COTTON GROWTH STAGE SPECIFIC IRRIGATION AND FIBER QUALITY RESPONSE IN THE GREAT PLAINS REGION

By

ANDREA JANICE ALTHOFF

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Thesis Approved:

Dr. Seth Byrd

Thesis Adviser

Dr. Jason Warren

Dr. Summit Sharma

Dr. Randy Norton

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Abstract: With decreasing water availability and increasing cotton (*Gossypium hirsutum L.*) production in the Great Plains region, a more efficient irrigation schedule and variety response needs to be assessed to make production more sustainable in this arid, short season environment. A two-year study was conducted in Goodwell, Oklahoma to determine a more efficient irrigation schedule using subsurface drip tape (SSD) and evaluating variety response. The performance of four early maturing cotton varieties was assessed under four irrigation treatments based on evapotranspiration (ET) replacement schedules of 90% ET, 63% ET, 90/63% ET, and 36% ET replacement. Crop growth and development, crop maturity, yield, and fiber quality properties were evaluated in response to variety and irrigation schedule. Excessive rainfall and reduced heat units in 2020 resulted in maturity delays, reduced yield, and poor fiber quality. There was minimal effect of irrigation treatments due to the excess rainfall, while differences in growth and yield parameters were present due to variety, with those exhibiting earlier maturing characteristics resulting in a 20 – 30% higher lint yield. Varietal differences were still present when growing conditions improved in 2021, and in this year irrigation treatments also influenced some growth parameters, as well as lint yield. Variety was more impactful on plant growth and development, as varieties exhibiting earlier maturing characteristics in 2020 again had lower node above white flower and height values. The lowest ET replacement irrigation treatment resulted in a 6 – 27% higher open boll percentage compared to all other treatments. The 90% ET and 63% ET treatments had 21 – 34% higher lint yields then all other irrigation treatments. The results of this study illustrate the importance of both correct variety selection and management in irrigated short season production environments.

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REVIEW OF LITERATURE

1.1 INTRODUCTION

Cotton is a vital part of three states in the Great Plains region (Guerrero and Hudson, 2008), specifically defined as northern High Plains of Texas, southwest and south central regions of Kansas, and the panhandle of Oklahoma. The northern High Plains region of Texas is made up of 23 counties, while the southwest and south-central regions of Kansas consist of 12 and 13 counties, respectively, and the Oklahoma Panhandle contains three counties. In total, these 51 counties planted 687,000 million hectares of upland cotton in both 2018 and 2019 (USDA, NASS, 2018-19). During this period, the panhandle of Oklahoma accounted for two percent of total acres planted, Kansas south central and southwest Region accounted for ten percent, and the northern High Plains region of Texas accounted for eighty-eight percent of planted acres within the Great Plains (USDA, NASS, 2018-19). The Great Plains region is significant to cotton production in the United States, as the three regions accounted for approximately 12 – 13 % of the U.S. total acres of upland cotton planted in 2018 and 2019 (USDA, NASS, 2018-19).

1.2 GROWTH AND DEVELOPMENT

Upland cotton (*Gossypium hirsutum L.)* is an indeterminate, tropical, woody perennial that produces an annual crop of fiber, oil, and meal (Constable and Bange, 2015). The term indeterminate refers to crops that have overlapping vegetative and reproductive growth stages (Constable and Rawson, 1980). This makes cotton a unique and challenging crop particularly in short season environments where optimizing both duration and maturity of reproductive growth is critical. During vegetative growth the plant is developing a root system, vegetative stems, and leaves. The plant slowly transitions to reproductive growth with the development of fruiting branches which produce fruiting sites that are initially flower buds, termed squares, while taproot development slows and generally halts near the occurrence of the first bloom (Oosterhuis and Zhao, 1994). On average, cotton takes around 180 days until maturity, although this can vary based on variety (Wells and Stewart, 2010).

Cotton growth and development can be generally categorized into five stages: vegetative, squaring, flowering, boll fill, and maturity. From germination until the first square or initiation of fruiting site, cotton can be classified as being in the vegetative stage (Edmisten, 2020). As described by Mauney (1986), a cotton seed can take up to two weeks from planting to emergence from the soil, although this is dependent upon environmental conditions, primarily moisture. Once the seedling emerges, the hypocotyl pulls the cotyledons out of the soil to develop an apical meristem. This kind of emergence is known as epigeal germination (Ritchie et al., 2007). Once the plant is established, resources are dedicated to development of a root system and production of monopodial, or vegetative branches and leaves to support fruit development (Constable and Rawson, 1980). Once cotton reaches approximately five main stem nodes, the plant will generally begin to increase the leaf area for each corresponding node. This will take place until the plant begins to equalize the root area and leaf area ratio (Mauney, 1986). A cotton plant shifts from vegetative to reproductive growth when the plant begins to develop modified leaves that form fruiting buds called squares located on sympodial, or fruiting branches (Stewart, 1986). Multiple fruiting sites, or positions, form on a single fruiting branch, with first position fruit located closest to the main stem and subsequent positions are termed second, third, or higher based on their location on the fruiting branch in relation to the main stem. The fruiting branch will often have a "zig-zag" growth pattern because of the development of each square (Ritchie et al., 2007). Under relatively favorable growing conditions, a new fruiting branch develops on three-day intervals while additional fruiting positions develop on a fruiting branch on six day intervals (Bednarz and Nichols, 2005; McClelland, 1916). Squares are referred to as pin head or match head square based on the size of the developing flower bud (Ritchie et al., 2007; Stewart, 1986). It takes approximately 25 to 30 days for a visible square to develop into a flower (Hesketh and Low, 1968; Martin, et al., 1923). The girth of the square compounds exponentially and the petals prepare for bloom, commonly referred to as the candle stage, a critical point, as now the flower buds begin relying on nearby leaves to provide resources (Robertson et al., 2007). Once the flower fully opens and is exposed to sunlight anthesis occurs. As the anthers burst open and pollen is deposited onto the stigma, the ovule is typically fertilized in a twelve to twenty-four-hour period after the anthesis (Stewart,1975; Wells, 2012). An important gauge of cotton growth and development during the flowering stage is the number of main stem nodes from the uppermost first position white flower to the terminal (Bourland et al., 2001). This measurement gives an insight into the fruiting capacity as once the first white flower forms the plant focuses the carbohydrate supply into developing the fruit, termed bolls, and away from any additional vegetative structures (Oosterhuis et al., 1992). Once the plant has bloomed all the way to the top of the terminal, the plant begins to shift all its energy and carbohydrates into the developing boll. This period is called cutout. Cutout is important because at this time, there will be no more harvestable fruit set on the plant (Mason, 1922). Cutout also usually happens around three to five nodes above white flower (Ritchie et al., 2007). There are several options for producers to use to terminate the growth of the crop and open bolls at the end of the season. The crop will naturally defoliate, or producers can apply harvest-aids or defoliants (Williford 1992). The primary goal of harvest aids is to provide for a timely harvest and minimize fiber degradation to weathering. Boll maturation, also termed boll fill, is the period during which both fiber and seed develop. Once the seeds and fiber fully develop or mature, the boll will naturally crack open, or boll openers can be used to hasten the boll opening process (Byrd et al., 2021). The boll cracks because the outer covering dries out and shrinks causing the fiber and seeds to bust open and enlarge and dry out as well (Wells, 2012). The plant has reached full maturity once all fully developed bolls are open and fully mature (Martin et al., 1923; Hawkins and Serviss, 1930).

After harvest and ginning, cotton fiber quality is assessed. Parameters of fiber quality are strongly related to cotton fiber development and are affected by both physiological and biochemical processes (DeLanghe, 1976). Measurements of fiber quality include fiber length and strength, fiber length uniformity, micronaire, color grade, trash, and leaf grade (Cotton Incorporated, 2018). Fiber length represents the average length of the upper (or longer) half fibers, while fiber length uniformity is expressed in a percentage because it shows the ratio of the mean length and the upper half mean length (Cotton Incorporated, 2018). Fiber length is primarily governed by a combination of the plant's genetics, management practices, and the growing environment. Fiber strength is expressed in grams per tex, with a tex equal to the weight in grams of one thousand meters of fiber and is highly influenced by variety genetics. Color grade shows the degree of reflectance and yellowness, while trash measures the amount of non-lint items contained in a mass of cotton fibers and the leaf grade measures the amount of leaf content in a mass of cotton fibers. Not only is color grade influenced by variety and environmental factors, but cotton color can change as it ages (Anonymous, 2018). Micronaire a measure of the cotton fiber's fineness and maturity (Cotton Incorporated, 2021), and refers to the amount of secondary wall development in the fibers (Meredith, 1984). This process is extremely important in short season irrigated cotton because many studies have shown how easily micronaire is affected by moisture, temperature, nutrients, and other environmental factors (Eaton and Ergle, 1952; Gipson and Joham, 1968,1969; Marani and Amirva, 1971; Pettigrew 1996). More specifically, Gipson and Joham found that micronaire decreased when temperatures at night dropped below twenty-five degrees Celsius (Gipson and Joam, 1968).

1.3 CROP WATER STATUS AND RESPONSE TO WATER STRESS

It has been well documented in cotton that water stress causes the plants turgor to decrease and interfere with functions of the plant causing an interruption in physiological processes (Hsiao, 1973; Kramer, 1995). Each growth stage has different water demands based on plant needs, and understanding these requirements is vital to developing a more efficient cotton irrigation schedule. The Food and Agriculture Organization (FAO) classifies cotton by water requirements and growth stages (FAO, 2022). The crop coefficient factor (Kc) is used along with reference evapotranspiration (ETo) values to determine the amount of water used by the plant (Brouwer and Heibloem, 1986). The crop coefficient (Kc) is a combination of specific crop characteristics and averaged effects of evaporation from the soil. ET values are the loss of water from the combination of soil surface evaporation and loss from crop transpiration (Allen et al., 1998). The FAO calculates the evaporation from a crop based on the crop and soil characteristics, along with the reference ET by the Penman-Monteith equation and a crop coefficient (Allen et al., 1998). The initial stage, defined as the period from planting until the crop covers ten percent of the ground, lasts around 30 days, and has a crop factor of 0.45 Kc. The crop development stage starts from end of the initial stage until the crop covers 70-80% of the ground. This stage lasts approximately 50 days and has a crop factor of 0.75 Kc. The mid-season stage starts at the end of the crop development stage and continues until crop reaches maturity, including flowering and boll set. This stage lasts around 60 days and has a crop factor of 1.15 Kc. And finally, late season begins at the end of mid-season stage and lasts until the day of harvest. Late season lasts approximately 50 days and has a crop factor of 0.75 Kc (FAO, 2022).

Differences in water requirements and how they affect different growth stages and components of yield are described in Wrona et al. (1999). Water requirements were the highest during the square initiation stage to the first flower stage. The lowest water requirement across the stages was from the end of peak bloom to maturity. Adequate lint yield, boll set, and lint per boll is the most sensitive to water stress during the square initiation to the first flower stage (Wrona et al., 1999).

Fisher and Udeigwe (2017) reports cotton water requirements in Cotton Incorporated's Cotton Irrigation Management for Humid regions. A study in northeast Louisiana reported that daily crop water use in the first 25 days after planting ranged from 0.508 – 0.762 mm per day. In the developmental stage, the average water use was around 5.588 mm per day and during midseason it was 6.858 mm per day. A comparative study in Stoneville, MS, reported similar numbers. Water use ranged from 1.27 mm per day during early season, 7.112 mm per day during peak season, and down to 3.048 mm per day after boll opening (Fisher and Udeigwe, 2017).

Mauney (1984) reported that water requirements are relatively low in the early stages, but sufficient moisture is required to ensure germination, emergence, and adequate stand establishment. During vegetative growth early in the season, water deficiency can result in a reduction in the plant's net assimilation rate and leaf area index (Mauney, 1984), and in severe or long-term water deficiency cases, inhibit the crop's reproductive capacity when it transitions into the fruiting stage (Oosterhuis and Jernstedt, 1999). This is due to a reduced capacity to produce resources required to support the development of fruiting structures (Bunce 1977). However, previous studies have determined that slight to moderate water deficit during vegetative growth, is not detrimental to crop productivity compared to deficits experienced during reproductive growth because of the reduced water requirements during this period and the crop may have more time to recover before shifting to fruiting (Guinn et al., 1981; Zonta et al., 2017; Loka et al., 2011). It has been reported that exposing cotton to deficit irrigation during vegetative growth may result in the plant developing a more extensive root system which allows the crop access to a larger area of the soil profile for water and nutrient uptake when demand peaks during reproductive growth (Stockton et al., 1961). Conversely, excess moisture can inhibit root development resulting in a shallow rooting system and results in a crop more prone to water stress (Loka et al., 2011). Additionally, excessive moisture can cause root rot which leads the young plant to desiccate and die. (Hank, 2010)

As the crop transitions into reproductive growth and begins to develop squares, water requirements increase, signaling the beginning of the most sensitive stage of reproduction (Brouwer and Heibloem, 1986; Chastain et al., 2016: Wrona et al., 1999). Studies by Smirnoff (1993) and Reddy et al. (2004) reported that water stress during the early squaring stage triggers the plant to increase the activity of antioxidant enzymes prompting the plant to shift back into homeostasis as a form of protection. If the water stress continues, the plant eventually faces the decrease of photosynthetic activity and pigment concentration, and an increase in antioxidant enzymes to mitigate any further abiotic and biotic stresses (Pilon, 2015). From a production standpoint, this can eventually lead to square shedding, which can be exacerbated if cloudy weather, heat stress, high plant populations, nutrient deficiency, disease and/or insect damage are also present (Burke and Ulloa, 2017; Constable and Rawson, 1980). While the plant will generally abort younger squares initially, severe stress can impact the majority of fruiting sites or can lead to delayed fruiting and, in turn, crop maturity if the stress occurs at the initiation of the squaring stage (Hearn, 1994; Hsiao, 1976). Excessive moisture during the squaring stage can lead to increased disease incidence and result in fruit shed and yield loss (Ritchie et al., 2017).

The flowering stage in cotton has the highest demand for daily water needs. The initiation of flowering coincides with the plant transitioning to an even greater proportion of resources to reproductive growth and away from vegetative growth, with a complete shift away from vegetative sinks by mid-bloom (Fisher, 1975). If the plant faces water stress during flowering, squares, flowers, or young bolls, could be shed, and the development of additional fruiting sites will be inhibited leading to yield loss (Burke and Ulloa, 2017 a,b). Water stress can further result in a reduction in development of fruit due to poor pollen formation, germination, and fertilization. Poor pollen longevity from water stress results from dehydrated pollen grains, which can cause poor delivery of the pollen to the ovules (Percy et al., 2006; Fisher, 1975). Water stress during flowering can also affect the fruit as water stress can cause poor ovule longevity resulting in boll shedding (Constable and Rawson, 1980; Percy et al., 2006; Fisher, 1975). Too much water during the flowering stage can lead to increased disease or fruit shed (Burke and Ulloa, 2019). Excessive irrigation can also lead to shallow roots and excessive growth, which can in turn cause the plant to focus on shifting nutrients into vegetative growth and disregarding reproductive growth, resulting in yield declines (Bruyn, 1982). As the flowering period progresses, seed and fiber in earlier set bolls begin to develop, which are water sensitive processes and can be inhibited due to water deficit (Pettigrew, 2004). This can lead to poor seed development and quality, lower yield, and poor lint quality due to carbohydrate shortages (Pettigrew, 2004).

Cotton is less sensitive to water stress once the bolls begin to mature. The natural boll opening, and leaf senescence process begin, and the plant prioritizes supplying resources to maturing fiber (Guinn and Mauney, 1984). However, if there is too much water at the time of boll opening and senescence, producers run the risk of regrowth or disease (Parks et al., 1978; Pettigrew, 2004; Spooner et al., 1958).

As cotton acreage in the U.S. expands into areas with shorter production environments than those found in the traditional Cotton Belt, new challenges are being faced by producers. For cotton produced in the Great Plains, the arid conditions must be addressed through efficient use of limited irrigation to optimize both production and fiber quality.

1.4 PRODUCTION ENVIRONMENT IN THE SOUTHERN GREAT PLAINS

The portions of Kansas, Oklahoma, and Texas that compose this region are characterized as arid environments due to the low annual rainfall, as this area's 30-year average annual rainfall is 435 mm (U.S. Climate Data, 2022). Crop production in these arid conditions relies on supplemental irrigation to achieve optimal yield and value. In addition, these three areas have similar soil structures that are associated with arid climates. The northern High Plains of Texas is composed of soil with a clay, caliche, and sand mixture (Texas A&M Forrest Service, 2020). Soils in the south central and southwest regions of Kansas are predominately loamy sands (Kansas Food Connection, 2017), while in the Oklahoma Panhandle there is a mixture of sandy loams and clay loams, with some humus poor soils (Carter and Gregory, 2008). This region relies on the Ogallala Aquifer as the primary water source for both municipal and agricultural use. The Ogallala Aquifer, also known as the High Plains Aquifer, is one of the world's largest known aquifers at 450,000 km^2 and is a main supplier of water to Nebraska, western Kansas, the panhandle of Oklahoma, and west Texas (McGuire, 2017; Quinn, 2015). The Ogallala also provides a limited supply of water to some parts of South Dakota, Wyoming, Colorado, and New Mexico (Musick et al., 1990). This aquifer supports regional economies all over the High Plains region and has been supplying water for crop production as well as human and animal consumption since 1911 (Howell et al., 1997). Following the dust bowl and other severe drought cycles during the 1900's, water withdrawal from the Ogallala has increased dramatically (Quinn, 2015), and presently 94% of the water pumped from the Ogallala is utilized for irrigation in this region (Snowden et al. 2014). In the Oklahoma panhandle specifically, 86% of all agriculture irrigation is sourced from this aquifer (OWRB, 2012). Due to low seasonal precipitation, the Ogallala Aquifer cannot naturally replenish itself fast enough, resulting in the aquifer having a net depletion (Howell et al., 2004). The water table in the Ogallala has dropped more than 30 meters since the 1940s (McGuire, 2017). The thickness in the saturated layer, or the part of the aquifer that retains water, has decreased by up to sixty percent in some areas (Quinn, 2015). The arid conditions also result in increased salinity of the water contained within the aquifer which has become an additional concern for irrigated producers when considering sustainable irrigation practices (Scanlon et al., 2010). This scenario supports a shift to more efficient irrigation practices to conserve water in Great Plains cotton production. One solution to implementing higher water use efficiency irrigation systems is developing a more efficient cotton irrigation schedule. This improved efficiency will also help prolong the natural resources of this region (Musick et al., 1990).

Because of the arid climate patterns and depletion of water resources in the Ogallala Aquifer, cotton has become a popular alternative in the High Plains region due to its low water demands and potentially high return on investment. In the Oklahoma panhandle region, approximately 170,000 hectares were planted to either corn, sorghum, soybeans, or cotton in 2019 (USDA, NASS, 2019). More specifically, between 2006 and 2019 the number of hectares of cotton planted in the three counties in the Oklahoma panhandle increased by 13,800 hectares. These three counties account for forty-seven percent of Oklahoma's corn hectares, thirteen percent of Oklahoma's wheat hectares, and sixty-two percent of Oklahoma's sorghum hectares in 2019 (USDA, NASS, 2018-19). In 2017, the three Oklahoma panhandle counties accounted for only three percent of the total cotton grown in the state of Oklahoma. However, in 2019 that number doubled and now those three counties plant six percent of Oklahoma's cotton hectares (USDA, NASS, 2018-19).

Instead of using days to maturity or days after planting, cotton growth is often measured in heat unit accumulation also referred to as growing degree days (DD) and is based on a temperature threshold at which the plant can grow (Hunsaker 1999; Sammis et al., 1985; Slack et al., 1996). No progress in growth and development in cotton occurs in temperatures below 15.6 ^{o}C (60 ^{o}F) (Fry, 1983). Thus, this value is used as the threshold temperature for degree days known as $DD_{15.6}$ (Bradow, 2010). Producers in the Oklahoma panhandle typically plant in late April to mid-May with harvest operations occurring October through December. Temperatures during planting range from 12 ^{o}C to 17 ^{o}C, while the average first freeze date for this area is in early October, providing a five-month window to grow a crop that generally requires 160 - 180 days to reach full maturity (Oklahoma Mesonet). This presents a challenge when compared to the longer seasons in other regions of the U.S. Cotton Belt. For example, during the typical production season in Georgia, 1,400 growing degree days ($DD_{15.6s}$) are accumulated and crop maturity is rarely an issue (Howell et al., 2004). The northern High Plains region, by comparison, will typically accumulate around 1,150 ($DD_{15.6s}$) heat units during the season, and is thus a more limited environment for season length which often challenges the crop reaching full maturity (Howell et al., 2004). A study in Lubbock, Texas by Wanjura et al. (2002), found that maximum lint yields were linearly related to monthly and seasonal heat units (HU) and less impacted by excessive irrigation.

Because of this short season environment, producers must employ production practices that capitalize on a more compact window of heat unit accumulation, with variety selection being one of the primary methods (Boman, OSU). There are three general maturity groups for cotton cultivars, classified as short season, medium season, or long/full season cultivars (Silvertooth, 2001). The maturity category of cotton varieties can have a big impact on cotton management specifically for irrigation in a short season environment. For example, early maturity varieties, which are favored for irrigated production in short growing seasons, flower within a more compact portion of nodes, therefore the target window for optimal water application is much smaller than a longer season variety that typically fruits over a larger range of nodes and time (Loka et al., 2011). Some examples of maturity issues are reduced effective flowering period, low micronaire, fruit loss, disease, or insect pressure (Snipes, 1994; Williford, 1992). By choosing an early to mid-season variety, this allows producers to narrow the window for error and curb maturity issues (Boman, OSU).

Maturity in cotton can be quantified through different measurements taken in the field, thus helping decipher differences between varieties and how they respond to environmental conditions. The main framework of a cotton plant depends on main-stem height, number and length of vegetative branches, and number and length of reproductive branches (Wells et al., 2010). Plant height just prior to the initiation of reproductive growth has a positive association with plant population density (Buxton et al., 1977; Leffler, 1983). Buxton et al. (1977) reported that cotton plants grown in populations of 14 to 21 plants/m^2 were 15-30% taller than plants grown in a population of 7 plants/m^2, reported 49 days after planting. Later maturing cotton varieties often have an extended period of vegetative development and produce a greater number of main stem nodes (Buxton et al., 1977; Jones and Wells, 1977). Recording number and position of fruiting sites produced by the plant will help explain maturity and determine final fiber production (Wells et al., 2010). Once the plant begins reproductive development, the production of main stem nodes slows, as flowering approaches the top of the terminal. Main stem nodes stop developing once the number of main stem nodes above a first position white flower reaches five, or once it reaches physiological cutout (Oosterhuis et al., 1992; Bourland et al., 2001). Bolls developing after physiological cut out have very little effect on final yield (Oosterhuis et al., 1992). As the plant matures, more first position flowers bloom vertically towards the top. Measuring this developmental progress is accomplished by recording the nodes above white flower (NAWF). This measurement reveals the differences in accelerated maturity based on position of the upmost first position bloom (Pettigrew et al., 2004; Whitaker et al., 2008). Water stress can affect the distribution of bolls on nodes. There are several other plant mapping parameters that indicate maturity based on different growth and development parameters on the plant. Recording node at first fruiting branch (NFFB) is dependent on a combination of genetic and environmental influences, but the first fruiting branch is key contributor to yield because it will set the most mature bolls (Wang et al., 2011). A cotton plant will mainly produce fruiting branches once reproductive growth initiates, but low population density, over-fertilization, and insect or disease pressure can cause vegetative branches to form (Ritchie et al., 2007). Another measurement taken to determine maturity is recording node of uppermost first position cracked boll (NUCB), with a boll being defined as cracked when lint is visible through sutures in carpel wall. This helps determine harvest aid application timing and the progress of boll cracking or opening will often be accelerated when plants are grown under water deficit conditions (Gwathmey et al., 2011). This plays a key factor in fiber quality because micronaire is the most sensitive fiber parameter to defoliating plants prematurely (Kerby et. al., 2010). Similar to NUCB, recording nodes at uppermost first position harvestable boll (NUHB) can be recorded to help monitor maturity and defoliation decisions (Kerby et al., 2010). The uppermost harvestable boll can help determine seed and fiber maturity (Gwathmey et al., 2016). A study found that a plant with 30% open bolls, the uppermost harvestable boll had seeds not yet mature, but at 70% open bolls on the plant, the uppermost harvestable boll contained seeds nearing maturity (Speed et al., 2004). A harvestable boll is defined as a closed boll that is >2 cm in diameter and turgid (Gwathmey et al., 2011). All these measurements are taken on first position bolls, as the first position bolls on the plant contribute 66 to 75% of the total yield of the plant (Ritchie et al., 2007). Recording total nodes and final height of the plant at the end of the season can also give key insight to the plant's development through the height to node ratio (Kerby et al., 2010). The number of nodes is associated with physiological age and the height of the plant can be influenced by stress factors. Height to node ratio can changed based on water stress, use of mepiquat chloride, and use of different cultivars (Kerby et al., 1998). Percent of open bolls can further explain the total number of bolls expected to contribute to harvest (Gwathmey et al., 2016). This measurement is recorded because a threshold of 60 to 65% open bolls is recommended for harvest aid application in the U.S. Cotton Belt (Leon et al., 2020; Faircloth et al., 2009; Snipes and Baskin, 1994). The harvest of immature bolls due to prolonged maturity can significantly reduce micronaire (Faircloth et al., 2004).

There are three primary maturity classification used in commercially available cotton varieties, these being early, mid, or late maturity varieties. The difference between these maturity classes are the differences in fruiting habits (Husman et al., 1996). An early season variety develops bolls over a shorter period of time and a majority of the lint yield is located in the lower main stem nodes. On the contrary, late season varieties have a longer period to develop bolls and have more vertical distribution of bolls that contribute to yield (Husman et al., 1996; Bednarz and Nichols, 2005). Early season varieties often perform better under limited heat units with optimal water supply (Rosenow et al., 1983; Snowden et al., 2013).

1.5 IRRIGATION MANAGEMENT IN THE OKLAHOMA PANHANDLE

While the Oklahoma panhandle provides a significant contribution to the state's production of grain crops, there has been an increase in cotton production primarily due to the crop's fit in this environment. Since irrigation availability is the most important factor when it comes to corn production in this region, limited water has made sustaining corn production in this area a challenge (Howell, 1997; Marek, 2017). Cotton in comparison, has lower water requirements allowing for profitable production in areas of reduced water availability (Howell et al., 2004; Wen et al., 2013). Irrigation methods in the High Plains region have changed over the past decades due to new technology and irrigation water availability. The amount of furrow irrigated production has continuously decreased due to higher yield potential and water use efficiency of sprinkler methods (Henggler, 1995). There have long been efforts to increase irrigation efficiency in this arid region, beginning with the invention of low energy precision application (LEPA) in the 1980s. LEPA is an irrigation method that applies water to soil surface at lower pressures using a tower-truss system that moves continuously through the field (Bordovsky, 2019). A further advancement in increasing irrigation efficiency came with the development of subsurface drip irrigation (SDI) and was introduced to growers in 1984 (Lyle, 1983). This was an innovative irrigation method that transformed and expediently increased water use efficiency for producers (Colaizzi, 2008). A subsurface drip irrigation system not only increases crop yields and water use efficiency, but it can even increase the soil temperature due to reduced evaporative cooling in comparison to most center pivots. Subsurface drip irrigation has shown potential to combat increasing drought conditions, decreasing Ogallala aquifer resources, and increasing energy costs. (Colaizzi, 2008).

Yield is not the only production parameter that can be optimized through irrigation, as drought stress can cause a reduction in micronaire because of the reduction of photosynthetic capacity (Eaton and Ergle, 1952; Marani and Amirav, 1971). Authors like Snowden and Ritchie (2013) reported that different amounts of irrigation can increase or decrease fiber micronaire in shorter season varieties based on boll position. Heithold and Pettigrew found that there was a higher percentage of first position bolls on fruiting branches which increased fiber quality and micronaire in dryland production. First position bolls are less susceptible to low micronaire due to excessive irrigation compared to bolls located on higher nodes (Heithold, 1997; Pettigrew, 1995).

Optimizing supplemental irrigation in cotton has long been an objective of studies from across the Cotton Belt. A study in Georgia by Bednarz et al. (2003) found that supplemental irrigation during the first three weeks of flowering in cotton can increase lint yield by more than 392 kg ha^{-1}. Another study in west Texas by Snowden et al. (2014) evaluated drought periods compared to fully irrigated cotton by withholding water from squaring to flowering, 3 weeks beginning at early flowering, 3 weeks beginning at peak bloom, and from peak bloom to crop termination. Plant height and nodes were reduced, compared to all other treatments when water was withheld during squaring. Withholding water during squaring, peak bloom, or late bloom reduced yield by 25 – 35% compared to full irrigation, while withholding water at early bloom resulted in a 60% yield decline compared to full irrigation. It was also observed that withholding water during squaring and the full irrigation treatment had longer, thicker, and more mature fiber than the other treatments (Snowden et al., 2014). Another study conducted in west Tennessee by Gwathmey et al. (2011) examined lint yield and crop maturity responses to irrigation in a short-season environment. Four treatments of supplemental drip irrigation consisted of 3.81, 2.54, 1.27 cm/wk, adjusted for rainfall and applied between first square and first open boll, and a non-irrigated check. An irrigation rate of 2.54 cm/wk, increased yield by approximately 38% in 3 of the 4 years when compared to a non-irrigated check. The 3.81 cm/wk irrigation treatment caused an increase in the number of fruiting branches 6.6 to 8.5 sympodial branches, increasing first position boll retention but delaying crop maturity when compared to the non-irrigated treatment. When significant, the 2.54 cm/wk treatment had higher yields than the 3.81 cm/wk treatment. This study found that maturity, as measured by nodes above cracked boll (number of main stem nodes above the highest first-position cracked boll to the highest potentially harvestable boll), and normalized vegetation index, was delayed an average of 0.56 days for every additional cm of water supplied between first square and first open boll (Gwathmey et al., 2011). Another study from west Tennessee conducted by Grant et al. (2017) examined the response of cotton to irrigation initiation timing and amount across various soil types. The three soils were classified as either low, medium, or high water holding capacity (WHC). Low WHC can be classified as sandy-textured soils ranging to high WHC which can be classified as more deep silt loam soils. Irrigation was applied at square, bloom, or post bloom at rates of either 3.81, 2.54, or 1.27 cm per week. Yield was highest all three years, ranging 377 – 1,081 kg ha^{-1} increase above all other treatments, in low WHC soil when 3.81 cm/week irrigation treatment was applied at square. while the intermediate or high WHC soil did not see a positive impact beyond 2.54 cm/wk (Grant, 2017). A study in west Tennessee by Wiggins et al. (2013), evaluated cotton responses to environmental conditions thought main-stem node counts, lint yield, lint quality, and yield stability of varieties. Evaluation of growth response in cotton was conducted weekly for five weeks, beginning at bloom. There was a 0.5 node increase for plants that received 7.6 cm of precipitation during blooming compared to the other treatments. Plants receiving 7.6 cm or precipitation during bloom had the highest yields at 1280 kg ha^{-1}. But micronaire was decreased for all varieties when greater than 7.6 cm of precipitation was received during bloom. Overall, earlier maturing varieties were taller and had increased number of main stem nodes, and more nodes above white flower in the first two weeks of measurements and resulted in a positive response to yield across the study regardless of precipitation amounts when compared to the later maturing varieties (Wiggins et al., 2013).

This understanding of growth stage response to water supply has been used in the development of irrigation scheduling tools, which also commonly employ ET. A study conducted in west Texas by Snowden et al. 2013, utilized various ET replacement levels to evaluate the interaction between cultivar maturity category and irrigation for water use efficiency (WUE) and yield. The three cultivars consisted of early-mid, mid, and mid-late maturity. The crop was irrigated uniformly from emergence to first square at 5 mm a day, at which point irrigation treatments consisting of severe-deficit (48% ET replacement), mild-deficit (69% ET replacement), and fully irrigated (83% ET replacement) were initiated. This study reported that the mid-late cultivar yielded 238 – 1,436 kg ha^{-1} more than the early maturing variety over one year across all treatments under conditions described as water limited but with adequate heat unit accumulation (Snowden et al., 2013). A study in southwest Texas by Wen et al. (2013), evaluated irrigation rates and timings and the impact on cotton performance and economic return. Irrigation treatments were applied by center pivot using a (LEPA) system. Irrigation scheduling was based on daily crop evapotranspiration (ETc) and consisted of four deficit irrigation treatments 80%, 70%, 60%, and 50% ETc (80T, 70T, 60T, and 50T). Two regulated deficit irrigation treatments (50R and 70R) applied irrigation based on morphological stages (planting to first flower, first flower to 25% open boll, and 25% open boll to 75% open boll). Yields for the 80T and control treatment were higher ranging from 1,243 kg ha^{-1} to 1,312 kg ha^{-1}, then the 70T and 50T treatments. Financial return was optimized in the 80T treatment due to increases in fiber length, uniformity, and strength, and base to discount micronaire values. The highest micronaire value was the 50R treatment, while fiber length, uniformity, and strength were highest for the control treatment. The 80T treatment produced the highest profit at \$574.96 ha^{-1} (Wen et al., 2013). A study in Georgia by Whitaker et al. 2008, shows the comparison of soil water use, crop maturity, lint yield, and fiber quality grown with subsurface drip (SSD) irrigation and overhead irrigation. Treatments included overhead irrigation (Overhead), SSD matched to overhead irrigation rates (SSD match), SSD based on soil water (SSD fed), with the Overhead and SSD fed applications based on soil moisture, and a non-irrigated treatment was also included. The overhead and SSD treatments applied 2.5 cm of water at each irrigation event. Over the three years of the study, the SSD fed treatment received 3, 5, and 12 more irrigation applications than the overhead, but they were fed in much smaller increments, 0.8 to 1.5 cm per application. The SSD fed treatment enhanced maturity as measured by NAWF and NACB, while both SSD treatments increased water use efficiency (WUE) 15 – 23% compared to overhead. Overhead irrigation had similar to lower micronaire than all other treatments, with all irrigation treatments having premium micronaire values (Whitaker et al., 2008). While yield is the primary concern of producers when determining an irrigation strategy for cotton, previous research has also determined that fiber quality parameters will also be impacted. In a study in Lubbock, Texas by Baker et al. (2015), dryland and well-watered cotton was compared against two different methods of irrigation scheduling, the stress time (ST) and crop water stress index (CWSI) methods. Stress time method triggered an irrigation event when air temperature exceeded 28 ^{o}C for either 5.5 or 8.5 hours in a single day, starting over every day. The CWSI method triggered an irrigation event when calculated CWSI exceeded 0.3 or 0.6. Micronaire was significantly reduced with greater crop water use in the well-watered treatment, compared to all other treatments. However, fiber length and strength were reduced with decreasing crop water use (Baker et al., 2015). Many studies have been conducted on growth stage specific irrigation practices across the southeast and Great Plains regions. Little work has been conducted to address this problem in the unique, shorter season environment of the northern High Plains region. Therefore, additional information and guidance on irrigation management would be useful to producers.

CHAPTER II

COTTON GROWTH STAGE SPECIFIC IRRIGATION AND FIBER QUALITY RESPONSE IN THE GREAT PLAINS REGION

2.1 INTRODUCTION

The Great Plains region is defined as the combination of south central and southwest Kansas, the panhandle of Oklahoma, and the Texas High Plains according to USDA Agricultural Zones. Since 2017, this region has accounted for twelve percent of the total United States upland cotton acreage planted (*Gossypium hirsutum* L.) (USDA, NASS, 2017-21). While the Oklahoma panhandle accounts for only two percent of the total acres in the region (USDA NASS, 2021), this area lies in the geographic center of cotton expansion for the Great Plains region. Cotton production in the Oklahoma panhandle is subject to the dry climate and short season length that is typical of the southern Great Plains. The average annual rainfall over the last 30 years in the region is 435 mm (U.S. Climate Data, 2022), while this area also accumulating an average of 136 fewer seasonal heat units compared to the southeast and midsouth regions of the U.S. Cotton Belt (Howell et al., 2004), creating additional challenges for cotton production (Wanjura et al., 2002).

To combat the arid conditions, producers in this region rely on supplemental irrigation (Bordovsky, 2019). Most of this irrigation water is sourced from the Ogallala Aquifer which covers about 450,658 square kilometers, and supports approximately one-fifth of corn, wheat, cotton, and cattle production in the United States (Dostie, 2018). Due to decreasing aquifer levels, there is increased interest in subsurface drip to improve irrigation efficiency (Bordovsky and Porter, 2008). An irrigation study in Georgia by Whitaker et al. (2005) compared overhead irrigation to sub surface drip irrigation (SSD) in cotton production and reported that SSD had 15 – 23% higher water use efficiency and similar or increased yield compared to overhead irrigation. A study in the northern high plains of Texas by Colaizzi et al. (2010) compared mid (MESA) and low (LESA) elevation spray applicators, low energy precision applicator (LEPA), and SSD irrigation methods in cotton production. This study reported SSD resulted in higher lint yields by approximately 100 kg ha^{-1} or more, and higher water use efficiency without impacting fiber quality compared to other treatments. Improving water use efficiency without negatively effecting yield or fiber quality is key for sustaining cotton production in an arid short season environment where a short fruiting window emphasizes the needed for timely delivery of adequate irrigation.

It is critical for crop water demands to be met in a timely fashion for successful cotton production in short season environments, as there is not enough season to make up for delays in growth or reproductive development. It is important to measure maturity in cotton growth via node above white flower (NAWF) as the development of nodes and potential fruiting sites slows and eventually stops when the number of main stem nodes above the first position white flower reaches five (Oosterhuis et al., 1992; Bourland et al., 2001). A study conducted in Mississippi by Pettigrew et al. (2004) found that constantly applied furrow irrigation (>80 cm total water received) delayed crop maturity by increasing the NAWF count in the irrigated treatments in comparison to the non-irrigated treatments. This caused the irrigated plants to sustain flowering later into the growing season and produced more main stem nodes. Studies in Tennessee report that for every additional cm of water supplied beyond the optimal amount, maturity was delayed as reflected by NAWF during the flowering period and nodes above cracked boll, when the crop neared maturity at the end of the season (Gwathmey et al., 2011; Wiggins et al., 2013).

It is well documented that water deficiency during different specific cotton growth stages can result in reductions in yield and fiber quality (Brouwer, 1986; Chastian et al., 2016; Wen et al., 2013). Water sensitivity in correlation to lint yield per acre, is at its highest from initiation of squaring to first flower (Wrona, 1990). Studies conducted in west Texas, reported that drought during the squaring stage resulted in a yield reduction of 25 – 35% when compared to cotton not exposed to water stress (Snowden et al., 2014). This holds true in longer season environments, as a study in Georgia reported that withholding water during the first three weeks of flowering reduced seedcotton yield 392 kg ha^{-1} compared to withholding water during the last six weeks of flowering to first open boll. In addition, withholding water from first square to first flower resulted in seedcotton yields 493 kg ha^{-1} less than treatments receiving irrigation during the flowering stage and the full irrigation treatment (Bednarz et al., 2003).

The quality of fiber produced by the crop is also highly responsive to water supply patterns and irrigation (Bradow and Davidonis, 2000; Snowden et al., 2013). There are four steps of fiber development: fiber initiation at 0-3 days post-anthesis (DPA), elongation at 0-20 DPA, thickening at 16-40 DPA, and maturation >40 DPA (Haigler et al., 2012). Any deviations from optimal weather and/or cultural practices during fiber development can alter fiber quality characteristics (Hake, 1990). In a study from the high plains Texas, Attia et al. (2015) reported increasing irrigation levels above the optimal amount resulted in an increase in fiber length and strength compared to dryland cotton. Studies such as Grimes et al. (1969), and Spooner et al. (1958) report similar findings, with increasing irrigation rates resulting in increases of mean fiber length and upper-half mean length. Water deficiencies during later flowering period and into fiber elongation stage can reduce fiber length (Marani and Amirav, 1971; Shimishi and Marani, 1971;

Hearn, 1994 and 1976). While there is not as much evidence of fiber strength effects, Hanson et al. (1956) found that increased fiber strength was correlated with a decrease in precipitation. Other studies including MacKenzie and VanSchaik (1963); Green and Culp (1990); Smith and Coyle (1997); report that fiber strength is correlated with genotype only. A genetic study conducted in central Texas found that fiber strength and length were negatively associated with yield components (Smith and Coyle, 1997). Micronaire is a measure of the cotton fiber's fineness and maturity; and it refers to the amount of secondary wall development in the fibers (Meredith, 1984). Micronaire values either too low or too high, can result in discounts (Bange et al., 2021). The most valuable micronaire values range between 3.7 – 4.2, also referred to as premium values (USDA Commodity Credit Corporation, 2022). A study in Georgia found premium micronaire has been established through adequate irrigation (Whitaker et al., 2008). Water stress causes an increase in micronaire because the carbohydrate supply is limited to a smaller number of bolls (Attia et al., 2015). Studies in Turkey, like Basal et al. (2009) and Dagdelen et al. (2009) compared non-irrigated, 25%, 50%, 75%, and 100% ET replacement irrigation treatments and found that the highest micronaire values were in the dryland or 25% ET irrigation treatments. A study by Feng et al. (2014) in Texas compared three irrigation treatments in daily amounts (0, 2.54 and 5.08 mm d^{-1}), while in Mississippi Pettigrew et al. (2004) compared a dryland treatment to a consistently irrigated treatment, both observed higher micronaire values in the dryland treatments compared to any treatment that received irrigation. These studies reported that with increasing water application, micronaire values decreased. In a short season environment, there is a lack of time and heat units to fully mature fiber, therefore, water application becomes critical for fiber maturity and micronaire values. Harvest of immature bolls due to prolonged maturity can significantly reduce micronaire (Faircloth et al., 2004). To mitigate the challenges of a short season, it becomes crucial to have the correct cotton variety selection and proper irrigation scheduling to overcome maturity and fiber quality issues.

Due to the Oklahoma panhandle's short growing season, proper variety selection is essential, as an early maturating variety can mitigate some of these challenges. However, there is often variation in the growth habit and performance when comparing varieties from different seed providers within the same maturity class. Oklahoma State University's Replicated Agronomic Cotton Evaluation (RACE) trials consistently report significant differences in yield and fiber quality between varieties within similar maturity categories that are considered a best fit for different locations and conditions (irrigated and dryland). The evidence from theses RACE trials proves that maturity classification alone can be too broad of a category and that other variety characteristics play a role in performance. For example, within the 2020 Texas County Irrigated RACE trial, all varieties were categorized as early or early-mid maturing and suitable for the short season environment, although lint yields ranged from 831 to 1,621 kg per ha^{-1} and loan values ranged from 16.19 to 20.67 cents per kg^{-1} (Byrd et al., 2020). Different seed providers contribute to the variability within maturity categories, as criteria and scope of maturity differences are not similar across all seed providers. A study in west Texas by Snowden et al. (2013), found that regardless of maturity classification, in a cooler, wetter year, all cultivars produced more fruit on higher sympodial branches prolonging maturity. Thus, suggesting that cultivar selection should be taken into consideration due to fruiting habits and environmental factors (Snowden et al., 2013). Another study in central Texas compared different irrigation regimens based on ET replacement, different maturity classes of cultivars, and tillage. This study found that under the 90% ET replacement treatment alone, cultivars classed in the same maturity rating had lint yields differences of 69-213 kg ha^{-1} (Attia et al., 2015).

Water continues to be the biggest limitation to agricultural production (Scanlon, 2010), and in a short season environment proper irrigation scheduling in cotton is critical to ensure both optimal yield and fiber quality. Cotton producers in the southern Great Plains, and the Oklahoma panhandle specifically, face decreasing water supplies, an abbreviated growing season, and are still adapting to the integration of cotton into their farming systems. To address these concerns and to provide decision making tools for producers in this region, a study was initiated to evaluate subsurface drip irrigation strategies for early maturating cotton varieties in a short season environment to optimize yield and fiber quality.

2.2 OBJECTIVES

This study had two primary objectives. The first objective was to quantify the plant growth, yield, and fiber quality resulting from SSD irrigated cotton across growth stage specific irrigation schedules based on ET. The second objective was to determine the impact of variety on irrigation response, specifically across four varieties from four different seed providers that are marketed as early maturating varieties to fit in this short season irrigated system. Information gained from this research will be utilized to develop irrigation recommendations for cotton grown under SSD irrigation, while also comparing the stability of these recommendations across varieties from various seed sources. The results of this study will provide early guidance for developing an irrigation management tool for cotton producers in this region and illustrate how growth stage specific irrigation scheduling and variety selection can be used to optimize water use efficiency.

2.3 MATERIALS AND METHODS

The experiment was conducted at Oklahoma Panhandle Research and Extension Center (OPREC) (36°35'22.62"N, 101°36'39.46"W; 1,007 m elevation) in Goodwell, Oklahoma during the 2020 and 2021 growing seasons. The 10-year average degree-day heat units for cotton in Goodwell is 1,240 ($GDD_{15.6}$) from 12 May to 15 November (Oklahoma Mesonet, 2022). The soil type at this research location is a Gruver clay loam classified as fine, mixed, superactive, mesic, aridic paleustoll (Soil Survey Staff NCRS, 2022). In 2020, granular MESZ (12-40-0-10S-1Zn) was applied at a rate of 14 kg ha $^{-1}$ and in 2021 no fertilizer was applied due to the residual nitrogen left from the previous year's soybean crop. All other inputs besides irrigation followed extension recommendations for irrigated cotton in this location.

Irrigation at the experiment site was delivered through SDI tape 30 cm below the surface spaced 152 cm apart. Cotton was planted in rows spaced 76 cm apart, as is common for the area, with an SDI tape located every other row middle. Each irrigation zone is 192 m long by 18 m wide, which encompasses 24 crop rows. The emitters on the tape are 60 cm apart pressurized at 89.6 kPa, which allows for flow rates of 53 liters per minute (LPM) per zone. Water flow was evaluated by MPT water meters (NetifimUSA, Fresno, CA) at the inlet of each zone and included totalizers that determined the total water applied during the season per zone. Real time kinematic global positioning (RTK GPS) was used to install the drip tape and for planting to ensure accurate placement of seed relative to the drip tape.

A split plot design was used to evaluate irrigation scheduling and cotton variety, with irrigation treatment serving as the whole plot factor and variety as the subplot factor. There were four irrigation schedules based on ET evaluated in this study, which were initiated at the beginning of the squaring period. Treatments included 90% ET replacement (90% ET), 63% ET replacement (63% ET), 36% of ET replacement (36% ET), and a treatment that replaced 90% ET during squaring, then 63% ET replacement once the flowering period began (90/63% ET). Four cotton varieties characterized as early-mid season maturity classes and marketed in the area by their respective companies were evaluated in the trial. This included NexGen® 3930 B3XF (NG 3930) classified as an early-medium maturity variety (Americot, Lubbock, TX), Stoneville® 4480 B3XF (ST 4480) an early-medium maturity variety (BASF, Research Triangle Park, NC), Dyna-Gro® 3385 (DG 3385) an early maturity variety (Loveland Products Inc., Loveland, CO), and Deltapine® 2012 B3XF (DP 2012) an early maturity variety (Bayer Crop Science, St. Louis, MO). Each irrigation zone consisted of a four row border on the edges of each zone and four row plots of the four cotton varieties randomized within the center 16 rows. Three replicates of each irrigation by variety combination were included in both years of the study. To determine irrigation amounts, the Mesonet (Oklahoma Mesonet, OK) irrigation scheduling tool was used which calculates ETo by the ASCE Penman Montieth Equation (ASCE, 2005). The details of the Mesonet irrigation scheduling tool are outlined in Sutherland et al. (2005). The minimum crop coefficient used by the Mesonet during the growing season for cotton is 0.30. All irrigation treatments in 2020 received 107 mm of pre-emergence irrigation applied through the drip system, followed by irrigation treatments initiated on 1 July, 2020 and ended 2 September, 2020. All irrigation treatments in 2021 received 34 mm of pre-emergence irrigation applied through the drip system, followed by irrigation treatments starting 29 June, 2021 through 30 August, 2021. Irrigation treatments were applied based on a new targeted amount each week based on rainfall occurrence Monday – Sunday. Irrigation treatments in 2020 were applied in alternating sets of two treatments at a time. In 2021 all four treatments were applied at the same time, twice per week and adjusted for rainfall. Cotton was planted on 16 May, 2020 and 12 May, 2021 at a seeding rate of 111,195 seeds ha^{-1} at a depth of 5 cm and a soil temperature of 25.28 ^{o}C (2020) and 15.94 ^{o}C (2021) with a four row John Deere MaxEmerge (Deere & Company, Moline, IL). The 2020 cotton crop was planted following cotton and the 2021 crop followed soybeans.

To quantify the impact of irrigation schedule and variety on crop performance, early season establishment, plant growth, reproductive development, yield, and fiber quality were examined. All in-season plant measurements were conducted on the center two rows of each plot. Stand counts were taken 10-14 days after emergence on 15 June, 2020 and 8 June, 2021 by quantifying all emerged plants in three meters of two rows. Plant growth measurements were collected on seven random and representative plants in each plot. Plant height was measured at eight leaf (8 lf) growth stage, first bloom (FB), two weeks (FB+2), four weeks after first bloom (FB+4), and six weeks after first bloom (FB+6) growth stages, while NAWF was quantified FB, FB+2, and FB+ 4. End of season maturity measurements were taken at 140 (2020) to 141 (2021) days after planting, prior to harvest aid application and targeting the point at which the crop reached approximately 60% open boll. Measurements at this stage included, final plant height, total nodes, node of first fruiting branch (NFFB), node of uppermost cracked boll (NUCB), and node of uppermost harvestable boll (NUHB). Percentage of open bolls was determined by counting all open and all closed harvestable bolls, in a three-meter length of one row. In an attempt to compare what was predicted to be the varieties with the biggest difference in maturity, the end of season measurements were only taken on DP 2012 and ST 4480 varieties in 2020. After reviewing the 2020 results, the measurements were taken on all varieties in 2021. Due to the excessive rainfall and lower seasonal heat unit accumulation, these were conducted prior to reaching 50% open boll in 2020.

All 101 m of all four rows of each plot was harvested on 6 November, 2020 and 15 November, 2021 with a John Deere 7460 (Deere & Company, Moline, IL) cotton stripper. Whole plot weights were collected using a LeeAgra weigh wagon equipped with load cells (LeeAgra, Inc., Lubbock, TX). After the plots were weighed, a four to five kg seed cotton sample was taken for ginning. These samples were weighed and subsampled to 600-700 g prior to ginning on a 20 saw Eagle Gin (Continental Gin Company, Birmingham, Alabama) located at the Oklahoma State University Agronomy Farm in Stillwater, OK. After ginning, 120 g lint sample was sent to Texas Tech University Fiber and Biopolymer Research Institute in Lubbock, Texas for classing and grading. Because the gin lacked a lint cleaner, leaf and color grade data was omitted from analysis and only the physical properties of micronaire, fiber length, fiber strength, and length uniformity were analyzed. Loan values were determined through the Cotton Incorporated Upland Cotton Loan Value Calculator (Cotton Inc., Cary, NC) with the leaf and color grades set to the base levels of 4 and 41, respectively, and using the value of $1.15 per kilogram for base quality fiber (USDA Commodity Credit Corporation, 2022). All data was subjected to analysis of variance (ANOVA) using a Proc Mixed Model in SAS version 9.4. The main effects and two-way interaction for the fixed effects of variety and irrigation were analyzed, and means were separated using Fisher's Protected LSD at an alpha level of 0.05. Due to differences in environmental conditions and crop performance, years were analyzed separately.

2.4 RESULTS

Climate and Irrigation. Seasonal precipitation, heat unit accumulation, and other experimental site information is included in Table 1. In 2020, 269 mm of the 344 mm of seasonal precipitation was received after the initiation of the irrigation treatments (Fig. 2A). Including precipitation and all irrigation during the reproductive period (48 to 140 DAP), the 90% ET treatment received a total of 490 mm of water through rainfall and irrigation, the 90/63% ET treatment received 430 mm, the 63% ET treatment received 420 mm, and the 36% ET treatment received 350mm of total water. The rainfall amount and patterns resulted in the targets for total water received (irrigation + rainfall) being exceeded in 2 out of the 10 weeks of irrigation in the 90% ET treatment, in 5 out of 10 weeks in the 90/63% ET treatment, 6 out of 10 weeks in the 63% ET treatment, and 8 out of 10 weeks in the 36% ET treatment. During the three-week squaring period alone, weekly targets were exceeded by 7 – 46 mm. These numerous significant rainfall events also contributed to the reduction in heat unit accumulation during the months of July, August, and October, which was 109 heat units lower than 2022 and 74 heat units lower than the 10-year average ($GDD_{15.6}$) (Figure 1). In 2021, 111 mm of the seasonal total of 260 mm of rainfall was received prior to the initiation of squaring and the irrigation treatments (Fig. 2B). The total water received in 2021, precipitation and all irrigation during the reproductive period (48 to 141 DAP), across all treatments was reduced, with the 90% ET treatment receiving a total of 320 mm, the 90%/63% ET treatment receiving 250 mm, the 63% ET treatment receiving 240 mm, and the 36% ET treatment receiving 150 mm (Figure 3B).The rainfall amount and patterns resulted in the targets for total water received (irrigation + rainfall) being exceeded in 3 out of the 9 weeks of irrigation in the 90% ET treatment, in 5 out of 9 weeks in the 90/63% ET treatment, 5 out of 9 weeks in the 63% ET treatment, and 7 out of 9 weeks in the 36% ET treatment. The rainfall received in 2020 exceeded the 2021 total by 54%, which led to the 90% ET replacement treatment in 2021 receiving less total water (320 mm) than the 36% ET treatment in 2020 (350 mm).

Plant Growth and Development. There was no irrigation by variety interaction or irrigation effect on plant population, height, or NAWF, although variety influenced these parameters in both years. In 2020, ST 4480 resulted in the lowest plant population and shorter plants at FB and FB+2 wk (Table 2), while DP 2012 and NG 3930 had the tallest plants at these dates, although there was no difference between NG 3930 and DG 3385 at FB+2 wk. The differences present in plant height were likely not biologically significant, as across all varieties plant heights differed by no more than 7 cm across both measurement dates. The varieties DG 3385 and NG 3930 had the lowest NAWF values at FB+2 wk and FB+4 wk, although the range of values across all four varieties never exceeded 0.6 nodes (Table 3). Variety had an effect on population again in 2021, with DP 2012 resulting in the greatest number of plants ha^{-1} (Table 2). Across all varieties there was an increase in establishment success in 2021 compared to 2020 as illustrated by an average increase of 30,000 plants ha^{-1}, likely due to better moisture conditions and more accurate planting depth. At all measurements of plant height during the flowering period, DG 3385 and NG 3930 produced the shortest plants, while DP 2012 was consistently taller than those two varieties, although there was no height difference between DP 2012 and ST 4480 at FB, FB+2 wk, and FB+6 wk. The differences between varieties in NAWF at FB and FB+2 wk followed a similar pattern to plant height, with the lowest values present in DG 3385 and NG 3930, although there was no difference between DP 2012 and NG 3930 at FB (Table 3). Similar to 2020, the actual differences in both plant height and NAWF between varieties were minimal, with the range in height values never exceeding 7 cm and NAWF differences again being less than one node.

End of Season Maturity. An interaction between variety and irrigation was present for NUCB in 2020 (Figure 4). There were no differences within ST 4480 between the irrigation treatments, however the biggest variation in NUCB values was present in DP 2012, with the 36% ET treatment being 1 – 3 nodes lower than all other treatments except the 90/63% ET and 63% ET schedule in DP 2021, and 90% ET schedule for ST 4480. Measurements of plant maturity parameters were initially planned to be recorded when plants had reached approximately 60% open bolls, prior to a harvest aid application. In 2020 the data was recorded 140 days after planting (DAP) though due to rainfall events and cool conditions open boll percentages were no higher than 10%. Harvest aids were successful in achieving adequate boll opening, but there was an obvious impact of this maturity delay on fiber quality which will be discussed in a later section. The two varieties that were subject to these end of season measurements in 2020 exhibited slight differences in plant height and node of first fruiting branch, with DP 2012 being 3.9 cm taller and producing a fruiting branch 0.7 nodes lower than ST 4480. DP 2012 had one node lower NUCB value than NFFB, due to the delayed maturity and lack of open bolls on plants. An interaction between irrigation and variety was present for total nodes in 2021. The pattern of this interaction reflected the in-season maturity comparisons collected in both years, with six of the seven treatments in the highest statistical group including either DP 2012 or ST 4480, and seven of the nine treatments outside of the highest group containing either DG 3385 or NG 3930 (Figure 5). Similar to other measurements of crop growth, the actual range in values was narrow, with only a two node difference across all irrigation and variety combinations. Measurements of crop maturity were taken at 141 DAP in 2021 at which point all treatments had reached at least 50% open. Like measurements taken earlier in the season, DG 3385 and NG 3930 produced plants approximately 5 – 6 cm shorter than DP 2012 and ST 4480 at the end of the season (Table 2). Unlike 2020, in 2021 there was an impact of irrigation on maturity characteristics, with the 36% ET treatment resulting in 1.1 – 1.4 higher NUCB and 13 – 27%

higher percentage of open bolls than either the 90% ET or 90/63% ET treatments, although there was no difference between the two treatments supplying the lowest amounts of ET replacement.

Yield. Yield parameters were not impacted by irrigation in 2020 while variety resulted in a seedcotton, turnout, and lint yield effect (Table 5). The varieties DG 3385 and NG 3930 resulted in approximate increases in seedcotton yield by 400 – 500 kg ha^{-1}, in turnout by 2.5 – 3%, and in lint yield by 200 – 290 kg ha^{-1} compared to DP 2012 and ST 4480. Although end of season maturity measurements were not collected on these varieties in 2020, this separation in variety performance follows trends observed in the in-season measurements in 2020 and 2021, and end of season measurements in 2021 that indicate DG 3385 and NG 3930 are earlier maturing varieties than DP 2012 and ST 4480. Similar to 2020, the main effect of variety impacted all yield components again in 2021. The variety DP 2012 produced less seedcotton than all other varieties by 204 – 278 kg ha^{-1}, while DG 3385 resulted in 2.2 and 3.8% higher turnout than DP 2012 and ST 4480, respectively (Table 5). The variety effect on lint yield in 2021 was the same as the previous year, although the differences were smaller, with DG 3385 and NG 3930 producing 81 – 174 kg ha^{-1} more lint than DP 2012 and ST 4480. Irrigation also had an impact on seedcotton and lint yield in 2021, likely due to the reduction in rainfall during reproductive growth compared to 2020. The 90% ET treatment resulted in 497 and 898 kg ha^{-1} more seedcotton compared to the 90/63% ET and 36% ET treatments, while the 63% ET treatment produced 583 kg ha^{-1} more seedcotton than the 36% ET treatment (Table 5). Lint yield followed a similar pattern, with yields increased by 210 and 398 kg ha^{-1} in the 90% ET treatment compared to the 90/63% treatment and the 36% ET treatment, respectively, and a 246 kg ha^{-1} increase in lint yield resulted from the 63% ET treatment compared to 36% ET.

Fiber Quality. The general trend across all fiber quality parameters in 2020 was low values indicative or poor quality fiber, specifically for micronaire (Table 6). This is a result of excessive rainfall and poor conditions that persisted during the majority of the 2020 season.

which is further illustrated by similar fiber quality values reported in a large plot non-irrigated variety trial located at this same location that also included DG 3385, DP 2012, and NG 3930 (Byrd et al., 2020). The lowest micronaire values resulted from DP 2012 and ST 4480, although the highest value recorded was only 2.7, well below the low end of the base range of 3.5 – 3.6 (USDA Commodity Credit Corporation, 2022), The variety DP 2012 also resulted in the lowest fiber length and length uniformity. ST 4480 resulted in the highest fiber strength which was 1.66 and 4 g tex^{-1} greater than NG 3930 and DP 2012, respectively. Similar to the yield results, DG 3385 and NG 3930 resulted in increases of gross value ha of \$243 - \$360 ha^{-1} over DP 2012 and ST 4480. The 36%ET treatment produced the highest micronaire value by 0.44 – 0.51, compared to the other treatments, although at 2.91 it still resulted in a value well below the low range of base values. In 2021 there was an interaction between variety and irrigation for fiber strength, with the greatest values achieved by DG 3385 under the 63% ET and 36% ET treatments, and ST 4480 under the 90% ET, 90/63% ET, and 36% ET treatments (Fig. 6). The more favorable environmental conditions in 2021 were also reflected in micronaire values, although like 2020, there was still an impact of variety as with the other fiber quality parameters. The variety DG 3385 resulted in the highest micronaire value although it was no different than NG 3930 (Table 6). However, although ST 4480 produced the lowest numerical micronaire value, it was the only value in the premium range of 3.7 – 4.2 (USDA Commodity Credit Corporation, 2022), thus within this year, represented a higher value of this parameter. Both NG 3930 and ST 4480 produced greater fiber length than DG 3385 and DP 2012, while NG 3930 had higher fiber length uniformity than both DP 2012 and ST 4480, and ST 4480 produced the highest fiber strength. As in 2020 gross value followed the same trend as lint yield, with DG 3385 and NG 3930 resulting in the highest value by \$100 - \$218 ha^{-1}, with ST 4480 also \$92 ha^{-1} greater than DP 2012. While no fiber quality parameters were affected by the irrigation treatments, not surprisingly, differences in gross values mirrored the lint yield results, with the 90% ET and 63% ET treatments resulting in

$96 ha^{-1} and $62 ha^{-1} over 36%ET, with the 90/63% schedule not different than any other irrigation treatment.

2.5 DISCUSSION

The difference in the growing conditions between the two years created stark differences in crop performance and quality, with the study location falling 74 heat units ($GGD_{15.6}$) below the 10-year average in 2020 (Oklahoma Mesonet, 2021). However, the trends observed within each year were generally stable, specifically regarding the impact of variety on growth, development, and yield. It is likely the short season in combination with excess rainfall received during the reproductive stages prolonged maturity, due to higher NAWF values and the low percentage (2 – 10%) of open bolls at 140 DAP in 2020. Gwathmey et al. (2011) reported that for every additional cm of water applied, crop maturity was delayed by an average of 0.56 days. This study was conducted in a relatively high precipitation and short season environment in west Tennessee, similar conditions to those present in the current study during 2020. In areas where the growing season is longer, Pettigrew et al. (2004) still found that flowering continued longer and cut out was reached six days later in the furrow irrigated treatments compared to the non-irrigated treatments in Mississippi. There was a consistent pattern both years for in-season maturity measurements, as a separation between varieties classified in the same maturity group, although the actual differences in these values was minimal. Similar minute differences are shown in studies between varieties in the midsouth reporting a 14 cm range in heights and 1 – 2 node difference between NAWF among four early and four late maturing varieties (Johnson and Pettigrew, 2006), southeast reporting a 15 cm range in heights and a < 1 node difference between NAWF among an early and late maturing variety (Byrd et al., 2019), and the high plains of Texas reporting no more than a 12 cm range in heights among one early, two mid-, and one mid- to late maturating variety (Snowden et al., 2014).

Similar to growth parameters, differences in yield and fiber quality within a group of varieties in a related maturity category are fairly common. The highest difference in lint yield between varieties was in 2020, with a 288 kg ha^{-1} difference, though the range reported in previous studies illustrates this difference can be much greater. Johnson and Pettigrew (2006) report up to a 522 kg ha^{-1} difference between four early and four late maturing varieties in Mississippi. An Official Variety Trial (OVT) by Pieralisi et al. (2021) reports a 383 kg ha^{-1} difference between three mid- and two early maturing varieties, grown in the northern half of Mississippi with various irrigation methods. Stancil and Jones (2020) report a 510 kg ha^{-1} difference between three early, one early to mid-, and one mid-maturing variety in Florence, South Carolina with various irrigation methods. A variety assessment conducted in Goodwell, Oklahoma by Byrd et al., (2020) reported up to a 789 kg ha $^{-1}$ difference between ten varieties all marked within the earlier maturating category and supplied with overhead irrigation. However, there are studies from the southern Great Plains that report a smaller difference in lint yield between similar maturing varieties. Snowden et al. (2013) reported a 106 kg ha^{-1} difference between three early, two mid-, and one mid- to late maturing variety, Attia et al., (2015) reported a 54 kg ha^{-1} between one early, two mid-, and one mid- to late maturing variety, while another study in the same area reports no variety effect on lint yield among two early and two late maturing varieties (Snowden et al., 2014). Variety effect on fiber quality parameters is common across the U. S. Cotton Belt. In the first year of the study, when more rainfall was received, micronaire values between varieties ranged similar to those recorded in both irrigated (2.37 – 3.12) and dryland (2.25 – 3.16) variety trials conducted at the same location that year (Byrd et al. 2020). Micronaire values falling into the discount range in 2020 can also attribute to the low turnout values (27 – 30%). Similar relationships have been reported by Byrd et al. (2020) in Oklahoma and Balkcom et al. (2010) in Alabama where cotton harvested with low turnout values (24 – 34%) also contained micronaire values within the low end of the discount range. However, in 2021 micronaire values between varieties ranged more closely to other studies in the region, such as 4.26 – 4.87 reported by Snowden et al. (2013) and 4.0 – 4.8 reported by Attia et al. (2015). Similar differences in micronaire values among varieties belonging to similar maturity classes have also been reported in the midsouth (Johnson and Pettigrew, 2006) and southeast (Stancil and Jones, 2020).

While there was little effect of irrigation on in-season growth and development in the current study, there are mixed results from previous studies that evaluate irrigation impact on cotton growth in similar environments. Attia et al. (2015) evaluated constant irrigation in different amounts throughout the season and reported no effect on early growth and development from cotton grown under rainfed, 45% ET replacement, 90% ET replacement, and full ET replacement, while Snowden et al. (2014) who reported 27 – 40% reduction in height and 7 – 13% reduction in total nodes when water was withheld during the squaring period. A drip irrigation study in Turkey by Basal et al. (2009) reported that 100% replacement of soil water depletion supported additional vegetative growth that resulted in additional monopodial branches and increased bolls on upper mainstem nodes compared to the non-irrigated treatments. Basal et al. (2009) also concluded that additional vegetative growth had a positive relationship with lint yield although in the current study irrigation had no impact on early growth and development but did influence lint yield, which is likely due to a combination of variety characteristics and the abbreviated season length typical of the Oklahoma panhandle. In Australia, Ballester et al. (2021) reported that irrigating to maintain soil matric potential between –100 and –120 kPa (low frequency) resulted in 60% open bolls being reached 10 days earlier compared to irrigating to maintain >–60 kPa soil matric potential (high frequency). Additional vegetative growth can delay maturity in cotton growth and can become a risk factor for lint yields in a short season environment like the Oklahoma panhandle. In the current study, the lowest ET replacement treatment resulted in 27% higher open boll percentage compared to the highest ET replacement treatment in 2021. This maturity delay due to increased or excessive irrigation agrees with the findings of previous studies, although finding a balance between maturity enhancement and optimizing yield is the primary challenge for irrigated cotton in a short season environment.

Yield increases in response to supplemental irrigation are not surprising in this region given the arid conditions that are typical, and the range of yield increases in the current study fall within those reported by previous studies from the southern Great Plains. A 63% yield increase resulting from full irrigation compared to moderate deficit was observed by Snowden et al., 2013), while Attia et al. (2015) reported a 53% yield increase from 90% ET replacement compared to 45% ET replacement. In the current study 21 – 34% higher lint yields were reported in the 90% ET and 63% ET compared to 90/63% ET and 36% ET irrigation treatments in 2021. In areas that experience a longer growing season when compared to the southern Great Plains, increasing irrigation does not always increase yields. An overhead, growth stage specific irrigation study in Georgia by Bednarz et al. (2003) found that in the first year of the study increasing irrigation increased lint yield, thus the 100% ET treatment had a 41% increase in lint yield compared to the dryland treatment. However, the second year of the study found that growth stage specific irrigation had a much larger impact, as cotton that received water from first flower plus three weeks to first flower plus six weeks had a 4% lint yield increase compared to the full irrigation treatment. In the third year of the study, 635 mm – 762 mm of rainfall was received during the growing season, and irrigation had no significant impact on lint yields. There are many studies in arid to semi-arid climates that have found micronaire to be impacted by irrigation amounts. In the southern Great Plains, studies have reported differences in micronaire ranging from 27 – 61% due to irrigation treatments (Attia et al., 2015; Feng et al., 2014), with increases in water supply resulting in a decrease of micronaire values, irrigation strategies are a critical consideration in this environment. Snowden et al. (2013) reported that micronaire increased by 10% when comparing severe deficit irrigation to full irrigation in one year of an SSD irrigation study. While this was conducted in the high plains of Texas, the increase in micronaire by increasing irrigation is a unique result and occurred because of an unusual increase in heat units (211 GGD $_{15.6}$ more than the 30-year average) and decrease in rainfall (299 mm less than the 30-year average). All micronaire values for the first year of the Snowden et al. (2013) study exceeded values over the premium micronaire range. The low loan value in 2020 of the current study was indicative of the fiber quality parameters observed that year and can at least in part be a result of delayed maturity from reduced heat units in combination with the irrigation treatments and rainfall supplying excessive water to the crop. While there was a 23% increase in loan value in one year of the current study, Feng et al. (2014) and Bordovsky et al. (2008) found no significant correlation between irrigation treatments and loan values both years of two scheduled SSD irrigation studies in west Texas. This would be similar to the results recorded in 2021 when the conditions of the study location were more typical of the average seasonal environment.

This study represents two distinct production years in Goodwell, Oklahoma, a location with a 30-year average of 435 mm (U.S. Climate Data, 2022). During the two years of the study, 344 mm of seasonal precipitation was received in 2020 compared to 260 mm received in 2021. While it may be difficult to implement findings from 2020 due to the relatively unusual rainfall pattern, yield differences due to irrigation in 2021 ranged from 21 – 34%. These values fall in line with previous studies from this region, along with impact of fiber quality and value. This emphasizes the support needed for a more dynamic and proactive irrigation scheduling tool for producers in this region.

2.6 CONCLUSION

Water application and variety selection influence cotton performance in ways that can help mitigate risk that a short season environment presents, as these environments increase the risk for reduced yield potential and poor fiber quality. Variety selection had the biggest impact on yield differences over both years of the current study. With lack of tools and resources for the producer, due to a short history of production, irrigation studies for the short season environment of the Oklahoma panhandle have yet to be thoroughly conducted. The results of this study can be utilized to identify inputs to aid the development of irrigation scheduling, including variety characteristics and irrigation method. In the future, investigating a more popular irrigation method such as overhead irrigation, as well as utilizing real-time weather information and forecasting, could have a tremendous impact on optimizing agricultural water use and cotton production. This study illustrates how critical variety selection is for cotton produced in this environment, and producers should be mindful of matching maturity characteristics to both geographic location as well as management style. By using the combination of variety selection and evaluation, with deficit irrigation scheduling, we can begin to evaluate irrigation specifically, as well as general production recommendations for shorter season environments. This can help achieve water use efficiency and production sustainability in this under-served but highly productive region.

Table 1. Experimental site details for Goodwell, Oklahoma 2020-2021.

Year	Pre-Emergence Irrigation[z] (mm)	Planting Date	Soil Temp (Celsius)[x]	Irrigation Treatment Start	Irrigation Treatment End	Harvest Date	Squaring to 50-60% Open Boll Heat Units[w]	Seasonal Rainfall (mm)[v]
2020	107	14 May 2020	25.3	1 July 2020	2 Sept. 2020	6 Nov. 2020	1404	344
2021	34	12 May 2021	15.9	29 June 2021	30 Aug. 2021	15 Nov. 2021	1603	260

[z] Pre-Emergence Irrigation was accounted for from planting date to the start of the irrigation treatments for both years.

[x] Soil temperatures taken at planting at a depth of 5 cm.

[w] Heat units were calculated from the Oklahoma Mesonet heat unit calculator and were collected from 48 DAP to 140 DAP (2020) and 141 DAP (2021).

[v] Seasonal rainfall was calculated from planting date to harvest date for 2020-2021.

Table 2. Plant population and plant heights (cm) at eight true leaf, first bloom, and 2, 4, and 6 weeks after first bloom for Goodwell, OK 2020 and 2021.

	Population[x] Plants ha^{-1}	**8-Lf**	**FB**	**FB+2**	**FB+4**	**FB+6**
		----	----	**(cm)**	----	----
2020						
Variety[z]						
Pr > F[v]	0.0023	0.1266	0.0003	0.0004	0.1523	n/a[w]
DG 3385	69426 a	16.0	65.1 a	73.1 b	78.2	
DP 2012	75884 a	15.8	67.3 a	75.8 a	80.9	
NG 3930	71040 a	15.9	67.0 a	73.8 ab	79.3	
ST 4480	54357 b	14.9	62.1 b	69.8 c	77.5	
pLSD[y]	*10654*	*n/s*	*2.29*	*2.44*	*n/s*	
2021						
Variety	<0.0001	0.0962	0.0048	0.0003	<0.0001	0.0044
DG 3385	100282 b	23.6	58.1 bc	63.2 b	65.1 c	64.5 bc
DP 2012	108713 a	23.5	61.9 a	69.1 a	71.1 a	68.7 a
NG 3930	86827 c	23.0	56.8 c	63.3 b	64.1 c	62.4 c
ST 4480	93465 bc	24.1	60.6 ab	67.6 a	68.5 b	67.5 ab
pLSD	*8141*	*n/s*	*2.87*	*2.91*	*2.57*	*3.44*

[z] Varieties planted include NexGen® 3930 B3XF, Stoneville® 4480 B3XF, Dyna-Gro® 3385, and Deltapine® 2012 BXF.

[y] n/s signifying not a significant set of values.

[x] Plant populations were taken at 33 DAP (2020) and 27 DAP (2021). Eight leaf heights were taken at 48 DAP (2020) and 47 DAP (2021). First bloom heights were taken at 75 DAP (2020 and 2021). Following every two weeks after.

[w] FB+6 heights were not recorded in the 2020 year (data not shown).

[v] For each parameter, means followed by the same letter within the same column for each year are not significantly different based on Fisher's Protected LSD at p≤0.05.

Table 3. Nodes above white flower at first bloom, two weeks after first bloom, and four weeks after first bloom for Goodwell, OK 2020 and 2021.

	FB[x]	**FB+2**	**FB+4**
2020			
Variety[z]			
Pr>F[v]	0.129	0.0258	0.0102
DG 3385	7.9	5.9 ab	2.3 b
DP 2012	8.2	6.1 a	2.6 ab
NG 3930	8.3	5.7 b	2.3 b
ST 4480	8.5	6.3 a	2.9 a
pLSD[y]	*n/s*	*0.37*	*0.40*
2021			
Variety			
Pr>F	0.011	0.0001	0.6787
DG 3385	6.7 c	3.5 c	0.6
DP 2012	7.2 ab	4.4 a	0.7
NG 3930	6.9 bc	3.9 b	0.7
ST 4480	7.3 a	4.4 a	0.6
pLSD	*0.35*	*0.40*	*n/s*

[z] Varieties planted include NexGen® 3930 B3XF, Stoneville® 4480 B3XF, Dyna-Gro® 3385, and Deltapine® 2012 BXF.

[y] n/s signifying not a significant set of values

[x] First bloom NAWF were taken at 75 DAP (2020 and 2021). Following every two weeks after.

[v] For each parameter, means followed by the same letter within the same column for each year are not significantly different based on Fisher's Protected LSD at $p \leq 0.05$.

Table 4. End of season maturity measurements including final plant height, NFFB, NUCB, NUHB, total nodes, and open bolls for Goodwell, OK 2020-2021.

	Plant Height[x] (cm)	**NFFB**	**NUCB**	**NUHB**	**Total Nodes**	**Open Bolls %**
2020 Variety[z]						
Pr>F[v]	0.0054	0.0037	0.102	0.0016	0.0028	0.3995
DP 2012	79.4 a	6.4 a	5.1	15.7	19.3 b	6
ST 4480	75.5 b	5.7 b	6.4	16.7	20.3 a	8
pLSD[u]	*2.38*	*0.40*	*n/s*	*0.49*	*0.45*	*n/s*
2020 Irrigation[y]						
Pr>F	0.299	0.4712	0.6230	0.3782	0.3419	0.2612
90%ET	81.8	6.3	4.8	16.7	20.3	2
90%/63% ET	78.0	6.2	5.6	16.9	20.5	4
63% ET	74.8	5.9	6.0	16.2	19.5	9
36% ET	75.1	5.9	6.8	15.1	19.0	10
pLSD	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*
2021 Variety						
Pr>F	<0.0001	0.2359	0.1592	0.2233	0.0100	0.0816
DG 3385	62.8 b	6.0	12.2	13.5	16.2 c	65
DP 2012	68.3 a	6.2	12.3	15.2	16.9 ab	62
NG 3930	62.9 b	6.1	12.3	13.7	16.4 bc	71
ST 4480	67.4 a	6.2	12.7	14.4	17.2 a	67
pLSD	*2.36*	*n/s*	*n/s*	*n/s*	*0.55*	*n/s*
2021 Irrigation						
Pr>F	0.51	0.0945	0.0474	0.4874	0.9324	0.006
90%ET	67.7	6.3	12.0 b	14.1	16.8	51 c
90%/63% ET	63.3	5.9	11.7 b	15.0	16.6	65 b
63% ET	65.9	6.0	12.7 ab	13.9	16.6	72 ab
36% ET	64.5	6.2	13.1 a	13.7	16.6	78 a
pLSD	*n/s*	*n/s*	*0.97*	*n/s*	*n/s*	*0.11*

[z] Varieties planted include NexGen® 3930 B3XF, Stoneville® 4480 B3XF, Dyna-Gro® 3385, and Deltapine® 2012 BXF.

[u] n/s signifying not a significant set of values

[y] Irrigation treatments include: 90% of evapotranspiration replacement (90% ET), 90% evapotranspiration replacement during squaring/ 63% evapotranspiration replacement during boom (90%/63% ET), and 63% of evapotranspiration replacement (63% ET), and 36% of evapotranspiration replacement (36% ET).

[x] Final height, node at first fruiting branch (NFFB), node of uppermost first position cracked boll (NUCB), node of uppermost first position harvestable boll (NUHB), total nodes, and percent open bolls were taken at 140 DAP (2020) and 141 DAP (2021). These measurements were taken at projected 50-60% open bolls and accounted for only harvestable bolls.

[v] For each parameter, means followed by the same letter within the same column for each year are not significantly different based on Fisher's Protected LSD at $p \leq 0.05$.

Table 5. Yield for seed cotton, turnout percentages, and lint yield for Goodwell, OK 2020-2021.

	Seed Cotton **kg ha^{-1}**	**Turnout** **%**	**Lint Yield** **kg ha^{-1}**
2020 Variety[z]			
Pr>F[v]	0.0049	0.0016	0.0001
DG 3385	4020 a	30.63 a	1234 a
DP 2012	3535 b	27.72 b	981 b
NG 3930	3906 a	30.32 a	1181 a
ST 4480	3405 b	27.87 b	946 b
pLSD[u]	*363.83*	*1.72*	*129.01*
2020 Irrigation[y]			
Pr>F	0.1964	0.0911	0.8144
90%ET	3943	27.88	1102
90%/63% ET	3799	28.88	1102
63% ET	3600	28.99	1049
36% ET	3524	30.78	1088
pLSD	*n/s*	*n/s*	*n/s*
2021 Variety			
Pr>F	0.0052	<0.0001	<0.0001
DG 3385	3215 a	45.41 a	1460 a
DP 2012	2991 b	42.95 b	1286 b
NG 3930	3269 a	43.23 b	1411 a
ST 4480	3195 a	41.64 c	1330 b
pLSD	*151.83*	*1.06*	*60.89*
2021 Irrigation			
Pr>F	0.0164	0.5996	0.0193
90%ET	3595 a	43.48	1562 a
90%/63% ET	3098 bc	43.64	1352 bc
63% ET	3280 ab	42.96	1410 ab
36% ET	2697 c	43.16	1164 c
pLSD	*460.45*	*n/s*	*209.19*

[z] Varieties planted include NexGen® 3930 B3XF, Stoneville® 4480 B3XF, Dyna-Gro® 3385, and Deltapine® 2012 BXF.

[u] n/s signifying not a significant set of values

[y] Irrigation treatments include: 90% of evapotranspiration replacement (90% ET), 90% evapotranspiration replacement during squaring/ 63% evapotranspiration replacement during boom (90%/63% ET), and 63% of evapotranspiration replacement (63% ET), and 36% of evapotranspiration replacement (36% ET).

[v] For each parameter, means followed by the same letter within the same column for each year are not significantly different based on Fisher's Protected LSD at p≤0.05.

Table 6. Fiber Quality measurements collected for Goodwell, OK 2020-2021.

	Micronaire	**Length** (cm)	**Uniformity** %	**Strength** g tex^{-1}	**Loan Value** \$ kg^{-1}	**Gross Value** \$ ha^{-1}
2020 Variety[z]						
Pr>F[v]	0.0027	0.0004	0.0052	<0.0001	0.0038	0.0002
DG 3385	2.72 a	2.92 a	80.6 a	28.9 ab	0.89 a	1107 a
DP 2012	2.37 b	2.83 b	78.9 b	25.7 c	0.75 b	747 b
NG 3930	2.66 a	2.91 a	80.8 a	28.1 b	0.88 a	1040 a
ST 4480	2.46 b	2.96 a	80.1 a	29.7 a	0.84 a	797 b
pLSD[u]	*0.19*	*0.02*	*1.09*	*1.03*	*0.075*	*167*
2020 Irrigation[y]						
Pr>F	0.0081	0.1175	0.2096	0.8672	0.0109	0.1783
90%ET	2.42 b	2.92	79.6	27.9	0.80 b	902
90%/63% ET	2.40 b	2.89	79.7	28.1	0.77 b	859
63% ET	2.47 b	2.93	80.3	28.1	0.82 b	879
36% ET	2.91 a	2.86	80.8	28.3	0.95 a	1050
pLSD	*0.25*	*n/s*	*n/s*	*n/s*	*0.089*	*n/s*
2021 Variety						
Pr>F	0.0088	0.0006	0.0076	0.0029	0.0438	<0.0001
DG 3385	4.44 a	2.76 b	81.7 ab	27.2 b	1.15 ab	1679 a
DP 2012	4.31 bc	2.76 b	80.8 b	26.5 b	1.13 b	1461 c
NG 3930	4.39 ab	2.83 a	82.4 a	27.0 b	1.17 a	1653 a
ST 4480	4.23 c	2.85 a	80.7 b	27.9 a	1.16 a	1553 b
pLSD	*0.12*	*0.02*	*1.06*	*0.69*	*0.03*	*75*
2021 Irrigation						
Pr>F	0.4034	0.5976	0.8732	0.7831	0.7074	0.0288
90%ET	4.40	2.81	81.5	26.9	1.16	1803 a
90%/63% ET	4.40	2.79	81.5	27.2	1.16	1568 ab
63% ET	4.32	2.81	81.4	27.1	1.16	1639 a
36% ET	4.25	2.77	81.1	27.3	1.15	1335 b
pLSD	*n/s*	*n/s*	*n/s*	*n/s*	*n/s*	*270*

[z] Varieties planted include NexGen® 3930 B3XF, Stoneville® 4480 B3XF, Dyna-Grow® 3385, and Deltapine® 2012 BXF.

[u] n/s signifying not a significant set of values

[y] Irrigation treatments include: 90% of evapotranspiration replacement (90% ET), 90% evapotranspiration replacement during squaring/ 63% evapotranspiration replacement during boom (90%/63% ET), and 63% of evapotranspiration replacement (63% ET), and 36% of evapotranspiration replacement (36% ET).

[v] For each parameter, means followed by the same letter within the same column for each year are not significantly different based on Fisher's Protected LSD at p≤0.05

Table 7. Analysis of Variance (p-values) for plant population, plant heights, and NAWF. Factors Include variety, irrigation treatments, and a two-way interaction of variety by irrigation treatment.

Factors	d.f[z]	Population	8-Leaf Height	FB Height	FB NAWF	FB+2 Height	FB+2 NAWF	FB+4 Height	FB+4 NAWF	FB+6 Height
Goodwell 2020										
Variety	3	0.0023	0.1270	0.0003	0.1290	0.0004	0.0258	0.1523	0.0102	n/a[w]
Irrigation	3	0.4067	0.3909	0.3110	0.7476	0.3101	0.7444	0.1544	0.2244	
Variety*Irrigation	9	0.6982	0.4736	0.2685	0.9822	0.896	0.9337	0.2466	0.4808	
Goodwell 2021										
Variety	3	<.0001	0.0962	0.0048	0.0110	0.0003	0.0001	<.0001	0.6787	0.0044
Irrigation	3	0.448	0.2967	0.3649	0.0821	0.4269	0.3026	0.0628	0.1671	0.5014
Variety*Irrigation	9	0.540	0.1669	0.6236	0.8668	0.7120	0.8382	0.1533	0.6658	0.5296

[z] Degrees of Freedom.

[w] FB+6 heights were not recorded in the 2020 year (data not shown).

[v] For each parameter, means followed by the same letter within the same column for each year are not significantly different based on Fisher's Protected LSD at $p \leq 0.05$.

Table 8. Analysis of Variance (p-values) for final plant height, NFFB, NUCB, NUHB, total nodes, and percent open bolls. Factors Include variety, irrigation treatments, and a two-way interaction of variety by irrigation treatment.

Factors	d.f[z]	Final Height	NFFB	NUCB	NUHB	Total Nodes	Percent Open Bolls
Goodwell 2020							
Variety	1	0.0054	0.0037	0.6330	0.1448	0.0028	0.3995
Irrigation	3	0.299	0.4712	0.7417	0.5913	0.3419	0.2612
Variety*Irrigation	3	0.622	0.9211	0.4155	0.4292	0.0447	0.7935
Goodwell 2021							
Variety	3	<.0001	0.2359	0.1592	0.2233	0.0100	0.0816
Irrigation	3	0.5100	0.0945	0.0474	0.4874	0.9324	0.0060
Variety*Irrigation	9	0.0527	0.0971	0.6219	0.5909	0.0464	0.9088

[z] Degrees of Freedom.

[v] For each parameter, means followed by the same letter within the same column for each year are not significantly different based on Fisher's Protected LSD at $p \leq 0.05$.

Table 9. Analysis of Variance (p-values) for seed cotton, turnout percentages, lint yield, fiber length, fiber strength, fiber uniformity, fiber micronaire, loan values, and gross values. Factors Include variety, irrigation treatments, and a two-way interaction of variety by irrigation treatment.

Factors	d.f[z]	Seed Cotton kg ha^{-1}	Turnout %	Lint Yield kg ha^{-1}	Length (cm)	Strength g tex^{-1}	Uniformity %	Mic	Loan $ kg	Gross $ kg ha^{-1}
Goodwell 2020										
Variety	3	0.0049	0.0016	0.0001	0.0004	<.0001	0.0052	0.0027	0.0038	0.0002
Irrigation	3	0.1964	0.0911	0.8144	0.1175	0.8672	0.2096	0.0081	0.0109	0.1783
Variety*Irrigation	9	0.9615	0.4814	0.8481	0.8576	0.6495	0.7672	0.4291	0.7459	0.8286
Goodwell 2021										
Variety	3	0.0052	<.0001	<.0001	0.0006	0.0029	0.0076	0.0088	0.0438	<.0001
Irrigation	3	0.0164	0.5996	0.0193	0.5976	0.7831	0.8732	0.4034	0.7074	0.0288
Variety*Irrigation	9	0.853	0.4014	0.693	0.7091	0.0371	0.6143	0.9229	0.069	0.8755

[z] Degrees of Freedom.

[v] For each parameter, means followed by the same letter within the same column for each year are not significantly different based on Fisher's Protected LSD at p≤0.05.

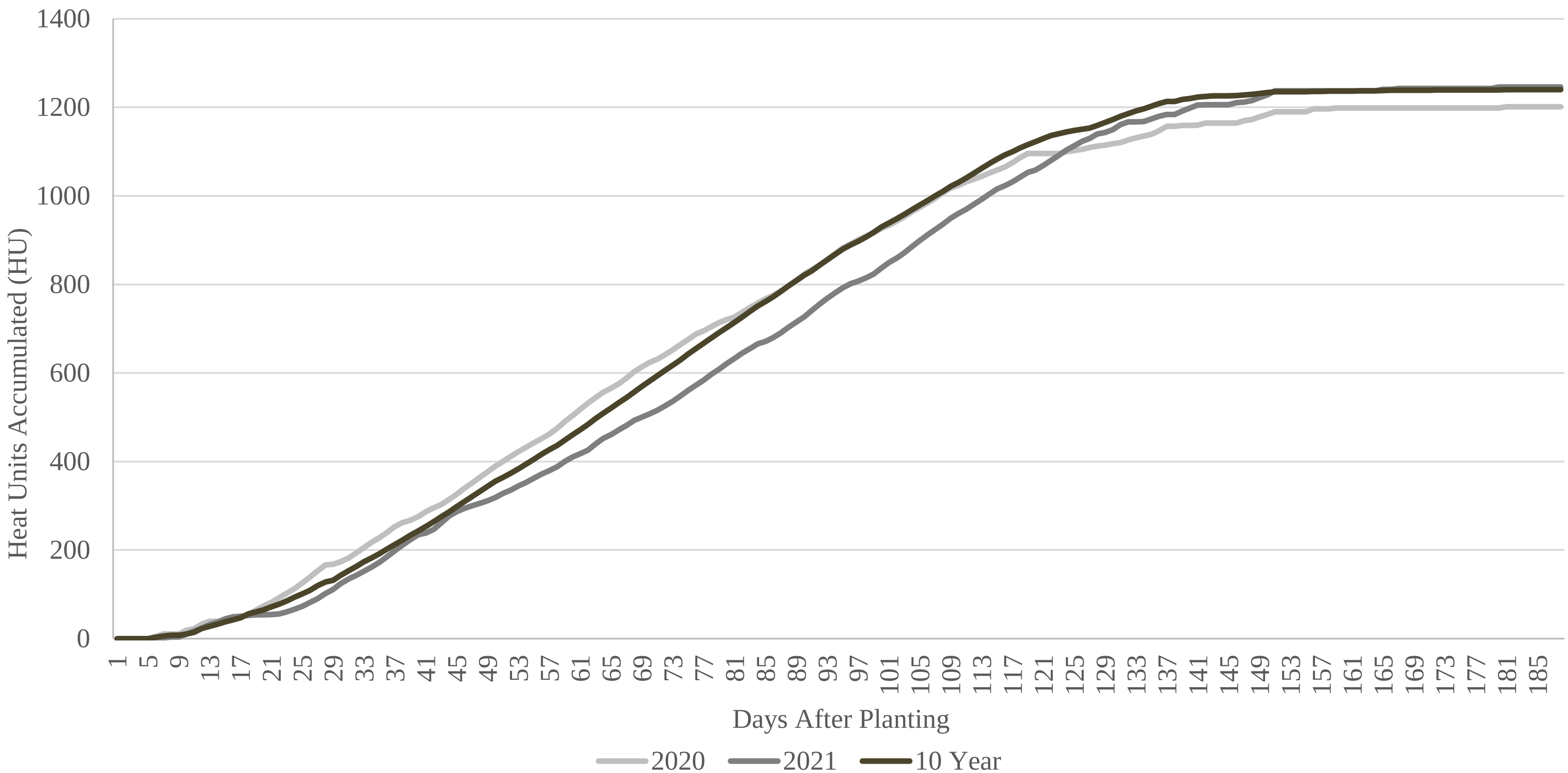

Figure 1 Shows heat units accumulated after planting to harvest (177 DAP 2020, 188 DAP 2021), from the Oklahoma Mesonet for both 2020 and 2021 site years, in comparison to the 10-year average (2010-2021).

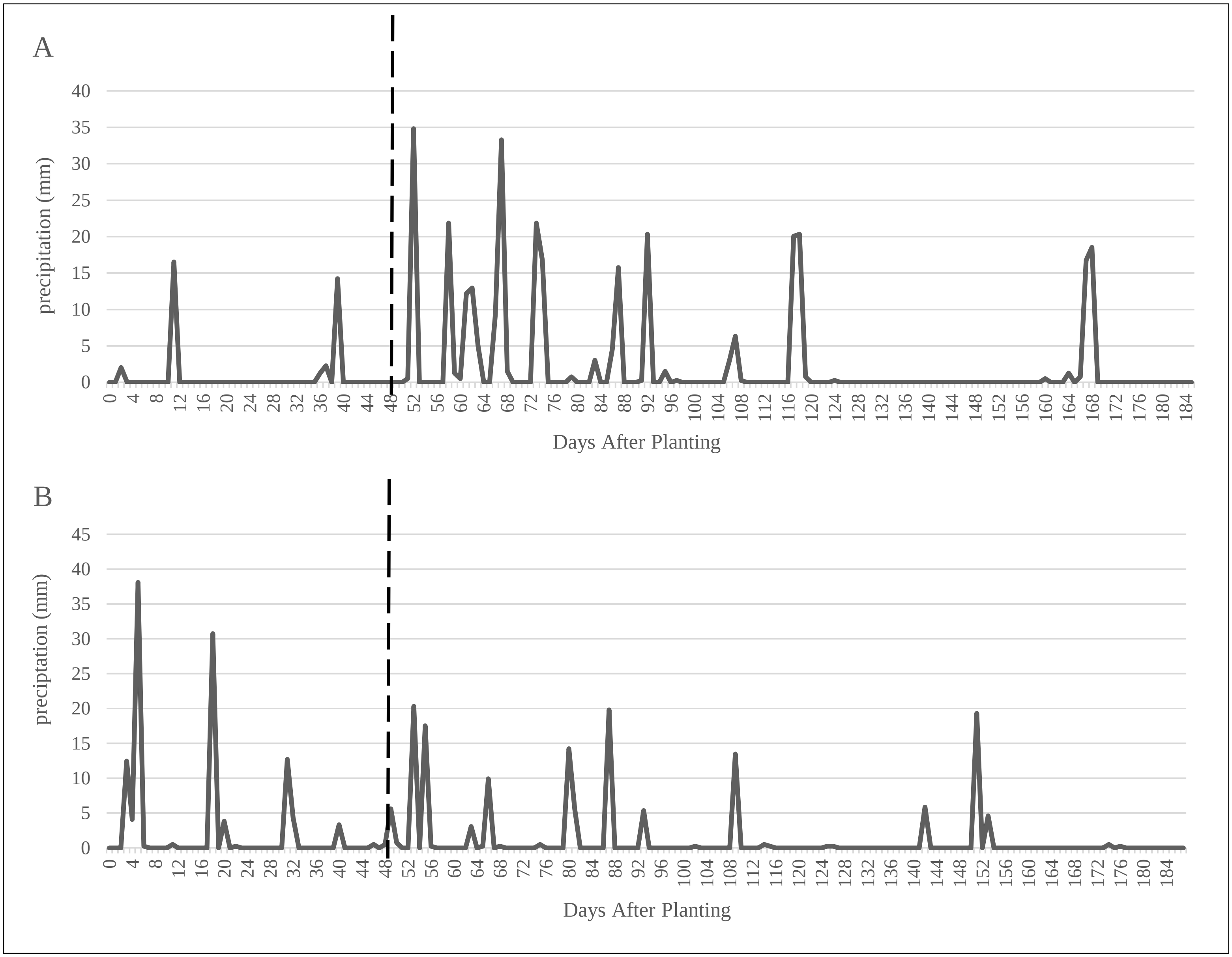

Figure 2. Rainfall in Goodwell, Oklahoma for the 2020 site year (A) and 2021 site year (B). Black dotted line represents the initiation of the irrigation treatments at the beginning of the squaring stage.

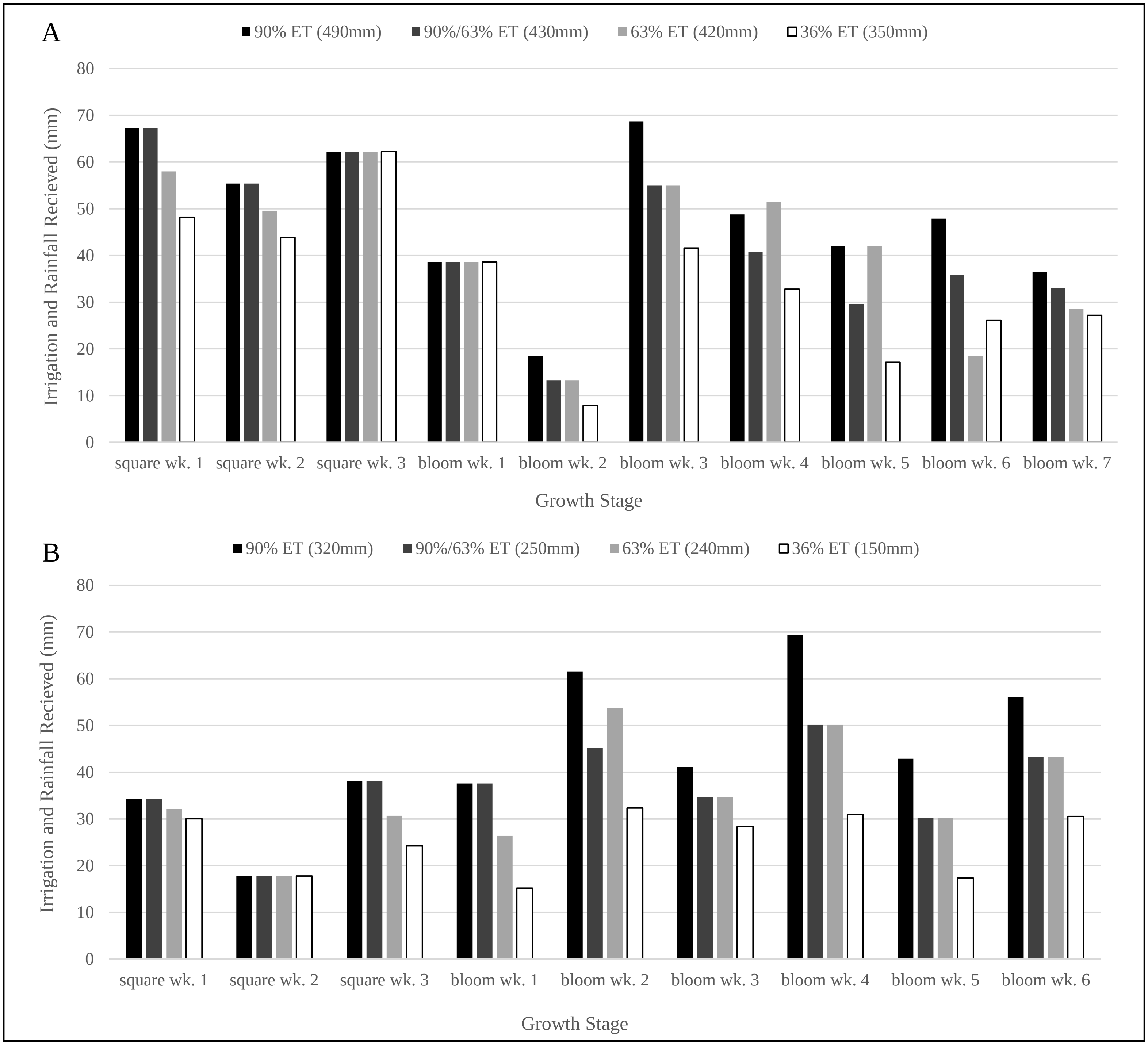

Figure 3. Weekly water received (irrigation and precipitation), within each irrigation treatment for the 2020 site year (A) and 2021 site year (B). Total seasonal water received in each treatment included in parenthesis beside treatment name.

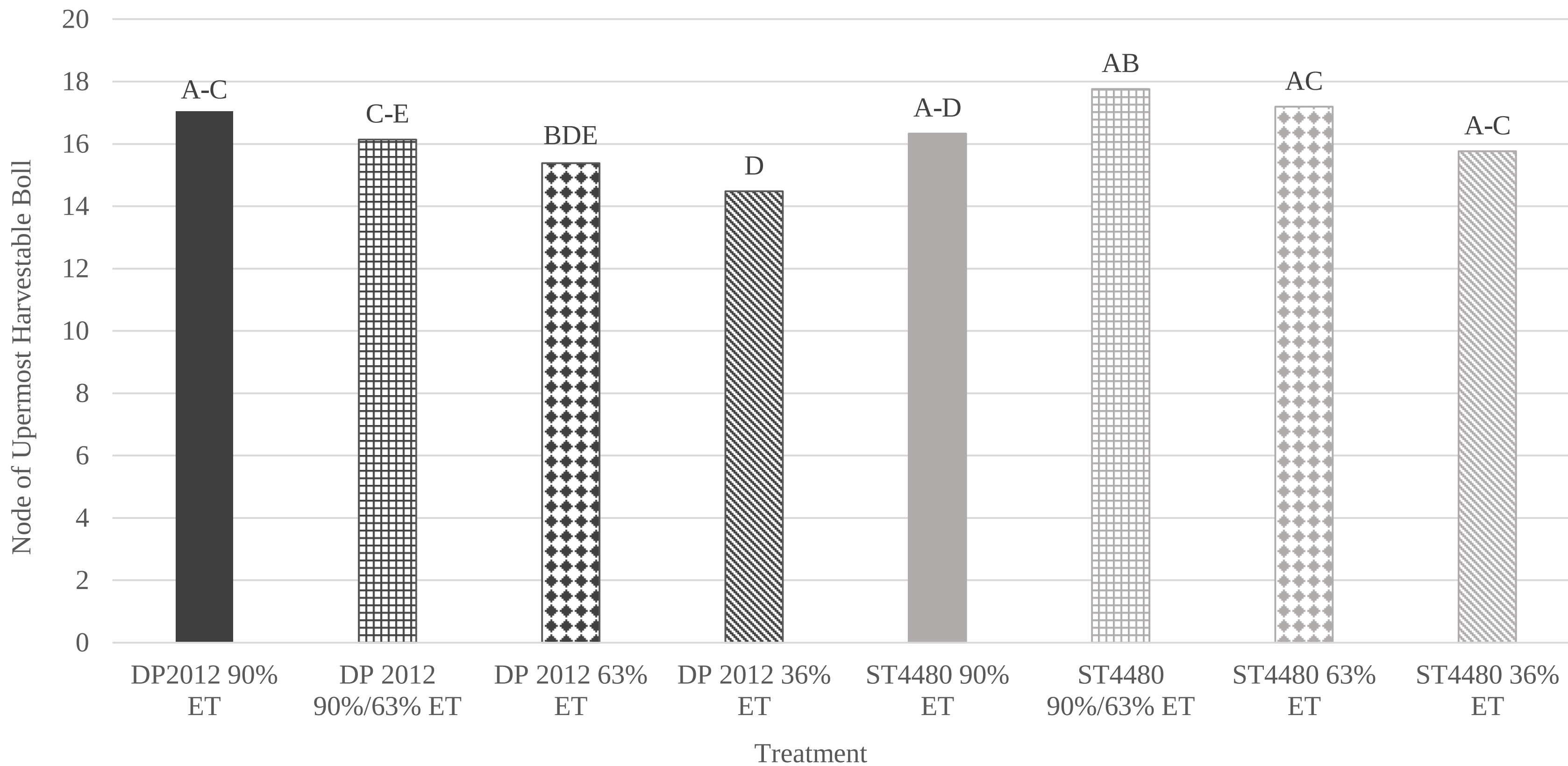

Figure 4. 2020 Node of upper most harvestable boll variety and irrigation interaction. *pLSD = 2.27*

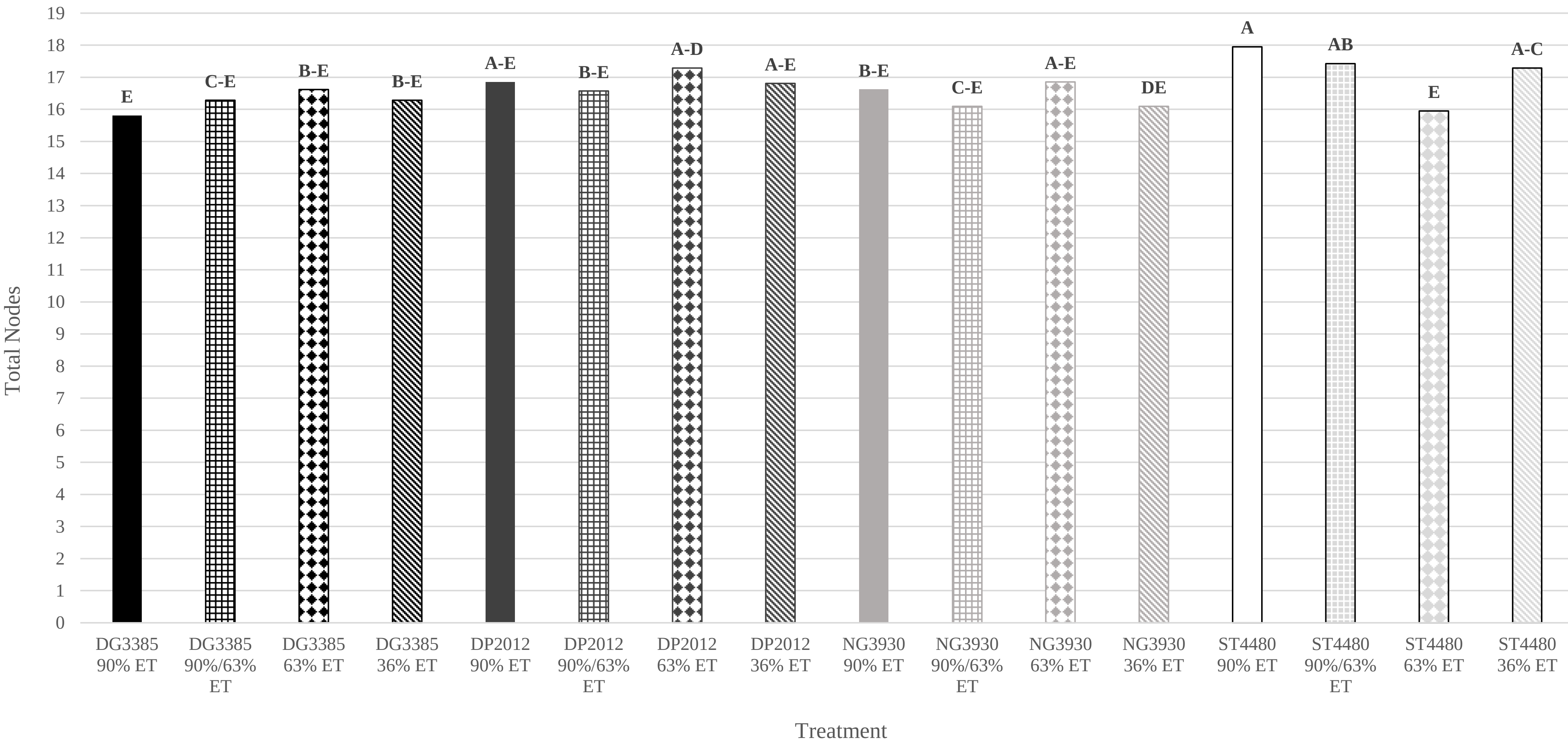

Figure 5. 2021 Total nodes variety and irrigation interaction. *pLSD = 1.20*

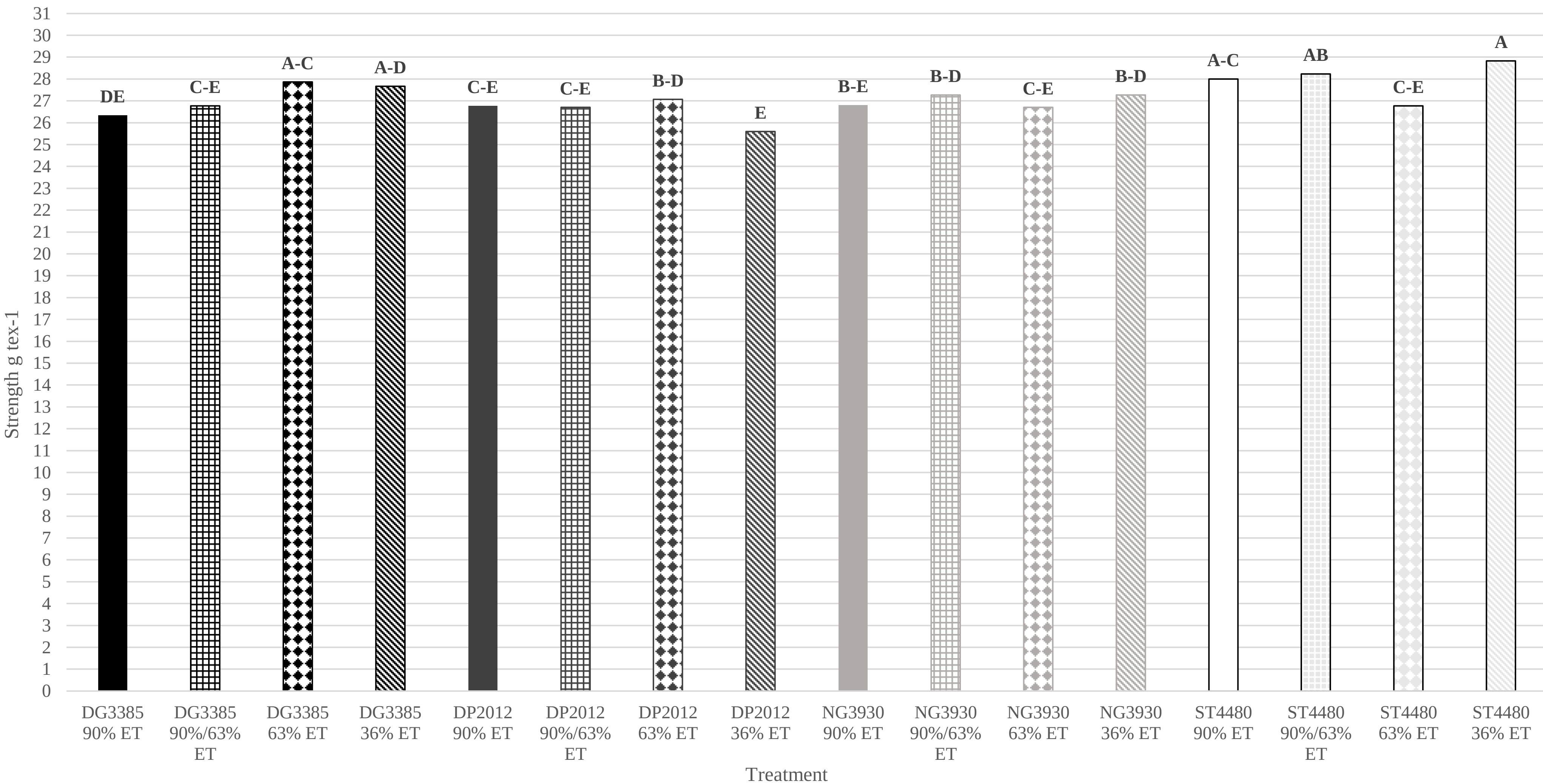

Figure 6. 2021 Strength values for variety by irrigation interaction. *pLSD= 1.3*

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VITA

Andrea Janice Althoff

Candidate for the Degree of

Master of Science

Thesis: COTTON GROWTH STAGE SPECIFIC IRRIGATION AND FIBER QUALITY RESPONSE IN THE GREAT PLAINS REGION

Major Field: Plant & Soil Sciences

Biographical:

Education:

Completed the requirements for the Master of Science in Plant & Soil Sciences at Oklahoma State University, Stillwater, Oklahoma in December, 2022.

Completed the requirements for the Bachelor of Science in Plant, Soil, and Environmental Science at West Texas A&M University, Canyon, Texas in 2020.

Completed the requirements for the Associates of Science in Agriculture at Northeastern Oklahoma A&M College, Miami, Oklahoma in 2018.

Experience:

2020 – 2022 – Graduate Research Assistant – Oklahoma State University
2019 – Cotton Seed Production Intern – U.S. Bayer Crop Science
2018 – Cotton Agronomy Intern – Texas A&M Agrilife Extension
2018 – Mushroom Production Intern – J-M Mushroom Farms
2018 – Regional Agronomy Intern – Ag Nutrien Services

Professional Memberships:

Students of Agronomy, Soils, and Environmental Sciences