CULTIVAR, IRRIGATION MANAGEMENT, AND PLANT GROWTH MANAGEMENT STRATEGY: EFFECTS ON COTTON GROWTH, MATURITY, YIELD, AND FIBER QUALITY

by

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(Under the Direction of John L. Snider)

ABSTRACT

This thesis addresses the effects of cultivar, irrigation, and plant growth management strategy on cotton growth, maturity, yield, and fiber quality. In both experimental years, there was an interaction between irrigation and mepiquat chloride (MC) management for plant height. In 2020, MC treatments hastened physiological maturity in irrigated plots, but had no effect in dryland plots. In 2020 yield responded positively to irrigation, and in 2021 yield responded negatively to irrigation. There was no effect of MC treatment or interaction between MC and any other effect for lint yield. Fiber length was reduced, whereas strength and micronaire were increased by drought stress in 2020. Increased fiber length, strength, uniformity, and micronaire were observed by MC application in both years. We conclude that aggressive MC management reduces growth, promotes earlier maturity under well-watered conditions, but does not necessarily interact with irrigation management to affect lint yield.

INDEX WORDS: Cotton, Irrigation, Mepiquat Chloride, Cultivar, and Rainfall

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DEDICATION

This work is dedicated to my parents for their love, support, and encouragement.

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INTRODUCTION AND LITERATURE REVIEW

Introduction

Cotton (*Gossypium hirsutum* L.) is an important cash crop and a major source of raw material for the textile industry. Importantly, the United States is the third largest cotton producer globally at 20.1 million bales, and Georgia ranks second only to Texas in cotton acreage at 566,560 hectares (USDA, 2019).

Drought stress can drastically limit cotton lint yield through negative impacts on a number of crop physiological processes. Generally, drought stress results in reductions in leaf area expansion, light interception by the canopy, and photosynthetic efficiency of individual leaves (Hsiao, 1973). Drought also decreases fruiting site production and/or boll retention (Guinn and Mauney, 1984). The end result is a decline in yield that is mainly due to reductions in boll number per plant and to a lesser extent, reductions in boll mass (Hu et al., 2018; Pettigrew, 2004a; Qian et al., 2020; Sharma et al., 2015; Wang et al., 2016). Water deficit can also reduce fiber quality due to reductions in fiber length and increases in fiber micronaire (Wang et al., 2016). Moisture deficit also results in earlier cotton maturity by reducing overall plant growth and development (Hearn, 1980; Whitaker et al., 2008). However, excess water results in rank growth and less light penetration to lower branches in the canopy, leading to poor fruit retention at lower nodes, delayed maturity, and in some instances, lower yield (Ermanis et al., 2020).

Due to the cotton plant's indeterminate growth habit and perennial origins, it requires sufficient vegetative growth to support reproductive development, but excess vegetative growth can be yield penalizing as noted above (Guinn, 1974). Plant Growth Regulators (PGR) are generally used in cotton to maintain a balance between vegetative and reproductive growth, facilitate fruit retention, and promote early maturity (Zhao and Oosterhuis, 2000). In the United States, the most commonly used plant growth regulator is Mepiquat Chloride (MC), with the most commonly referenced formulation being a 4.2 % solution of N-N dimethyl piperidinium chloride referred to by the original trade name as Pix®. Cotton growth response to MC rates and timings can be influenced by water availability and vigor of the cotton cultivar of interest. While there has been a substantial amount of effort expended to understand cotton response to MC, the near-constant release of advanced cotton cultivars necessitates re-evaluation for a particular region. Thus, the objective of the study was to evaluate the effects of MC management, irrigation, and cultivar on crop growth, maturity, yield, and fiber quality for Upland cotton in Georgia.

Literature review

Effects of water deficit on growth, maturity, and yield of cotton

Water stress poses the greatest challenge to the production of crops in the southeastern United States of America (USA). This region is characterized as a warm, humid climate (Sun, 2013). While this area commonly receives more rainfall than is typically needed to support cotton growth and yield, this rainfall is not always distributed in the timings and amounts needed for key growth stages (Bednarz et al., 2002). Thus, some level of water stress during the growing season is common in this region (Ennahli, 2003).

One of the primary ways in which water deficiency influences productivity is by limiting plant growth. Water is essential for cell enlargement, chemical reactions, and nutrient transport (Kramer, 1963). Several studies have been carried out in the past to determine the effect of drought on cotton growth, and it is evident that water stress results in a decrease in plant height and number of mainstem nodes (Ball et al., 1994; Gerik et al., 1996; Jordan, 1970; McMichael and Hesketh, 1982). Even more importantly, water stress decreases leaf area per plant, which is mainly due to a decrease in leaf number rather than leaf size (Loka, 2012). There is also more abscission of old leaves than the initiation of new leaves (Loka and Oosterhuis, 2012). However, Pettigrew (2004b) and Chastain et al. (2016) observed that there was a decrease in leaf size with an increase in moisture stress. Pace et al. (1999) reported that there were fewer mainstem leaf nodes and stem dry weights for cotton grown under water deficit conditions compared to those of the control, whereas root to shoot ratio was decreased when the plant was grown under low moisture conditions as reported by McMichael and Quisenberry (1991). Malik et al. (1979), reported that shoot growth was affected more than root growth, and Pace et al. (1999) reported that there was an increase in root length, but there was a decrease in root diameter of cotton seedlings grown under water deficit conditions.

In addition to affecting leaf area, water stress also limits source strength by decreasing the physiological activity of individual leaves. Wullschleger and Oosterhuis (1990) observed a decrease in stomatal conductance with an increase in moisture deficit, and leaf photochemistry can also be negatively affected under drought stress conditions (Cornic and Massacci, 1996). Likewise, Chastain et al. (2014) reported a decrease in net photosynthesis by increasing photorespiration and decreasing stomatal conductance in water-stressed cotton. Moreover, Chaves and Oliveira (2004) noted a declined in carbon dioxide diffusion to the chloroplast was the major cause of reduced photosynthesis of water-stressed plants. The response of respiration rates to moisture deficit is variable and depends upon the duration and severity of stress, changes in activity of respiratory enzymes, and the type and age of the tissue (Atkin and Macherel, 2009). Some researchers observed a decrease in respiration rate at mild drought stress, but an increase in respiration rate under severe moisture deficit (Atkin and Macherel, 2009; Flexas et al., 2006). However, Snider et al. (2015) noted a decrease in respiration rate during the flowering period that was also associated with drought-induced yield reductions.

Water stress during vegetative and reproductive development significantly reduces yield of cotton (Boyer, 1982). For example, Hu et al. (2018) reported up to 44% reduction in lint yield relative to well-watered plots under severe moisture deficit. Likewise, Karademir et al. (2011) noted 48.04% and 49.41% reductions in seedcotton yield and fiber yield, respectively, in water-stressed cotton. While drought stress can limit yield when experienced at any stage, it is generally accepted that early flowering and boll development are particularly sensitive stages (Constable and Hearn, 1981; Cull et al., 1981; De Kock et al., 1990; Snowden et al., 2014; Turner et al., 1986). Snowden et al. (2014) imposed drought at different growth stages in cotton and pointed out that water deficit stress during squaring resulted in shorter plants; however, water stress during early flowering caused the greatest reductions in yield and fiber quality.

When drought stress limits lint yields in cotton, the primary driver of yield loss is often a reduction in the number of bolls produced per unit land area (Grimes and Yamada, 1982; Hu et al., 2018; Pettigrew, 2004a; Sharma et al., 2015). This reduction in boll number is either the result of having fewer fruiting sites per plant or having reduced fruit retention. For example, De Kock et al. (1990) observed that fewer bolls reached maturity following drought exposure, but the size and weight of bolls increased due to greater lint growth. Hu et al. (2018) documented significant reductions in seed number per boll and boll mass under drought, but these declines were offset by increased lint percent or lint weight per seed. As a result, nearly all yield loss under drought was accounted for by reductions in boll number per unit land area. Similarly, Heitholt (1993) reported a positive correlation between boll retention and cotton yield. McMichael et al. (1973) reported that boll abscission was most likely to occur if drought was experienced within fourteen days of anthesis; whereas, bolls are retained if drought occurs after that period. McMichael et al. (1973) also reported a linear relationship between boll shedding rates and pre-dawn leaf water potential.

Fiber properties are relatively insensitive to moisture deficit, but severe water stress can result in reductions in overall fiber quality (Bennett, 1967; Witt et al., 2020). Cotton fiber development is divided into four phases: initiation, elongation, thickening, and maturation (Basra and Malik, 1984). Fiber length is determined during the cell elongation phase (first three weeks) (Gokani and Thaker, 2002), and water stress is known to limit fiber growth. Fiber elongation requires loosening of the cell wall and turgor pressure. Moisture deficit decreases turgor pressure and impairs fiber elongation and decreases fiber length (Karademir et al., 2011; Lokhande and Reddy, 2014; Reddy et al., 1992; Ruan et al., 2001; Wanjura et al., 2006). Rabadia et al. (1999) reported that there was a strong correlation between leaf water potential and deposition of dry matter in the developing fiber. Tang et al. (2017) reported that deposition of carbohydrate decreased under water stress conditions because of a decrease in the activity of enzymes such as vacuolar invertase and sucrose synthase. The response of micronaire to water stress is inconsistent in the literature. Eaton and Ergle (1952) reported that extreme water stress during fiber development resulted in a decrease in micronaire, whereas Hu et al. (2018) and Lokhande and Reddy (2014) reported micronaire increased under severe drought conditions. From previous experiments, it was found that water stress either reduced fiber uniformity (Lokhande and Reddy, 2014) or did not change uniformity (Karademir et al., 2011) of the cotton fiber.

The cotton plant is an indeterminate with a perennial growth habit; however, we grow cotton as an annual crop, so the maturity of the cotton plant is also affected by growth conditions.

Under low water availability, vegetative and reproductive growth are inhibited, and the plant will produce fewer fruiting sites, resulting in earlier maturation and reduced yield (Hearn, 1980). Drought that occurs prior to bloom will produce plants with fewer nodes above white flower at first flower and will hasten cutout. Not surprisingly, moisture stress during the early stage of growth has a more pronounced effect on crop maturity than drought occurring during later stages of growth (Loka, 2012).

Effects of excessive water on growth, maturity, and yield of cotton

Cotton is a unique row crop due to its indeterminate growth habit. As noted above, drought results in low yield and poor fiber quality, but excessive water application causes more vegetative growth and can also reduce yield and fiber quality. A larger cotton plant will typically have more fruiting sites on which to set bolls; however, light penetration to lower branches in the canopy decreases along with boll retention. Additionally, excess vegetative growth has the potential to increase disease and pest incidence (Hearn, 1980). Therefore, a cotton plant growing under high moisture levels produces more vegetative growth (Onder et al., 2009) which can result in boll loss from lower nodes on the plant (Ritchie, 2007). Cetin and Bilgel (2002) reported that high moisture levels resulted in higher shedding of cotton flowers, floral buds, and bolls, which decreases cotton yield. Ermanis et al. (2020) recently documented significant reductions in lint yield in Georgia due to application of irrigation water during the growing season. Even though irrigated plants produced high levels of biomass, their harvest index (ratio of lint yield to total biomass) was greatly reduced due to poor fruit retention. DeTar (2008) reported that the final plant height of cotton plants grown under excess soil moisture conditions was high, which decreased harvest efficiency.

Guinn and Mauney (1984) reported that the lygus population increases with an increase in water availability, which can cause increased boll shed and low yield. Excessive irrigation is also known to delay maturity, thereby increasing growing season length. For example, DeTar (2008) suggested that excessive irrigation extends growing season length by delaying the date of cutout relative to plants receiving an optimal soil moisture regime. Bronson et al. (2001) and DeLaune et al. (2012) also reported that excessive soil moisture resulted in excessive vegetative growth and delayed crop maturity.

Effects of PGR on growth, maturity, and yield of cotton

Plant hormones are naturally-occurring, endogenously-synthesized organic compounds that affect plant physiological processes at low concentrations (Davies, 2010). They are produced in one part of the plant and are often transported to the other parts of the plant if the site of hormone action is different from the site of production. In addition to naturally-occurring plant hormones, crop growth, development, and physiological processes can be altered by using synthetic compounds called plant growth regulators (PGRs). Most PGRs generate their desired responses by mimicking or inhibiting (Gianfagna, 1995) the activity of five major classes of plant hormones: auxin, gibberellin, cytokinin, abscisic acid, and ethylene.

Plant growth regulators are mostly used in cotton production as harvest-aids or to control vegetative growth (Cothren and Oosterhuis, 2010). Often the term “PGR” is used in cotton as a synonym for a group of chemical compounds that inhibit gibberellic acid synthesis, thereby reducing internode elongation. Among the various chemicals used as PGRs in cotton, mepiquat chloride (MC) is one of the most widely utilized for growth control (Cothren and Oosterhuis, 2010). MC inhibits the production of gibberellic acid, thereby decreasing vegetative growth by reducing cell expansion. The rate and timing of MC directly influences growth control and development of the cotton plant. Reddy et al. (1996) reported a decrease in plant height, stem elongation, leaf area, and node number that was linearly associated with increases in application rate of MC. Similarly, Crozat and Kasemsap (1997) and Reddy et al. (1992) reported that MC application results in shorter internode length and reduces number of nodes, thus decreasing plant height. Niakan and Habibi (2013) observed the effects of different MC application rates on vegetative growth of cotton and found that stem length, node number, leaf number, and leaf area decreased with higher MC application rates; however, fresh and dry weight of individual leaves was increased. The authors suggested that the increase in fresh and dry weight of the leaf was mainly due to thickening of leaf parenchyma and an increase in leaf chlorophyll content, carbohydrates, and protein. Likewise, Walter et al. (1980) reported that MC-induced reductions in leaf size was associated with increases in individual leaf thickness. In addition, Stewart (2005) observed darker green, more compact (more nodes in a shorter vertical distance), and shorter cotton plants when treated with MC. According to Hand et al. (2021), under optimum condition, 0.22 L ha^{-1} of MC (4.2 % solution of N-N dimethyl piperidinium chloride) should be applied to field-grown cotton starting at the initiation of squaring, and subsequent applications should be based upon plant growth. However, in many irrigated cotton fields in the southeast, a typical management strategy is to make the first application of 0.58 to 1.17 L ha^{-1} at first bloom or just prior to bloom plus a subsequent application, if needed, of 1.17 L ha^{-1} two to three weeks afterwards. For vigorous cotton varieties grown under conditions promoting rank growth, a more aggressive strategy is often employed that utilizes a pre-bloom application of 0.58 to 0.88 L ha^{-1} MC, in addition to the two applications noted above.

The application of MC to cotton may increase (Armstrong et al., 1982; Cook and Kennedy, 2000; Kerby, 1983; Oosterhuis and Egilla, 1996; Vistro et al., 2017; York, 1983a), decrease (Crawford, 1981; Thomas, 1975; Tung et al., 2018), or not affect (Heilman and Brown, 1981; Stuart et al., 1984) cotton yields. As noted above, this is likely because growth control depends upon timing, environmental conditions, cultivar, other management practices, and rate of application. The application of MC alters canopy development, distribution of photo-assimilates, source-sink relationship, and light interception, thereby influencing fruit retention patterns. Thus, positive yield responses to MC usually depend on fruit retention (especially of first position bolls) on lower reproductive branches (Jenkins et al., 1990; Mauney, 1984). For example, vigorous growth of cotton plants can result in excessive leaf area, causing greater boll shed on lower branches, which favors further vegetative growth and delays maturity. In contrast, Kerby et al. (1986) reported that MC-treated cotton plants had more retention of floral buds and bolls on lower sympodial branches, leading to higher yields and earlier crop maturity. These improvements in retention are likely due to either a positive shift in vegetative to reproductive balance or due to greater light penetration into the canopy. Similarly, Biles and Cothren (2001) reported higher fruit retention, lower square abortion, and earlier maturity of cotton plants treated with MC. Similarly, Zakaria et al. (2006) documented more opened bolls per plant, higher boll weight, seed index, and lint yield for cotton plants sprayed with MC, relative to untreated plants. Other authors have observed higher boll retention, more sympodial bolls per branch, but a reduction in total number of bolls per plant (Gwathmey and Clement, 2010). Copur et al. (2010) and Gencsoylu (2009) observed that fiber quality (length, fineness, strength, and uniformity) was not affected by the use of MC on cotton.

As noted above, MC can hasten crop maturity. One way to assess physiological maturity of cotton is by quantifying the time required to reach cutout. Cutout date is typically determined by counting the number of mainstem nodes above the uppermost, first-position white flower (NAWF) and determining the point in the season at which NAWF = 3 (Bednarz and Nichols, 2005) or 5 (Bourland et al., 1992). The use of MC helps to maintain the balance between vegetative and reproductive growth, which improves early fruit set, thereby constraining further vegetative growth and triggering early maturity (Kerby, 1983; Kerby, 1985; McCarty and Hedin, 1994; Zhao and Oosterhuis, 2000). Furthermore, York (1983b) studied the response of cotton to MC with varying N rates and plant populations and found that when environmental conditions and nitrogen favor excessive vegetative growth of cotton, application of MC helps to reduce vegetative growth and promote early maturity. Thus, it is possible that the irrigation-induced excesses in vegetative growth could be partially offset by more aggressive MC management strategies.

The application of MC does not necessarily produce desirable outcomes in cotton. Sometimes, depending upon crop characteristics, environmental conditions, and application rate, undesirable outcomes may occur such as a decrease in yield and fiber quality. For example, Thomas (1975) reported a significant reduction in seedcotton yield when PGRs were applied at first flower, mostly due to reductions in late boll set. Yield reduction was higher when PGRs were applied at first flower than applying PGRs two weeks after peak flowering. Similarly, Tung et al. (2018) revealed that under late sowing and high-density planting conditions, the application of MC reduces yield and yield components (boll number and lint percentage) significantly. Furthermore, Ren et al. (2013) observed a significant reduction in lint yield by decreasing boll density and lint percentage when MC was applied at the squaring stage. Planting date can strongly affect cotton response to MC. Cathey and Meredith (1988) reported that application of MC resulted in a 4.5 %

reduction in lint yield for early planted plots; however, lint yield was increased for optimum and late-planted cotton treated with MC. Moreover, environmental conditions such as extreme drought result in a shorter plant height, and application of MC results in a low seedcotton yield (Reddy et al., 1992). In addition, Kerby (1985) observed a decrease in gin turnout and lint proportion, when MC was applied at first flower. Thus, it is better to consider plant and environmental conditions before applying MC in a cotton field.

As noted elsewhere, the application of MC doesn’t necessarily increase yield and fiber quality of the cotton; however, it is well-known to provide some indirect benefits for many cotton production systems. Because excessive vegetative growth tends to delay maturity, the application of MC helps to ensure timely maturity by maintaining balance between vegetative and reproductive growth, which facilitates timely harvest. This is especially important in systems where rank growth is historically a problem because shortening the growing season decreases the amount of pests need to be managed and limit the likelihood of yield loss caused by adverse, late-season weather. Additionally, producing shorter cotton plants decreases propensity for lodging, and allows for greater light penetration and air flow through the cotton canopy (Hand et al. 2021).

Response of different cotton cultivars to PGRs

Different cotton cultivars have different growth habits, canopy sizes, and maturities. Some cotton cultivars are tall and grow aggressively, whereas some are short and have limited vegetative growth (Gwathmey and Craig, 2003). Thus, the rates and timings of MC applications must take into account varietal differences.

Bader (1985) reported a significant decrease in plant height, canopy width, lateral internode distance, and boll maturation period for MC-treated plants. However, these responses were more pronounced in a late-maturing variety than an early-maturing variety. Hoskinson and Krueger (1982) also observed significant cultivar x MC interactions for yield. Likewise, Gwathmey and Craig (2003) studied the response of different cotton cultivars to MC for maturity and indicated that significant interactions occurred between MC and cultivar. They noted more significant effects of MC on late-maturing, indeterminate cotton cultivars than early maturing cultivars for controlling growth and promoting earliness. Field experiments conducted by Johnson and Pettigrew (2006) revealed significant interactions between PGR and cotton cultivar for yield and fiber quality. They applied mepiquat pentaborate to four early and four late maturing cultivars and found that lint yield was increased in one cultivar and decreased for all other cultivars. Wright and Roberts (2000) reported that application of MC did not affect the yield of Sicot 189; however, reductions in yield of approximately 5% were observed for S40 receiving MC application. They also noted that the cultivar S40 matured 6 days earlier than untreated S40, yet cultivar Sicot 189 did not show a significant change in maturity period. In addition, Singh et al. (2009) reported a measurable interaction between PGRs and cotton cultivars for seedcotton yield, boll weight, and harvest index.

In contrast, Cathey and Meredith (1988) studied the response of five different cotton cultivars (with different maturities) to MC and reported no significant MC × cultivar interactions for plant height, boll production, and yield. Similarly, York (1983a) studied the response of 14 different cotton cultivars to MC in 8 different environments and observed no significant MC x cultivar interactions for plant height, maturity, fiber length, lint percent, number of bolls produced, seed weight, or number of seed per boll. They only observed MC x cultivar interactions for yield, fiber strength, micronaire, and fiber length uniformity for one environment. Berry et al. (2009)

observed no significant interaction between PGR application and cultivar for height, maturity, or yield of cotton.

Response of cotton to PGRs at different moisture levels

The effect of PGRs on plant growth can be altered by several environmental factors such as temperature, water, humidity, and sunlight (Stover and Greene, 2005). As noted previously, water availability strongly influences growth, so it would be logical to assume that water availability and MC application strategy would interact to influence plant growth and possibly yield. However, peer-reviewed literature addressing the interaction between these two management inputs is limited for field-grown cotton.

Reddy et al. (1992) carried out a controlled environment experiment to evaluate the interaction between MC and irrigation levels in cotton; however, they observed no interactions between the two treatments for plant growth or development. Another controlled environment study by Fernandez et al. (1991) reported that there was a significant interaction between MC application and water level in cotton. They observed an increase in root to shoot ratio only when MC was applied under water deficit conditions. They also documented that application of MC significantly decreased leaf growth in well-watered cotton plants, whereas application of MC had little impact on leaf expansion in water-stressed plants. Similarly, Robertson et al. (2007) observed a significant interaction between PGR application and irrigation level for plant height in cotton. They used two regimes of MC (typical and aggressive) and two irrigation treatments (timely initiation and delayed). They noted that cotton plants were taller when they were timely irrigated and were treated with a typical PGR regime than all other treatments. They also documented reductions in the height-to-node ratio under aggressive PGR management.

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CHAPTER 2

[1]CULTIVAR, IRRIGATION MANAGEMENT, AND MEPIQUAT CHLORIDE STRATEGY: EFFECTS ON COTTON GROWTH, MATURITY, YIELD, AND FIBER QUALITY

Chalise, D.P., Snider, J., Hand, C., Roberts, P., Vellidis, G., Ermanis, A., Collins, G.D., Lacerda, L.N., Cohen, Y., Pokhrel, A., Parkash, V., and Lee, J.M. Accepted to Field Crops Research.

ABSTRACT

Drought negatively affects cotton growth and yield, whereas excessive irrigation can limit yield through excessive vegetative growth and poor fruit retention. Mepiquat chloride (MC) application limits plant height, improves fruit retention and hastens maturity in responsive cultivars. Thus, the objective of this study was to address the effects of cultivar, irrigation, and MC strategy on cotton growth, maturity, yield, and fiber quality. Therefore, a field study was carried out using three cultivars, three different irrigation treatments, and three different MC treatments during the 2020 and 2021 growing seasons. In both years there was an interaction between irrigation and MC management for plant height. In 2020, MC treatments hastened cutout by two to three weeks in irrigated plots but did not affect cutout date in dryland plots. 2020 and 2021 differed substantially in rainfall (347 mm and 735 mm, respectively from planting to harvest). 2020 was a dry year in which yield responded positively to irrigation and 2021 was a wet year in which yield responded negatively to irrigation. There was no effect of MC treatments or interaction between MC and any other effect on lint yield. Fiber length was reduced, whereas strength and micronaire were increased by drought stress in 2020. Increased fiber length, strength, uniformity, and micronaire were observed by MC application in both years. Therefore, we can conclude that aggressive MC management reduces vegetative growth, promotes earlier physiological maturity under well-watered conditions, and affects fiber quality, but does not necessarily interact with irrigation management to affect lint yield.

Keywords: Cotton; Irrigation; Mepiquat chloride; Cultivar

1. Introduction

Cotton (*Gossypium hirsutum* L.) is an important crop for the textile industry (Chakravarthy et al., 2014), and the United States of America (USA) is the third-largest cotton producer and a leader in cotton export (Avelar et al., 2020). Approximately 40% of USA cotton production is under irrigated conditions. In Georgia, approximately half of the cotton acreage is under rainfed conditions (Vellidis et al., 2016). This is particularly notable since Georgia is the second largest cotton producing state in the country with approximately 0.5 million hectares of cotton grown in Georgia annually (Hand et al., 2021). Most cotton is produced in the Coastal Plain of Georgia, where soils are coarse textured with high sand contents, and the climate is classified as subtropical and humid. As with many cotton production regions throughout the world, growing seasons are long and characterized by high temperatures during the summer months (average temperature, vapor pressure deficit, and solar radiation of 26.49 ºC, 0.78 kPa, and 19.27 MJ m^{-2}, respectively) (http://www.georgiaweather.net/). While the southeastern USA (Alabama, Florida, Georgia, Kentucky, Maryland, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia) commonly receives more rainfall (about 1270 mm annually) than is typically needed (450 mm) to support cotton growth and yield, this rainfall is not always distributed in the timings and amounts needed for key growth stages (Bednarz et al., 2002). Thus, some level of water stress during the growing season is common in this region (Ennahli, 2003). However, in some years, excessive rainfall (greater than the crop water requirement) lower levels of incoming solar radiation results in excessive vegetative growth and less light penetration to lower branches in the canopy, leading to poor fruit retention at lower nodes, delayed maturity, and in some instances, lower yield (Ermanis et al., 2021). Similarly, different cotton cultivars have different growth habits, canopy sizes, and maturities. Some cotton cultivars are tall and grow aggressively, whereas some are short and have limited vegetative growth (Gwathmey and Craig, 2003). Furthermore, growth, maturity, yield, and fiber quality are strongly influenced by the balance between vegetative and reproductive growth. Generally, Plant Growth Regulators (PGR) are used in cotton to maintain a balance between vegetative and reproductive growth, facilitate fruit retention, and promote early maturity (Zhao and Oosterhuis, 2000). In the United States, the most commonly used plant growth regulator in cotton is Mepiquat Chloride (MC), with the most commonly referenced formulation being a 4.2% solution of N-N dimethyl piperidinium chloride often referred to by the original trade name as Pix®. The MC is an anti-gibberellic acid plant growth regulator whose application inhibits gibberellic acid biosynthesis, thereby reducing cell elongation and controlling excessive vegetative growth. The application rates and timings of MC can be influenced by water availability and vigor of the cotton cultivar of interest (Hand et al., 2021). According to Hand et al. (2021), in many cotton fields in the southeast, a typical management strategy is to make the first application of 0.58 to 1.17 L ha^{-1} of MC at first bloom or just prior to bloom plus a subsequent application, if needed (height to node ratio greater than 4.6 cm), of 1.17 L ha^{-1} two to three weeks afterward. For vigorous cotton varieties grown under conditions promoting excessive growth, a more aggressive strategy is often employed that utilizes a pre-bloom application of 0.58 to 0.88 L ha^{-1} of MC, in addition to the two applications noted above.

Drought reduces plant growth, lint yield, fiber quality, and it can hasten maturity. Several studies have been carried out in the past to determine the effect of drought on cotton growth, and it is evident that water stress results in a decrease in plant height and number of mainstem nodes (Ball et al., 1994; Gerik et al., 1996; Jordan, 1970; McMichael and Hesketh, 1982). Pace et al. (1999) reported that there were fewer mainstem leaf nodes and lower stem dry weights for cotton grown under water deficit conditions (water was not applied from 36 days after planting to 49 days after planting) in a growth room compared to those of the control (water was applied as per requirement). Likewise, soil moisture deficit also results in earlier cotton maturity by reducing overall plant growth and development (Hearn, 1980; Whitaker et al., 2008). Drought that occurs prior to bloom will produce plants with fewer nodes above white flower (NAWF) at first flower and will hasten cutout. Similarly, drought stress can drastically limit cotton lint yield through negative impacts on a number of crop physiological processes. Generally, drought stress results in reductions in leaf area expansion, light interception by the canopy, and photosynthetic efficiency of individual leaves (Hsiao, 1973). Drought also decreases fruiting site production and/or boll retention (Guinn and Mauney, 1984). The end result is a decline in yield that is mainly due to reductions in boll number per plant and to a lesser extent, reductions in boll mass (Hu et al., 2018; Pettigrew, 2004; Qian et al., 2020; Sharma et al., 2015; Wang et al., 2016). Although fiber properties are relatively insensitive to moisture deficit, severe water stress can result in reductions in overall fiber quality (Bennett, 1967; Witt et al., 2020). Fiber elongation requires loosening of the cell wall and turgor pressure. Moisture deficit decreases turgor pressure and impairs fiber elongation and decreases final fiber length (Karademir et al., 2011; Lokhande and Reddy, 2014; Reddy et al., 1992; Ruan et al., 2001; Wanjura et al., 2006). Rabadia et al. (1999) reported that there was a strong correlation between leaf water potential and deposition of dry matter in the developing fiber. Tang et al. (2017) reported that deposition of carbohydrates decreased under water stress conditions because of a decrease in the activity of enzymes such as vacuolar invertase and sucrose synthase. The response of micronaire to water stress is inconsistent in the literature. Eaton and Ergle (1952) reported that extreme water stress during fiber development resulted in a decrease in micronaire, whereas Hu et al. (2018) and Lokhande and Reddy (2014) reported micronaire increased under severe drought conditions. From previous experiments, it was found that water stress either reduced fiber uniformity (Lokhande and Reddy, 2014) or did not change uniformity (Karademir et al., 2011) of the cotton fiber.

Due to the cotton plant's indeterminate growth habit and perennial origins, it requires sufficient vegetative growth to support reproductive development, but excess vegetative growth can be yield-penalizing (Guinn, 1974). Excessive water application (greater than typical rates of crop evapotranspiration needed to maximize yield) causes more vegetative growth and can also reduce yield and fiber quality. A larger cotton plant will typically have more fruiting sites on which to set bolls; however, light penetration to lower branches in the canopy decreases along with boll retention. Excessive irrigation is also known to delay maturity, thereby increasing growing season length (Ermanis et al., 2021).

The rate and timing of MC directly influence growth control, yield, and fiber quality of cotton. Reddy et al. (1996) reported a decrease in plant height, stem elongation, leaf area, and node number that was linearly associated with increases in application rate of MC. Similarly, Crozat and Kasemsap (1997) and Reddy et al. (1992) reported that MC application results in shorter internode length and reduces number of nodes, thus decreasing plant height. The application of MC to cotton may increase (Armstrong et al., 1982; Cook and Kennedy, 2000; Kerby, 1983; Oosterhuis and Egilla, 1996; Vistro et al., 2017; York, 1983a), decrease (Crawford, 1981; Thomas, 1975; Tung et al., 2018), or not affect (Heilman and Brown, 1981; Stuart et al., 1984) cotton yield. This is likely because growth control depends upon timing of application, environmental conditions, cultivar, rate of MC application, and other management practices. The application of MC alters canopy development, distribution of photo-assimilates, source-sink relationship, and light interception, thereby influencing fruit retention patterns. Thus, positive yield responses to MC usually depend on fruit retention (especially of first position bolls) on lower reproductive branches (Jenkins et al., 1990; Mauney, 1984). As noted above, MC can hasten crop maturity. One way to assess physiological maturity of the crop is by quantifying the time required to reach cutout. Cutout date is typically determined by counting the number of mainstem nodes above the uppermost, first-position white flower (NAWF) and determining the point in the season at which NAWF = 3 (more suitable indicator of cutout date in the southeastern USA) (Bednarz and Nichols, 2005) or 5 (Bourland et al., 1992). The use of MC helps to maintain the balance between vegetative and reproductive growth, which improves early fruit set, thereby constraining further vegetative growth and triggering early maturity (Kerby, 1983; Kerby, 1985; McCarty and Hedin, 1994; Zhao and Oosterhuis, 2000). Hand et al. (2021), reported that aggressive MC strategy was often employed to control vegetative growth of vigorous cotton cultivars, thus it is possible that the irrigation-induced excesses in vegetative growth could be partially offset by more aggressive MC management strategies. O'Berry et al. (2009) reported that aggressive MC management hastened maturity, thereby reducing yield in early maturing cultivars with limited growth potential. Thus, aggressive MC management might also cause early maturity and yield reduction compared to a moderate MC strategy in cotton grown under rainfed conditions (water limited).

Mepiquat chloride (MC) is widely used in Georgia cotton production. However, the effects of MC on cotton growth and agronomic performance can be influenced by genotype and other management conditions. For example, some cotton plants have limited vegetative growth and are early maturing, whereas others have excessive vegetative growth or later maturity. Additionally, excessive water availability can result in excessive vegetative growth and delayed maturity, whereas moisture deficit limits growth, hastens maturity, and can limit yield (Hand et al., 2021). We hypothesized that plant growth and agronomic response to MC management would be dependent on cultivar and water availability. While there is extensive information addressing MC effects in cotton, peer-reviewed literature addressing how cultivar and irrigation interact to influence growth, maturity, and yield response to MC management are limited. The currently proposed research will address this knowledge gap, and results of this experiment will aid in the development of situation-specific MC management strategies in the southeastern US. Thus, the objective of the study was to evaluate the effects of MC management, irrigation, and cultivar on crop growth, maturity, yield, and fiber quality for Upland cotton in Georgia.

2. Materials and methods

2.1. Study site details and general management practices

The research was carried out at the University of Georgia C.M. Stripling Irrigation Research Park near Camilla in Southwestern Georgia during the 2020 and 2021 growing seasons. The soil at the experimental site is a Lucy loamy sand (loamy, kaolinitic, thermic Arenic kandiudults) (Snider et al., 2015). The weather data, including maximum and minimum temperature, rainfall, and evapotranspiration for the study site were obtained from the on-site weather station at Stripling Irrigation Research Park, which is part of the statewide Georgia Weather Network (http://www.georgiaweather.net/index.php?variable=YC&site=CAMILLA). Weather data are provided in Table 1 for both years. Cotton seeds were planted on May 13th and May 6th in 2020 and 2021, respectively. The seeding rate was 9.8 seeds per meter, inter-row spacing was 0.91 m, and planting depth was 2.5 cm. Plant density was determined 2 weeks after planting in both years to optimize yield and fiber quality and was within the recommended range of 6.56 to 8.20 plants per meter (Hand et al., 2021). Agronomic practices such as seedbed preparation, fertilization, pest management, and weed control were carried out in all plots based upon University of Georgia Cooperative Extension Service recommendations (Hand et al., 2021).

2.2. Treatments and experimental design

The study was conducted using a split-split plot design with three replications. There were three center-pivot irrigation systems (blocks) and within each pivot, there were three unique irrigation treatments (whole plot factor). Similarly, there were three MC treatments (sub-plot factor) nested within each irrigation treatment and within MC treatment, there were three randomized sub-plots, each representing one of three possible cultivars. Thus, there were 27 treatments and a total of 81 plots within each growing season. There were three irrigation treatments [Dryland, 100% crop evapotranspiration (ET_c), and 125% ET_c]. The dryland treatment received no irrigation after squaring. The 100% ET_c treatment was considered our well-watered treatment, receiving supplemental irrigation (ET requirements minus rainfall) to meet 100% of crop evapotranspiration demands. The 125% ET_c treatment was our over-irrigated treatment receiving supplemental irrigation to target 125% of crop evapotranspiration. Uniform irrigation was imposed with over-head sprinkler irrigation until the cotton plant reached the squaring stage to ensure a uniform plant stand. Just after squaring, differential irrigation treatments were initiated. Reference evapotranspiration (ET_0) was determined using a Modified Penman-Monteith equation as described in Vellidis et al. (2014). Crop evapotranspiration (ET_c) was determined by multiplying reference evapotranspiration (ET_0) by a growth stage-specific crop coefficient (K_c; based on heat unit accumulation).

$$ET_c = ET_0 \times K_c$$

The total daily evapotranspiration loss of water was then used to calculate the root zone soil water deficit. Every morning during the growing season, root zone soil water deficit was calculated using daily weather data, including maximum and minimum temperature, rainfall, and evapotranspiration data. If there was any rainfall then it was deducted from the root zone soil water deficit (the difference between field capacity and available soil water), and irrigation was triggered when the root zone soil water deficit was greater than 16.2 mm. The greatest amount of water that can be applied per day by the overhead sprinkler irrigation system without causing runoff in the study site was 19.0 mm, and we assumed an irrigation system efficiency of 85%. Thus, the total rainfall plus irrigation applied based upon root zone soil water deficit (calculated from daily evapotranspiration loss including other factors) represented the 100% ET_c treatment. Similarly, for 125% ET_c treatment, soil water deficit was calculated using 1.25 times daily evapotranspiration loss and by keeping other factors the same as 100% $ET_{c,}$ and irrigation was triggered when soil water deficit was greater than 16.2 mm. Thus, differences in the amount of irrigation water applied between well-watered and over-irrigated treatments was due to differences in irrigation frequency. For example, in 2020, dryland plots, well-watered, and over-irrigated plots received irrigation water during a whole growing season 2, 13, and 15 times respectively. Similarly, in 2021, dryland plots, well-watered, and over-irrigated plots received irrigation water during a whole growing season 3, 9, and 12 times respectively. Irrigation was terminated at the first open boll stage for our latest maturing treatment. Three different MC (4.2% solution of N, N - dimethyl piperidinium chloride) treatments were used in the current study. The first MC treatment was a control treatment, receiving no MC application. The second MC treatment was the moderate MC treatment, where 0.88 L ha^{-1} was applied at first flower and 1.17 L ha^{-1} at two weeks after the first application. The third MC treatment was an aggressive treatment, where the first application of 0.73 L ha^{-1} was made at the 8 true leaf stage (the start of the squaring stage), the second application of 0.88 L ha^{-1}at first flower stage, and the third application of 1.17 L ha^{-1} at two weeks after first flower. Moreover, three different cotton cultivars [DP 1646 B2XF (the most commonly grown cultivar in Georgia, relatively shorter in the early season and has less vegetative growth, and earlier maturity than the other cultivars), DG 3615 B3XF (medium-tall plant height, highest yields in official variety trials), and DG 3799 B3XF (tall plant height, relatively vigorous cultivar, highest yielding cultivar in on-farm variety trials, and later maturity)] were randomized within each irrigation treatment, MC strategy, and replicate block (Hand et al., 2021).

2.3. In-season measurements

Beginning at first flower, the number of mainstem nodes above the uppermost, first position white flower (NAWF) were counted biweekly on five plants per plot (plants were randomly chosen to provide a better representation of each plot), and these data were eventually used to define cutout date for each plot. Cutout date refers to the growth stage of the cotton crop where production of new vegetative growth and reproductive site ceases. In Georgia, cutout date is defined as the date when NAWF = 3 (Bednarz and Nichols, 2005). We plotted the NAWF versus days after planting (DAP) and utilized linear regression to estimate cutout date when NAWF = 3 (Figure 1).

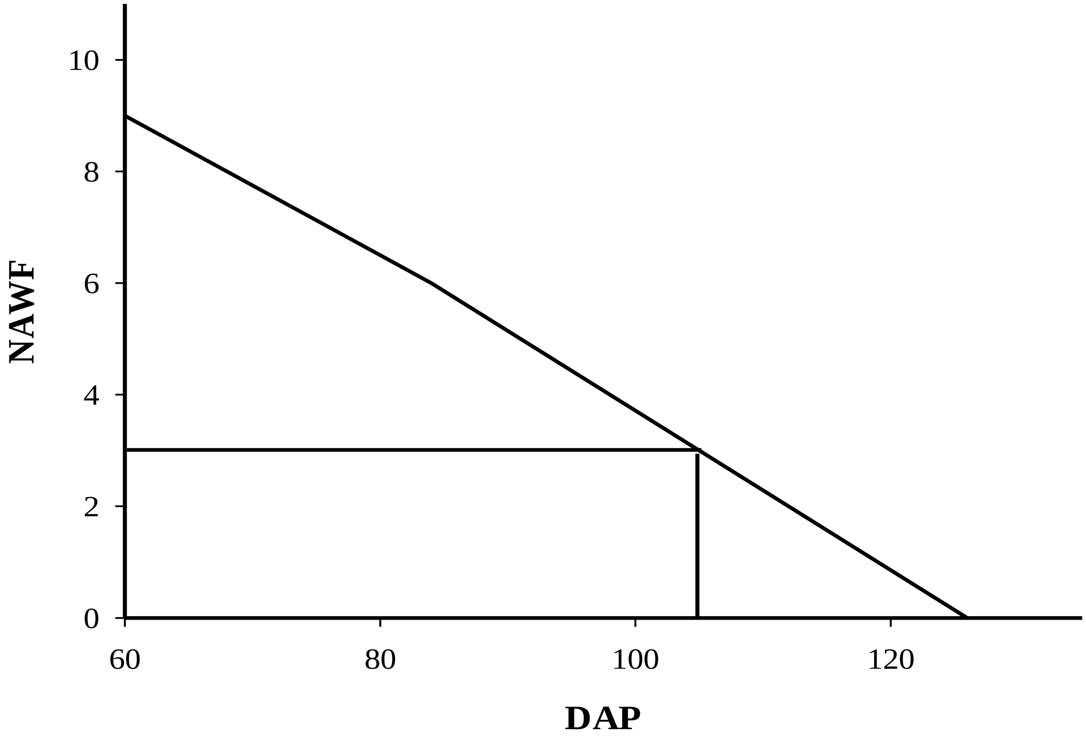

Figure 1. Sample graph showing methods used to determine cutout date. The Y- axis represents the number of nodes above the uppermost, first position white flower (NAWF) and the X- axis represents days after planting (DAP). The DAP value at 3 NAWF represents the cutout date (105 DAP in this instance).

2.4. End-of-season measurements

Defoliants were applied to the cotton crop when approximately 60% of the bolls opened in the latest maturing treatment. This was done to promote leaf drop and opening of mature bolls that were still unopened on the plant at the time of defoliation. Defoliants were applied on October 1st and September 29th in 2020 and 2021, respectively. After defoliation and prior to mechanical harvest, final plant height (in cm), number of mainstem nodes per plant, and node of the uppermost harvestable boll were determined. An unopened but harvestable boll that would contribute to lint yield once harvest aids are applied is defined as a boll that is turgid and more than 2 cm in diameter

(Gwathmey et al., 2011); however, in the current study, all assessments were conducted after harvest aids were applied, so the uppermost harvestable boll in each plot was the same as the uppermost open boll. The center two rows of each plot were harvested mechanically using a two-row spindle picker (John Deere 9930) on November 2nd and October 19th in 2020 and 2021, respectively. Thereafter, seedcotton was weighed in the field using a hanging scale (Intercomp 100773 CS 200 hanging scale). Seedcotton was then sent to the University of Georgia MicroGin located in Tifton, Georgia for ginning. A MicroGin is a downscaled version of a commercial gin that provides realistic estimates of gin turnout (Li et al., 2011). After ginning, the weight of the lint was taken and gin turnout was determined by dividing lint weight by seedcotton weight. Lint yield (in kg ha^{-1}) was estimated by multiplying the original seedcotton weight by gin turnout and accounting for harvested land area. Approximately a 0.5 kg sample of ginned fiber was sent to the USDA classing office in Memphis, Tennessee for determination of fiber length, strength, micronaire, and uniformity.

2.5. Statistical analysis

Plots were arranged according to a split-split plot, randomized complete block design, where irrigation was considered the whole plot factor, MC as a subplot factor, and cultivar as a sub-sub plot factor. Block, Whole plot, sub-plot, and sub-sub plot were considered random effects and irrigation, MC, and cultivar were considered fixed effects. First, to determine if there were any year by treatment interactions, a two-way mixed-effects analysis of variance (ANOVA) was conducted where year and treatment were considered fixed effects, and each combination of irrigation, MC treatment, and cultivar was considered a unique treatment with 27 total treatments. Only total number of mainstem nodes per plant, fiber length, and uniformity showed no significant year by treatment interaction, and the rest of the parameters (final plant height, node of uppermost harvestable boll, cutout date, lint yield, fiber strength, and micronaire) showed significant year by treatment interactions. Therefore, a three-way mixed-effect analysis of variance (ANOVA) was used within each year and data were presented separately for both years. Within each year. replication was considered random effects as were whole plots (replication x irrigation treatments), sub-plots (replication x irrigation x MC treatments), and sub-sub plots (replication x irrigation x MC x cultivar). Cultivar, irrigation, and MC were considered fixed effects with three levels for each treatment. Post hoc analysis was carried out using Fisher's protected least significant difference test ($\alpha = 0.05$) to determine differences between treatment means. Sigma Plot 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 characterization and irrigation

Weather conditions at C.M. Stripling Irrigation Research Park were substantially different for the two growing seasons (May 13 to November 2, 2020 and May 6 to October 19, 2021) in terms of rainfall and average temperature (Table 1). The first growing season (2020) was relatively drier than the second growing season (2021). For example, total rainfall for the 2020 growing season (from planting until harvest) was slightly less than half (347 mm) of the 2021 growing season (735 mm). In contrast, minimum and maximum daily temperatures were slightly higher for 2020 than 2021 (by 1.7 and 1.5 °C respectively). Total irrigation applied for the 2021 growing season was lower than the 2020 growing season. Dryland plots received slightly more than double the total water (early season irrigation plus rainfall) in the 2021 growing season than the 2020 growing season. Similarly, 100% ET_c and 125% ET_c plots received approximately 50% more total water in the 2021 growing season than the 2020 growing season. Average vapor pressure deficit (0.8 kPa) was found same for two growing seasons, whereas average solar radiation was slightly higher in 2021 growing season (18.1 MJ m^{-2}) compared to 2020 growing season (17.3 MJ m^{-2}).

Table 1. Cumulative season-long irrigation, rainfall, and total water received from rainfall plus irrigation, average daily minimum and maximum temperature, average vapor pressure deficit (VPD), and average solar radiation for three different irrigation treatments [Dryland, Well-watered (100% ET_c), and Over-irrigated (125% ET_c)] during the 2020 and 2021 growing seasons for a field site near Camilla, GA.

Year	Treatment	Irrigation (cm)	Rainfall (cm)	Total water (cm)	Average T_{min} (°C)	Average T_{max} (°C)	Average VPD (kPa)	Average solar radiation (MJ m^{-2})
2020	Dryland	3.6	34.7	38.3	21.6	33.0	0.8	17.3
	100% ET_c	25.6	34.7	60.3	21.6	33.0	0.8	17.3
	125% ET_c	29.0	34.7	63.7	21.6	33.0	0.8	17.3
2021	Dryland	5.1	73.5	78.6	19.9	31.5	0.8	18.1
	100% ET_c	16.5	73.5	90.0	19.9	31.5	0.8	18.1
	125% ET_c	22.3	73.5	95.8	19.9	31.5	0.8	18.1

3.2. Growth and physiological maturity

3.2.1. Final plant height

Table 2. Mixed model ANOVA results for irrigation, cultivar, mepiquat chloride (MC), cultivar × irrigation, cultivar × MC, irrigation × MC, and cultivar × irrigation × MC on final plant height, node of uppermost harvestable boll (NUHB), total mainstem nodes, and cutout date during the 2020 and 2021 growing seasons for a field site near Camilla, GA.

	P Value							
Source	**Plant Height**		**NUHB**		**Total Node**		**Cutout Date**	
	2020	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**
Irrigation (I)	<0.001*	<0.001*	<0.001*	0.281	0.121	0.001*	<0.001*	0.201
MC	<0.001*	<0.001*	0.020*	<0.001*	0.002*	<0.001*	<0.001*	<0.001*
Cultivar (C)	0.038*	0.002*	0.324	<0.001*	0.001*	<0.001*	0.173	0. 617
C × I	0.290	0.185	0.272	0.094	0.412	0.346	0.839	0.932
C × MC	0.272	0.578	0.982	0.099	0.986	0.581	0.933	0.638
I × MC	<0.001*	0.047*	0.189	0.139	0.982	0.200	0.002*	0.400
C × I × MC	0.777	0.764	0.327	0.077	0.249	0.400	0.929	0.984

*Significant (P ≤ 0.05) main effects or interactions

Cultivar, irrigation, and MC treatment significantly affected plant height, and there was significant irrigation by MC interaction observed for final plant height in both years, with the shortest plants observed in aggressively-treated plots under dryland conditions (88.5 cm and 89.7 cm in 2020 and 2021 respectively) (Table 2 and Figure 2). The tallest plants were observed in over-irrigated plots with no MC application in 2020 (172.4 cm), whereas in 2021, the tallest plants were observed in well-watered plots with no MC application (157.0 cm) (Figure 2). The effects of MC treatment on plant height were more pronounced under irrigated conditions than under dryland conditions in 2020 (a dry year). For example, aggressively-treated plots under dryland conditions were 19.0 cm shorter than untreated plots, whereas aggressive MC treatment decreased plant height by 42.6 and 56.6 cm in the 100% and 125% ET_c treatments, respectively. Similarly, plant height was statistically different among cotton cultivars in both years (Table 2). When considered across all irrigation and MC treatments, in 2020, the tallest plants were observed for cultivar DG 3799 B3XF (124.7 cm), which was not statistically different from DP 1646 B2XF (120.8 cm), but significantly taller than DG 3615 B3XF (116.9 cm). In 2021, the tallest plants were observed for DP 1646 B2XF (130.4 cm), which was not statistically different from DG 3799 B3XF (127.1 cm), but significantly taller than DG 3615 B3XF (121.3 cm) (Figure 3).

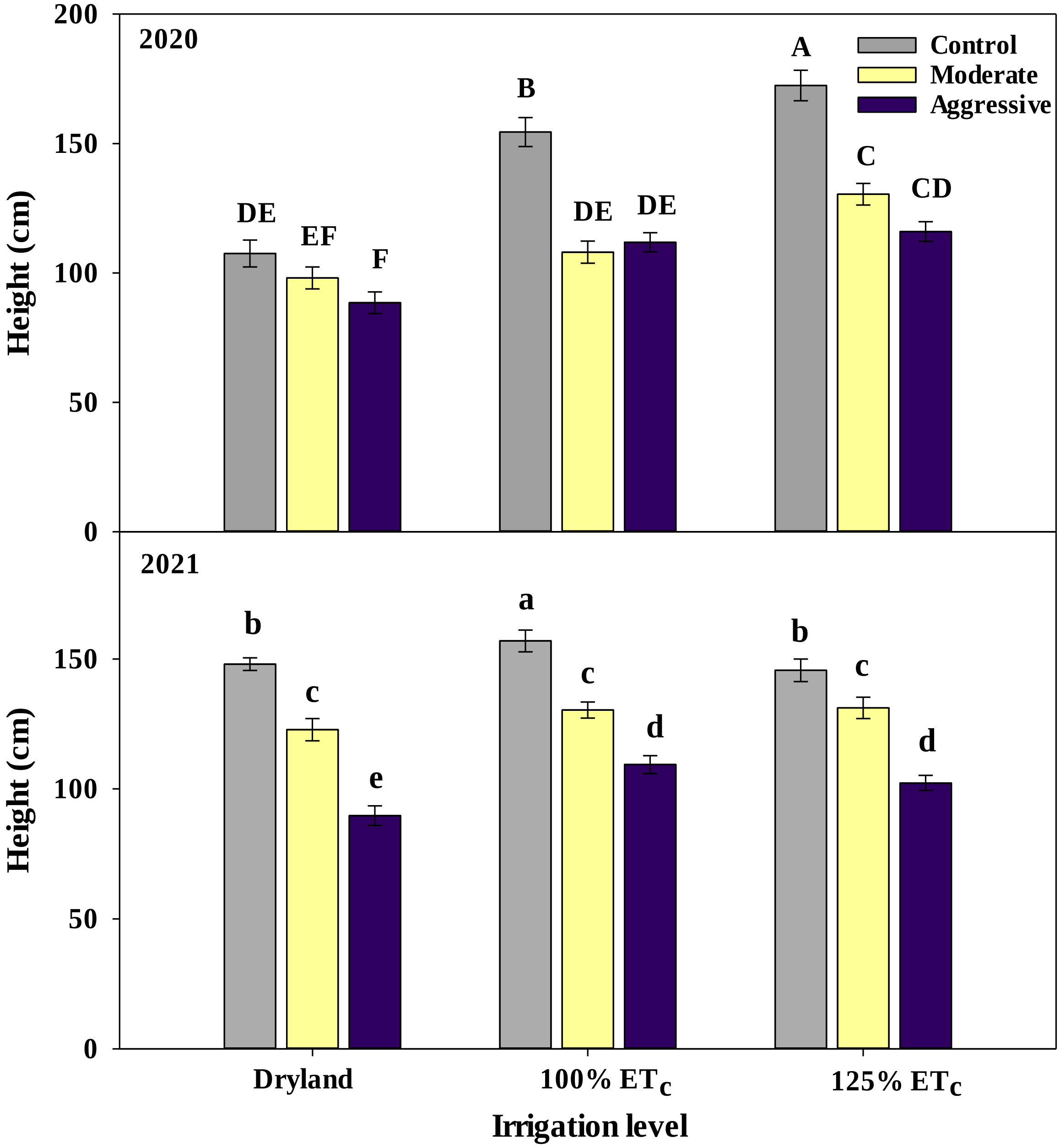

Figure 2. Effects of three irrigation treatments [Dryland, Well-watered (100% ET$_c$), and Over-irrigated (125% ET$_c$)] and three mepiquat chloride (MC) treatments (Control, Moderate, and Aggressive) on final plant height during the 2020 and 2021 growing seasons for a field site near Camilla, GA. Bars represent means ± standard error, and bars not sharing a common letter within a given year are considered significantly different ($P \leq 0.05$).

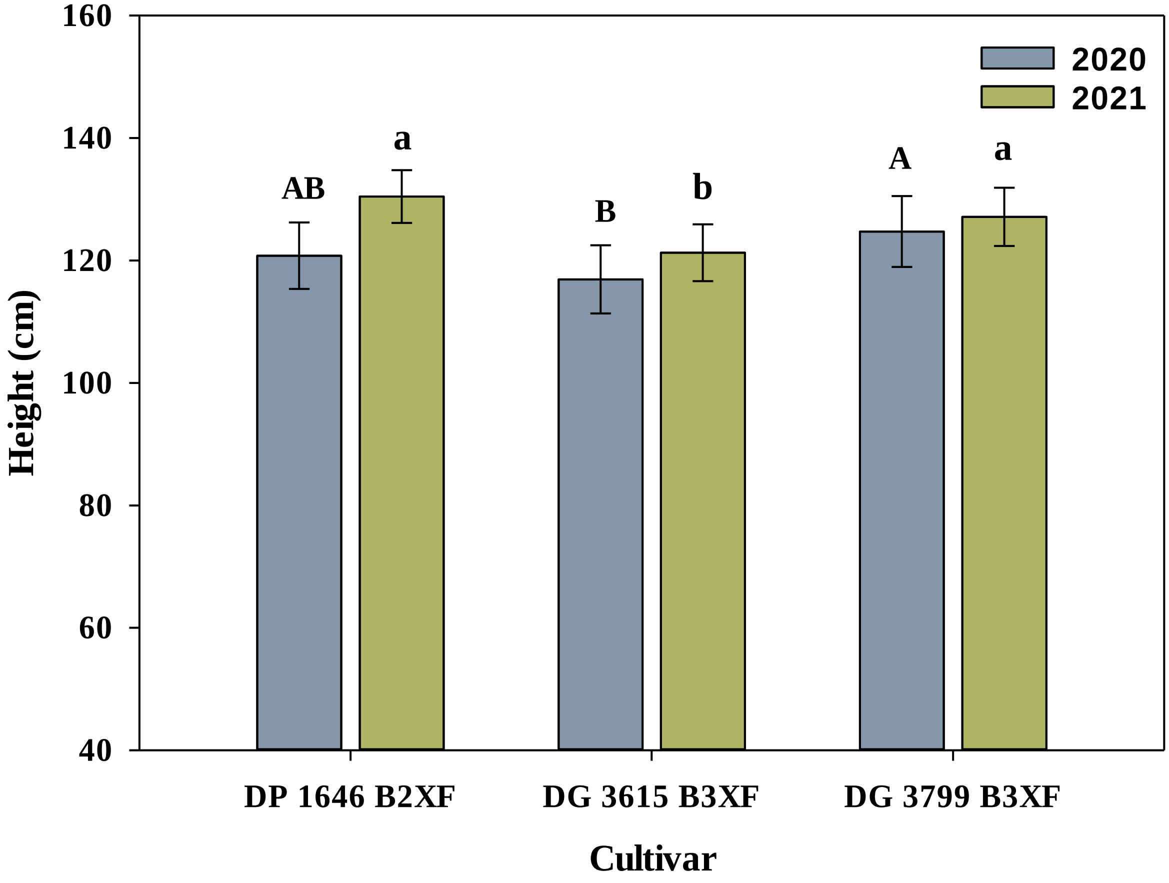

Figure 3. Final plant height (cm) for three cotton cultivars (DP 1646 B2XF, DG 3615 B3XF, and DG 3799 B3XF) during the 2020 and 2021 growing seasons at a field site near Camilla, GA. Bars represent means ± standard error, and bars not sharing a common letter within a given year are considered significantly different ($P \leq 0.05$).

3.2.2. Total mainstem nodes

Total mainstem nodes per plant were only affected by MC treatment and cultivar in 2020 and by irrigation treatment, MC treatment, and cultivar in 2021, but no interactions between treatments were observed in both years (Table 2). In 2020, control plots (23.6) had significantly higher total mainstem nodes per plant than moderately (21.9) and aggressively MC-treated plots (22.1). Cultivars DP 1646 B2XF (23.6) and DG 3799 B3XF (22.7) produced more total mainstem nodes per plant than cultivar DG 3615 B3XF (21.4). In 2021, well-watered plots (22.1) had significantly more total mainstem nodes per plant than dryland (20.5) and over-irrigated plots (20.8). Untreated plots had significantly more mainstem nodes per plant (22.7) than MC-treated plots. Within the MC-treated plots, moderately-treated plots had significantly more mainstem nodes per plant (20.8) than aggressively-treated plots (19.9). The cultivar DP 1646 B2XF had significantly greater total mainstem nodes plant (22.7) than cultivars DG 3799 B3XF (20.8) and DG 3615 B3XF (19.9) (Table 3).

Table 3. Mean values for node of uppermost harvestable boll (NUHB) and total mainstem nodes per plant for three cultivars (DP 1646 B2XF, DG 3615 B3XF, and DG 3799 B3XF), three irrigation treatments [Dryland, Well-watered (100% ET_c), and Over-irrigated (125% ET_c)], and three mepiquat chloride (MC) treatments (Control, Moderate, and Aggressive) during the 2020 and 2021 growing seasons for a field site near Camilla, GA. Values are means (n = 9) and values not sharing a common letter within each cultivar, irrigation, or MC treatment and within the same year are significantly different ($P \leq 0.05$).

		NUHB		**Total nodes plant^{-1}**	
		2020	**2021**	**2020**	**2021**
Irrigation					
	Dryland	14.8B	15.8a	22.0A	20.5b
	100% ET_c	17.3A	15.8a	22.5A	22.1a
	125% ET_c	16.6A	16.1a	23.1A	20.8b
MC					
	Control	16.9A	17.0a	23.6A	22.7a
	Moderate	16.1AB	16.1b	21.9B	20.8b
	Aggressive	15.7B	14.5c	22.1B	19.9c
Cultivar					
	DP 1646 B2XF	16.4A	17.0a	23.6A	22.7a
	DG 3615 B3XF	15.9A	15.1b	21.4B	19.9c
	DG 3799 B3XF	16.4A	15.5b	22.7A	20.8b

3.2.3. Node of the uppermost harvestable boll (NUHB)

NUHB was affected only by irrigation and MC treatment in 2020, whereas only MC treatment and cultivar affected NUHB in 2021 (Table 2). In 2020, dryland plots had significantly lower NUHB (14.8) than well-watered (17.3) and over-irrigated plots (16.6). Aggressively-treated plots had significantly lower NUHB (15.7) than control plots (16.9), but not significantly lower than moderately-treated plots (16.1). In 2021, control plots had significantly higher NUHB (17.0) than MC-treated plots (16.1 and 14.5 for moderately and aggressively-treated plots, respectively). Among the three cultivars, DP 1646 B2XF had higher NUHB (17.0) than DG 3615 B3XF (15.1) and DG 3799 B3XF (15.5) in 2021 (Table 3).

3.2.4. Cutout date

A significant irrigation by MC interaction was observed for cutout date in the 2020 growing season, whereas cutout date differed only with MC treatment in the 2021 growing season (Table 2). In 2020, irrespective of MC treatments, dryland plots reached cutout earlier (approximately 84 DAP) than irrigated plots. Similarly, MC-treated plots reached cutout approximately 2 weeks prior (100 DAP) to the control (114 DAP) in well-watered plots and approximately 3 weeks prior (100 DAP) to the control (121 DAP) in over-irrigated plots (Figure 4). In 2021, aggressively-treated plots reached cutout (90 DAP) earlier than moderately-treated (94 DAP) and control plots (103 DAP) (Figure 5).

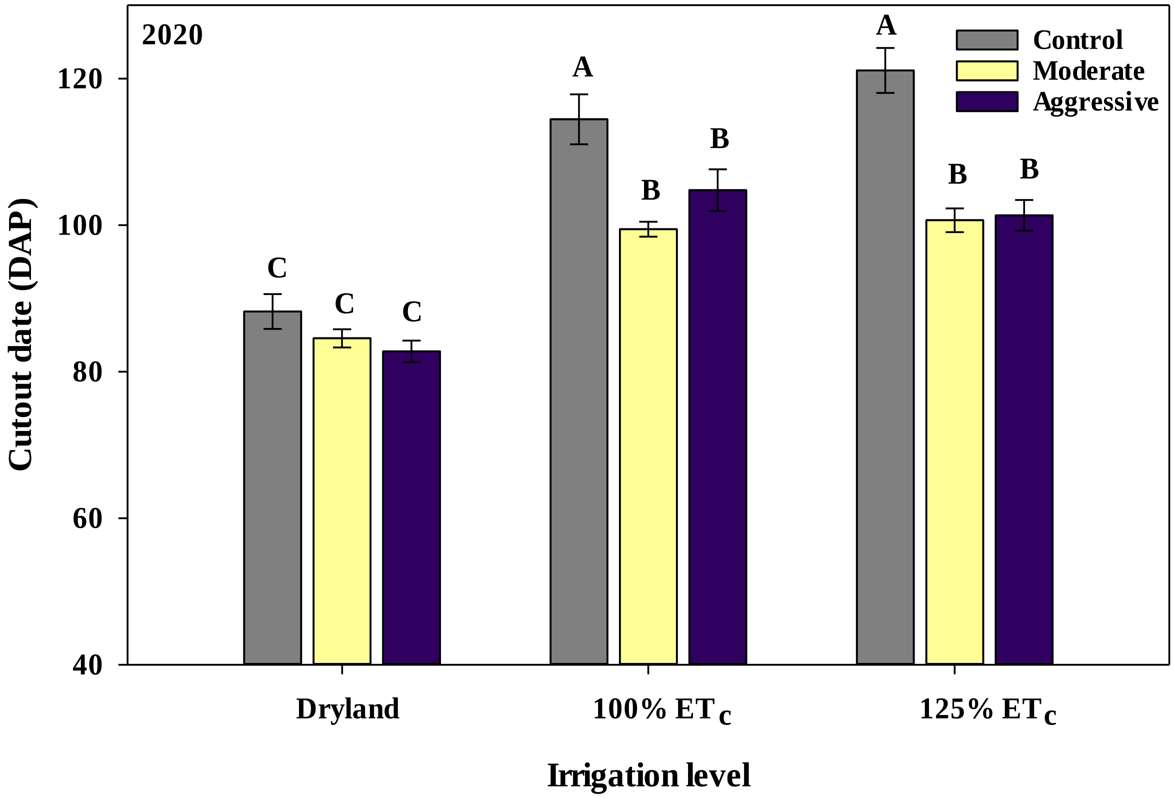

Figure 4. Effects of three irrigation treatments [Dryland, Well-watered (100% ET$_c$), and Over-irrigated (125% ET$_c$)] and three mepiquat chloride (MC) treatments (Control, Moderate, and Aggressive) on cutout date (DAP) during the 2020 growing season for a field site near Camilla, GA. Bars represent means ± standard error, and bars not sharing a common letter are considered significantly different ($P \leq 0.05$).

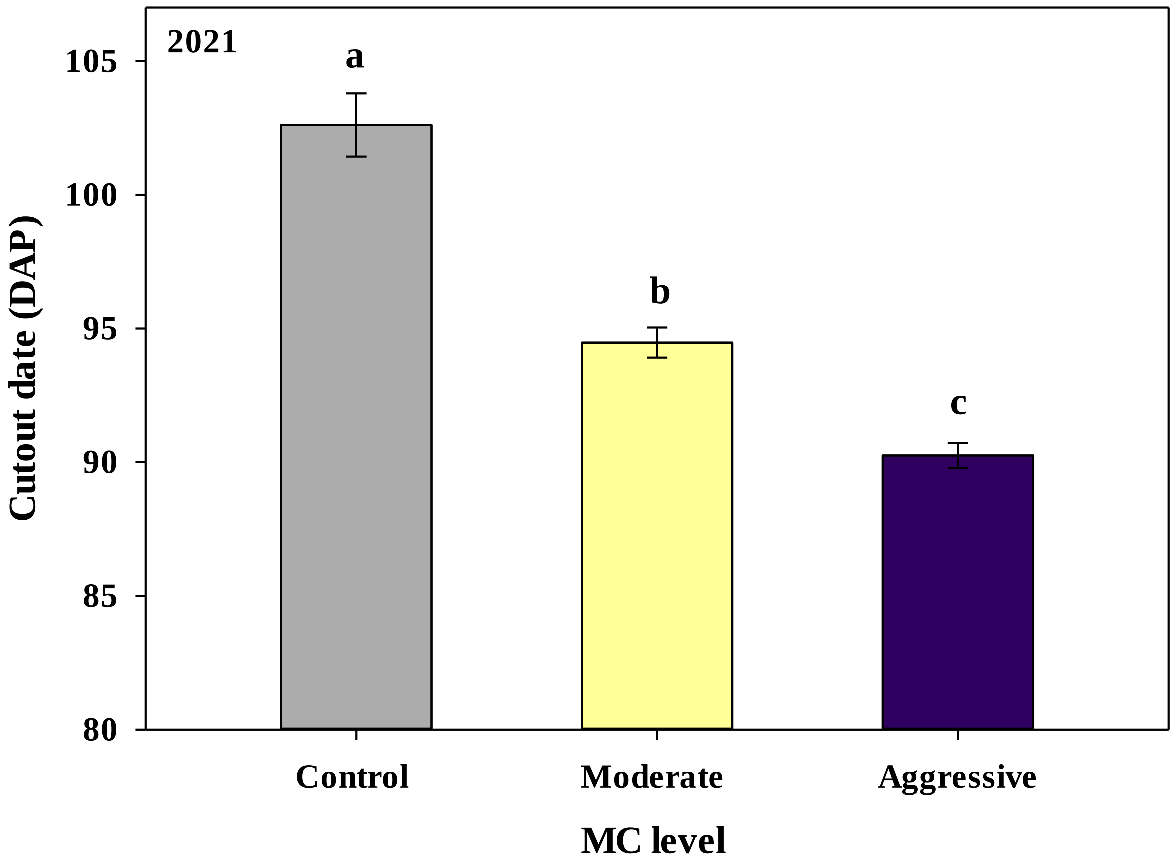

Figure 5. Effects of three mepiquat chloride (MC) treatments (Control, Moderate, and Aggressive) on cutout date (DAP) during the 2021 growing season for a field site near Camilla, GA. Bars represent means ± standard error, and bars not sharing a common letter are considered significantly different ($P \leq 0.05$).

3.3. Yield and fiber quality

3.3.1. Lint yield

Table 4. Mixed model ANOVA results for irrigation, cultivar, mepiquat chloride (MC), cultivar × irrigation, cultivar × MC, irrigation × MC, and cultivar × irrigation × MC on lint yield, fiber length, strength, uniformity, and micronaire during the 2020 and 2021 growing seasons for a field site near Camilla, GA.

	P Value									
Source	**Lint Yield**		**Fiber Length**		**Fiber Strength**		**Uniformity**		**Micronaire**	
	2020	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**
Irrigation (I)	<0.001*	0.001*	0.022*	0.119	0.005*	0.604	0.316	0.358	<0.001*	0.003*
MC	0.077	0.093	0.008*	0.007*	0.046*	0.065	0.652	0.004*	0.031*	<0.001*
Cultivar (C)	0.094	<0.001*	<0.001*	<0.001*	<0.001*	0.347	<0.001*	0.073	0.044*	<0.001*
C × I	0.191	0.170	0.114	0.615	0.057	0.105	0.015*	0.656	0.698	0.387
C × MC	0.737	0.177	0.567	0.435	0.170	0.180	0.436	0.622	0.847	0.614
I × MC	0.187	0.125	0.919	0.971	0.555	0.321	0.417	0.640	0.421	0.946
C × I × MC	0.800	0.293	0.751	0.513	0.668	0.853	0.929	0.981	0.838	0.704

*Significant ($P \leq 0.05$) main effects or interactions

Lint yield was affected only by irrigation level in 2020. However, lint yield was only affected by irrigation and cultivar in 2021 (Table 4). For example, in 2020 (the drier of the two seasons) dryland plots had significantly lower lint yield (1196 kg ha^{-1}) compared to irrigated plots (1597 and 1544 kg ha^{-1} for well-watered and over-irrigated plots, respectively). In 2021 (the wetter of the two seasons), the highest lint yield was observed for dryland plots (1236 kg ha^{-1}) which was significantly higher than well-watered (1112 kg ha^{-1}) and over-irrigated plots (1114 kg ha^{-1}) (Figure 6). In 2021, cultivar DP 1646 B2XF produced significantly higher yield (1315 kg ha^{-1}) than cultivar DG 3615 B3XF (1106 kg ha^{-1}) and DG 3799 B3XF (1041 kg ha^{-1}) (Figure 7).

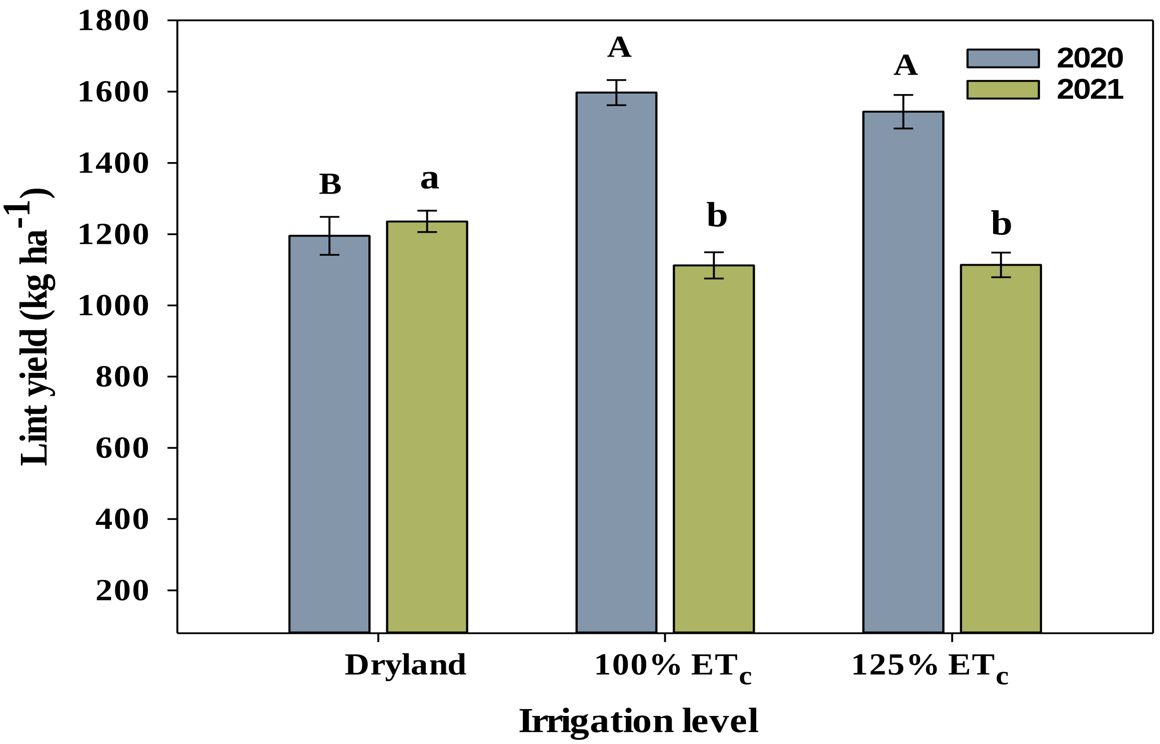

Figure 6. Effects of three irrigation treatments [Dryland, Well-watered (100% ET$_c$), and Over-irrigated (125% ET$_c$)] on lint yield (kg ha^{-1}) during the 2020 and 2021 growing seasons for a field site near Camilla, GA. Bars represent means ± standard error, and bars not sharing a common letter within a given year are considered significantly different ($P \leq 0.05$).

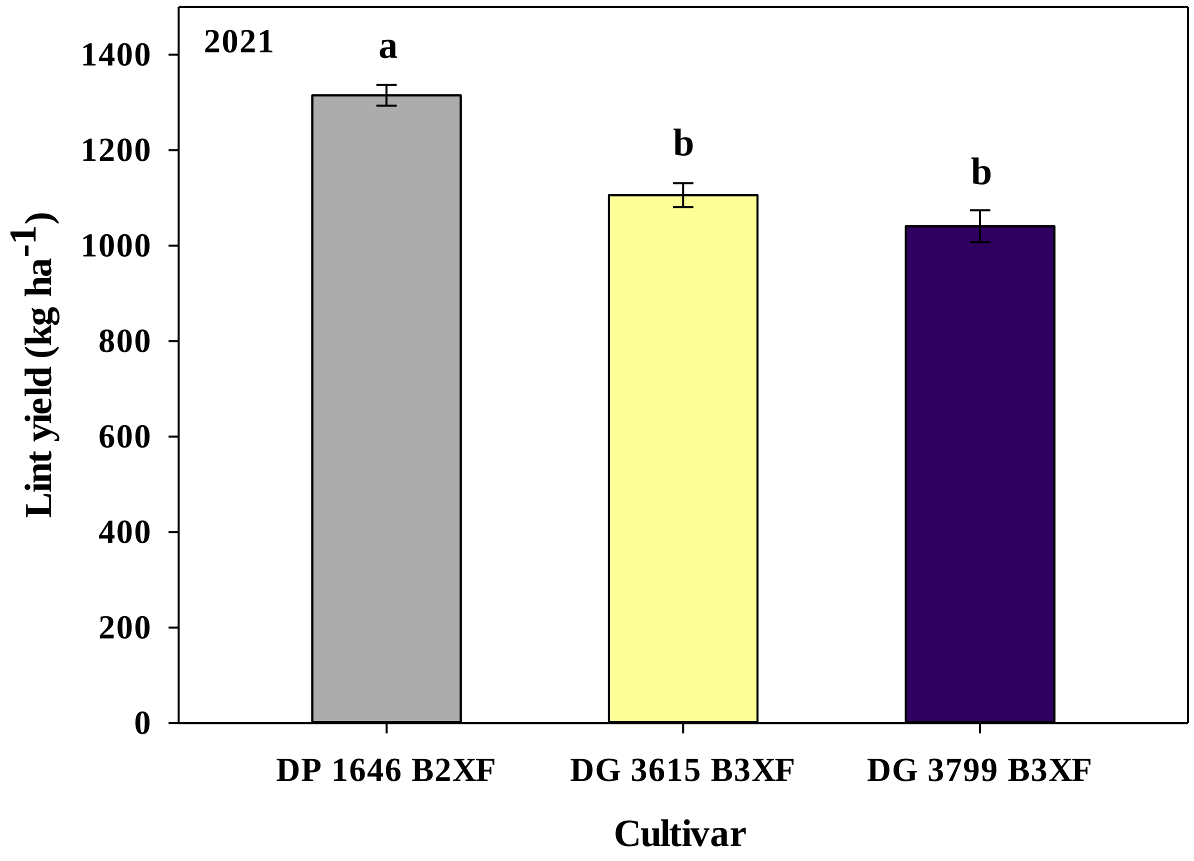

Figure 7. Lint yield (kg ha^{-1}) for three cotton cultivars (DP 1646 B2XF, DG 3615 B3XF, and DG 3799 B3XF) during the 2021 growing season for a field site near Camilla, GA. Bars represent means ± standard error, and bars not sharing a common letter are considered significantly different ($P \leq 0.05$).

3.3.2. Fiber quality

3.3.2.1. Fiber length

Fiber length was significantly affected by irrigation, MC, and cultivar in 2020 (no interactions), whereas fiber length was only affected by MC and cultivar in 2021 (Table 4). In 2020, longer fibers were observed for over-irrigated plots (3.10 cm) compared to dryland (3.05 cm). Aggressively-treated plots had longer fibers (3.10 cm) compared to the control plots (3.04 cm), but similar fiber lengths to moderately-treated plots (3.07 cm). Moreover, longer fibers were observed for cultivar DP 1646 B2XF (3.18 cm) when compared to cultivar DG 3615 B3XF (3.03 cm) and DG 3799 B3XF (3.00 cm). In 2021, control plots had significantly shorter fibers (2.89 cm) compared to aggressively-treated plots (2.94 cm) and moderately-treated plots (2.92 cm). Cultivar DP 1646 B2XF produced longer fibers (3.05 cm) than cultivar DG 3615 B3XF (2.85 cm) and DG 3799 B3XF (2.85 cm) (Table 5).

Table 5. Mean fiber length, fiber strength, uniformity, and micronaire for three cultivars (DP 1646 B2XF, DG 3615 B3XF, and DG 3799 B3XF), three irrigation treatments [Dryland, Well-watered (100% ET_c), and Over-irrigated (125% ET_c)], and three mepiquat chloride (MC) treatments (Control, Moderate, and Aggressive) during the 2020 and 2021 growing seasons for a field site near Camilla, GA. Values are means (n = 9) and values not sharing a common letter within each cultivar, 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**	
	2020	2021	2020	2021	2020	2021	2020	2021
Irrigation								
Dryland	3.05B	2.90a	32.4A	30.0a	82.9A	81.5a	4.56A	4.76a
100% ET_c	3.07AB	2.93a	31.4B	30.2a	83.1A	81.7a	4.10B	4.63b
125% ET_c	3.10A	2.92a	31.9AB	30.3a	83.4A	81.8a	4.12B	4.73a
MC								
Control	3.04B	2.89b	31.4B	29.8a	82.9A	81.2b	4.16B	4.57b
Moderate	3.07AB	2.92a	32.0AB	30.2a	83.2A	81.8a	4.34A	4.80a
Aggressive	3.10A	2.94a	32.2A	30.5a	83.2A	82.0a	4.28AB	4.75a
Cultivar								
DP 1646 B2XF	3.18A	3.05a	30.3B	30.1a	84.4A	81.9a	4.31A	4.43b
DG 3615 B3XF	3.03B	2.85b	32.6A	30.4a	82.6B	81.6a	4.31A	4.83a
DG 3799 B3XF	3.00B	2.85b	32.8A	30.1a	82.4B	81.4a	4.16B	4.86a

3.3.2.2. Fiber strength

Fiber strength was affected by cultivar, irrigation, and MC in 2020 growing season (no interactions), but there was no effect of cultivar, irrigation, or MC treatment in the 2021 growing season (Table 4). In the 2020 growing season, dryland plots produced stronger fiber (32.4 g tex^{-1}) than the well-watered treatment (31.4 g tex^{-1}) and comparable fiber strengths to over-irrigated plots (31.9 g tex^{-1}). Fiber strength was higher for aggressively-treated plots (32.2 g tex^{-1}) compared to control plots (31.4 g tex^{-1}) which were comparable to moderately-treated plots (32.0 g tex^{-1}). Moreover, cultivar DG 3799 B3XF (32.8 g tex^{-1}) and DG 3615 B3XF (32.6 g tex^{-1}) produced stronger fibers than the cultivar DP 1646 B2XF (30.3 g tex^{-1}) (Table 5).

3.3.2.3. Uniformity

Uniformity was only significantly affected by cultivar and there was an interaction between cultivar and irrigation treatment during the 2020 growing season. In 2021, only MC treatment affected uniformity (Table 4). For example, in 2020, cultivar DP 1646 B2XF produced more uniform fiber (84.4%) than cultivar DG 3799 B3XF (82.4%) and DG 3615 B3XF (82.6%) (Table 5). Cultivar DP 1646 B2XF under over-irrigated conditions produced more uniform fiber (85.0%) which was similar to the uniformity of DP 1646 B2XF (85.0%) in well-watered conditions, but significantly higher than cultivar DG 3615 B3XF and DG 3799 B3XF in both well-watered (82.7 and 81.8% respectively) and over-irrigated conditions (82.4 and 82.7% respectively) and cultivar DP 1646 B2XF in dryland conditions (83.1%). Cultivar DG 3799 B3XF under well-watered conditions produced less uniform fiber (81.8%) compared to cultivar DP 1646 B2XF across all irrigation treatments (Figure 8). In 2021, control plots produced significantly less uniform fiber (81.2%) than MC-treated plots (81.8% and 82.0% for moderately and aggressively-treated plots, respectively) (Table 5).

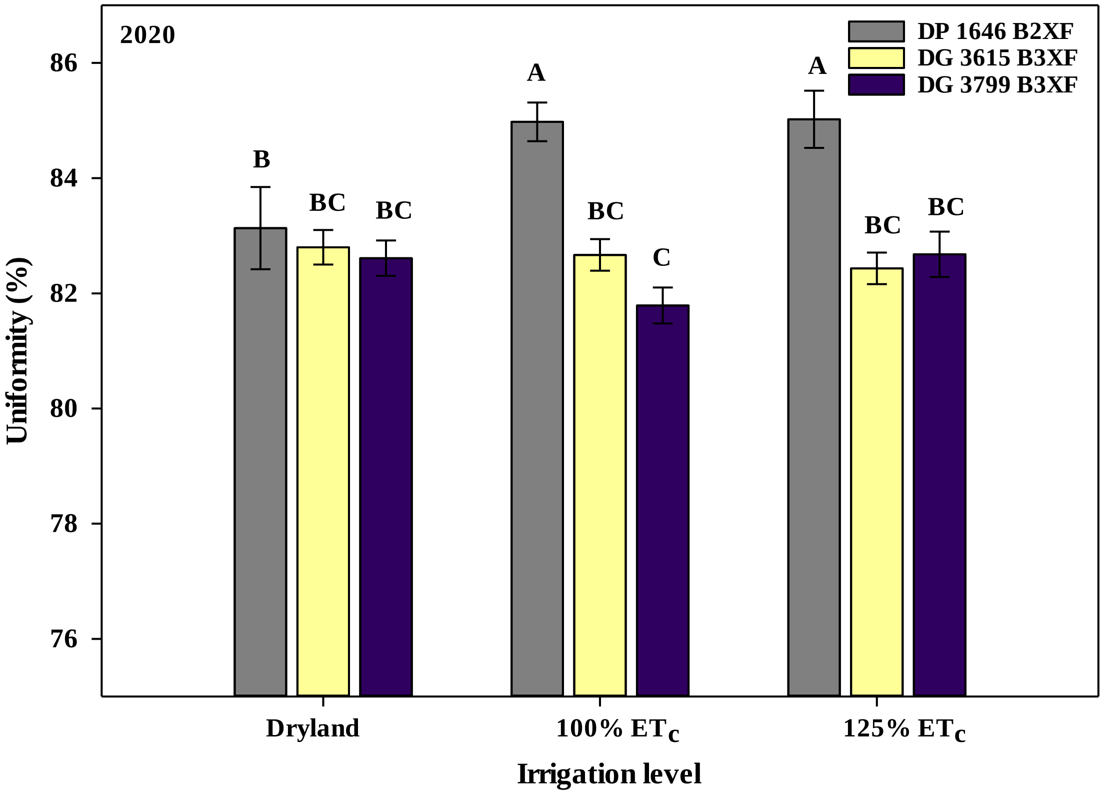

Figure 8. Effects of three cultivars (DP 1646 B2XF, DG 3615 B3XF, and DG 3799 B3XF) and three irrigation treatments [Dryland, Well-watered (100% ET$_c$), and Over-irrigated (125% ET$_c$)] on uniformity (%) during the 2020 growing season for a field site near Camilla, GA. Bars represent means ± standard error, and bars not sharing a common letter are considered significantly different ($P \leq 0.05$).

3.3.2.4. Micronaire

Micronaire value was affected by cultivar, irrigation, and MC treatment in both growing seasons. No two-way or three-way interactions were observed for micronaire value (Table 4). For example, in 2020 dryland plots had higher micronaire (4.56) than well-watered (4.10) and over-irrigated plots (4.12). Moderately-treated plots had higher micronaire (4.34) than control (4.16) but comparable micronaire to aggressively-treated plots (4.28). Moreover, cultivar DG 3615 B3XF (4.31) and DP 1646 B2XF (4.31) had higher micronaire values than cultivar DG 3799 B3XF (4.16). In 2021, dryland (4.76) and over-irrigated (4.73) plots had higher micronaire values than well-watered plots (4.63). Moreover, control plots had lower micronaire values (4.57) compared to moderately MC-treated (4.80) and aggressively-treated (4.75) plots. Finally, cultivar DP 1646 B2XF (4.43) had lower micronaire values than cultivar DG 3799 B3XF (4.86) and DG 3615 B3XF (4.83) (Table 5).

4. Discussion

The objective of the current study was to evaluate the MC, irrigation, and cultivar effect on growth, physiological maturity, yield, and fiber quality of cotton. The 2020 and 2021 growing seasons provided an opportunity to evaluate the effect of the aforementioned factors on plant growth, physiological maturity, yield, and fiber quality during two growing seasons with substantial differences in rainfall. For example, according to Bednarz et al. (2002), the total water requirement during a growing season to optimize cotton production in the southeastern USA is slightly more than 450 mm. The 2020 growing season was generally drier, and thus had higher total irrigation applied in irrigated plots, compared with the 2021 growing season. In 2020, total rainfall was 347 mm which was below crop water requirements, thus there was some level of drought stress during the growing season in dryland plots. However, in the 2021 growing season, total rainfall was 735 mm which was more than the total water requirement for cotton in the southeastern USA (Table 1).

In 2020, yield responded positively to irrigation, where the highest yield was observed in well-watered plots (1597 kg ha^{-1}) and the lowest yield was observed in dryland plots (1196 kg ha^{-1}) (Figure 6). This yield reduction for drought-stressed cotton was within the same range (7.23 to 49.41%) as previously published experiments documenting cotton yield loss under moderate drought stress (Hu et al., 2018; Karademir et al., 2011). Drought reduces overall plant growth and development and was evidenced in the current study as a decrease in plant height and NUHB in dryland plots compared to irrigated plots (Figure 2 and Table 3). Drought reduces turgor pressure (Hsiao, 1973), which is essential for cell elongation, thereby decreasing plant growth. Similar results were observed in other past studies. For example, previous studies documented that water stress results in decreased plant height and mainstem node production (Meeks et al., 2017; Pace et al., 1999). Plants reached cutout earlier in dryland plots compared to irrigated plots (Figure 4). Under low water availability, vegetative and reproductive growth is inhibited, and the plant produces fewer fruiting sites, resulting in earlier maturation and lower yield (Hearn, 1980). Irrigated plots that received no MC applications took a longer period of time to reach cutout which was due to more vegetative growth as has been described previously (Bronson et al., 2001; DeLaune et al., 2012; DeTar, 2008). Likewise, we observed a decrease in fiber length in dryland plots compared to irrigated plots, which has been associated with a lack of turgor pressure during the elongation phase of fiber development (Hu et al., 2018). Stronger fibers were produced in the dryland plots than well-watered plots (Table 5). The stronger fiber produced in dryland plots may be due to reductions in boll retention, so more cellulose could be deposited in fewer developing fibers (Hu et al., 2018). We did not observe MC effects on lint yield. However, MC application had a significant effect on plant height, total mainstem nodes, and physiological maturity (Table 2). MC application reduces cell elongation and expansion, thus resulting in shorter plants with fewer mainstem nodes and NUHB (Reddy et al., 1992). MC treatment had increased fiber length, strength, and micronaire in our current study (Table 5). Increased fiber quality might be due to a decrease in plant height and more light penetration to lower branches. Greater light penetration to lower branches favors higher photosynthesis, thus more carbohydrate will be available for fiber growth in individual bolls (Kerby, 1985). We observed inconsistent responses of cultivar to growth, yield, and fiber quality. It seems reasonable to assume that cultivar variation on growth, yield, and fiber quality was mainly due to cultivar characteristics (York, 1983a).

In 2021, yield responded negatively to irrigation where the highest yield was observed for dryland plots (1236 kg ha^{-1}) and the lowest yield for well-watered plots (1112 kg ha^{-1}) (Figure 6). Excess water during the growing season can cause more vegetative growth and reduce boll retention (Ermanis et al., 2021). A larger cotton plant will typically have more fruiting sites on which to set bolls; however, light penetration to lower branches in the canopy decreases along with boll retention. Additionally, excess vegetative growth has the potential to increase disease and pest incidence (Hearn, 1980). Therefore, a cotton plant growing under high moisture levels produces more vegetative growth (Onder et al., 2009) which can result in shedding of floral buds or bolls from lower nodes on the plant, which decreases yield (Cetin and Bilgel, 2002; Ritchie, 2007). In contrast, we observed taller plants in well-watered plots compared to over-irrigated plots in 2021, which might be due to leaching of nutrients caused by excessive rainfall plus irrigation (Grimes et al., 1969; Cholpankulov et al., 2005). Overirrigated plots were notably more chlorotic than dryland and well-watered plots at later growth stages during the 2021 growing season (personal observation). There was no drought stress during the 2021 growing season; therefore, there was no significant difference in NUHB, cutout date, fiber length, strength, or uniformity among different irrigation treatments. MC application had a significant effect on plant height, total mainstem nodes, and physiological maturity, but not on lint yield. MC application results in inhibition of growth by reducing further cell expansion, thus resulting in shorter plants with fewer mainstem nodes and NUHB (Gwathmey and Craig, 2003). We observed shorter plants with a smaller number of mainstem nodes for aggressively MC-treated plots compared to moderately-treated plots (Table 3). When MC is applied at an early stage of cotton growth and development, it will reduce plant height and mainstem nodes to a greater extent than applying at later stages of growth, as MC reduces further cell expansion and inhibits new growth (Kerby et al., 1986). Furthermore, MC application resulted in earlier physiological maturity (Figure 5). As noted previously, application of MC reduces vegetative growth, thereby promoting early flowering and fruit set (York, 1983b). There were significant cultivar effects for growth, yield, and fiber quality, but trends were not the same from one year to the next. This is not entirely surprising, given the substantial differences in growth conditions between the two growing seasons. Additionally, previous research conducted in large-plot on-farm variety trials has illustrated that production environment can account for a substantial percentage of total yield and fiber quality variability when evaluating well-adapted cultivars for the same production region (Snider et al., 2013). Thus, if there is an excess of vegetative growth (either due to excessive rainfall, growing habits of the cultivar) then some negative consequences of excessive vegetative growth can be mitigated by following an aggressive or moderate MC application strategy. Height can be reduced and physiological maturity can be hastened, thereby increasing harvest efficiency and decreasing the length of the growing season without penalizing yields.

5. Conclusions

The objective of this research was to evaluate the effects of cultivar, irrigation management, and MC strategy on growth, physiological maturity, yield, and fiber quality in cotton. We were able to make the following conclusions from this experiment. Yield responded positively to irrigation in a dry year (2020) and negatively to irrigation in a wet year (2021). No direct effects of MC application or interactions between growth management strategy and any other factor were observed for lint yield. However, MC application significantly reduced plant growth and hastened physiological maturity, especially in irrigated plots during the 2020 growing season. We also observed some increases in fiber quality parameters (length, strength, uniformity, and micronaire) with MC application. Furthermore, higher yield was produced by a cultivar DP 1646 B2XF compared to DG 3615 B3XF and DG 3799 B3XF in an excessive rainfall year (2021). Therefore, we can conclude that MC application did not alter cotton yield response to irrigation in either dry or wet growing seasons. However, MC treatment had positive effects such as reductions in vegetative growth, hastened physiological maturity (effectively shortening the growing season), and positively affects fiber quality, especially in irrigated plots during otherwise dry growing seasons.

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CHAPTER 3

CONCLUSIONS

This field research was carried out during the 2020 and 2021 growing seasons in Camilla, GA with the objective of evaluating how cultivar, irrigation management, and plant growth management strategy interact with each other to affect cotton growth, maturity, yield, and fiber quality in the Southeastern USA. Plant growth measurements such as plant height and total mainstem nodes were counted at the end of the season to determine the effect of different treatments on these growth parameters. Similarly, nodes above white flower (NAWF) were counted biweekly after flowering to determine physiological maturity date (cutout date). After harvesting, lint yield and fiber quality data were also recorded.

The two growing seasons differed substantially in rainfall. The 2020 growing season was drier than a typical year in which total rainfall from planting to harvest was 34.7 cm, whereas the 2021 growing season was a wet year in which total rainfall from planting to harvest was 73.5 cm. Yield responded positively to irrigation in 2020, where the highest yield was recorded in well-watered plots and the lowest yield was recorded in dryland plots. Yield responded negatively to irrigation in 2021 in which the highest yield was recorded in dryland plots compared to irrigated plots. No direct effects of MC application or interactions between growth management strategy and any other factor were observed for lint yield. However, MC application significantly reduced plant growth and hastened physiological maturity, especially in irrigated plots during the 2020 growing season. We also observed some improvements in fiber quality (length, strength, uniformity, and micronaire) with MC application. In a wetter year like the 2021 growing season, plants reached physiological maturity earlier in aggressive MC-treated plots compared to moderately-treated plots. We can conclude that MC management strategy did not alter cotton yield response to irrigation in either dry or wet growing seasons. However, MC treatment reduces vegetative growth, hastens physiological maturity (effectively shortening the growing season), and can affect fiber quality, especially in irrigated plots during dry growing seasons.