{AB}	96.6^{BC}	95.7^{BC}
45 kPa, Mod.	33.1	43.5	50.7^{A}	62.3^{A}	80.6^{A}	89.2^{AB}	95.8^{A}	106.0^{A}	101.2^{AB}	100.8^{B}
45 kPa, Low	31.6	43.1	48.3^{ABC}	62.7^{A}	82.2^{A}	91.7^{A}	97.5^{A}	104.3^{AB}	97.0^{BC}	93.9^{BC}
SI App, High	30.6	43.3	48.7^{AB}	59.9^{A}	78.7^{A}	92.1^{A}	98.6^{A}	107.0^{BC}	105.8^{A}	107.8^{A}
SI App, Mod.	30.7	43.3	48.0^{ABC}	59.2^{AB}	77.4^{A}	84.5^{BC}	93.2^{A}	99.5^{BC}	97.4^{BC}	98.8^{BC}
SI App, Low	30.1	42.3	44.1^{C}	55.0^{B}	69.9^{B}	80.2^{C}	86.4^{B}	94.5^{CD}	93.6^{C}	92.6^{C}
p-value	0.5144	0.4318	0.0012	0.0121	0.0009	<0.0001	0.0019	0.0005	0.0002	0.0002

Note: letters with the same connecting letter are considered statistically similar at $p \leq 0.1$

Similarities in height can be observed between both the 2023 and 2024 growing seasons. One of these is the reduced height seen in the lower population and rainfed treatments throughout the majority of the growing season. However, contrasting the two years, a few differences are also apparent. An example of this would be throughout the middle to later part of the growing season significantly taller plants were observed in the 45 kPa treatment, compared to the SI App and rainfed treatment, until the 106 DAP measurements (Table 13). This variation between irrigation strategies had a larger effect throughout the majority of the growing season than population significantly influencing the interactions between treatment combinations, particularly before the 64 DAP measurements.

Boll Distribution

In 2024 boll distribution was evaluated to explore potential crop yield factors influencing irrigation use or uptake. Findings show increased boll loads per plant in the low population compared to high and average populations (p = 0.0019). However, no significant differences in boll rot percentages could be attributed to population (p = 0.1770) (Figure 17). Although the low population had significantly higher numbers of bolls per plant at all positions, the number of total bolls per hectare was directly tied to the population (Table 14). Similar situations have been documented by Sapkota et al., (2023) inferring that boll size varied greatly to compensate for differences in boll quantity.

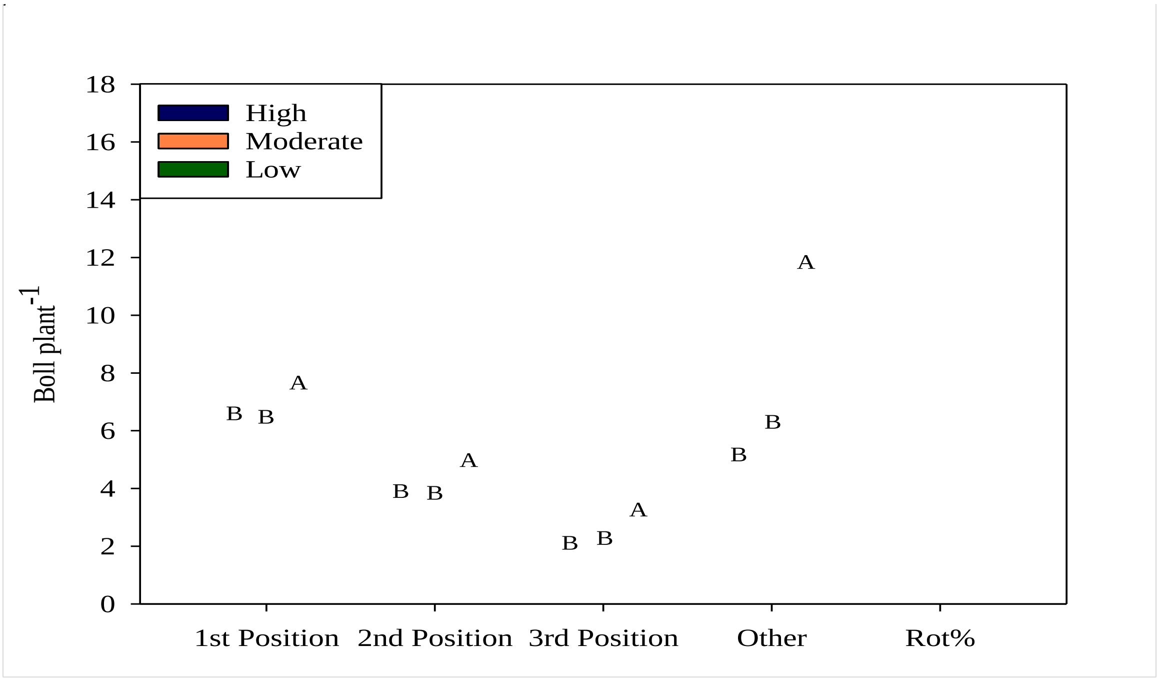

Figure 17: Boll counts by fruiting position for each population represented in the study.

Boll counts per hectare were only affected by irrigation for bolls other than those in the first and second positions. Specifically, there was an increased number of monopodial and other position bolls in the rainfed plots (Table 14). The SI App had similar third position boll loads to the 45 kPa and rainfed treatments, while the 45 kPa treatment was significantly lower than the rainfed. However, the rainfed plots produced significantly more lateral bolls in terms of non-1st through 3rd position bolls than other treatments (Figure 18). Boll rot percentage was the highest in the SI App treatments and the lowest in the 45 kPa plots. Contrary to prior assumptions, no boll rot variation was observed between any of the populations in 2024. No variation in number of internodes was observed in any of the treatments.

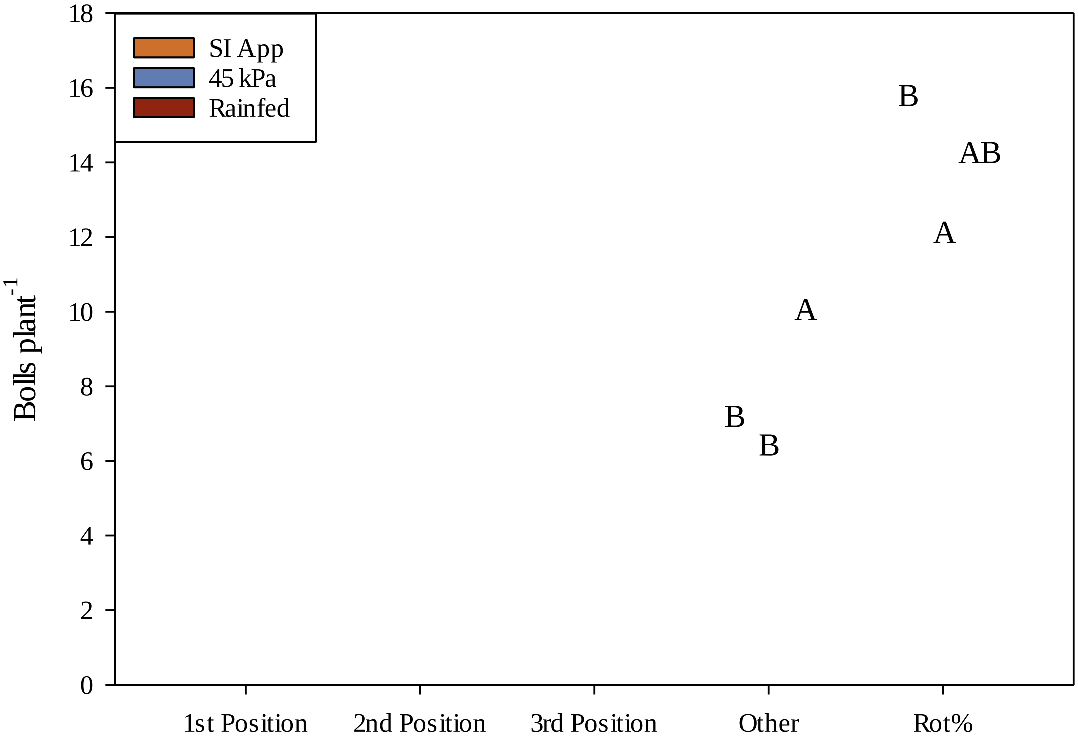

Figure 18: Boll counts based on fruiting position for each irrigation treatment in the study.

Table 14: Summary of boll distribution and statistical significance in response to population and irrigation treatments in 2024.

	Bolls ha $^{-1}$					Boll Rot (%)	Nodes
Irrigation	1st Position	2nd Position	3rd Position	Other	Total		
SI App	313359	175104	101551^{AB}	280824^{B}	870839^{B}	15.3^{A}	21.6
45 kPa	301963	177300	83377^{B}	241094^{B}	803734^{B}	11.6^{B}	21.5
Rainfed	332290	199804	113559^{A}	446486^{A}	1092139^{A}	13.7^{AB}	21.5
p-value	0.2505	0.1324	0.0954	0.0004	0.0004	0.1082	0.9838
Population							
High	423998^{A}	238404^{A}	116184	325166	1103752^{A}	12.2	21.1
Mod.	300791^{B}	172351^{B}	94409	292009	859560^{B}	15.4	21.5
Low	222823^{C}	141453^{C}	87893	351230	803400^{B}	13.0	21.8
p-value	<0.0001	<0.0001	0.1071	0.5500	0.0002	0.1770	0.6596
Irrigation x Population							
Rainfed, High	473037^{A}	276127^{A}	160697^{A}	624680^{A}	1534540^{A}	10.7	21.5
Rainfed, Mod.	284873^{CDE}	164667^{BCDE}	79040^{BC}	307927^{B}	836507^{B}	16.8	20.8
Rainfed, Low	238960^{E}	158620^{CDE}	100940^{ABC}	406850^{AB}	905370^{B}	13.8	22.1
45 kPa, High	425507^{AB}	208227^{BC}	58847^{C}	142590^{B}	835170^{B}	12.3	20.4
45 kPa, Mod.	265113DE	195953^{BCD}	111973^{ABC}	279933^{B}	852973^{B}	10.6	22.2
45, kPa, Low	215270^{E}	127720^{E}	79310^{BC}	300760^{B}	723060^{B}	11.9	21.8
SI App, High	373450^{BC}	230860^{AB}	129010^{AB}	208227^{B}	941547^{B}	15.4	21.5
SI App, Mod.	352387^{BCD}	156433^{CDE}	92213^{ABC}	288167^{B}	889200^{B}	17.0	21.6
SI App, Low	214240^{E}	138020DE	83430^{BC}	346080^{B}	781770^{B}	13.5	21.6
p-value	0.0035	0.0511	0.0028	0.0033	0.0008	0.6858	0.0764

Note: letters with the same connecting letter are considered statistically similar at $p \leq 0.1$

Discussion and Conclusions

The objectives of the current study were to identify differences in irrigation requirements and yield based on cotton population density and determine if irrigation frequency can be reduced to maintain profitability at lower plant populations. In contrast, an increase in irrigation requirements was observed as population density decreased. Also, no benefit or reduction in lint yields, IWUE, or profitability in lower populations across both years of the study was observed. These findings are similar to the results in IWUE observed by Chen et al., (2019) in China who also saw no difference in IWUE between various populations, as well as reduced irrigation requirements in higher populations. Similar yield results have been observed in the high plains of Texas when researching density effects on fiber quality attributes of cotton (Feng et al., 2014). Because of this, the increased risk of yield reductions documented by Adams et al., (2019) is likely to offset the initial savings when cotton is planted for final stands below 35,000. However, a final population around 50,000 plants/ha appears to be an acceptable middle ground between the high populations that have historically been planted throughout the southeast (Baker, 1976; Feng et al., 2014; Gwathmey et al., 2011; Hand et al., 2022). In situations where irrigation water may be restricted higher populations may be less likely to experience moisture stress and perform better because of the lower irrigation requirements when using single-row conventional planting configurations.

Because of the variation in canopy dimensions, which was very comparable to other similar studies, the canopy microclimate was potentially affected (Ethridge et al., 2022; Hake, Burch, et al., 1991; P. H. Jost & Cothren, 2000; Kaggwa-Asiimwe et al., 2013; Siebert et al., 2006b). Further research should be done to evaluate canopy microclimate and transpiration rates within various populations. Some of the variation in irrigation requirements observed could be driven by variations in the canopy development rate affecting transpiration rates (Sinclair & Ghanem, 2020). There is also limited knowledge of the effects of plant density and spacing on canopy temperature relative humidity and vapor pressure deficit as measured by (Marois et al., 2004).

The boll distribution data collected in 2024 agrees with the findings of Sapkota et al., (2023), and assumes variations in boll mass or lint per seed which can also be affected by moisture stress (Pettygrew 2004; Sharma et al., 2015). However, because there were no variations in lint yield, lint turnout, or seed index between both irrigated treatments in 2024, other factors that could explain similar yield despite variations in boll quantity would be an influence of population on intra-boll yield components such as the number of seeds per boll, fibers per seed, and single fiber weight (Lawton et al., 2024; Hu et al., 2018, Groves et al., 2016). Because lint turnout results from 2023 were not replicated in 2024 more localized studies investigating variations in boll distribution within various densities, irrigation strategies, and stand uniformities within one-row configurations (intra-row spacing) could help further explain these variations before conclusions could be confidently formed.

These data show that the free-to-use SI App can be as effective of an irrigation scheduling tool as sensor-based scheduling techniques, despite the increased incidence of boll rot observed compared to the 45 kPa threshold in 2024. Based on the 2023 results, lint turnout increased compared to the other irrigation treatments. This makes it an attractive option to farmers and producers with accurate and reliable on-farm weather data, who may not be willing to invest in a soil moisture sensing system.

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CHAPTER V

CONCLUSIONS AND FUTURE WORKS

Conclusions

In conclusion, these studies demonstrate the benefit of proper irrigation timing and management. As more scheduling tools become available, understanding the differences between different irrigation scheduling strategies will become increasingly imperative. The result of this study shows the negative effects of over-irrigation as seen in the 20 kPa and checkbook scheduling methods. It also shows the detrimental effects of drought stress, in agreement with our initial hypothesis, reinforcing the importance of good irrigation scheduling tools like a 45 kPa weighted average, the UGA SmartIrrigation App, or a well-vetted commercially available platform. Using one of these tools has shown that it can help increase yield, irrigation water use efficiency, and profitability. It also highlighted the importance of reliable weather data on irrigation scheduling as forecast and rainfall accumulations.

However, contrary to our second hypothesis, we saw an increase in irrigation frequency as the cotton population decreased. Nevertheless, in populations as low as 30,900 plants ha^{-1}, no significant reductions in yield were observed in 2023 or 2024. Because of this, the increases in irrigation inputs offset the initial savings from reduced seed inputs, negating the value of reducing seeding rates. Also, based on soil moisture measurements from the 2024 growing season, no significant variations in soil moisture depletion rates could be observed in 2024, despite anecdotal differences in 2023.

Through both growing seasons, large amounts of variations in canopy architecture were observed; however through peak bloom in both years, the plots irrigated by the SI App were in the widest groupings. Similarly, plots irrigated based on the 45 kPa SWT were among the tallest, while the low populations were among the shortest in both growing seasons. Analysis of boll distribution in 2024 revealed increased boll loads per plant in lower populations. However, this did not translate to higher boll loads per hectare as the difference was not enough to surpass the increase in population.

Future works

This project was the first two years of the project and serves as a foundation for further research. Because of this data collection should remain ongoing to validate the findings of the boll distribution and intra-boll parameters. Moving into the 2025 growing season plans to continue using the current treatment structure with the addition of a second variety as a subplot factor. Additional work in the future may include a multi-year analysis to further refine the soil moisture depletion findings based on the procedures outlined in this paper. Further questions have been raised regarding variations in crop maturity between treatments, varietal effects, canopy microclimate, and parameters affecting lint turnout.

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