THE EFFECT OF PLANT GROWTH MANAGEMENT ON COTTON SUSCEPTIBILITY TO DROUGHT DURING THE FLOWERING AND BOLL FILLING STAGES

by

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(Under the Direction of John L. Snider)

ABSTRACT

This thesis addressed the effects of growth management on drought susceptibility in field-grown cotton, and assesses the underlying yield component responses to drought and mepiquat chloride (MC) application. For both the 2021 and 2022 seasons, aggressive MC management consistently reduced plant height, number of mainstem nodes, and the length of the fourth internode below the plant terminal. Yield was more stable in response to drought for aggressively managed plants, yet aggressive MC management penalized yields relative to untreated plants in high yield situations. Aggressive MC treatment produced greater seed surface area, seed number boll^{-1}, and boll mass than untreated plants, but fewer bolls per unit land area than untreated plants under well-watered conditions. We concluded that aggressive MC management stabilized yields in response to drought-stress, but penalized yield overall. We can conclude that lint yield reductions due to irrigation or MC management were primarily associated with changes in boll density.

INDEX WORDS: Cotton, Mepiquat Chloride, Drought, Yield components, and Plant growth

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DEDICATION

I would like to dedicate this work to my Mimi, Mom, and Dad. I truly thank them for all their continued love, encouragement, and support throughout my life and while I have pursued graduate education.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Introduction

Water is essential for plant growth and development, and drought during a growing season can quickly halt reproductive and vegetative growth. In the United States, around 67% of crop loss over the past 50 years has been associated with drought (Comas et al., 2013). Cotton yield losses in the Southeastern U.S. can be as large as 1,178 kg/ha, and in severe drought cases, a $697 per ha reduction in net revenue has been observed (Ermanis et al., 2021). During the growing season cotton has a peak water use of 3.81 cm/week (Hand et al., 2021) at the peak bloom stage of crop development.

In addition to water use, producers must also consider the use of Plant Growth Regulators (PGR) in their cotton production system. The PGR mepiquat chloride (MC) manages excessive vegetative growth by decreasing plant height, limiting the number of mainstem nodes, and shortening internode length (Reddy et al., 1992). MC has been used in cotton research and cotton production since the late 1970's and early 1980's, commonly referred by the tradename Pix (Kerby 1985). The relationship between MC and drought has been studied in cotton seedlings (Xu and Taylor, 1992) and the relationship between MC and growth (Reddy et al., 1992) has been studied extensively, but no previous studies have examined the relationship between MC-based plant growth management and cotton's yield susceptibility to drought during peak water use. This study will evaluate MC's ability to influence drought susceptibility during the flowering and boll filling stages in cotton. The currently proposed study will compare the response of aggressively treated PGR and untreated cotton to drought exposure during the peak bloom phase of growth.

Literature Review

Drought negatively impacts physiological processes and yield components

Water is the most limiting resource for crop growth and development (Loka and Oosterhuis, 2012). Therefore, water management is vital to the success of cultivating row crops such as cotton (*Gossypium hirsutum).* Cotton grown in the Southeastern United States receives over 130 cm of rain per year in hot humid conditions (Mullen et al., 2009; Chastain et al., 2016). In humid conditions, drought-stressed plants do not experience moisture stress as quickly as plants grown in arid regions. Humid conditions have greater moisture content in the air, and plants experience slower water loss due to reduced vapor pressure deficit (Pettigrew, 2004b). Even with frequent rainfall events occurring, periods of drought can occur during the growing season. A prominent sign of drought is cotton plants wilting in the field; however, once wilting is observed, yield potential has already been decreased (Hand et al., 2021). Drought stress in cotton can limit photosynthetic activity, vegetative growth, reproductive growth, yield components, and fiber quality (Snowden et al., 2014; Meeks et al., 2019; Chastain et al., 2014; Pettigrew, 2004a).

A decline in net photosynthesis results in less carbohydrate production for plants, which in turn results in yield reductions. In Chastain et al. (2014), net photosynthesis measurements taken in dryland cotton compared to irrigated cotton plots were significantly lower by 54%, 14%, and 29% depending on the sample date and year. In water-deficient conditions, a reduction in net photosynthesis occurred along with a decline in stomatal conductance. The large differences in net photosynthesis also correlated with the dryland plots yielding less than irrigated plots. A reduction in plant height can be observed in response to low soil moisture. Research conducted by Pettigrew (2004b), showed that cotton grown in dryland conditions had a 16% reduction in height, 35% reduction in leaf area index (LAI), and a 32% reduction in overall vegetative growth compared to irrigated plots. Plants that have access to water can uptake water through the root system and increase biomass and vegetative growth because water is not a growth-limiting factor in this situation. In water-stressed conditions, plants must use the water they have for survival, which limits new plant growth and expansion. The number of mainstem nodes also correlates with vegetative and reproductive growth in cotton. In irrigated conditions, plant height and the number of mainstem nodes are increased compared to non-irrigated conditions. Pettigrew (2004a) and Wiggins et al. (2014) both observed a slower growth and development in dryland plots and greater height and number of mainstem nodes in irrigated plots. Good growth and development early on and throughout the season set the stage for reproductive development to occur, which could result in greater yields at the end of the season (Wiggins et al., 2014).

Reproductive growth in cotton consists of the production of fruiting sites (squares, flowers, and bolls). Since cotton is an indeterminate crop, both reproductive and vegetative growth are occurring simultaneously. Therefore, water demand is highest when cotton begins to bloom and set bolls (Hand et al., 2021; Pettigrew, 2004a). Fruiting site production is a key factor in the production of a successful cotton crop. For example, the greater the number of fruiting sites a cotton plant has, the greater the yield potential. Drought occurring in the early season will negatively affect plant growth and decrease the total number of fruiting sites on which to set bolls (Schaefer et al., 2018; Snowden et al., 2014). Flowering in cotton gives rise to boll production which in turn produces lint. Drought conditions can slow subsequent flowering rates and research conducted by Guinn and Mauney (1984) showed that a reduction in flowering rate due to water-stressed conditions does not start to recover until after 3 weeks. Pettigrew (2004a) saw that cotton grown under dryland conditions had significantly less blooms per unit ground area than irrigated plots.

Drought occurring during flowering and boll development can increase square and young boll abscission and lower fruit retention levels while altering fruit distribution patterns (Meeks et al., 2017; Snowden et al., 2014). Snowden et al. (2014) observed that first position fruit retention was slightly above 60% at node 7 but steadily decreased from 50% at node 8 to only 20% at node 10 when plants were exposed to water-deficit at early flowering. Regarding fruit distribution patterns, in drought conditions, boll retention is higher in the bottom portion of the canopy, and fewer bolls are produced at higher nodes (Pabuayon et al., 2020). Boll distribution in cotton also corresponds to the timing of a drought event (Schaefer et al., 2018). Low water levels before flowering resulted in fewer bolls produced on lower sympodial branches; however, once returned to a well-watered status the plants were able to put on more bolls in the upper canopy. However, drought stressed plants did not produce as much vegetative growth for the upper bolls as compared to the other water regimes. The most notable effects of drought were observed during the middle of the growing season. Lack of water during early flowering caused a decline in boll production and poor retention on the upper fruiting branches. Even when these plants were returned to a well-watered status, the plant could not compensate for boll loss during this period. In addition to boll loss, boll distribution was significantly less in the middle of the crop canopy (Schaefer et al., 2018).

Boll production is a large sink for cotton plants (Pabuayon et al., 2020). The crop must distribute carbohydrates between vegetative growth and boll production which requires adequate water. Not surprisingly, boll biomass was decreased on higher fruiting branches when the crop was exposed to drought. The reduction in boll biomass due to drought was seen as a 0%-8%

decrease on the second and third fruiting branches and a 5%-34% decrease on the tenth and eleventh fruiting branches (Wang et al., 2016).

Cotton yields and fiber quality strongly impact economic productivity. Therefore, a drought-stressed condition during the growing season can negatively impact fiber quality parameters. Wang et al. (2016) showed that reductions in soil moisture resulted in reductions in fiber length and strength with the greatest fiber quality reduction being seen on upper fruiting branches. Micronaire gradually decreased with drought stress one year and increased during moderate drought conditions in another year. However, in this study, the researchers correlated micronaire to the fruit maturation period. The fruiting maturation period is dependent on environmental conditions such as water status and temperature. It is logical to assume that under well-watered conditions fruit maturity can occur without interruption and have improved fiber quality because these bolls were able to mature and develop fibers for a longer uninterrupted period. Hu et al. (2018) showed an increase in micronaire with increasing drought severity. From the results, Hu et al. (2018) concluded that severe drought conditions reduced the number of fibers produced, but produced fibers that were thicker and heavier than plants with a well-watered status. Research by Wiggins et al. (2014) also found that micronaire, fiber length, fiber strength, and fiber length uniformity were influenced by water levels. Dryland plots exhibited 82.2% uniformity while irrigated plots had 83.2% uniformity.

The timing of a drought stress period can also influence fiber quality parameters. Snowden et al. (2014) showed that water stress during the third week of bloom and peak bloom to termination reduced fiber length. It was concluded that water-stressed conditions at this stage did not allow cotton fibers to fully mature. Plants that experienced drought stress during early squaring and plants that received adequate irrigation throughout the season had similar fiber quality and had the highest fineness and maturity ratios when compared with other treatments in which drought was experienced at later developmental stages. In this situation, drought stress did not influence the elongation and development of cotton fibers in this earlier stage of development. The square does not contain maturing fibers like developing bolls contain. In the irrigated plots, fiber elongation and maturation could occur without problems due to adequate water supply. Drought occurring at early flowering is likely to have substantial reduction in yield and fiber quality (Snowden et al., 2014).

How PGR management affects cotton

Plant Growth Regulator (PGR) application has been a widely used management practice in cotton production. The most commonly used PGR in cotton is a 4.2% solution of mepiquat chloride [N, N-dimethylpiperidinium chloride] commonly referred to by the tradename Pix (Zhao and Oosterhuis, 2000). Mepiquat chloride (MC) applications can decrease overall plant height, encourage more compact plant growth, improve fruit retention, and hasten physiological maturity (Biles and Cothren, 2001; Kerby et al., 1986; Reddy et al., 1992; Stuart et al., 1984; Hake et al.,1991).

MC is a gibberellic acid inhibitor that limits cell expansion and elongation. The actively growing plant tissues such as leaves and stems are the most influenced by MC applications. Active plant growth is needed for MC to work because this is the site where cell expansion and elongation is occurring. If MC were applied to older more mature plant tissue, the effect of MC would be minimal because there is no actively growing plant tissue (Hake et al., 1991). Research conducted by Kerby (1985) recorded a decrease in overall height when plants received an application of MC. The author also showed that MC application decreased the number of mainstem nodes from 21.8 in untreated plots to 20.8 in MC-treated plots. Differences in plant height were observed in plants treated with MC versus non-treated when soil moisture levels were sufficient (Stuart et al., 1984). The number of mainstem nodes and internode length was significantly lower in plots treated with MC, regardless of temperature conditions as seen by Reddy et al. (1990). Differences of 15.24-25.4cm in final plant height and 30% shorter plants were observed with MC application (Gwathmey and Craig 2003; Stuart et al., 1984). MC application reduced LAI by 16% when compared to untreated plants (Gwathmey and Clement, 2010). A more compact cotton canopy can increase machine harvest efficiency, increase air flow in the canopy, and reduce disease potential (Gwathmey and Clement, 2010; Tung et al., 2020; Zhao et al., 2017).

Applying MC can have a positive effect on boll retention (Hake et al., 1991; Tung et al., 2020). Research conducted in Tennessee showed that MC application slightly increased the percentage of fruiting sites occupied by bolls and increased the proportion of boll set on the first five fruiting branches (Gwathmey and Clement 2010). Whereas Reddy et al. (1992) saw a mix of positive and negative effects of MC application on the total number of bolls at harvest. It was concluded that MC affected different cotton cultivars differently and that soil moisture was the driving factor in the number of harvestable bolls produced by the plant. This supports the notion that water is the most limiting factor for plant growth. Plants treated with MC had increased retention at nodes 12 or below (Kerby et al., 1986).

Physiological maturity is related to the number of nodes above first-position white flowers (NAWF) remaining on a cotton plant throughout the growing season. Physiological maturity is also referred to as cutout and can be estimated as the time during the growing season at which NAWF is less than five (Hand et al., 2021). Bednarz and Nichols (2005) concluded that in the lower Coastal Plain, three NAWF was a better indicator of the timing cutout than five. Based on this information a producer can estimate the timing of maturity in cotton (Hand et al., 2021).

Physiological maturity occurred 6 days earlier in MC treated plots compared with untreated plots as described by Gwathmey and Craig (2003). There were also cultivar-specific interactions between single and multiple MC applications. The data suggest that cultivars with different growth habits respond differently when PGRs are applied. As mentioned previously in this review, MC reduces plant height and the number of mainstem nodes. Therefore, plants with fewer mainstem nodes will be able to reach physiological maturity faster. The greater the number of mainstem nodes, the longer it will take for the plant to reach maturity.

Yield responses to MC applications have varied from negative responses, positive responses, or no responses (Cook and Kennedy, 2000). It is logical to think that MC application may increase cotton yields because MC improves boll retention. Research conducted by Cook and Kennedy, 2000 evaluated the effects of bud removal with varying MC applications and evaluated yield responses. Flower buds were removed at a rate of 0, 20, and 40% after the buds were visible for a period of 10-14days. In response to bud loss, the cotton plants responded by compensating for the bud loss by putting more energy into the second-position fruit. Early-bloom applications of MC resulted in more open bolls and higher and greater retention on the second position in the lower part of the plant canopy. Monopodial yields increased in yields with low-rate multiple applications of MC in 20% bud loss treatment. The lint yield increase was twice as much compared to the other treatment combinations. The authors concluded that MC benefitted fruit retention and significantly increased yields in some cases (Cook and Kennedy, 2000).

Several strategies can be used when applying PGRs (Hand et al., 2021; Edmisten et al., 2022; Cook and Kennedy, 2000). One of the most commonly used strategies for cotton producers in the Southeastern United States is the early bloom strategy. This consist of applying approximately 0.59L ha^{-1} to 1.17L ha^{-1} at early bloom if the crop is at least 61cm tall. Early bloom is considered five to six white blooms per 7.62m of row. If the crop is showing more vegetative growth, then another MC application following early bloom is warranted (Edmisten et al., 2022). Since producers are not growing in the same conditions, PGR management must be evaluated on a site-specific basis. Growers must consider crop growth stage, cotton cultivar, irrigation, and fertility inputs when evaluating their PGR management strategy (Hand et al., 2021; Edmisten et al., 2022).

Growth management and cotton response to water availability

When applying PGRs to cotton, producers must keep in mind the crop's access to water. Factors that influence crop water use and accessibility include water holding capacity of the soil, the size of the crop, and water demand at varying growth stages (Hand et al., 2021; Edmisten et al., 2022). In the Coastal Plain region of Georgia, sandy loams are common for row crop production. Due to the large pore soil particle sizes, water can percolate through the soil profile at a rapid rate and have a lower water holding capacity.

For plants to have access to water deeper in the soil profile a well-developed root system must be established. Research conducted by Cordeiro et al. (2021) evaluated the effects of MC application timing and root growth response. The results showed that MC application in the early reproductive stage caused a linear decrease in root length as the MC application rate increased. Early MC application decreased root length, but there was an increase in dry weight and root volume with increased MC application rates. A reduction in root length in response to MC application in the early stages could increase the potential for water deficit stress at later stages by decreasing root access to soil moisture in deeper layers of the soil profile.

Crop water use is positively associated with plant growth; therefore, the vegetative growth reductions observed in PGR treated cotton have the potential to decrease water demands. For example, PGR application produces a smaller canopy, reduced leaf area index (LAI), shortened internodes, and decreased plant height as mentioned earlier in the review (Biles and Cothren, 2001; Kerby et al., 1986; Reddy et al., 1992; Stuart et al., 1984; Hake et al.,1991; Gwathmey and Clement, 2010; Tung et al., 2020). Faster growing crop canopies have higher rates of transpiration and water loss (Sinclair et al., 1984). Plant-based predictions of transpiration show that Radiation Use Efficiency (RUE) and LAI (both of which drive biomass production) are strongly correlated with transpiration rates (Sinclair and Ghanem, 2020). Since RUE is relatively stable, variations in canopy size (LAI) could substantially alter rates of crop water use. Cotton plants not treated with PGRs produce more crop biomass and develop larger canopies (Ermanis et al., 2021). Therefore, it is reasonable to assume that increased leaf surface area would lead to greater transpiration rates. Fernandez et al. (1992) showed that MC treated plants exhibited reductions in leaf area, whole plant carbon uptake, and transpiration when compared with untreated plants under well-watered conditions. All of these factors combined would be expected to cause significant reductions in crop evapotranspiration for MC treated plots (Fernandez et al., 1992).

Peak water use for cotton is approximately 3.8cm per week and occurs roughly around the 3rd week of flowering (Hand et al., 2021). Episodic drought during peak water use results in fruit loss and decreased boll retention (Snowden et al., 2014). A crop that is well-watered (presumably with extensive vegetative growth) and then suddenly exposed to water-stress will be less likely to acclimate slowly, causing fruit abscission to increase due to a sudden lack of water. Water deficient conditions occurring at peak bloom caused a decrease in boll retention in the upper nodes of the crop canopy in previous reports (Snowden et al., 2014). The same authors showed that bolls in the lower canopy were less prone to abscising, indicating that the crop invested energy into the more mature bolls and did not utilize resources to fuel the growth of new bolls (Snowden et al., 2014).

When using the early bloom strategy for PGR management (often with a necessary follow up application two weeks later), the timing of MC application can roughly coincide with peak water use in cotton (Edmisten et al., 2022; Hand et al., 2021). It is logical to assume that MC application coupled with water-deficit conditions could be an added stress to a developing crop. Research conducted by Fernandez et al. (1991) evaluated the interaction between PGR management and irrigation treatment for crop biomass partitioning. MC treatment in both well-watered and drought-stressed conditions did not significantly affect biomass accumulation on a whole plant basis; however, MC did inhibit the growth of branches in both water treatments. MC-treated plants under water-stress saw a significantly lower shoot/root ratio of 2.5 compared to almost 4 in well-watered, untreated plants (Fernandez et al., 1991). MC treatment also affected root growth in both well-watered and drought-stressed conditions.MC treatment promoted the growth of fine roots in both water treatments; but the promotion of root growth was dependent on moisture availability (Fernandez et al., 1991). Cordeiro et al. (2021) observed that MC application in the early reproductive stage was seen to decrease root length and increase root length when applied at a later stage. Both of these experiments imply that the effects of MC application can be positive influence when applied in well-watered conditions; however, when in water-deficient conditions the root length and biomass are decreased.

Plant water status is also affected by MC application (Fernandez et al., 1992). Under water-deficient conditions, MC-treated plants were able to maintain turgor pressure for a longer period due to leaf water potential and solute potential declining at a slower rate. This shows that MC treatment can delay the onset of water deficit stress effects (Fernandez et al., 1992). Stuart et al. (1984) saw similar results where pressure potential values were higher in MC-treated plots.

Water-deficit conditions can negatively impact growth and yield parameters. The application of MC can reduce rank vegetative growth, improve boll retention, produce a smaller, more compact-plant, and hasten physiological maturity. There is a large amount of research focusing solely on the effect of water-deficit conditions or solely on the effect of PGR strategy, but documenting a relationship between PGR management and drought susceptibility are limited. MC application could influence drought susceptibility. MC application can limit root length when applied at certain growth stages; therefore, suggesting that MC application could increase drought susceptibility (Cordeiro et al., 2021). However, plant water status is improved in plants treated with MC under drought conditions, where the crop delays the onset of drought stress conditions and maintains turgor pressure for a longer period than untreated plants (Fernandez et al., 1992; Stuart et al., 1984). Furthermore, MC application decreases canopy growth, which causes the plant to exhibit more conservative water use. This could decrease drought susceptibility by slowing down the rate of soil water depletion.

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CHAPTER 2

THE EFFECT OF PLANT GROWTH MANAGEMENT ON COTTON SUSCEPTIBILITY TO DROUGHT DURING THE FLOWERING AND BOLL FILLING STAGES

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ABSTRACT

CONTEXT OR PROBLEM; Drought can substantially limit yield in cotton, and water loss in any crop is closely associated with plant growth, but studies addressing the effects of growth management on drought sensitivity are limited in cotton. OBJECTIVE; We tested the hypothesis that aggressive plant growth management would decrease cotton susceptibility to drought during flowering and boll development. METHODS; Cotton was grown at a field site near Tifton, GA during the 2021 and 2022 growing seasons. Treatments included mepiquat chloride (MC) strategies (aggressive and untreated) and two water availability treatments (well-watered and drought-stressed). At approximately 2 weeks after first flower, water was withheld from the drought-stressed treatment for a three-week period, and well-watered plots were kept irrigated using a regionally accepted water balance approach. Measurements throughout the season included heights, nodes, length of the fourth internode below the plant terminal, nodes above white flower (NAWF), and soil moisture. End-of-season measurements included lint yield, fiber quality, and yield component assessments. RESULTS; MC treatment significantly affected plant height, mainstem node number, 4th internode length, and cutout date. Soil moisture was significantly reduced during the drought stress period. Aggressive MC treated plots showed more yield stability than untreated in response to drought, but did not reach the same lint yield, boll density, or uniformity as well-watered, untreated plots. Aggressive MC treatment produced greater seed surface area, seed number boll^{-1}, and boll mass. CONCLUSIONS; Aggressive MC management may increase yield stability in response to drought, but penalize yield under well-watered conditions. Among the potential components driving yield, boll number per unit land area was the most important contributor. IMPLICATIONS or SIGNIFICANCE; Our findings highlight the potential for aggressive MC management to mitigate drought risk, but future efforts should

evaluate this possibility in a broader range of cultivars adapted for production in the southeastern United States.

Keywords: Cotton; Mepiquat chloride; Drought; Yield Components; Plant growth

1. Introduction

Water is the most limiting resource for cotton (*Gossypium hirsutum L.*) growth and development (Loka, 2012), and efficient water management is vital to ensure sustainable cotton production. Annually, the Southeastern United States receives over 130 cm of rain per year in hot, humid conditions (Mullen et al., 2009; Chastain et al., 2016). Furthermore, humid regions have greater moisture content in the air, and plants experience slower water loss due to reduced vapor pressure deficit (Pettigrew, 2004b). However, even with frequent rainfall events and relatively low vapor pressure deficit, the coarse-textured soils of the Coastal Plain have a limited water holding capacity, and periods of drought stress can occur during the growing season (Busscher et al., 2006). Thus, even short-lived drought events at key stages of development can negatively impact fruit retention, yield, and fiber quality (Chastain et al., 2014; Hu et al., 2018; Meeks et al., 2019; Pettigrew, 2004a; Snowden et al., 2014). Total cotton water demands for a growing season in Georgia are approximately 42 cm (Hand et al., 2022). Depending on seasonal rainfall amounts and environmental conditions in Georgia, 20-24% of the total water requirement for cotton is met by supplemental irrigation. (Mullen et al., 2009).

Cotton response to progressive drought stress includes reductions in vegetative growth, photosynthetic activity of individual leaves, fruit retention, yield, and fiber quality (Snowden et al., 2014; Meeks et al., 2019; Chastain et al., 2014; Pettigrew, 2004a). Cotton is particularly susceptible to drought stress occurring during flowering and boll development. Peak water use for cotton is approximately 3.8 cm per week and occurs at approximately the 3rd week of flowering (Hand et al., 2022). Schaefer et al. (2018) observed significantly lower boll production in the upper part of the crop canopy when water deficit conditions occurred around first bloom. Yield reductions of 25 to 35 percent, lower boll retention in the upper crop canopy, and decreased fiber length were documented when drought occurred at peak bloom (Snowden et al., 2014).

In addition to water use, producers must also consider the use of Plant Growth Regulators (PGR) in their cotton production system. The most commonly used PGR in cotton is a 4.2% solution of mepiquat chloride (MC) [N, N-dimethylpiperidinium chloride] commonly referred to by the former tradename Pix (Zhao and Oosterhuis, 2000). MC is a gibberellic acid inhibitor that limits cell expansion and elongation, thereby decreasing internode length (Hake et al.,1991). Differences of 15.24 to 25.4 cm in final plant height (30% height reduction) were previously observed with MC application for field-grown cotton (Gwathmey and Craig, 2003; Stuart et al., 1984). Research conducted in Tennessee showed that MC application slightly increased the percentage of fruiting sites occupied by bolls and increased the proportion of bolls set on the first five fruiting branches (Gwathmey and Clement 2010). By comparison, Reddy et al. (1992) saw a mix of positive and negative effects of MC application on the total number of bolls at harvest. Application of MC also hastens maturity in cotton, where Gwathmey and Craig (2003) showed that cessation of new vegetative growth (cutout) occurred 6 days earlier in MC-treated plots compared with untreated plots in Tennessee. Recent research conducted in Georgia showed that cotton treated with MC reached cutout between 2 and 3 weeks earlier than untreated plants under well-watered conditions (Chalise et al., 2022). One of the most commonly used MC strategies for cotton producers in the Southeastern United States is the early bloom strategy. This consists of applying approximately 25 g ai ha^{-1} to 49 g ai ha^{-1} at early bloom if the crop is at least 61 cm tall. Early bloom is considered five to six white blooms per 7.62 m of row. If the crop is showing more vegetative growth, then another MC application following early bloom is warranted (Edmisten et al., 2023). Aggressive MC management would include an additional MC application at squaring along with the early bloom strategy (Chalise et al., 2022).

Crop water use is positively associated with plant growth; therefore, the vegetative growth reductions observed in MC-treated cotton have the potential to decrease water demands. For example, MC application produces a smaller canopy, reduced leaf area index (LAI), shortened internodes, and decreased plant height as mentioned above (Biles and Cothren, 2001; Kerby et al., 1986; Reddy et al., 1992; Stuart et al., 1984; Hake et al., 1991; Gwathmey and Clement, 2010; Tung et al., 2020). Faster-growing crop canopies have higher rates of transpiration and water loss (Sinclair et al., 1984). Plant-based predictions of transpiration also show that radiation use efficiency (RUE) and leaf area development drive biomass production, which is strongly correlated with transpiration rates (Sinclair and Ghanem, 2020). Since RUE is relatively stable, variations in canopy size (LAI) could substantially alter rates of crop water use. Fernandez et al. (1992) showed that MC-treated cotton plants exhibited reductions in leaf area, whole-plant carbon uptake, and transpiration when compared with untreated plants under well-watered conditions. All of these factors combined would be expected to cause significant reductions in crop evapotranspiration for MC-treated cotton (Fernandez et al., 1992).

Studies assessing the interaction between growth management and drought susceptibility are limited for cotton. Thus, it is unclear whether MC increases or decreases cotton susceptibility to drought. For example, research conducted by Fernandez et al. (1991) evaluated the interaction between MC management and irrigation treatment for crop biomass partitioning. MC treatment in both well-watered and drought-stressed conditions did not significantly affect biomass accumulation on a whole-plant basis. MC-treated plants under water stress exhibited a significantly lower shoot/root ratio of 2.5 compared to almost 4 in well-watered, untreated plants (Fernandez et al., 1991). Cordeiro et al. (2021) observed that MC application in the early reproductive stage decreased root length, but increased root length when applied at a later stage. It has also been reported that MC application positively impacts water status (Fernandez et al., 1992). For example, under water-deficient conditions, MC-treated plants were able to maintain turgor pressure for a longer period due to declines in solute potential under water deficit. This shows that MC treatment can delay the onset of water deficit stress effects (Fernandez et al., 1992) since turgor pressure is a key determinant of physiological activity under drought stress (Pritchard 2007). Stuart et al. (1984) saw similar results where pressure potential values were higher in MC-treated plots.

There is extensive research focusing solely on the effect of water-deficit or MC strategy, but reports documenting a relationship between MC management and drought susceptibility are limited for field-grown cotton. MC application could influence drought susceptibility in two possible ways. MC application has been shown to limit root length when applied at early growth stages, suggesting that MC application could increase drought susceptibility (Cordeiro et al., 2021). However, canopy growth and presumably, transpiration rates would be decreased by MC application (Reddy et al., 1990; Fernandez et al., 1991) potentially delaying the onset of water deficit stress. Furthermore, plant water status is improved in plants treated with MC under drought conditions, where the crop maintains turgor pressure for a longer period than untreated plants (Fernandez et al., 1992; Stuart et al., 1984). Thus, aggressive MC management early in development could decrease cotton susceptibility to drought during later growth stages with peak water demands. We hypothesized that aggressive MC management would decrease cotton susceptibility to drought during flowering and boll development, leading to greater yield stability. The objectives of this study were to evaluate the effects of growth management on drought susceptibility in field-grown cotton, and assess the underlying yield component responses to drought and MC application.

2. Materials and Methods

2.1 Study site details and general management practices

The research experiment was carried out at the University of Georgia Bowen Research Farm at the Coastal Plain Experimental Station (31.48046, -83.43913) near Tifton, Georgia, USA during the 2021 and 2022 growing seasons. The soil at the experimental site is a Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 0 to 2% slopes (Perkins et al., 1984). Rainfall for both seasons was obtained from the on-site weather station at the Bowen Research Farm which is part of the Georgia Environmental Monitoring Network (http://www.georgiaweather.net). Seeds of one commercial cotton variety PHY 580 [Dow AgroSciences] were planted on May 25th and May 16th in 2021 and 2022, respectively. PHY 580 was selected for this experiment because it is marketed for production in the southeastern U.S., exhibits full season maturity, and has medium to tall plant height (https://phytogencottonseed.com/varieties/details/phy-580-w3fe). The seeding rate was 10 seeds per linear meter, inter-row spacing was 0.91 m, and the planting depth was 2.5 cm. Stand counts were conducted approximately two weeks after planting, and in-row plant density was at or above levels needed to maximize yield (Hand et al., 2022). Agronomic practices such as tillage, row spacing, seeding rate, seedbed preparation, weed management, and insect management followed the University of Georgia Cooperative Extension Service recommendations (Hand et al., 2022).

2.2 Treatments and experimental design

The experimental design utilized was a randomized block, split-plot experiment, with irrigation treatment being the whole plot factor and MC treatment being the subplot factor. There were six replicate plots for each treatment combination for a total of 24 plots. Each plot was 2 rows wide (1.8 m) and 4.6 m in length. The irrigation treatments consisted of a well-watered control treatment in which plots received irrigation according to the UGA checkbook method (Hand et al., 2022), and a drought-stressed treatment. The drought-stressed treatment followed UGA checkbook irrigation recommendations until the 3rd week of bloom. Water was withheld for 3 weeks then plots were returned to a well-watered status according to the UGA checkbook method.

Successful implementation of irrigation treatments required the use of drip irrigation and large rain exclusion shelters. Specifically, all plots were grown uncovered until flowering, when three large (9.1 x 39.3 m) rain-exclusion shelters with transparent plastic film were pulled into place over all experimental plots to prevent rainfall. Because water was delivered to plots via subsurface drip irrigation, drought-stressed and well-watered treatment were imposed in each shelter. Two-row buffer strips of cotton plants separated treatment areas from the edge of the shelter and separated adjacent irrigation treatments within the same shelter to prevent water intrusion. To prevent rainfall from entering the shelter by flowing down the row middles, dams were built on the front and back of each shelter. MC treatments were an aggressive MC management strategy and an untreated control. The aggressive treatment received foliar applications of MC (4.2% solution of N, N-dimethylpiperidinium chloride) using a CO_2-powered backpack sprayer (MODEL T-4 backpack sprayer Bellspray, INC.) at rates of 31 g ai ha^{-1} at the 8-leaf stage (squaring), 37 g ai ha^{-1} at first flower, and 49 g ai ha^{-1} two weeks after first flower. Untreated plots received no applications of MC.

2.3 In-season measurements

In-season measurements began at the 8-leaf stage of development, which is also the start of floral bud development (the squaring stage). Measurements were conducted weekly for the duration of the growing season and consisted of plant height (cm), the number of mainstem nodes per plant, and the length of the fourth internode below the plant terminal. Cell elongation in a developing internode ceases between the fourth and fifth internode; therefore, this is the most recently matured internode and a standard indicator of plant responsiveness to MC (Brown and Sandlin, 2019; Guthrie et al.,1993). Soil moisture measurements were conducted in each plot using a Field Scout TDR 350 soil moisture meter (Spectrum Technologies, Inc.). To accurately measure volumetric water content (VWC %) soil probes (20.32 cm in length) were used along with setting the meter for sand-based fields. These moisture readings were taken in the rows of each plot. Starting at flowering, weekly assessments of the number of mainstem nodes above the first position white flower (NAWF) were recorded to determine physiological maturity (cutout). Specifically, NAWF was plotted versus days after planting and a linear function was used to estimate the date at which NAWF = 3. Cutout refers to the stage of crop development at which new vegetative growth ceases and NAWF = 3 is a generally accepted definition of cutout timing for cotton grown in the Southeastern United States (Bednarz and Nichols, 2005). All weekly plant measurements were taken from five plants per plot and averaged prior to statistical analysis.

2.4 End-of-season measurements

At the end of the growing season, five plants per plot were marked with flagging tape at the uppermost harvestable boll. Once the flagged bolls had opened, seedcotton (fiber plus seed) was harvested as described below. This method was employed because no defoliants were applied inside the rainout shelter. In each plot, two 1.83 m sections (3.66 m total) were hand harvested from the middle of each plot. While hand harvesting, the number of total harvestable bolls per plant were documented. The dates of harvest were November 2nd, 2021 and September 27th, 2022. Thereafter, seedcotton was weighed using a portable scale (AMPUT 3kg 0.1g Electronic Table Bench Scale) and ginned using a laboratory saw gin (Continental Eagle PTY. LTD.). After ginning, lint weight was determined and lint percent was calculated by dividing lint weight by seed cotton weight. Lint yield was estimated by multiplying the original seedcotton weight by gin turnout and considering the harvested land area. Approximately a 0.5 kg sample of ginned fiber was sent to the USDA classing office in Memphis, Tennessee, USA to determine fiber length, strength, micronaire, and uniformity.

2.5 Yield Components

As noted above, the total number of plants and harvestable bolls were recorded for each hand harvested section within a given plot. Boll density was estimated as bolls per hectare. Samples were ginned to obtain lint and seed weight, and the mass of 100 fuzzy seeds was determined to calculate average seed mass. From these data, other parameters were estimated: seed cotton weight boll^{-1} (g), seed index (g per 100 seed), and seed number boll^{-1}. Average seed surface area (SSA) was estimated from seed index as SSA = 35.74 + 6.59 × seed index. Lint weight boll^{-1} (g) was calculated as harvested lint weight per plot divided by number of bolls per plot. Lint index (lint weight per 100 seed) was determined by dividing lint weight per boll by seed number per boll and multiplying by 100. Fibers seed^{-1} was calculated by dividing lint index by estimated individual fiber weight. Individual fiber weight (µg) was calculated as [fiber length (cm) x length uniformity (%) x (micronaire ÷ 1,000,000)]. Fiber density was determined by dividing fibers per seed by SSA (Bourland and Gbur, 2018; Groves and Bourland, 2010; Hu et al., 2018).

2.6 Statistical analysis

The design of our experiment was a randomized block, split-plot experiment, with irrigation treatment being the whole plot factor and MC treatment being the sub-plot factor. There were six replicate plots for each treatment combination for a total of 24 plots. Because of differences in earliness of MC effects on growth parameters, length of the growing season, and weather conditions, 2021 and 2022 were analyzed separately. A mixed-effects analysis of variance (ANOVA) was used for assessing treatment effects between the parameters of interest. Specifically, block (rain-exclusion shelter) and [block x irrigation] were considered random effects, and irrigation, MC treatment, and [irrigation x MC] were considered fixed effects. For means separation, post hoc analysis was carried out using Fisher's protected least significant difference test at (α = 0.05). For variables that were measured on multiple sampling dates throughout the growing season, the aforementioned analysis was conducted within each sample date. Importantly, for soil moisture, there was no effect of MC treatment or interaction between MC treatment and irrigation, so soil moisture data was only presented for the irrigation effect. Similarly, because irrigation treatments were initiated at the second week of bloom, effects of irrigation or interactions between irrigation and MC management were rarely observed for growth parameters. Therefore, only the MC effect is presented for plant growth and development parameters. SigmaPlot 14.0 (Systat Software Inc., San Jose, CA) was used for constructing graphs and JMP® Pro 16.0.0 (SAS, Cary, NC) was used for all statistical analyses.

3. Results

3.1 Environmental conditions and irrigation

Average maximum and minimum temperatures at the University of Georgia Bowen Research Farm were, 30.3 °C and 19.8 °C (2021) and 32.4 °C and 20.9 °C (2022) (Table 1). Less irrigation was applied in the 2021 season due to frequent rainfall events occurring prior to imposing irrigation treatments. 11.2 cm of irrigation was withheld from the drought-stressed treatment in both 2021 and 2022 when compared to the well-watered treatment. In 2022, 3.3 cm more of additional irrigation was applied, relative to the 2021 growing season, to meet seasonal water requirements for cotton. Rainfall amounts were considered in making irrigation decisions until the rain exclusion shelters were put in place. At that time, all water received by the crop was applied via subsurface irrigation.

Table 1. Cumulative season-long irrigation, rainfall, total water received from rainfall plus irrigation, and average daily minimum and maximum temperature for two different irrigation treatments [Drought-Stressed and Well-Watered] during the 2021 and 2022 growing seasons for a field site in Tifton, GA, USA.

Year	Treatment	Irrigation (cm)	Rainfall (cm)*	Total water (cm)	Average T_{min} (ºC)	Average T_{max} (ºC)
2021	Drought-Stressed	24.0	25.2	49.2	19.8	30.3
	Well-Watered	35.2	25.2	60.4	19.8	30.3
2022	Drought-Stressed	27.3	22.3	49.6	20.9	32.4
	Well-Watered	38.5	22.3	60.8	20.9	32.4

*Rainfall after shelters were in place were not considered in rainfall totals for this table.

There was a significant irrigation treatment effect on soil moisture throughout the three-week drought stress period in both years, with the exception of the first measurement after treatments were imposed in 2022 (Figure 1). Specifically, the drought-stressed treatment had significantly lower soil moisture levels when compared to the well-watered treatment during the three-week drought stress period. In 2021, drought stressed soil moisture was as much as 91 percent lower than the well-watered treatment and as much as 98 percent lower than well-watered treatment in 2022. Soil moisture levels were higher at the start of the drought stress period in 2021 compared to 2022, and the visual severity of drought in plots where water was withheld was more prominent in 2022 than in the 2021 season (personal observation). Irrigation was terminated once 10 percent of all harvestable bolls were open (Hand et., 2022).

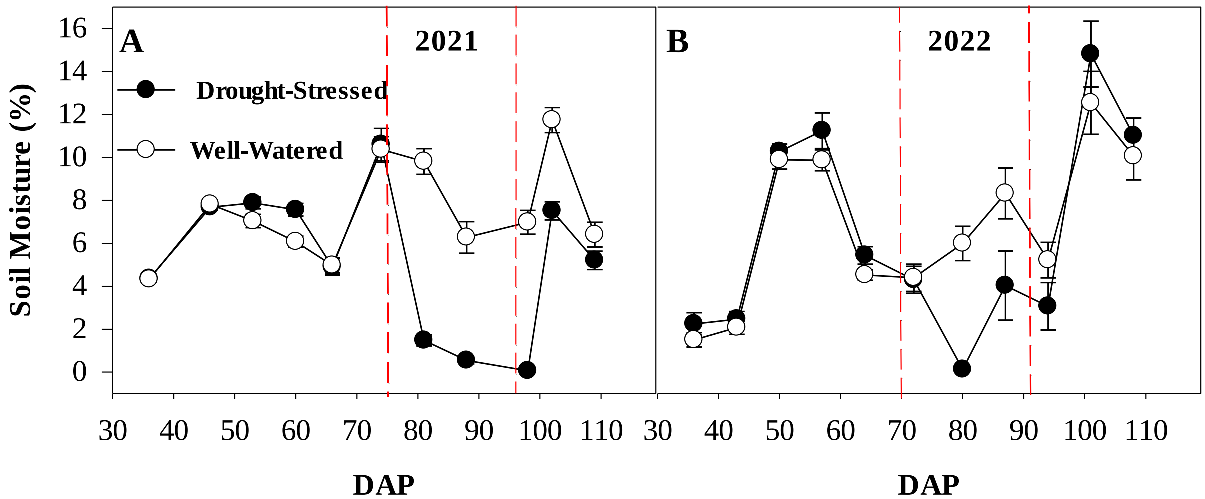

Figure 1. Effect of irrigation treatment on soil moisture levels throughout the 2021 and 2022 cotton growing season for a field site in Tifton, GA, USA. The red dashed lines indicate the initiation and termination of the 3-week drought-stress period. Values are means ± standard error (n = 12), and black circles represent the drought stressed treatment, whereas white circles represent the well-watered treatment.

3.2 Growth and development

There was a significant effect of MC treatment on the total number of mainstem nodes beginning at 72 days after planting (DAP) for 2021 and 43 DAP in 2022 (Figure 2). Significant MC effects were observed for all subsequent sample dates throughout the growing season. For both 2021 and 2022, the aggressive MC treatment produced plants with approximately 2 less mainstem nodes compared to untreated plants by the end of the season. The length of the 4th internode below the terminal of the plant was significantly affected by MC treatment beginning at 53 DAP in 2021 and 43 DAP in 2022 and continuing throughout the remainder of the growing season. Aggressive MC management significantly reduced the 4th internode length when compared with untreated plants (Figure 2). Specifically, the aggressive treatment reduced 4th internode length by as much as 2.5 and 2.6 cm compared to untreated plants during the 2021 and 2022 growing seasons, respectively.

Plant height was significantly reduced in the aggressive MC treatment for both the 2021 and 2022 seasons (Figure 2). Aggressively treated plants were 44.5 cm (2021) and 39.9 cm (2022) shorter than untreated plants by the end of the growing season. A significant MC effect was first observed at 51 DAP in 2021 and 43 DAP in 2022 and continued throughout the growing season.

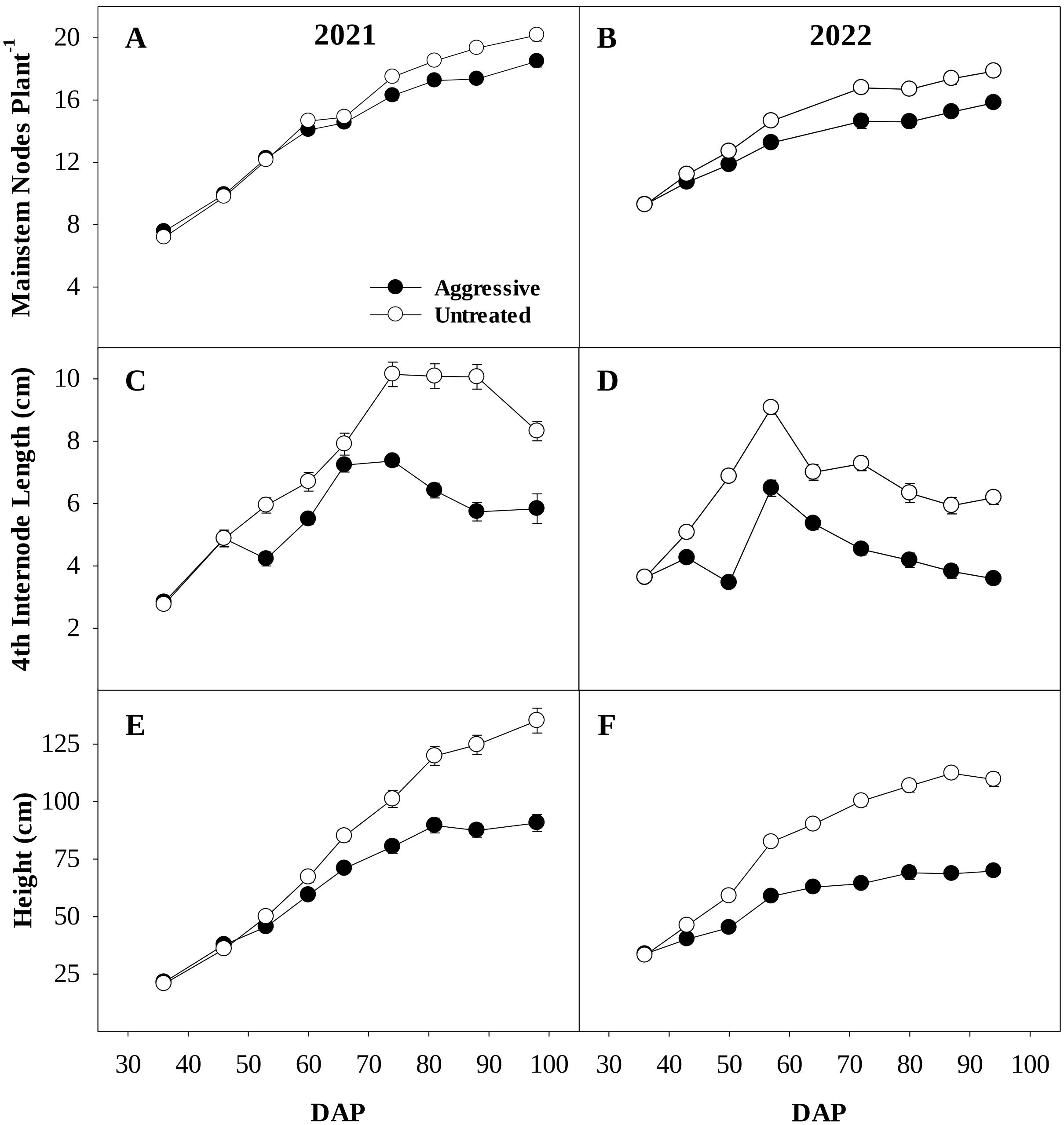

Figure 2. Effect of MC treatment on mainstem nodes plant^{-1} (A and B), 4th internode length (C and D), and plant height (E and F) during the 2021 and 2022 growing seasons for a field site in Tifton, GA, USA. Values are means ± standard error (n = 12), and black circles represent the aggressive MC management treatment, whereas white circles represent the untreated control.

Aggressive MC management caused plants to reach cutout faster when compared to the untreated control (Figure 3). A significant effect of MC treatment on the number of mainstem nodes above the uppermost, first position white flower (NAWF) was first observed at 66 DAP in 2021 and 57 DAP in 2022. NAWF values for aggressively managed plots were as much as two nodes fewer than for untreated plants in 2021 and two nodes fewer than untreated plots in 2022 by the end of the growing season. The number of days required to reach cutout were significantly reduced by aggressive MC management compared to untreated plants (Figure 4). In both years (2021 and 2022) cutout was reached nine days earlier with aggressive MC management than in untreated plants. In 2021 untreated plants reached cutout at 101 DAP compared with 92 DAP for the aggressive treatment. In 2022, untreated plants reached cutout at 86 DAP, whereas aggressively managed plants reached cutout at 77 DAP. In 2022, both the untreated control and the aggressive MC treatment reached cutout earlier than in 2021.

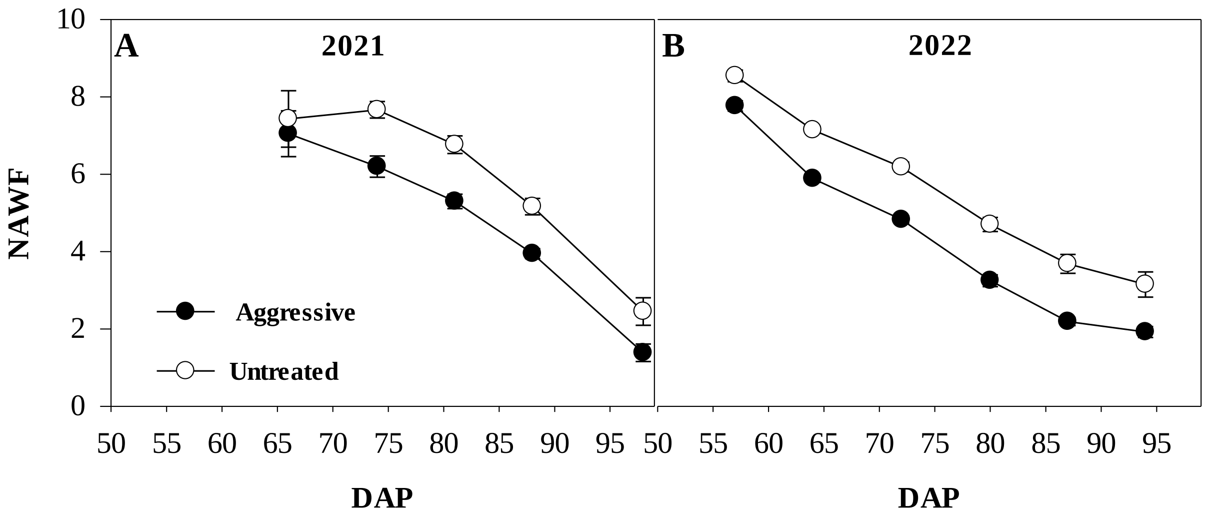

Figure 3. Effects of MC treatment on NAWF during the 2021 (A) and 2022 (B) growing season for a field site in Tifton, GA, USA. Values are means ± standard error (n = 12), and black circles represent the aggressive MC management treatment, whereas white circles represent the untreated control.

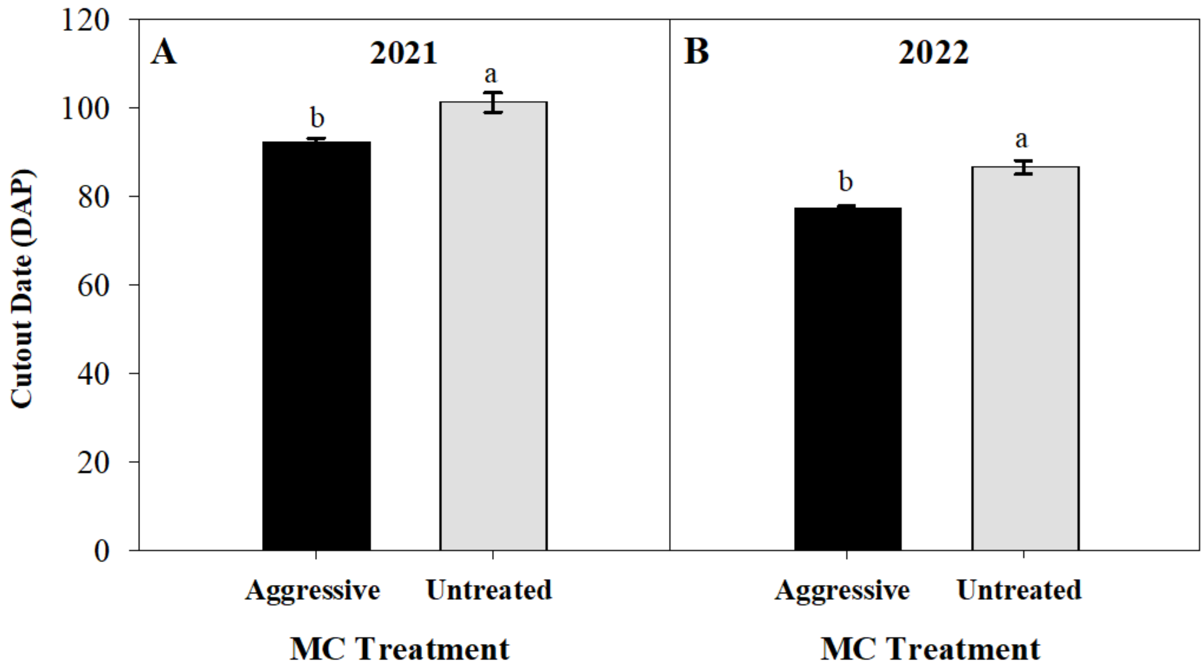

Figure 4. Effects of MC treatments on cutout date (DAP) during the 2021 (A) and 2022 (B) growing season for a field site in Tifton, GA, USA. Bars represent means ± standard error, and bars not sharing a common letter are considered significantly different ($P \leq 0.05$).

3.4 Lint Yield and Yield Components

There was not a significant interaction between MC management and irrigation treatment during the 2021 growing season with respect to lint yield. Lint yield was only affected by MC treatment in 2021. For example, in this season, lint yields for MC-treated plots averaged 1081 kg ha^{-1}, which was 24% lower than lint yields for untreated plots (Figure 5). A significant interaction was observed between MC management and irrigation treatment during the 2022 season (Figure 5). Lint yield in aggressively treated plots were 691 kg ha^{-1} under drought-stress and 761 kg ha^{-1} in well-watered conditions. Lint yield in untreated control plots were 642 kg ha^{-1} under drought and 1077 kg ha^{-1} in well-watered plots. Overall, the yields in 2021 were higher in all plots when compared to 2022. Boll density (boll number per hectare) exhibited similar trends as lint yield in 2022 (Figure 5). There was not a significant effect of MC, irrigation, or interaction between MC management and irrigation in 2021. A significant interaction between MC treatment and irrigation was observed in 2022 for boll density. Boll density in aggressively-treated plots was 451,294 boll ha^{-1} in drought-stressed plots and 469,226 boll ha^{-1} in well-watered plots. Boll density in untreated plots was 481,181 boll ha^{-1} in drought-stressed plots and 725,756 boll ha^{-1} in well-watered plots.

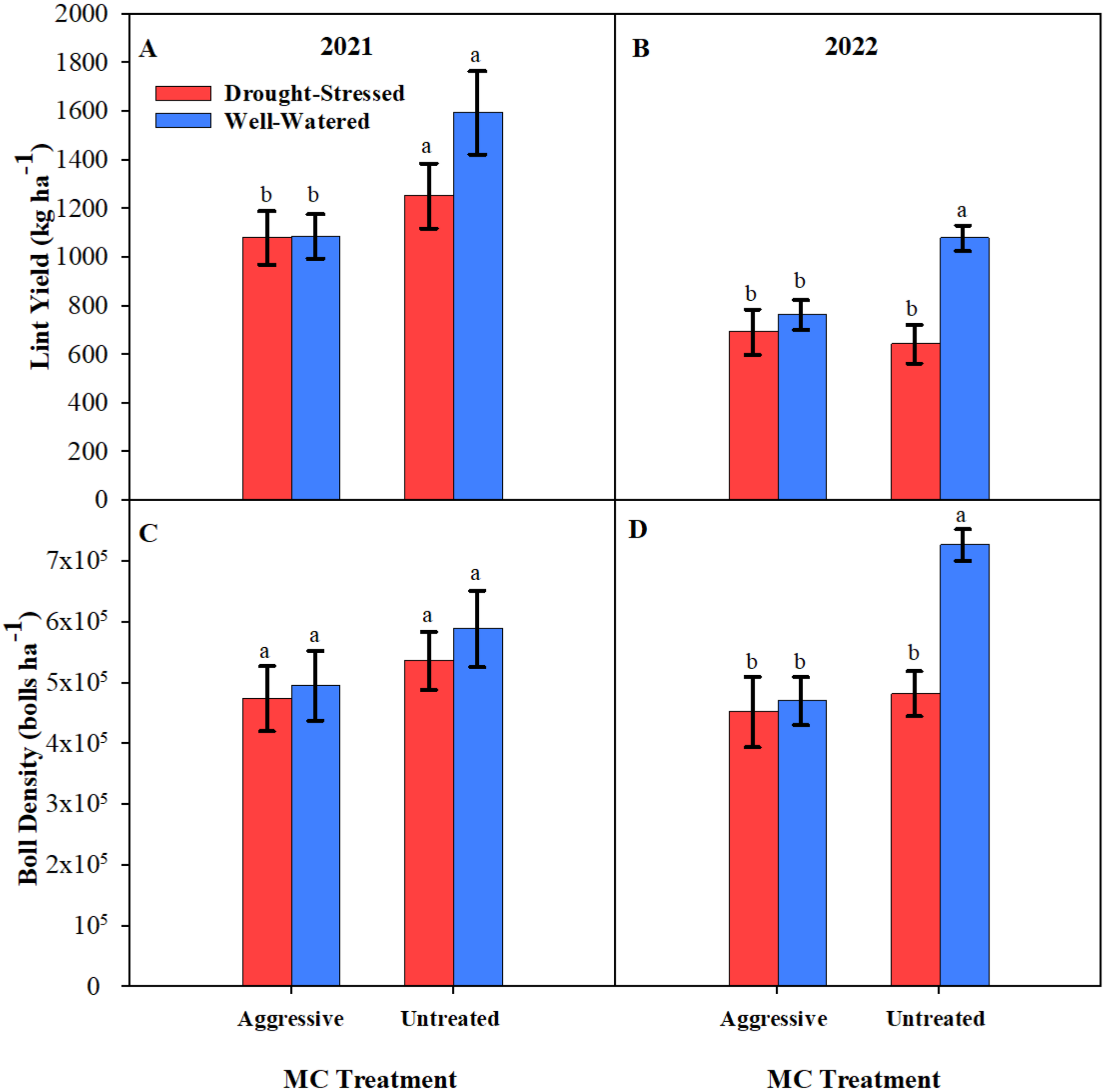

Figure 5. The effect of MC management and irrigation treatment on lint yield and boll density during the 2021 and 2022 growing seasons for a field site in Tifton, GA, USA. Bars represent means ± standard error (n =6), and bars not sharing a common letter are considered significantly different ($P \leq 0.05$).

Lint percent was not affected by MC, irrigation, or MC by irrigation interaction in 2021 (Table 2). However, there was a significant MC effect on lint percent in 2022, where lint percent was 42.72% in untreated plots and 40.70% for the aggressive treatment. Seed number boll^{-1} was also not affected by any factor in 2021, yet a significant effect of MC management and an effect of irrigation was observed in 2022. During the 2022 season, well-watered plots had more seeds per boll (22.26 seed boll^{-1}) when compared to drought-stressed plants (20.07 seed boll^{-1}). Aggressive MC management increased seed number boll^{-1} in 2022 compared to untreated, where aggressively treated plants had approximately two more seeds per boll than untreated. Seed index was not significantly affected by irrigation, and no interaction between MC and irrigation was observed in either the 2021 or 2022 growing season. In contrast, aggressive MC management alone significantly increased seed index in both years. For example, the seed index values for the aggressive treatment were 10.98 (2021) and 10.00 (2022) g 100 seed^{-1}, whereas the untreated averaged seed index values of 9.67 and 8.97 for 2021 and 2022, respectively. Boll mass was not affected by irrigation in 2021 or the MC by irrigation interaction in 2021 or 2022. In both years, boll mass was higher in aggressively managed plants than in untreated plants. Boll mass values in the aggressive treatment were 4.98 and 3.88 g boll^{-1} for 2021 and 2022, whereas bolls from untreated plots were 4.57 and 3.28 g boll^{-1} for 2021 and 2022. In 2022, significant irrigation effects were observed. Boll mass values in 2022 were 3.77 g boll^{-1} in well-watered plants and 3.38 g boll^{-1} in drought-stressed plants.

Fiber density and individual fiber weight were not significantly impacted by MC, irrigation, or MC by irrigation (Table 3). Seed surface area (SSA) was significantly greater in aggressively managed plots when compared to untreated plots in both 2021 and 2022. For example, SSA in aggressively treated plots averaged 108.07 (2021) and 101.64 mm^2 (2022), while untreated values were 99.44 and 94.83 mm^2 for 2021 and 2022, respectively.

Table 2. Mean lint percent, seed number per boll, seed index, and boll mass for two irrigation treatments (Drought-Stressed and Well-Watered) and two mepiquat chloride (MC) treatments (Aggressive and Untreated) during the 2021 and 2022 growing season for a field site in Tifton, GA, USA. Values are means (n = 12 for irrigation means, 12 for MC means, and 6 for Irrigation x MC means) and the values not sharing a common letter within each irrigation or MC treatment and within the same year are significantly different ($P \leq 0.05$).

		Lint Percent (%)		**Seed Number Boll^{-1}**		**Seed Index (g 100 seed^{-1})**		**Boll Mass Seedcotton Weight boll^{-1} (g)**	
		2021	2022	2021	2022	2021	2022	2021	2022
Irrigation									
	Drought-Stressed (D)	41.51a	42.16a	24.48a	20.07b	10.32a	9.29a	4.71a	3.38b
	Well-Watered (W)	41.79a	41.26a	25.22a	22.26a	10.33a	9.67a	4.48a	3.77a
MC									
	Aggressive (A)	41.35a	40.70b	24.73a	22.21a	10.98a	10.00a	4.98a	3.88a
	Untreated (U)	41.96a	42.72a	24.97a	20.12b	9.67b	8.97b	4.57b	3.28b
Irrigation x MC									
	DA	41.54a	40.90a	24.31a	21.71a	10.95a	9.77a	4.91a	3.74a
	WA	41.17a	40.50a	25.14a	22.71a	11.00a	10.23a	5.05a	4.02a
	DU	41.49a	43.43a	24.65a	18.43a	9.68a	8.82a	4.50a	3.03a
	WU	42.42a	42.02a	25.29a	21.18a	9.64a	9.12a	4.64a	3.53a

Table 3. Mean fiber density, individual fiber weight, and seed surface area for two irrigation treatments (Drought-Stressed and Well-Watered) and two mepiquat chloride (MC) treatments (Aggressive and Untreated) during the 2021 and 2022 growing season for a field site in Tifton, GA, USA. Values are means (n = 12 for irrigation means, 12 for MC means, and 6 for Irrigation x MC means) and the values not sharing a common letter within each irrigation or MC treatment and within the same year are significantly different ($P \leq 0.05$).

	Fiber Density ($no./mm^2$)		**Individual Fiber Weight (µg)**		**Seed Surface Area (mm^2)**	
	2021	2022	2021	2022	2021	2022
Irrigation						
Drought-Stressed (D)	0.0175a	0.0189a	4.41a	3.94a	103.73a	96.97a
Well-Watered (W)	0.0174a	0.0167a	4.47a	4.23a	103.78a	99.50a
MC						
Aggressive (A)	0.0174a	0.0174a	4.44a	4.04a	108.07a	101.64a
Untreated (U)	0.0175a	0.0182a	4.44a	4.13a	99.44b	94.83b
Irrigation x MC						
DA	0.0174a	0.0180a	4.48a	3.93a	107.90a	100.10a
WA	0.0174a	0.0168a	4.41a	4.14a	108.23a	103.18a
DU	0.0176a	0.0199a	4.34a	3.94a	99.55a	93.84a
WU	0.0174a	0.0165a	4.53a	4.32a	99.33a	95.82a

3.5 Fiber quality

Fiber length and micronaire was not affected by MC, irrigation, or MC by irrigation interaction in 2021 or 2022 (Table 4). A significant MC management and irrigation effect was observed for fiber strength in 2021 only. Fiber strength was 35.37 g tex^{-1} in drought-stressed plants when compared to 34.15 g tex^{-1} in well-watered plants. Fiber strength in the aggressive treatment was 35.58 g tex^{-1}, whereas fiber strength in untreated plants was 33.94 g tex^{-1}. Uniformity was not significantly impacted by MC, irrigation, or MC by irrigation interaction in 2021. However, there was a significant irrigation effect and MC by irrigation interaction for uniformity in 2022, similar to lint yield observations. Uniformity in the drought-stressed treatment was 82.16% while well-watered plants had fiber length uniformity of 83.38%. Uniformity in aggressively treated plots was 82.48 % under drought and 82.93% in well-watered conditions. Uniformity in untreated plots was 81.83% under drought and 83.83% in well-watered treatment.

Table 4. Mean fiber length, fiber strength, uniformity, and micronaire for two irrigation treatments (Drought-Stressed and Well-Watered) and two mepiquat chloride (MC) treatments (Aggressive and Untreated) during the 2021 and 2022 growing season for a field site in Tifton, GA, USA. Values are means (n = 12 for irrigation means, 12 for MC means, and 6 for Irrigation x MC means) and the values not sharing a common letter within each irrigation or MC treatment and within the same year are significantly different ($P \leq 0.05$).

	Fiber Length (cm)		**Fiber Strength (g tex^{-1})**		**Uniformity (%)**		**Micronaire**	
	2021	2022	2021	2022	2021	2022	2021	2022
Irrigation								
Drought-Stressed (D)	3.00a	2.77a	35.37a	31.29a	84.72a	82.16b	4.41a	4.38a
Well-Watered (W)	3.06a	2.87a	34.15b	31.90a	85.38a	83.38a	4.35a	4.49a
MC								
Aggressive (A)	3.05a	2.82a	35.58a	31.67a	85.15a	82.71a	4.35a	4.39a
Untreated (U)	3.01a	2.82a	33.94b	31.53a	84.95a	82.83a	4.40a	4.48a
Irrigation x MC								
DA	3.03a	2.79a	36.67a	31.47a	84.87a	82.48bc	4.43a	4.35a
WA	3.07a	2.86a	34.48a	31.87a	85.43a	82.93ab	4.27a	4.43a
DU	2.98a	2.76a	34.07a	31.12a	84.57a	81.83c	4.38a	4.42a
WU	3.04a	2.88a	33.82a	31.93a	85.33a	83.83a	4.43a	4.55a

4. Discussion

As previously noted, even short periods of drought in the southeastern United states can cause lint yield reductions in cotton, particularly when experienced at key growth stages such as flowering and boll development (Snowden et al., 2014). Large, more rapidly-growing plants exhibit high rates of water loss (Sinclair and Ghanem, 2020), and plant growth regulators like MC, reduce vegetative growth by decreasing internode length and individual leaf area (Reddy et al., 1992; Fernandez et al., 1991). Thus, the current study specifically addressed the hypothesis that that pre-drought MC management would influence drought susceptibility during flowering and boll development. The objectives of the current study were to evaluate the effects of growth management on drought susceptibility in field-grown cotton, and assess the underlying yield component responses to drought and MC application.

4.1 Growth parameters and yield

Firstly, significant pre-drought vegetative growth control was achieved in both seasons. For both the 2021 and 2022 seasons, aggressive MC management consistently reduced final plant height, number of mainstem nodes, and the length of the fourth internode below the plant terminal. Reductions in growth parameters ranged from 11 percent for number of mainstem nodes to 35 percent for plant height over the two growing seasons. Furthermore, the number of days after planting required for the cotton crop to reach cutout was reduced by 10 percent due to aggressive MC management. Similarly, numerous studies have previously reported that MC applications decrease overall plant height, producing a more compact plant, and hastening physiological maturity (Chalise et al., 2022; Biles and Cothren, 2001; Hake et al.,1991 Kerby et al., 1986; Reddy et al., 1992; Stuart et al., 1984). Although significant MC effects on growth parameters were observed earlier in the 2022 growing season than 2021, all MC applications were completed and growth reductions were observed prior to imposing drought stress. For example, significant MC effects on plant height began at 72 DAP in 2021 and 43 DAP in 2022. Drought stress imposition was applied beginning at the third week of bloom which occurred at 75 DAP in 2021 and 70 DAP in 2022.

Despite there being significant differences in soil moisture throughout the drought stress period (Figure 1), lint yields were only significantly affected (reduced) by MC application during the 2021 season and not by irrigation treatment (Figure 5). There was also no interaction between MC and irrigation in 2021, despite a numerical decline in mean yield of 341 kg ha^{-1} in untreated, drought stressed plots compared with untreated, well-watered plots. In contrast, a significant interaction between MC and irrigation was observed in 2022 (Figure 5), indicating that MC-treated plants respond to drought differently than untreated plants. Well-watered untreated plots in 2022 had the highest lint yields of 1077 kg ha^{-1} while drought-stressed, untreated plots yielded 642 kg ha^{-1} (Figure 5). This represents a 40% drought-induced reduction in lint yield for untreated plants. Snowden et al. (2014) saw 25 to 35% yield reductions when drought occurred for 3 weeks starting at peak bloom in West Texas. In contrast, MC-treated plots were unresponsive to drought in the 2022 season, where yields averaged 726 kg ha^{-1} for both well-watered and drought-stressed plants. Fernandez et al. (1991) saw that MC-treated plants produced a more compact canopy, and less leaf area, indicating that less water would likely be lost through transpiration (Fernandez et al., 1992; Sinclair and Ghanem, 2020). Thus, it was anticipated that aggressive MC management would decrease cotton susceptibility to drought during flowering and boll development. Although our findings indicate that yield is more stable in response to drought for aggressively managed plants, they also show that aggressive MC management can penalize yields relative to untreated plants (Figure 5). Previous observed cotton yield responses to MC application include yield increases, yield reductions, and no change in yield relative to untreated plants (Cook and Kennedy, 2000; Tung et al., 2018; Stuart et al., 1984). It is important to note that cotton response to MC application is highly dependent on cultivar (Gwathmey and Craig, 2003; Chalise et al., 2022) and aggressiveness of the MC strategy (Chalise et al. 2022, Hand et al., 2022; Edmisten et al., 2023). Thus, the inclusion of a broader range of cultivars and the addition of a more moderate MC management strategy will allow us to make broader assertions about the effects of plant growth management on drought susceptibility in cotton in the future.

4.2 Yield Components and Fiber Quality

Lint yield is the product of three factors: boll density (bolls ha^{-1}), boll mass (g $boll^{-1}$), and lint percent (percentage of lint weight to seedcotton weight in each sample) (Groves et al., 2016; Groves et al., 2010). Boll density followed a similar trend as lint yield for the 2022 season (Figure 5). In 2021, there was no interaction between MC management and irrigation for boll density, but there was an interaction in 2022. When an interaction was observed, boll density in aggressively treated plots was stable at an average of 460,260 bolls ha^{-1}. However, untreated MC plots exhibited a significant reduction in boll density of 33.7% due to drought-stress. The observations are comparable to trends seen by Sharma et al. (2015) where boll number accounted for 90% of water-induced yield variation. Numerous other studies have also shown positive associations between lint yield and boll density due to variations in water availability (Cathey and Meredith, 1988; Hu et al. 2018). Boll mass was not a major contributor to lint yield variation in the current study. For example, there was no interaction between MC management and irrigation for boll mass during the 2022 season (Table 2), despite there being a significant interaction for lint yield and boll density (Figure 5). Furthermore, when differences in boll mass were observed, MC treated plants had the highest boll mass while simultaneously having the lowest lint yield (Table 2 and Figure 5).

Similarly, Sharma et al. (2015) found that drought induced reductions in boll mass could account for only 10% of water induced lint yield variation.

In a previous field study conducted in Georgia, Hu et al. (2018) indicated that boll mass only declined in the most severely drought stressed treatments, but these declines were offset by increases in lint percent. In the current study, there was no effect of irrigation or an interaction between MC and irrigation for lint percent in either 2021 or 2022. Lint percent was not likely a significant contributor to lint yield variation observed in the current study. Furthermore, lint percent was only significantly affected by MC treatment in 2022 (Table 2). In the aforementioned season, aggressive MC management reduced lint percent relative to the untreated control but increased seed per boll^{-1}, seed mass (seed index), and seed surface area (Table 2 and 3). Similar results were observed by Cathey and Meredith (1988), where MC application increased seed per boll^{-1} and seed index, but reduced lint percent. Irrigation also impacted seed boll^{-1} in 2022 where well-watered plots had approximately 2 more seeds boll^{-1} (Table 2) than drought stressed plants. Similar observations were made by Hu et al. (2018), showing that drought reduced seed number per boll. Collectively, we can conclude that lint yield reductions due to irrigation or MC management were primarily associated with changes in boll density. Aggressive MC management decreased vegetative growth, leading to greater individual boll mass, but increased boll size was due to increases in seed production or seed size, not increased lint percent. The findings of the current study may also be of value to commercial seed suppliers. For example, cotton is known for having poor seedling vigor relative to other major row crop species (Snider et al., 2015, 2021), and individual seed mass is positively associated with cultivar-specific variation in seedling vigor among upland cotton cultivars (Snider et al., 2014, 2016; Virk et al., 2019; 2020). We show that seed mass can be increased by altering MC management strategy, which could positively affect seedling vigor for the subsequently planted crop.

Fiber length and micronaire values were not affected by MC, irrigation, and no interaction between MC and irrigation was observed for these parameters (Table 4). Previous research has shown that drought stress sufficient to cause reductions in fiber length also leads to higher micronaire values (Chalise et al., 2022; Hu et al., 2018). Since there was no effect of drought or MC treatment on fiber length in the current study, changes in micronaire would also not be expected. Fiber strength was significantly increased in the drought stressed treatment for the 2021 season. Fiber strength was greater in drought-stressed plots than in the well-watered treatment (Table 4), and in aggressive MC management treatments compared with the control. Hu et al. (2018) showed a similar response of increased fiber strength in response to drought during flowering and boll development. Higher fiber strength values due to MC application were also observed by Chalise et al. (2022), indicating that MC application has positive effects on some fiber quality properties. Similar to lint yield trends, uniformity declined under drought stress for plants not receiving aggressive growth management. Thus, in addition to ensuring yield stability under drought, MC treatment also ensures a more stable response of fiber uniformity to water availability.

5. Conclusions

The objectives of the current study were to evaluate the effects of growth management on drought susceptibility in field-grown cotton, and assess the underlying yield component responses to drought and MC application. For both growing seasons, aggressive MC management consistently reduced final plant height, number of mainstem nodes, and the length of the fourth internode below the plant terminal. Although our findings indicate that yield is more stable in response to drought for aggressively controlled plants, they also show that aggressive MC management can penalize yields relative to untreated plants under irrigated conditions. Future research should address the applicability of these findings to a broad range of cultivars and determine if a more moderate MC strategy would lessen drought susceptibility while ensuring high yields in well-watered conditions. We also can conclude that lint yield reductions due to irrigation or MC management were primarily associated with changes in boll density. Aggressive MC management decreased vegetative growth, leading to greater individual boll mass, but increased boll size was due to increases in seed production or seed size, not increased fiber production per seed.

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CHAPTER 3

CONCLUSIONS

A field trial near Tifton, GA was conducted to evaluate the effects of mepiquat chloride (MC) management on drought susceptibility during the flowering and boll filling period on growth and development, lint yield, yield components, and fiber quality. For both the 2021 and 2022 growing season, aggressive MC management consistently reduced plant growth and hastened cutout. Yield was unaffected by drought for aggressively managed plots, whereas untreated plots exhibited significant reductions in yield when exposed to drought. Although our findings indicate that yield is more stable in response to drought for aggressively controlled plants, they also show that aggressive MC management can penalize yields relative to untreated plants under irrigated conditions. Future research should address the applicability of these findings to a broad range of cultivars and determine if a more moderate MC strategy would lessen drought susceptibility while ensuring high yields in well-watered conditions. We also can conclude that lint yield reductions due to irrigation or MC management were primarily associated with changes in boll density. Aggressive MC management decreased vegetative growth, leading to greater individual boll mass, but increased boll size due was due to increases in seed production or seed size, not increased fiber production per seed. Thus, MC-induced increases in individual boll mass did not positively affect final lint yield.