ABSTRACT

SPIVEY, TODD ALAN. Upland Cotton Growth and Yield Response to the Interactions of Planting Date with Irrigation Strategies, Soil Tillage Systems, and Agronomic Inputs. (Under the direction of Dr. Keith Edmisten.)

Environmental conditions at planting and through early development strongly influence the growth and yield of upland cotton during the remainder of the season and can vary considerably due to the timing of planting. Therefore, research was conducted from 2014 to 2016 to determine the effects of interactions of planting date with irrigation strategies, soil tillage systems, and agronomic inputs on cotton growth and yield.

Tillage practices, cover crops, and planting dates are three major practices that can influence soil moisture and temperature conditions at planting. Research was conducted to compare cotton growth and yield in short-term, reduced-till systems with that grown on conventional raised beds at multiple planting dates, with and without a cover crop. Plant populations and crop growth rates were not reduced by any spring tillage compared to conventionally tilled cotton and crop growth rates were reduced by stale seedbeds in only 25% of comparisons. Only late planted cotton in 2014 showed minor yield differences due to tillage system and tillage did not influence yield when pooled across year and location for all remaining environments. These findings indicate that cotton grown in these reduced-till systems is comparable to cotton grown in conventional systems in typical eastern North Carolina soils.

Along with the increasing cost of cotton production, growers are often pressured to incur additional expenses in the name of plant health. Research was conducted with cooperators in Mississippi, Missouri, and Virginia to determine the agronomic and economic value of five representative inputs used in cotton production systems on growth and yield compared to current extension recommendations. Each input was included both individually and in a high-input treatment consisting of all five inputs together at both an early and late planting date. Regardless of planting date, lint yield was not increased by any input compared to extension recommendations though late-planted cotton had lower yields than early-planted

cotton. Due to the lack of observed differences, the costs of the additional inputs were not recuperated and should not be recommended as blanket agronomic treatments in the name of plant health.

Although research has shown that irrigation can increase yields in North Carolina, only 2.7% of North Carolina's planted hectares are irrigated. A field study was conducted to investigate the impact of subsurface drip irrigation (SDI) on growth and yield of early- and late-maturing cotton cultivars at three planting dates. The effect of SDI on cotton growth and yield was strongly influenced by rainfall and yield was only increased by SDI in 2015 and 2016. Planting date did not influence yield under irrigated conditions and was highly dependent on the environment when under non-irrigated conditions. The results from this study are similar to previous findings in that, in years with reduced or poorly distributed rainfall, SDI will increase cotton development, fruit retention, and yield in North Carolina, independent of planting date and cultivar.

Economic evaluation of irrigation is difficult however and field-based studies are often not suited for determining the effects of long-term weather patterns on the economics of irrigation. Using CSM-CROPGRO-Cotton, crop model simulations were used to evaluate the agronomic value of irrigation to cotton production using historical weather data for 11 counties in North Carolina. An investment analysis was then conducted to determine the economic feasibility of irrigation use in cotton. The agronomic and economic responses to irrigation were both strongly dependent on seasonal rainfall, and yields of non-irrigated cotton were reduced by more than 10% of fully-irrigated yields in over 80% of simulated site-years. The results of the long-term simulations and economic analysis suggest that irrigation is a feasible investment for cotton producers in North Carolina as positive returns were observed for all 11 counties.

Upland Cotton Growth and Yield Response to the Interactions of Planting Date with Irrigation Strategies, Soil Tillage Systems, and Agronomic Inputs

by
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DEDICATION

This dissertation is dedicated to my wife, Cortney Mode Spivey. She has supported me from day one and the goals that I have reached would not have been possible without her.

BIOGRAPHY

Todd Alan Spivey was the second son born to Rex Spivey and Debbie Barbour Spivey in Raleigh, North Carolina on 17 July 1990. He was raised in the McGee's Crossroads community near Benson, NC where he graduated from West Johnston High School in 2008. Todd was active in West Johnston High School's FFA chapter as well as the varsity baseball program.

In 2012, Todd graduated from North Carolina State University with a Bachelor's Degree in Turfgrass Science. During his undergraduate career at North Carolina State University he was a member of the Agronomy Club and Turfgrass Club. In the summer of 2012, he was admitted into the graduate school of North Carolina State University in the Department of Crop Science in which Todd completed his Master of Science in 2014 under the direction of Dr. Keith Edmisten while working closely with Dr. Jack Bacheler and Dr. Dominic Reisig. While working towards his degree he was an active member of the North Carolina State University Crop Science Graduate Student Association and served as president from 2013 to 2014.

After the completion of his M.S., Todd remained at North Carolina State to pursue his Ph.D. in Crop Science under the direction of Dr. Keith Edmisten to be completed in the spring of 2017. During his tenure as a student at North Carolina State from 2008 through 2017, Todd was afforded opportunities to learn and work with colleagues in the cotton industry both locally in North Carolina as well as nationally and internationally. More importantly, he made many friends along the way, including one he would marry in 2014, Cortney Mode Spivey.

Todd's academic career was long and challenging and the milestones accomplished could not have been reached without the strength and support of family, friends, and mentors that he has received, and will continue to receive, as he takes the next step in pursuing a life-long career in the agricultural industry.

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Deep appreciation is extended to my wife, my parents, and my family for their never ending love and support. Above all, I thank the Lord for his many blessings, love, forgiveness, and the many opportunities he has presented me.

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HOW COTTON GROWS: SEED TO CELLULOSE

Four *Gossypium* species have been domesticated across the world, two of which are economically grown in the United States. *Gossypium barbadense*, pima cotton, is grown in the arid southwest United States and is known for its extra-long staple length. *Gossypium hirsutum* is the most commonly cultivated species, due to its adaptability to a wide range of environments, and accounts for some 90% of the annual cotton crop globally and about 98% of the US crop (USDA-NASS, 2016; Wendel and Cronn, 2003).

The US cotton industry contributes about 30% of the world's cotton fiber exports, of which 75% will be used for manufacturing of apparel (NCC, 2016). Cotton fiber exports earn the United States almost five billion dollars annually, accounting for only seven percent of the economic activity provided by the cotton industry to the US economy (NCC, 2016). Cottonseed also contributes to the profitability of the cotton industry. An average of five million tons of cottonseed are produced annually, of which six billion pounds are used for livestock and dairy cattle feed alongside that pressed for cottonseed oil for human consumption and industrial chemicals (NCC, 2016; Smith and Cothren, 1999).

Cotton development can be divided into four main growth stages: germination and seedling development, leaf area and canopy development, flowering and boll development, and maturation (Oosterhuis, 1990; Oosterhuis and Jernstedt, 1999). Often the shifts between these stages are not always clear and well defined. With each stage comes new anatomy, developing upon that of the preceding stage, with physiological processes functioning under its own specific requirements (Oosterhuis and Jernstedt, 1999). Grower understanding of this is important for obtaining maximum yields with optimal fiber quality.

GERMINATION AND SEEDLING DEVELOPMENT

Though cotton is the world's leading natural fiber, the purpose of these single-celled trichomes is to protect and disperse the cottonseed (Wang et al,. 2004; Wendel and Cronn, 2003; Wilkins et al., 2000). Cottonseed germination begins with the imbibition of water into the seed through the chalazal aperture (Christiansen and Moore, 1959; Christiansen and Rowland, 1986). The water then moves around the periphery of the seed to the radicle where it is taken up into the embryo (Oosterhuis and Jernstedt, 1999). The uptake of water in the

first twelve hours is rapid, with the water content of the embryo increasing from 10% to 40-80% (Christiansen and Rowland, 1986; Cothren, 1990; Dewez, 1964). Within the first day after imbibition begins, enzymes are activated for glycolysis for energy production and in the oxidative pentose phosphate pathway for production of metabolic and structural intermediates and NADPH (Cothren, 1999; Purvis and Fites, 1979).

Imbibing seeds and seedlings are especially sensitive to cool temperatures up to 160 h after planting and growth can cease when temperatures reach below 16° C (Bauer, 2015; Steiner and Jacobsen, 1992). The optimal temperature for cotton seedling emergence is approximately 30° C and Nabi and Mullins (2008) showed a reduction in shoot growth of 44% in the first 180 h after planting when soil temperatures are reduced by only 10° C (Bradow and Bauer, 2010).

Without the capability of photosynthesis during germination and early seedling development, the seed requires the breakdown of stored carbohydrates, lipids, and proteins. In an oilseed crop, such as cotton, lipids are a primary form of stored carbon in the mature seed. Lipids are not easily transported from the cotyledons to other developing tissues of a germinating seedling; therefore, stored lipids are broken down and converted to sucrose for mobilization. This process occurs in three distinct bodies; oleosomes, glyoxysomes, and mitochondria (Cothren, 1999; Taiz and Zieger, 2010). In the oleosome, triglycerides are hydrolyzed into fatty acids by lipases and moved to the glyoxysome for further conversion to succinate as part of the glyoxylate cycle (Taiz and Zeiger, 2010). Malate can either be produced in the mitochondria from succinate or in the glyoxysome by malate synthesis acting on acetyl CoA, a product from the oxidation of fatty acids (Cothren, 1999). Malate can then be converted to glucose and subsequently sucrose in the cytosol. During this breakdown of lipids to sucrose, acetyl-CoA is formed, of which, approximately 30% is used for mitochondrial respiration and energy production while the remaining 70% is converted completely to sucrose (Taiz and Zeiger, 2010). Studies have shown during the breakdown of the stored carbohydrates and lipids, there is little weight loss from seed to emerged seedling, indicating that the majority of early metabolic activity is a conversion of stored lipids to sucrose and subsequent structural components (Christiansen and Rowland, 1986; Taiz and

Zeiger, 2010; White, 1958). White (1958) found that the depletion of storage lipids in germinating cottonseeds occurs around 14 days after germination (DAG).

With the onset of metabolic activity converting stored carbon to usable energy for the plant, seedling development increases and the radicle, cotton taproot, will emerge in two to three days (Oosterhuis and Jernstedt, 1999). The taproot develops rapidly in the early stages of seedling development and can reach depths of more than 25 cm by the time the cotyledons unfold in 5 to 10 DAG (Oosterhuis and Jernstedt, 1999; Taylor and Ratliff, 1969). Lateral, or secondary, roots will also begin to develop as the seedling begins emerging from the soil.

After the radicle begins to emerge, the hypocotyl, made up of the seedling tissues between the cotyledons and the radicle, begins to expand. As the hypocotyl expands rapidly, an arch forms, pulling the cotyledons and epicotyl upwards, towards, and eventually through, the soil surface. This emergence is described as epigeal emergence, after which the hypocotyl will straighten and the cotyledons will unfold. As the cotyledons unfold they become capable of photosynthesis, becoming the main energy source for the developing seedling as the stored carbon becomes depleted. At germination, the seed also contains the shoot tissues of the epicotyl, consisting of a shortened internode and the first node with the undeveloped tissues of the first true leaf and shoot apical meristem (Christiansen and Rowlan, 1986; Mauney, 1984; Oosterhuis and Jernstedt, 1999).

The transition from heterotrophic seedling, relying solely on stored carbon, to an autotrophic plant begins as the seedling emerges from the soil. Phytochrome A is depleted as red light converts phytochrome$_r$ to phytochrome$_{fr}$, resulting in a shift from phytochrome A to phytochrome B (Cothren, 1999). This shift from phytochrome A to B results in the de-etiolation of the seedling and development of photosynthesizing tissue (Cothren, 1999).

LEAF AREA AND CANOPY DEVELOPMENT

The main axis stem begins to develop with the elongation of the shoot apical meristem. A vegetative structure, the monopodial growth of the main stem is comprised of nodes, where main stem leaves develop, and internodes. Seedling development is initially slow as it does not have any differentiated true leaves able to unfold immediately after

germination. By the time the first true leaf begins unfolding however, the plant has already developed an additional six or seven leaf primordia (Mauney, 1984). This initial growth typically results in an unbranched plant with four to five nodes and elongated internodes. The stem is similar to a typical dicot with vascular bundles arranged around the central pith. These vascular bundles are made up of the primary xylem and phloem separated by the vascular cambium with xylem to the interior and phloem to the exterior (Oosterhuis and Jernstedt, 1999; Taiz and Zeiger, 2010).

At each node, a main stem leaf develops from the shoot apical meristem. The leaf primordium will develop beneath the protection of the stipules that, at this stage, will elongate faster than the true leaf (Mauney, 1984). When developing, the leaves will become lobed while still beneath the stipules. Typically the first true leaf is not lobed and the leaves become increasingly deeper lobed until the typical leaf shape is formed at the sixth to tenth nodes (Mauney, 1984; Mauney, 1986). Phyllotaxy is the arrangement of the leaves on the stem. Cotton leaves are arranged in a phyllotactic spiral around the stem with each successive leaf being a 3/8 turn above the previous (Mauney, 1984; Oosterhuis, 1990; Oosterhuis and Jernstedt, 1999).

Typically in the third leaf below the apical meristem, a developing axillary meristem becomes visible in the axil of the true leaf (Mauney, 1984; Mauney, 1986). An axillary bud will develop at every prophyll and true leaf on the plant though many will remain dormant. Each axillary bud can develop a branch by differentiating first a prophyll leaf, followed by stem tissue of an internode, and another true leaf (Mauney, 1984; Mauney, 1986; Oosterhuis, 1990; Oosterhuis and Jernstedt, 1999).

Axillary meristems at each true leaf can produce two types of branches, monopodial or sympodial. Monopodial branches, or vegetative branches, typically occur at the third to fifth main stem nodes, as the axillary buds at the first to third nodes are often aborted. Similar to the primary axis, monopodial branches have an upright growth habit, develop from a single terminal meristem, and additional branches can develop at each node from an axillary bud (Mauney, 1984; Mauney, 1986; Oosterhuis and Jernstedt, 1999).

The first sympodial branch, or fruiting branch, typically occurs from the fifth to eighth main stem node. Thereafter, they develop continually through the remainder of the season. These sympodial branches initially develop similar to monopodial branches in that a prophyll leaf, internode, and true leaf are differentiated. The meristem of the sympodial branch however, is consumed by the differentiation of the flower and is terminated (Mauney, 1984). With the termination of the sympodial branch at the flower, the axillary meristem in the first sympodial leaf is activated, resulting in another sequence of prophyll, internode, true leaf, flower (Mauney, 1984; Mauney, 1986; Oosterhuis, 1990; Oosterhuis and Jernstedt, 1999). This process of termination and activation of a new axillary meristem is what causes the typical zigzag appearance of cotton fruiting branches. Once the first sympodial branch begins differentiation, the plant does not revert back to monopodial branching, with rare exceptions that are not well defined (Mauney, 1986; Oosterhuis and Jernstedt, 1999).

Canopy development continues with development of both main stem true leaves and true leaves on monopodial and sympodial branches. Leaf area increases according to a sigmoidal pattern with slow increases during the first weeks following emergence, followed by rapid increases in leaf area during early fruiting (Oosterhuis and Jernstedt, 1999). Main stem leaves account for approximately 40% of the total leaf area of the plant and reach their maximum leaf area before first bloom, while the sympodial leaf area, which makes up about 60% of the total leaf area at maximum, continues to increase for about a month following first bloom (Mutsaers, 1983; Oosterhuis and Jernstedt, 1999).

Water is required for cell expansion and even moderate water stress can reduce stem elongation, stem and leaf dry weights, total nodes, and leaf area (Loka et al., 2011; McMichael and Hesketh, 1982; Pace et al., 1999; Turner et al., 1986). Severe water stress reduces vegetative growth but can also lead to the destruction of present tissue. Abscission of leaves and destruction of chloroplast and mitochondria are also associated with severe water stress (Berlin et al, 1982; Bondada and Oosterhuis, 2002; McMichael et al., 1972).

Leaves also contain vascular bundles in which the xylem tissue is on the upper side of the leaf separated, in main veins, from the phloem tissues on the lower side of the leaf (Oosterhuis and Jernstedt, 1999). Although more numerous on the lower side of the leaf,

stomata occur on both the upper and lower sides of the leaf. Cotton stomata have an epicuticular ledge that partially covers the stomatal pore as well as an internal cuticle that extends down through the stomatal cavity (Oosterhuis and Jernstedt, 1999; Wullschleger and Oosterhuis, 1989). Both of these adaptations of cotton stomata have been implicated in drought tolerance of cotton (Oosterhuis and Jernstedt, 1999; Wullschleger and Oosterhuis, 1989). A waxy cuticle covers both sides of the leaf surface just above the epidermal cell layer. The cuticle is made up of cutin and wax initiated at the outer walls of the epidermal cells (Bondada et al., 1994).

The interception of radiant energy to be used for photosynthesis is the most important function of leaves. Photosynthesis occurs in the chloroplasts of cells and is comprised of both light reactions, production of ATP and NADPH, and dark reactions, assimilation and fixation of carbon into various forms for plant use. The light reactions are initiated when photons of light excite chlorophyll in the light harvesting complexes associated with photosystem II (PSII). Through this excitation, an electron (e^-) is released into the system from chlorophyll P680. The released e^- is subsequently replaced by the stripping of an e^-, by chlorophyll P680, from H_2O which was split by the manganese cluster in PSII, thus beginning the photosynthetic e^- transport chain. This e^- transport chain, through plastoquinone$_{QB}$ and photosystem I (PSI), results in the production of NADPH and the pH gradient between the lumen and stroma responsible for the production of ATP through ATPsynthase.

Once ATP and NADPH have been produced in the light reactions, fixation of CO_2 through the Calvin cycle can occur. Thioredoxin (TRX), reduced with e^- from the photosynthetic e^- transport chain, is required to activate enzymes in the Calvin cycle for the fixation of carbon. RuBisCO activase, glyceraldehyde phosphate-DH, fructose-1,6-phosphatase, and ribulose phosphate kinase all require activation by reduced TRX for the assimilation of carbon to occur. When the reductive reactions of the Calvin Cycle are activated, RuBisCO fixes the carbon into the first intermediate, 3-phosphoglycerate (3-PGA), then onto triose phosphates (TP) through the addition of ATP and NADPH. At this point, TPs can continue through the Calvin cycle for storage as starch in the chloroplast or

regeneration of necessary molecules of the Calvin cycle, or they can be exported from the chloroplast for further plant function.

Photosynthetic rates in leaves depend upon irradiance level and CO_2 concentration. With no other limiting factors, maximum photosynthetic rates occur at the light saturation point at which increased light will not result in any further increase in photosynthetic rate (Cothren, 1999; Taiz and Zeiger, 2010). Leaves of *G. hirsutum* have been shown to maximize available sunlight by tracking the light (Ehleringer and Hammond, 1987; Wells, 2011). Ehleringer and Hammond (1987) found that the cosine of incidence of radiation was almost one, nearly perpendicular, between 0700 and 1500 h. Leaves of *G. barbadense* however, do not show this same changing leaf position throughout the day (Wells, 2011).

Leaf location in the canopy will also affect the light received by a leaf so that lower leaves will receive less light due to shading of the upper canopy. Enriched in far-red light, shade converts phytochrome$_{fr}$ to phytochrome$_{r}$, resulting in morphological distinctions including increased internode lengths and reduced branching (Wells, 2011). An increase in shade has been shown to increase the rate of leaf and fruit abscission due to a reduction of photosynthesis and carbohydrate concentrations in leaves and bolls (Zhao and Oosterhuis, 1998). To this point, Pettigrew (1994) observed increased cotton lint yields when lower canopy light was increased due to reflectance of light or removal of neighboring plants.

Photosynthetic rates are also increased with increased CO_2 concentrations. RuBisCO in C_3 plants is able to fix both CO_2 and O_2 with a higher affinity for CO_2 but at a very slow reaction rate. Although RuBisCO has a higher affinity for CO_2, the ratio of CO_2:O_2 of the atmosphere is fairly low. With increased CO_2:O_2 ratios, photorespiration rates will be decreased and in turn, net photosynthetic production is increased (Cothren, 1999; Taiz and Zeiger, 2010).

Photosynthesis is reduced under water-stress conditions as well, either by stomatal or metabolic changes (Loka et al., 2011). Although cotton plants grown under controlled conditions in pots have shown complete stomatal closure, field studies report only a partial closure of stomata even under low water potentials (Ackerson et al., 1977; Bierolai and Hopmans, 1975; Harris, 1973; Jordan and Ritchie, 1971). Regardless of the complete or

partial closure of stomata, the result is a reduction of CO_2 diffusion to the site of carboxylation and overall reduction in photosynthesis (Loka et al., 2011). Non-stomatal factors reducing net photosynthetic production include a reduced capacity of ribulose 1,5-bisphosphate regeneration, a reduction in activity of ATP-synthase, and an increase in photorespiration during water stress to prevent the buildup of damaging reactive oxygen species (ROS) (Gimenez et al., 1992; Massacci et al., 2008; Pettigrew, 2004; Tezara et al., 1999).

FLOWERING

The differentiation of the first floral bud typically occurs at the two- to three-leaf stage. Day and night temperatures along with quality and intensity of light at this stage can affect the location of this first fruiting branch (Mauney, 1986). Hesketh et al. (1972) and Mauney (1966) both showed that though low temperatures would delay the initiation of flowering, low temperatures, especially night time temperatures, would actually lower the node of the first fruiting branch. Regardless of when the first fruiting branch occurs however, the transition occurs over the entire plant at once. This can be seen in that the number of nodes between the cotyledons and the first main stem sympodial branch, is the same as the number of nodes between the cotyledons and the first sympodial branch off of a monopodial branch (Mauney, 1984).

As previously discussed, sympodial branches develop identically through the development of the first true leaf. Thereafter, the meristem begins to differentiate into the floral bud. Mauney (2012) discusses the differentiation of the floral forms from the sympodial meristematic tissue. A whorl of three bracts develops over the meristematic tissue, marking the termination of the vegetative elongation. Subsequent differentiation of the floral bud includes the calyx, corolla, androecium, and finally the gynoecium including three to five carpels (Mauney, 2012). From initiation, the pinhead stage of the floral bud occurs in about three weeks, followed by another three weeks before the flower will bloom. Pollen and ovule initiation occurs about three weeks prior to anthesis, similar to the time frame of the pinhead stage (Stewart, 1986). The number of ovules in a boll directly

influences fiber production. Being subjected to water stress at this time can reduce the number of ovules per boll (Loka and Oosterhuis, 2012; Mauney, 1986).

The growth stage at which the plant is most sensitive to water stress is disputed, whether this is during early bloom, peak bloom, or boll development after bloom (Loka et al., 2011; Loka and Oosterhuis, 2012; Orgaz et al., 1992; Radin et al., 1992). Guinn and Mauney (1984) determined however, that regardless of the most sensitive growth stage of cotton, the greatest cause for a reduction in cotton yield is the reduction in the number of flowers, and the number of ovules per flower, that occur three weeks after severe water stress (Loka and Oosterhuis, 2012). This reduction in the number of flowers is due to the response of vegetative growth to water stress and the lack of production of new fruiting branches (Guinn and Mauney, 1984; Mauney, 1986).

Flowering initially increases up the main stem with a typical vertical flowering interval (VFI) of about three days, decreasing as the season progresses to about four days (Mauney, 2012; Oosterhuis and Jernstedt, 1999). Horizontal flowering interval (HFI), the rate at which flowers develop on the same branch, is about six days (Oosterhuis and Jernstedt, 1999). The rate at which main stem nodes are developed on the plant also begins at three days but declines to approximately ten days per main stem leaf as the season progresses (Mauney, 2012). The difference in these developmental rates cause flowering to catch up with nodal development until no new flowers can be developed. At this point, the plant has reached physiological cutout and main stem node production will cease until the carbohydrate stress of boll development is reduced (Mauney, 1986; Mauney, 2012; Oosterhuis and Jernstedt, 1999)

BOLL DEVELOPMENT

When anthesis occurs, the anthers deposit pollen onto the stigma. The pollen subsequently germinates and the pollen tube begins to grow. Poor fertilization and low seed number can occur at high temperatures due to the sensitivity of pollen tube growth (Snider et al., 2011). Twelve to 30 hours following anthesis, fertilization of the egg and endosperm occurs; after four to five days the embryo begins to develop (Mauney, 2012; Stewart, 1986).

The ovule and endosperm develop rapidly followed slowly at first by the embryo which is sustained by the endosperm. The endosperm is ultimately absorbed into the cotyledons which fill the ovule about 24 days after anthesis (DPA) (Leffler, 1976).

Although main stem leaves contribute mainly to vegetative production of both the main stem and sympodial branches, small percentages of the assimilate originating in main stem leaves are translocated to the fruiting structures (Brown, 1968; Oosterhuis and Urwiler, 1988; Wullschleger and Oosterhuis, 1990). Brown (1968) showed that assimilate originating in the main stem is translocated through the phloem to sympodia on the same side of the main stem as the originating leaf. Assimilate originating in the sympodial leaves is almost exclusively translocated to the fruiting structures (Ashley, 1972; Constable and Rawson, 1980). Because carbon production is not synchronized with carbon utilization however, importation of some carbon is still necessary. Mainstem node 8 bolls, for instance, required importation of 60% of carbon; node 10 required 50%, 37%, and 21% imported carbon at the first, second, and third fruiting position; and node 12 bolls did not require imported carbon for boll development (Wullschleger and Oosterhuis, 1990). The developing bolls obtain water and nutrients from subtending leaves through functional phloem in the capsule walls and central column of the boll (Van Iersel et al., 1995). Van Iersel et al. (1995) showed that the xylem vessels do not mature until more than three weeks after boll development has already begun.

The cotton fiber is a single-celled trichome that elongates from the epidermal layer of the ovule and is developed through three main phases: initiation, elongation, and the thickening of the secondary cell wall (DeLanghe, 1986, Seagull and Giavalis, 2004). Initiation occurs when select epidermal cells of the ovule begin to differentiate and protrude from the surrounding cells, similar to a balloon shape, as described by DeLanghe (1986) and Stiff and Haigler (2012). This initiation typically begins shortly before anthesis and can continue to 5 DPA (Seagull and Giavalis, 2004; Stewart, 1975). The central vacuole will expand into the expanding initial and by 2 DPA will take up most of the cell while the nucleus will migrate towards the tip where it will remain.

Each ovule will have on average approximately 16,000 fiber initials with the ratio of differentiated fiber initials to non-differentiated epidermal cells of one to three shortly after anthesis (Seagull and Giavalis, 2004; Stewart, 1975). Because this density of fiber initials at 0 to 1 DPA is positively correlated with lint percentage, humans have been selecting for higher densities of fiber initials during the domestication of cotton (Butterworth et al., 2009; Li et al., 2009). Studies have implicated phytohormones, gibberellic acid (GA) and auxin (IAA), as well as ROS in the initiation of fibers on the ovule. Liao et al. (2009) showed that the addition of a GA biosynthesis inhibitor reduced the number of fiber initials and Yang et al. (2006) found homologs of genes, from other species, involved in GA biosynthesis in cotton. Zhang et al. (2011) showed IAA build up in the ovule at 0 DPA in wild type cotton but not in a fiberless mutant. ROS have also been shown to initiate fiber development on ovules. Zhang et al. (2010) observed fiber initials on a fiberless mutant after being treated with H_2O_2 at 0 DPA.

Fiber elongation begins as early as 1 DPA, becoming more evident at 2 DPA (DeLanghe, 1986; Stewart, 1975; Stiff and Haigler, 2012). The fiber initials begin to elongate and are oriented towards the micropylar end of the cotton seed as the initials begin to taper at the tip (Stewart, 1975). The elongating fibers begin twisting together to form tissue-like bundles as early as 2 to 3 DPA causing a contortion of the fibers (DeLanghe, 1986; Singh et al., 2009). The cotton fiber middle lamella (CFML), an outer layer of the fibers primary cell wall, joins together neighboring fibers creating a unified cell wall, not unlike other plant cell tissues (Singh et al., 2009). The bundles elongate in curved path to surround the seed and the surrounding growth expands until contacting the boll wall by 3 to 5 DPA (Singh et al., 2009; Stiff and Haigler, 2012). At a rate of up to 2 mm day^{-1}, by 14 DPA the fibers will be approximately 20 mm in length and 25 to 35 mm in length by 20 DPA (DeLanghe, 1986; Stiff and Haigler, 2012).

Fiber elongation is driven by the maintenance of high turgor pressure (Oosterhuis and Jernstedt, 1999; Ruan et al., 2001; Stewart, 1975; Stiff and Haigler, 2012). Two of the main regulating factors include the force of turgor pressure against the cell walls as well as the duration of turgor pressure (Ruan et al., 2001; Ruan, 2007). This increased turgor pressure is

achieved through the influx of water, driven by osmotic potential caused mainly by osmotically active soluble sugars, K^+, and malate (Cosgrove, 1997; Ruan et al., 1997, Yang et al., 2016). Expansin proteins, along with other minor enzymes, allow for the loosening of the cell wall to allow for the increased turgor pressure to feed elongation, as shown by the presence of the expansin gene in elongating fibers (Cosgrove, 1997; Ruan et al., 2001; Yang et al., 2016).

To maintain the turgor pressure required for cell expansion, the fiber will reversibly gate the plasmodesmata between the fiber and the ovule (Ruan et al., 2001; Stiff and Haigler, 2012). Ruan et al. (2001) showed that the fiber plasmodesmata would close about 10 DPA and was reopened about 16 DPA. The K^+ and sucrose transporter genes, that facilitate the import of K^+ and sucrose across the plasma membrane, were highly expressed at 10 DPA, resulting in elevated osmotic and turgor potentials during this period of rapid elongation (Ruan et al., 2001; Ruan, 2007). The turgor pressure of the fiber was observed to be similar to the seed coat cells before and after this reversible gating of the plasmodesmata, but elevated during the period of rapid elongation when the plasmodesmata were closed.

The growth type of elongating fiber cells is still an arguing point for scientists (Kim and Triplett, 2001; Qin and Zhu, 2011). One school of thought is that fiber elongation occurs though a diffuse growth pattern based on the fact that the cortical microtubules and cellulose microfibrils are transversely oriented, restricting radial expansion and increasing longitudinal expansion (Seagull, 1990). In a typical tip-growing cell, microtubules are arranged parallel to growth and are typically absent from the growing point (Qin and Zhu, 2011). Other studies have shown that a Ca^{2+} concentration gradient in the fiber tips, along with the response of the Ca^{2+} gradient to ROS, is similar to other tip-growing cells such as root hairs and pollen tubes (Foreman et al., 2003; Huang et al., 2008; Li et al., 2007; Wymer et al., 1997). Qin and Zhu (2011) presented another theory of linear growth, suggesting that cotton fibers elongate through a combination of both diffuse- and tip-growth.

After fiber elongation is complete, around 20 DPA, secondary cell wall thickening begins, although there is transition phase around 16 to18 DPA in which some overlap in the two processes occurs (DeLanghe, 1986; Stiff and Haigler, 2012). During this transition, the

CFML will begin to degrade as the production of cellulose begins to slowly increase (Singhe et al., 2009). This thickening occurs with the deposition of almost pure cellulose, with crystalline cellulose percentages ranging from 90% in wild-type fiber to 92% in modern, transgenic cultivar fibers (Abidi et al., 2010; Haigler et al., 2007; Stiff and Haigler, 2012). Stiff and Haigler (2012) point out however, that due to the methods used to determine the percent of crystalline cellulose, an underestimation of cellulose was likely to occur and that actual cellulose percentage is most likely greater than 95%. Although the genes responsible for fiber elongation are similar to primary wall synthesis genes, genes supporting secondary cell wall thickening are orthologs of genes responsible for secondary wall deposition in xylem tissues of vascular plants (Betancur et al., 2010).

Abidi et al. (2010) briefly described the process of cellulose formation in fibers. Supplied sucrose is transformed by enzymes to glucose and fructose, which is ultimately converted to glucose as well. Several glucose units, through polymerization reactions between glucose units, are then converted into cellulose macromolecules. Although cellulose synthesis can occur from UDP-glucose, cellulose synthesis is more efficient when sucrose is the supplied substrate (Abidi et al., 2010). During secondary cell wall thickening, nearly 80% of the imported carbon is directed to cellulose synthesis (Haigler et al., 2007).

Developing bolls tend to be less sensitive to water stress than leaves and young fruiting structures as they are essentially non-transpiring and are thus more resistant to water loss (Loka and Oosterhuis, 2012; Wullschleger and Oosterhuis, 1990). Although young bolls, with immature xylem connections, are isolated from the whole plant water status, water stress during boll development does decrease yields as bolls prior to 14 DPA will abscise in response to water stress while bolls beyond 14 DPA are generally retained (McMichael et al., 1973). This response of young bolls to water stress is due to the influence of whole plant water deficit on the hormone balance of developing bolls (Guinn, 1976; Guinn and Brummett, 1988). Ethylene evolution rates along with levels of IAA and abscisic acid (ABA) were found to be greater in bolls under water stress than bolls under adequate water conditions (Guinn, 1976; Guinn and Brummett, 1988).

It is not known what finally signals maturation, the termination of secondary cell wall thickening processes. Similarly to xylem elements, it is proposed that programmed cell death could be triggered by ROS (Kim and Triplett, 2001). However signaled, after secondary cell wall thickening, the boll will open and the individual fibers will dry down and collapse into a typical bean shape around 40 to 60 DPA (Stiff and Haigler, 2012).

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COTTON GROWTH AND YIELD RESPONSE TO SHORT-TERM TILLAGE SYSTEMS AND PLANTING DATE IN NORTH CAROLINA

ABSTRACT

In North Carolina it is recommended that cotton (*Gossypium hirsutum* L.) planting occur only after soil temperatures reach 18° C by 10 AM and when warm, dry conditions are predicted for the next five to seven days. These recommendations are based on previous findings showing a reduction in emergence and slowed seedling development when soil temperatures reach 16° C or less in the presence of excess soil moisture. Tillage practices, cover crops, and planting dates are three major factors that can influence soil moisture and temperature conditions at planting. The objective of this study was to evaluate cotton growth, development, and yield in short-term (single season) reduced-till systems with conventional raised beds at multiple planting dates, with and without a cover crop. The study was conducted in North Carolina near Lewiston-Woodville and Rocky Mount from 2014 through 2016. Treatments included six tillage systems of fall and spring conventional raised beds and flat strip tillage planted in early and late May, with and without a wheat (*Triticum aestivum* L.) cover crop. Soil temperatures taken at planting at 5-cm depth in 2015 and 2016 were highest in plots without any spring tillage and in plots with a cover crop in both years and at both locations. With the exception of fall strip tillage, no tillage systems reduced plant populations compared to conventionally tilled cotton in any environment. Crop growth rates, calculated from early season plant samples, were not lower compared to conventional plots by any spring strip-till systems and reduced in only four planting date environments by stale seedbeds. In 2016, in-row soil resistance was measured from 0- to 30-cm depth using a conical penetrometer both at planting and post-harvest. Plots without any spring tillage had the greatest soil resistance for all measurements and depths. All plots with spring tillage had similar soil resistance to at least the 15-cm depth from which point the conventional spring beds had the least soil resistance through the 30-cm profile. Late planted cotton in 2014 showed minor, inconsistent yield differences, as influenced by tillage system, with pre-plant spring strip till having the greatest yields at both locations. When pooled across year and location for the remaining site-year environments, however, tillage system did not influence cotton yield. Similar to previous research, that cotton can be grown in reduced-till systems

with yields comparable to cotton grown in conventional systems in typical eastern North Carolina soils.

INTRODUCTION

Cotton seedlings are susceptible to extended periods of cool, wet soils which can result in reduced and non-uniform stands (Bradow and Bauer, 2010). Imbibing seeds and seedlings are especially sensitive to cool temperatures up to 160 h after planting and growth can cease when temperatures fall below 16° C (Bauer, 2015; Steiner and Jacobsen, 1992). The optimal temperature for cotton seedling emergence is approximately 30° C and Nabi and Mullins (2008) reported a reduction in shoot growth of 44% in the first 180 h after planting when soil temperatures are reduced by only 10° C (Bradow and Bauer, 2010).

Studies have shown that tillage reduces soil moisture at field capacity by as much as 12% by disturbing the soil surface and increasing macropores through which soil water can drain or potentially evaporate (Karlen et al., 1994; Licht and Al-Kaisi, 2005; Zibilske and Bradford, 2007). Tillage-related reductions in soil moisture effectively reduce the soil heat capacity allowing the soil to gain or lose heat faster than in no-till systems (Hillel, 1998). Licht and Al-Kaisi (2005) and Radke (1982) both showed that surface tillage can cause an increase in soil temperatures during daytime hours compared to no-till systems though they have little effect during cool weather. It has been well documented that systems with increased tillage typically have greater daily maximum soil temperatures while varying little in daily minimum soil temperatures compared to no-till systems (Fortin and Hamill, 1994; Fortin and Pierce, 1990; Kladivko et al., 1986).

As revealed in the review by Toliver et al. (2012), tillage effects are often dependent on soil texture. The review of over 400 studies in the southeast United States, pairing conventional and reduced tillage systems, showed that cotton yields are typically greater in no-till systems on sands but lower on loams when compared to conventional tillage (Toliver et al., 2012).

A high soil strength layer can develop in many coastal plain soils restricting root growth of various crops (Busscher and Bauer, 2003; Busscher et al., 1995; Busscher et al., 2006; Kashirad et al., 1967). Naturally occurring hardpans and tillage pans are generally associated with structureless soils, low in organic matter, in a highly weathered, eluviated horizon. These conditions occur in over 50% of coastal plain soils (Busscher et al., 1995;

Busscher et al., 2006; Pabin et al., 1998). Busscher and Bauer (2003) reported penetration resistance (PR) values as high as 4.4 MPa in coastal plain soils. The authors also observed reduced cotton root growth with PR values as low as 2.5 MPa and a 50% reduction in root growth at values of 3.5 MPa, though the reduction in roots did not influence final lint yield (Busscher and Bauer, 2003). Gerard et al. (1982) determined that at soil strength values of 6.0 to 7.0 MPa in coarse-textured soils and 2.5 MPa in clay soils, root growth would be stopped. To alleviate the high strength layers, generally occurring just below the plow layer, subsoiling (deep tillage) is often required annually as hardpans typically begin to reform within one year (Busscher et al., 1995; Threadgill, 1982). Several studies have recently shown that the effects of subsoiling or deep slit tillage may result in an acceptable reduction of hardpan soil strength over multiple years (Busscher and Bauer, 2003; Busscher et al., 1995; Busscher et al., 2006; Laboski et al., 1998).

Maintaining adequate crop growth in clay soils however, requires PR and bulk densities of less than 2.5 MPa and 1.2 Mg m^{-3}, respectively (Gerard, 1982; Snider and Oosterhuis, 2015). Because clay soils are made up of fine particles, increasing bulk density would reduce macropores by forcing small particles into the available macropores. Increasing bulk density in clay soils can reduce porosity to the point that water is held too tightly to be available to the plant or root growth is restricted as the soil strength is too high. A high bulk density in clay soils can also prevent gas exchange with the atmosphere possibly leading to inadequate oxygenation of the soil. Jones (1983) showed that critical bulk density for root growth restriction is inversely related to clay content. As clay content increases, a lower bulk density must be maintained to prevent restriction of root growth. Tillage typically breaks up clay aggregates and reduces organic matter, and over time, intensive tillage can increase the bulk density in clay soils (Brady and Weil, 2010; Meijer et al., 2016). A balance must be reached in soils with high clay content to not decrease soil structure with tillage, which could lead to an increase of bulk density, while still controlling the effects of compaction over time. A similar trend is seen with organic soils in that intensive tillage over time can break down the organic matter in the soil, reducing the benefits given by producing cotton on an organic soil (Brady and Weil, 2010).

Minimizing tillage can also reduce a grower's ability to adequately supply nutrients to the root zone, particularly immobile soil nutrients such as phosphorus and potassium. Without incorporation of these immobile nutrients, P and K can build up in the surface layers and still remain deficient in the root zone (Robbins and Voss, 1991). Phosphorus and K concentrations were 3.5 times higher in the top 5 cm than from 5- to 15-cm depth in no-till systems (Robbins and Voss, 1991). Meijer et al. (2016) recommended correcting all nutrient deficiencies and pH concerns before implementing a no- or reduced-till system.

Tillage also has many indirect effects on cotton growth by influencing plant pests and diseases (Keonning et al., 2004; Parajulee et al., 2006; Rothrock, 2012). In wet years, cotton yields can be reduced when planting on flat, reduced or no-till land. Drainage away from the seed, and subsequent roots, is increased when planting on conventionally-tilled raised beds compared to no-till systems, especially in soils with poor drainage (Kargas et al., 2012; Schwartz et al., 2010). Excess soil moisture at planting in reduce-tilled systems can lead to increased incidence of seedling disease (Colyer and Vernon, 2005; Keonning and Collins, 2016; Minton and Garber, 1983; Rothrock et al., 2012). Reduced tillage can also cause an increase in seedling disease complex causal pathogens due to the pathogens overwintering in remaining root residues (Bell, 1999; Colyer and Vernon, 2005; Rothrock et al., 2012; Sumner et al., 1995).

Insect and nematode pests can also be influenced by tillage systems. Several cultural practices, including conservation tillage and the use of winter cover crops, have been shown to reduce thrips pressure in early season cotton (Knight et al., 2015; Parajulee et al., 2006; Toews et al., 2010). Parajulee et al. (2006) found that western flower thrips numbers were reduced three-fold under conservation tillage when compared to conventional raised beds. Toews et al. (2010) found that thrips pressure reached threshold levels in Georgia less than half as often when cotton was grown with strip tillage than when grown on conventional raised beds. Similarly, significant reductions in early season thrips abundance were observed in cotton following a cover crop (Toews et al., 2010).

Tillage practices to manage nematodes vary by species, though cotton injury from nematodes is highly dependent on soil texture. Increased injury often occurs on coarse

textured soils with positive association with increasing sand content (Keonning and Collins, 2016; Keonning et al., 2004). Lock et al. (2013) showed that tillage increased the population density of reniform nematodes. Alternatively, Columbia lance nematodes' effect on cotton growth can be minimized by subsoiling, especially in fields where a hardpan reduces root development (Keonning and Collins, 2016; Keonning et al., 2004). Jordan et al. (2008) showed that populations of lesion nematode were higher in conventional tillage when compared to reduced tillage but spiral and sting nematodes were lower in conventional tillage when compared to reduced-tillage systems.

The use of cover crops can also play an important role in early-season soil temperatures. It has been well documented that although plastic mulches can increase soil temperatures, organic mulches, including previous crop residue and terminated winter cover crops, tend to reduce the daily maximum soil temperature (Dabney et al., 2001; Vos and Sumarni, 1997). Fortin and Hamill (1994) found that cover crops left standing, compared to terminated cover crops flat on the soil surface, can increase daily maximum soil temperatures. Cover crops that are incorporated into the soil however, typically have little impact on soil temperature (Dabney et al., 2001).

Though multiple comparisons exist between reduced and conventional tillage, there has been only limited research conducted on these tillage systems with various timings of implementation. The objective of this study was to evaluate short-term tillage systems implemented either in the fall or spring, under different environmental conditions, planting dates, and locations and their influence on cotton growth and development in North Carolina.

MATERIALS AND METHODS

Research was conducted from 2014 to 2016 in North Carolina comparing varying short-term (single season) tillage systems at multiple planting dates, with and without the use of a winter cover crop. The experiment was conducted at both the Peanut Belt Research Station (PBRS) located near Lewiston-Woodville, NC on a Norfolk sandy loam (Fine-loamy, kaolinitic, thermic Typic Kandiudults), a Goldsboro sandy loam (Fine-loamy, siliceous, subactive, thermic Aquic Paleudults), and a Rains sandy loam (Fine-loamy, siliceous,

semiactive, thermic Typic Paleaquults) in 2014, 2015, and 2016, respectively, and at the Upper Coastal Plain Research Station (UCPRS) near Rocky Mount, NC on a Aycock very fine sandy loam (Fine-silty, siliceous, subactive, thermic Typic Paleudults), a Rains fine sandy loam, and a Norfolk loamy sand in 2014, 2015, and 2016, respectively. Treatments were arranged in a split plot design with planting date serving as whole plot units and a factorial of tillage system with and without a winter cover crop as subplot units. Plots for each combination of planting date and tillage system were four rows (91-cm row spacing) by 12 m in length, with each combination replicated four times. Plots were planted with Stoneville 4946 GLB2 (Bayer Crop Science, Raleigh, NC) at a rate of 9.8 seed per m row (108,160 seed ha^{-1}) with 112 kg ha^{-1} of 18-46-0 starter fertilizer. Cotton was maintained using North Carolina extension recommendations in regards to all pest management, fertility, and harvest decisions (Edmisten, 2016).

The planting dates used in this study were chosen to represent both early and late planted cotton in eastern North Carolina and ranged from 2 May to 9 May for the early planting, and from 21 May to 29 May for the late planting (Table 1). Six tillage systems were implemented in either the fall or spring and consisted of two bedded systems at varying times, three strip-tilled systems at varying times, and one system including fall bedding followed by strip tillage in the spring (Table 2). All bedded systems were subsoiled at a depth of 30 cm and bedded and strip-till systems were applied with a strip tillage implement consisting of two sets of coulters and basket attachments following in-row subsoiling at 30-cm depth. Two spring strip-till systems were included in the spring, one implemented the day of planting and one implemented two weeks prior to planting. The latter treatment was included after grower testimony of herbicide injury in at-planting, strip-till cotton as the seed bed settled forming a channel directly above the seed. The latter treatment might also prevent reduction of pre-plant herbicide efficacy activity due to soil disturbance at planting. In all years, tillage was implemented directly into corn residue from the previous season at the PBRS. At UCPRS the field was prepared by both disking and field cultivating in the fall before any tillage system treatments were implemented.

Each of the tillage systems was included with and without wheat cover crop drilled each fall on the date of fall tillage implementation (Table 1). The cover crop consisted of the wheat variety NC Yadkin, drilled at a rate of 145 kg ha^{-1}. The cover crop was burned down prior to any tillage implementation in the spring and was either left standing or incorporated into the soil depending on the tillage system, but no cover crop was left flat on the soil surface.

Beginning in 2015, soil temperatures at a 5-cm depth were measured at planting directly beneath the seed furrow. Temperatures were measured within three days of planting between 1000 h and 1100 h for all environments with the exception of the early planting at the UCPRS in 2016. Soil temperatures at that time were measured in the afternoon hours on the day of planting, between 1500 h and 1600 h because of impending poor weather.

Measurements of soil PR were taken from the center of the row in 2016, using a Fieldscout SC900 Soil Compaction Meter (Spectrum Technologies, Inc., Aurora, Illinois) with a 12.5-mm diameter cone. Penetration resistance values are presented in 5-cm depth increments from 0- to 30-cm depth. Penetration resistance measurements were taken at PBRS and UCPRS both at planting and post-harvest and each location and measurement timing are presented separately due to the influence of soil type and soil moisture at the time of the measurement.

Early season plant samples were taken by cutting plants at the soil surface from 0.5 m of row from each of the two outside rows for a total of 1 m at 15, 25, and 35 days after planting (DAP). Plant samples were then dried at 100° C for 48 h, at which point a sample would be weighed and returned to the drier. This same sample would be weighed every 24 h until a constant weight was reached. After a constant weight was reached in the sample, all plant samples were weighed to determine the dry weight of plant material. Of the plant samples taken at 15, 25, and 35 DAP, the dry weight of each sample was used to calculate the mean crop growth rate (CGR) for the three intervals beginning at emergence (DW = 0). Crop growth rate was calculated using the following relationship: $CGR=(DW_2 – DW_1)/days$, where DW_2 is the dry weights at the second date and DW_1 is the dry weight at the first sampling date. Plant population was determined two weeks after emergence.

The two center rows of each plot were machine harvested from late October through early November in each season and seed cotton samples from each plot were ginned to determine turnout lint percentage. Data were analyzed as a split plot design and subjected to analysis of variance using the PROC GLM in SAS 9.4 (SAS Institute Inc., Cary, North Carolina) with corrected error terms for fixed and random effects. Means were separated using Fisher's Protected LSD test at $P \leq 0.05$ (Carmer et al., 1989; Moore and Dixon, 2015). Lint percentage of each sample was analyzed as described, and it was determined that lint percentage did not differ due to main effects when pooled over 2014 and 2016 environments. Therefore, these seed cotton yields were converted to lint yield with the average lint percentage of 42%. When pooled over both locations in 2015, lint percentage was influenced by the main effect of planting date. Seed cotton yields for these environments were converted to lint yield using the average lint turnout of 47% for the early planting date and 44% for the late planting date.

RESULTS AND DISCUSSION

Precipitation totals for the period from one week prior to planting until three weeks following planting are presented in Figure 1 (CRONOS, 2016). The rainfall total during this period surrounding the early planting date in 2014 at PBRS was over 12 cm; however, 8.5 cm of this total came in one precipitation event that occurred two weeks after planting. Locations for the early planting date in 2016 received over 17 cm and 10 cm during this four-week period at PBRS and UCPRS, respectively. During this period surrounding the early planting date, measureable rainfall was received at PBRS on 17 of 28 days and on 15 of 28 days at UCPRS.

With the exception of soil PR, the interaction of planting date and tillage was significant for most of the data measured and therefore will be presented by planting date.

In 2015, the interaction of environment and tillage was significant for soil temperatures taken at the late planting date but was not significant for soil temperatures taken at the early planting date (Table 3). Plots without any spring tillage had the greatest soil temperatures and plots with conventional tillage had the lowest soil temperatures at planting.

In 2016, the interaction of environment and tillage was significant for soil temperatures taken at the early planting date, but was not significant for soil temperatures taken at the late planting date (Table 3). Trends in 2016 were similar to those observed in 2015. Plots without spring tillage had the greatest soil temperatures and conventional tillage plots had the lowest, with the exception of the early planting date at UCPRS in which conventionally-tilled plots had the greatest soil temperatures. The measurements taken for the early planting at UCPRS in 2016 were taken on the afternoon of planting between 1500 h and 1600 h, compared to all other measurements which were taken between 1000 h and 1100 h. This is similar to previous findings in that increasing tillage intensity will yield a greater increase in maximum soil temperatures during daytime hours (Kladivko et al., 1986; Licht and Al-Kaisi, 2005; Radke, 1982). The presence of a cover crop increased soil temperatures when pooled across year, location, and planting date with no interactions (Table 3). The cover crop was either left standing or incorporated, depending on the tillage system, and the findings were similar to those previously reported in that standing cover crops can increase soil temperatures (Fortin and Hamill, 1994)

The interaction of environment and tillage was significant for plant population as was the interaction between planting date and tillage with the exception of plant populations measured at UCPRS in 2016 (Table 4). The early planting date tended to have greater plant populations than the late planted in all environments except in 2016 when PBRS received 17 cm of precipitation around the early planting date, reducing the plant population of early planted cotton. Plant populations were the lowest in fall strip tillage systems and the greatest in pre-plant strip tillage systems in five of six environments when differences were observed. Fall strip tillage systems reduced plant populations an average of 26% compared to the plots with the greatest plant populations. With the exception of fall strip till systems, all strip till and stale seedbed systems had plant populations as great or greater than conventional tillage systems in all environments when differences were observed. The presence or absence of a cover crop did not influence plant populations.

Penetration resistance was measured only for the late planting date at PBRS and only the early planting date at UCPRS. Due to the influence of soil water content and soil type on

PR measurements, comparisons were made only within location and measurement timing. At-planting measurements taken at UCPRS tended to have lower PR throughout the profile than that measured post-harvest, most likely due to the shorter interval between the date of tillage implementation and the date of PR measurement (Figure 2). These differences were not as apparent at PBRS, with three tillage systems having greater PR at planting, at various depths throughout the profile, when compared to those measured post-harvest (Figure 3). Unlike UCPRS, the lack of differences between the at-planting and post-harvest measurement at PBRS is most likely due to increased soil water content after harvest, though this was not measured.

Soil PR at PBRS was greatest through all depths in plots without any spring tillage both at planting (Table 5) and post-harvest (Table 6). At UCPRS, for both at-planting (Table 7) and post-harvest measurements (Table 8), plots without spring tillage had the greatest PR through the 15-cm depth. From 15 to 30 cm, both at-plant and pre-plant strip till had high PR similar to plots without spring tillage. In all measurements, plots with some form of spring tillage had similar PR through at least 15-cm depth, from which point conventional tillage had the least PR throughout the remainder of the profile.

Early planting CGR means from emergence to 15 DAP were pooled across all 2014 and 2016 environments as there was no significant interaction between environment and tillage. Crop growth rate means from 2015 are presented by location due to a significant interaction of location and tillage (Table 9). Late planting means were pooled across all environments, except for UCPRS in 2014 when measurements were not taken, due to the lack of significant interactions of environment and tillage. Cotton grown under fall strip tillage was the only cotton to be among the lowest averaging CGR in every environment. This tillage system reduced emergence to 15 DAP CGR by an average of 17% compared to the plots with the greatest CGR. Pre-plant, strip-till systems had the greatest emergence to 15 DAP CGR in all but one environment and did not differ from the greatest CGR in this environment.

Similar trends were observed in mean CGR from 15 to 25 DAP CGR because the fall strip-till system reduced CGR by an average of 42% compared to tillage systems with the

greatest CGR (Table 10). With the exception of only PBRS in 2016, all mean CGR values from 15 to 25 DAP were pooled as there were no significant interactions between planting date, environment, or tillage. There was no difference in CGR between tillage systems at the early planting date at PBRS in 2016. This lack of differences is most likely due to the excess precipitation received around the early planting date at this site, as previously discussed. Plots without any spring tillage at the late planting date, however, had reduced 15 DAP to 25 DAP CGR compared to plots including some form of spring tillage. When pooled across all remaining environments, the fall strip-till system had the lowest CGR while pre-plant strip tillage had the greatest, with all plots with some form of spring tillage being similar.

When pooled across all environments in 2014 and 2016 no differences in 25 to 35 DAP mean CGR values were observed between tillage treatments in early planted cotton, nor were differences observed in late planted cotton at UCPRS in 2014 (Table 11). When differences were observed in all remaining environments, the fall strip-till system had among the lowest mean CGR values.

Across all three CGR values calculated, the pre-plant strip-till system was the only tillage system to have the greatest, or similar to the greatest, CGR in every environment when differences were observed. Stale seedbeds and strip-till systems did however, have CGR values as great, or greater than, conventional-till systems in 26 of 30 and 30 of 30 comparisons, respectively. Although the late planted cotton tended to have a greater average CGR due to increased temperatures as the seasons progressed, the presence, or absence, of a cover crop influenced the average CGR in only two environments. The absence of a cover crop increased emergence to 15 DAP CGR in early planted cotton at PBRS in 2015 (Table 9) and increased 15 DAP to 25 DAP CGR by 20% in the late planted cotton at PBRS in 2016 (Table 10). The lack of a response in CGR to the presence of a cover crop in most environments is similar to previous findings, especially when high residue levels are not achieved (Price et al., 2016; Reddy et al., 2004).

Similar to previous research, tillage and planting date did not influence lint percentage when pooled across 2014 and 2016 (O'Berry et al., 2008; Pettigrew and Meredith,

2009; Wrather et al., 2008). However, early-planted cotton in 2015 had greater lint percentage compared to that of the late-planted cotton.

In the first year of the study, 2014, a significant interaction between planting date and tillage system was observed for cotton lint yield (Table 12). Early planted cotton yield was not influenced by tillage system or cover crop. Minor, inconsistent differences in late planted cotton however, were observed at both locations. Cotton grown under the pre-plant strip-till system had the greatest yield at both locations, while fall strip till plots and conventional till plots had the lowest yields at PBRS and UCPRS, respectively. Cotton lint yield did not differ as influenced by tillage or planting date in all of 2015 and 2016 environments (Table 12). This lack of difference due to planting date is not uncommon for the dates used in this study. Edmisten and Collins (2016) reported that on average, late planted yields did not tend to fall below early planted yields unless planting extends past 10 June in North Carolina.

Although the influence of cover crop on most of the data observed during this study was inconsistent at best, the presence of a cover crop did increase cotton lint yields in 2015 and 2016 (Table 12). Although not quantified in this study, this increase in lint yield could be due to increased soil water content in plots with a cover crop as described by Fortin and Hamill (1994) and Radke (1982), although it is questionable as to whether the cover crop biomass achieved in this study could significantly affect soil water content. Cover crops can also reduce thrips abundance in early-season cotton, though there were no symptoms of increased thrips injury in any plots.

CONCLUSIONS

With the exception of the fall strip-till system, stale seedbeds and strip-till systems rarely differed from the conventional-till system in most of the measured data. Soil temperatures were lower in plots with spring tillage and most often lowest in conventional-till plots, though these temperatures were taken in the morning hours and soil temperatures would most likely increase throughout the day. As shown by the soil temperatures taken between 1500 h and 1600 h at UCPRS in 2016, it is possible that plots with spring tillage would have higher maximum daily soil temperatures compared to plots without spring

tillage. This would be due to a reduced heat capacity in the soil and the influence of air temperatures on shallow soil temperatures as discussed by Licht and Al-Kaisi (2005). Plant populations were never reduced by any tillage system compared to conventional-till plots, except for fall strip till, and early season CGR was reduced by stale seedbeds in only three planting date environments while never being reduced by any spring strip tillage. Penetration resistance was the lowest in conventional-till plots but, as also reported by Busscher and Bauer (2003), reduced soil strength did not lead to an increase in yields. Yields did not differ, with the exception of late planted cotton in 2014, in which conventional-till cotton had the lowest yields at one location. These results indicate that these reduced-till systems are comparable to conventional tillage in eastern North Carolina cotton production.

As discussed in the review by Toliver et al. (2012), however, cotton does not respond to tillage equally in all soil textures. The data in this study were collected on similar, sandy loam soils. Cotton grown on varying soil types, even in North Carolina, may respond differently to these tillage systems. This study is also limited in the evaluation of cotton response to the presence of a cover crop. Although planting of the cover crop was as timely as possible, due to the timing of the previous crop harvest, the cover crop was not established early enough, nor managed, to ensure the presence of a high residue cover for cotton planting.

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Table 1. Dates of implementation of fall tillage, cover crop planting, pre-plant spring tillage, and planting date at Peanut Belt Research Station (PBRS) and at Upper Coastal Plain Research Station (UCPRS) for both early and late planted cotton from 2014 to 2016.

		PBRS			UCPRS		
		Fall Till & Cover	Pre-Plant† Spring Till	Plant Date	Fall Till & Cover	Pre-Plant Spring Till	Plant Date
2014	Early	18 Nov	28 Apr	5 May	19 Nov	28 Apr	9 May
	Late		20 May	28 May		19 May	29 May
2015	Early	2 Dec	23 Apr	6 May	4 Dec	23 Apr	8 May
	Late		6 May	21 May		8 May	22 May
2016	Early	7 Dec	18 Apr	5 May	18 Nov	18 Apr	2 May
	Late		10 May	24 May		11 May	25 May

† All spring tillage was implemented the day of planting with the exception of pre-plant strip till which was implemented two weeks prior to the day of planting.

Table 2. Description of short-term tillage systems evaluated at the Peanut Belt Research Station and at the Upper Coastal Plain Research Station from 2014 to 2016.

Tillage System	Fall Tillage	Spring Tillage
Conventional	-	Bed
Fall Strip Till	Strip Till	-
Stale Seedbed	Bed	-
At-Plant Strip Till	-	Strip Till
Pre-Plant Strip Till[§]	-	Strip Till
Fall Bed/Spring Strip	Bed	Strip Till

† All spring tillage was implemented the day of planting with the exception of pre-plant strip till which was implemented two weeks prior to the day of planting.

Table 3. Influence of six tillage systems and cover crop on soil temperatures for early and late planted cotton in 2015 and 2016 at both the Peanut Belt Research Station (PBRS) and the Upper Coastal Plain Research Station (UCPRS). Early planting means in 2015 and late planting means in 2016 were pooled across location as there was no significant interaction between location and tillage. Cover crop means were pooled across location, year, and planting date as there was no significant interaction.

	Early Plant			Late Plant			2015-2016
Tillage System	2015	2016		2015		2016	
		PBRS	UCPRS	PBRS	UCPRS		
	Temperature (^{o}C)						
Conventional	17.98 c†	17.22 cd	26.17 a	24.86 bc	24.17 c	22.87 b	-
Fall Strip Till	18.76 a	17.43 a	25.59 b	24.93 bc	24.43 a	23.91 a	-
Stale Seedbed	18.65 a	17.15 de	26.04 b	25.21 a	24.36 ab	23.66 a	-
At-Plant Strip Till	18.34 b	17.30 bc	25.29 b	24.83 c	24.38 ab	22.78 b	-
Pre-Plant Strip Till	18.25 b	17.38 ab	24.79 c	24.96 bc	24.28 bc	23.00 b	-
Fall Bed/Spring Strip	18.30 b	17.05 e	25.29 b	25.09 ab	24.19 c	22.94 b	-
LSD	0.14	0.122	0.38	0.23	0.14	0.41	-
Cover Crop	-	-	-	-	-	-	21.94 a
Bare	-	-	-	-	-	-	21.86 b
LSD	-	-	-	-	-	-	0.07

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 4. Influence of six tillage systems and planting date on plant populations at the Peanut Belt Research Station (PBRS) and at the Upper Coastal Plain Research Station (UCPRS) for both early and late planted cotton in 2015 and 2016.

Tillage System	PBRS				UCPRS		
	2015		2016		2015		2016
	Early	Late	Early	Late	Early	Late	
	plants ha^{-1}						
Conventional	94592 a†	75763 b	60745	81815 a	82264 b	82264 cd	94368 abc
Fall Strip Till	77109 b	45727 c	59176	46848 b	96610 a	77333 d	82152 d
Stale Seedbed	93920 a	67246 b	58504	43261 b	93023 a	92799 ab	90670 bc
At-Plant Strip Till	91678 a	74643 b	52452	74195 a	94144 a	86299 bc	95153 ab
Pre-Plant Strip Till	97731 a	88764 a	65677	73970 a	100869 a	97730 a	89773 c
Fall Bed/Spring Strip	97282 a	71953 b	57831	80919 a	96386 a	78677 cd	97170 a
LSD	7054	10150	-	9336	8351	7947	5133
Planting Date							
Early	92052		59064		93883		96759
Late	70683		66835		85850		86336

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 5. Influence of six tillage systems on at-planting soil penetration resistance from 0- to 30-cm depth at the Peanut Belt Research Station.

	Soil Depth (cm)					
Tillage	0-5	5-10	10-15	15-20	20-25	25-30
	Penetration Resistance (MPa)					
Conventional	0.13	0.17 b†	0.11 c	0.07 c	0.06 d	0.08 c
Fall Strip Till	0.16	0.49 a	0.63 a	0.66 a	1.00 a	2.31 a
Stale Seedbed	0.18	0.57 a	0.74 a	0.76 a	1.03 a	2.05 a
At-Plant Strip Till	0.13	0.25 b	0.26 b	0.20 b	0.49 bc	1.46 b
Pre-Plant Strip Till	0.11	0.20 b	0.16 bc	0.17 bc	0.55 b	1.36 b
Fall Bed/Spring Strip	0.11	0.25 b	0.18 bc	0.09 bc	0.11 cd	1.14 b
LSD	-	0.12	0.14	0.12	0.38	0.55

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 6. Influence of six tillage systems on post-harvest soil penetration resistance from 0- to 30-cm depth at the Peanut Belt Research Station.

	Soil Depth (cm)					
Tillage System	0-5	5-10	10-15	15-20	20-25	25-30
	Penetration Resistance (MPa)					
Conventional	0.13 b†	0.21 cd	0.27 bc	0.34 b	0.43 b	0.46 e
Fall Strip Till	0.27 a	0.56 a	0.68 a	0.86 a	1.28 a	2.91 ab
Stale Seedbed	0.16 b	0.42 b	0.60 a	0.94 a	1.58 a	3.11 a
At-Plant Strip Till	0.17 b	0.23 cd	0.14 c	0.24 b	0.43 b	1.89 cd
Pre-Plant Strip Till	0.18 b	0.34 bc	0.33 b	0.37 b	0.72 b	2.40 bc
Fall Bed/Spring Strip	0.12 b	0.18 d	0.14 c	0.18 b	0.34 b	1.65 d
LSD	0.08	0.14	0.15	0.21	0.39	0.62

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 7. Influence of six tillage systems on at-planting soil penetration resistance from 0- to 30-cm depth at the Upper Coastal Plain Research Station.

	Soil Depth (cm)					
Tillage System	0-5	5-10	10-15	15-20	20-25	25-30
	Penetration Resistance (MPa)					
Conventional	0.39 b†	0.61 b	0.57 c	0.66 b	0.63 c	0.69 b
Fall Strip Till	0.62 a	1.19 a	1.30 a	1.53 a	1.89 ab	1.69 a
Stale Seedbed	0.52 ab	1.03 a	1.20 ab	1.66 a	2.24 a	2.24 a
At-Plant Strip Till	0.36 b	0.60 b	0.78 c	1.13 ab	1.39 abc	2.03 a
Pre-Plant Strip Till	0.50 ab	0.75 b	0.87 bc	1.16 ab	1.50 abc	1.89 a
Fall Bed/Spring Strip	0.41 b	0.54 b	0.69 c	0.81 b	1.13 bc	1.69 a
LSD	0.18	0.23	0.41	0.68	0.87	0.76

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 8. Influence of six tillage systems on post-harvest soil penetration resistance from 0- to 30-cm depth at Upper Coastal Plain Research Station.

	Soil Depth (cm)					
Tillage	0-5	5-10	10-15	15-20	20-25	25-30
	Penetration Resistance (MPa)					
Conventional	0.43 c†	0.80 c	0.99 c	1.28 c	1.28 c	1.48 c
Fall Strip Till	1.11 a	1.92 a	2.22 a	2.87 a	2.88 a	2.85 ab
Stale Seedbed	0.66 b	1.30 b	1.96 ab	2.33 ab	2.94 a	3.41 a
At-Plant Strip Till	0.63 bc	1.05 bc	1.40 bc	2.40 ab	2.72 ab	3.59 a
Pre-Plant Strip Till	0.64 bc	1.16 bc	1.17 c	1.66 bc	1.88 bc	2.23 bc
Fall Bed/Spring Strip	0.52 bc	0.99 bc	1.29 c	1.78 bc	2.95 a	3.59 a
LSD	0.22	0.42	0.60	0.77	0.91	0.88

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 9. Influence of six tillage systems and presence of a cover crop on average crop growth rate (CGR) from emergence to 15 days after planting for early and late planted cotton from 2014 to 2016 at both Peanut Belt Research Station (PBRS) and Upper Coastal Plain Research Station (UCPRS). Early planting means were pooled across all 2014 and 2016 environments as there was no significant interaction between environment and tillage while 2015 means are presented by location. Late planting means were pooled across all environments except for UCPRS in 2014 when measurements were not taken.

	----------Early Plant----------			Late Plant
	2014, 2016	2015		2014 - 2016
Tillage System		PBRS	UCPRS	
	----------CGR (g m^{-2} d^{-1})----------			
Conventional	0.146 bc†	0.925 b	0.963 a	0.448 b
Fall Strip Till	0.148 bc	0.855 c	0.900 b	0.365 c
Stale Seedbed	0.164 ab	0.940 ab	0.897 b	0.465 b
At-Plant Strip Till	0.126 c	0.930 ab	0.899 b	0.454 b
Pre-Plant Strip Till	0.177 a	0.975 a	0.944 a	0.536 a
Fall Bed/Spring Strip	0.138 bc	0.954 ab	0.929 ab	0.470 a
LSD	0.028	0.148	0.034	0.44
Cover Crop	0.153	0.913 b	0.918	0.452
Bare	0.146	0.946 a	0.926	0.470
LSD	-	0.026	-	-

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 10. Influence of six tillage systems and presence of a cover crop on average crop growth rate (CGR) from 15 days after planting to 25 days after planting for early and late planted cotton from 2014 to 2016 at both Peanut Belt Research Station (PBRS) and Upper Coastal Plain Research Station. With the exception of PBRS 2016, all means were pooled across year, location, and planting date as there were no significant interactions. There was an interaction of planting date and tillage at PBRS in 2016 and means are presented for each planting date separately.

		PBRS 2016	
Tillage System	2014-2016	Early Plant	Late Plant
	---------- CGR (gram m^{-2} day^{-1}) ----------		
Conventional	0.518 ab†	0.06	1.205 ab
Fall Strip Till	0.317 c	0.049	0.907 bc
Stale Seedbed	0.471 b	0.052	0.791 c
At-Plant Strip Till	0.512 ab	0.062	1.441 a
Pre-Plant Strip Till	0.603 a	0.098	1.304 a
Fall Bed/Spring Strip	0.574 ab	0.052	1.375 a
LSD	0.104	-	0.339
Cover Crop	0.499	0.062	1.060 b
Bare	0.508	0.063	1.281 a
LSD	-	-	0.196

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 11. Influence of six tillage systems on average crop growth rate (CGR) from 25 days after planting to 35 days after planting at Peanut Belt Research Station (PBRS) and at Upper Coastal Plain Research Station (UCPRS) for both early and late planted cotton from 2014 to 2016. Early planting means were pooled across locations and years for 2014 and 2016 and only across locations in 2015. Late planted means are pooled across location for each year with the exception of 2014 which is presented by location.

	Early Plant		Late Plant			
Tillage System	2014,2016	2015	2014		2015	2016
			PBRS	UCPRS		
	---------- CGR (gram m-2 day-1) ----------					
Conventional	0.674	0.503 bc†	1.918 b	0.605	1.567 cd	4.233 a
Fall Strip Till	0.805	0.278 d	2.367 b	1.056	1.173 d	2.395 b
Stale Seedbed	0.733	0.656 ab	2.358 b	1.143	1.867 bc	2.649 b
At-Plant Strip Till	0.710	0.813 a	1.732 b	0.812	2.213 ab	4.177 a
Pre-Plant Strip Till	0.875	0.752 ab	3.607 a	0.739	2.462 a	3.697 a
Fall Bed/Spring Strip	0.805	0.723 ab	2.619 ab	1.233	1.525 cd	4.211 a
LSD	-	0.291	1.067	-	0.590	0.830

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 12. Influence of six tillage systems and presence of a cover crop on cotton lint yield for early and late planted cotton from 2014 to 2016 at both Peanut Belt Research Station (PBRS) and Upper Coastal Plain Research Station (UCPRS). Early planted cotton yields were pooled across both locations in 2014 while late planted cotton is presented by location due to a significant interaction of tillage and location. Cotton lint yields in all 2015 and 2016 environments are pooled across year, planting date and location.

	2014			2015-2016
	Early Plant	Late Plant		
Tillage System		PBRS	UCPRS	
	----------	Lint yield (kg ha^{-1})	----------	
Conventional	1895	1987 ab†	1132 b	1239
Fall Strip Till	1879	1580 c	1349 a	1194
Stale Seedbed	1910	1864 ab	1362 a	1178
At-Plant Strip Till	1845	1842 b	1257 ab	1258
Pre-Plant Strip Till	1784	2046 a	1365 a	1214
Fall Bed/Spring Strip	1828	1979 ab	1181 b	1244
LSD	-	184	167	-
Cover Crop	1832	1901	1267	1245 a
Bare	1881	1865	1286	1198 b
LSD	-	-	-	34

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

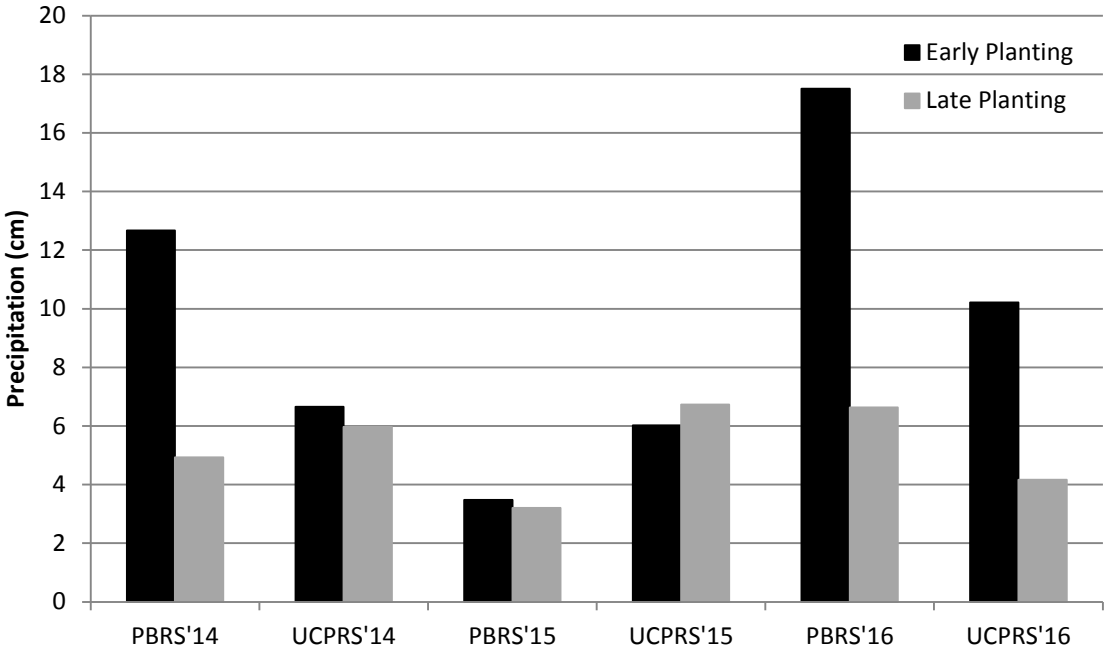

Figure 1. Precipitation totals for the period from one week prior to until three weeks following each planting date by location and year. During this period surrounding the early planting date, measureable rainfall occurred at Peanut Belt Research Station (PBRS) on 17 of 28 days, and on 15 of 28 days at Upper Coastal Plain Research Station (UCPRS).

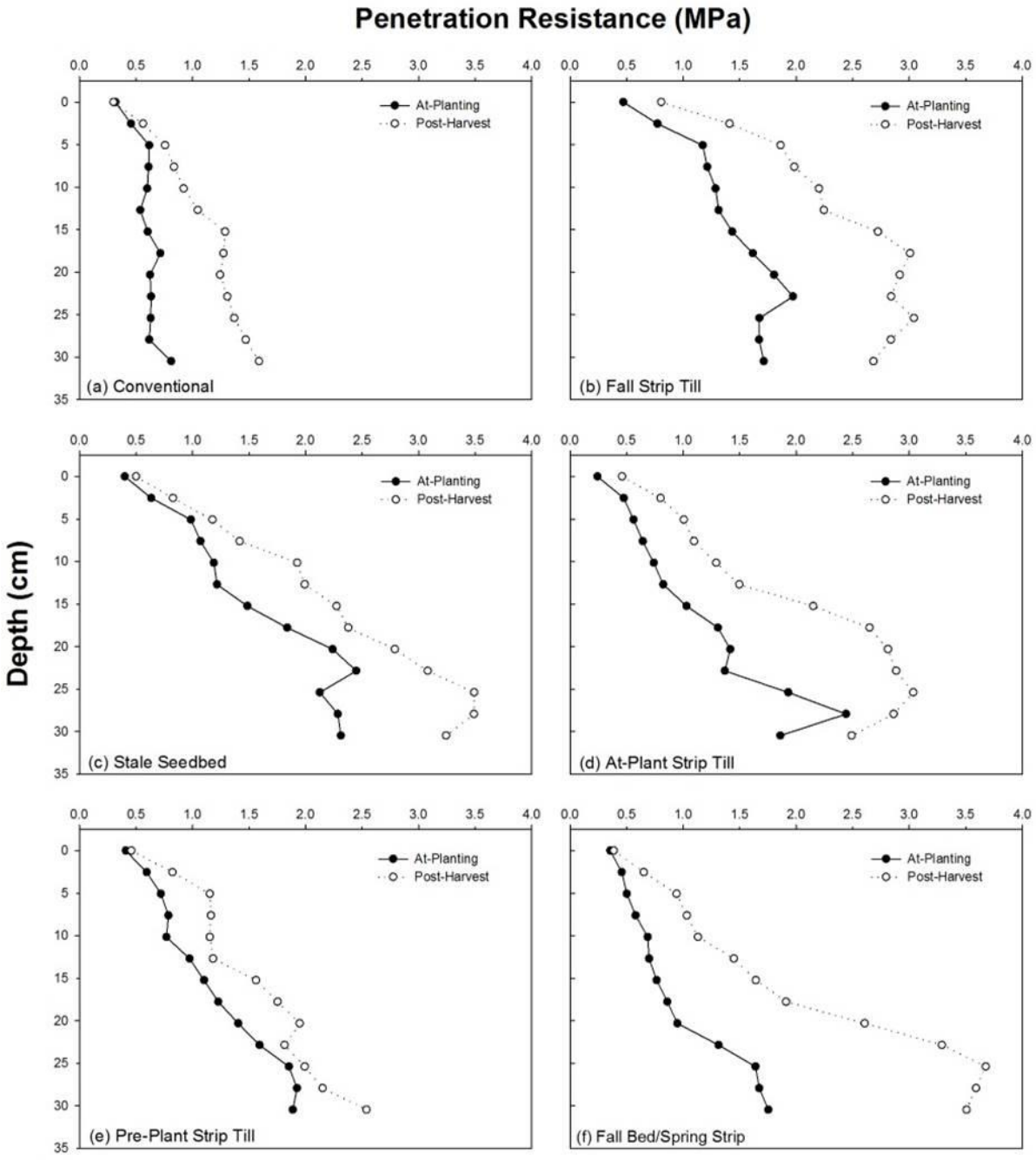

Figure 2. Observed penetration resistance (PR) plotted against soil depth per tillage system at planting and post-harvest at the Upper Coastal Plain Research Station. Soil water contents were different at planting and post-harvest and PR is not directly comparable

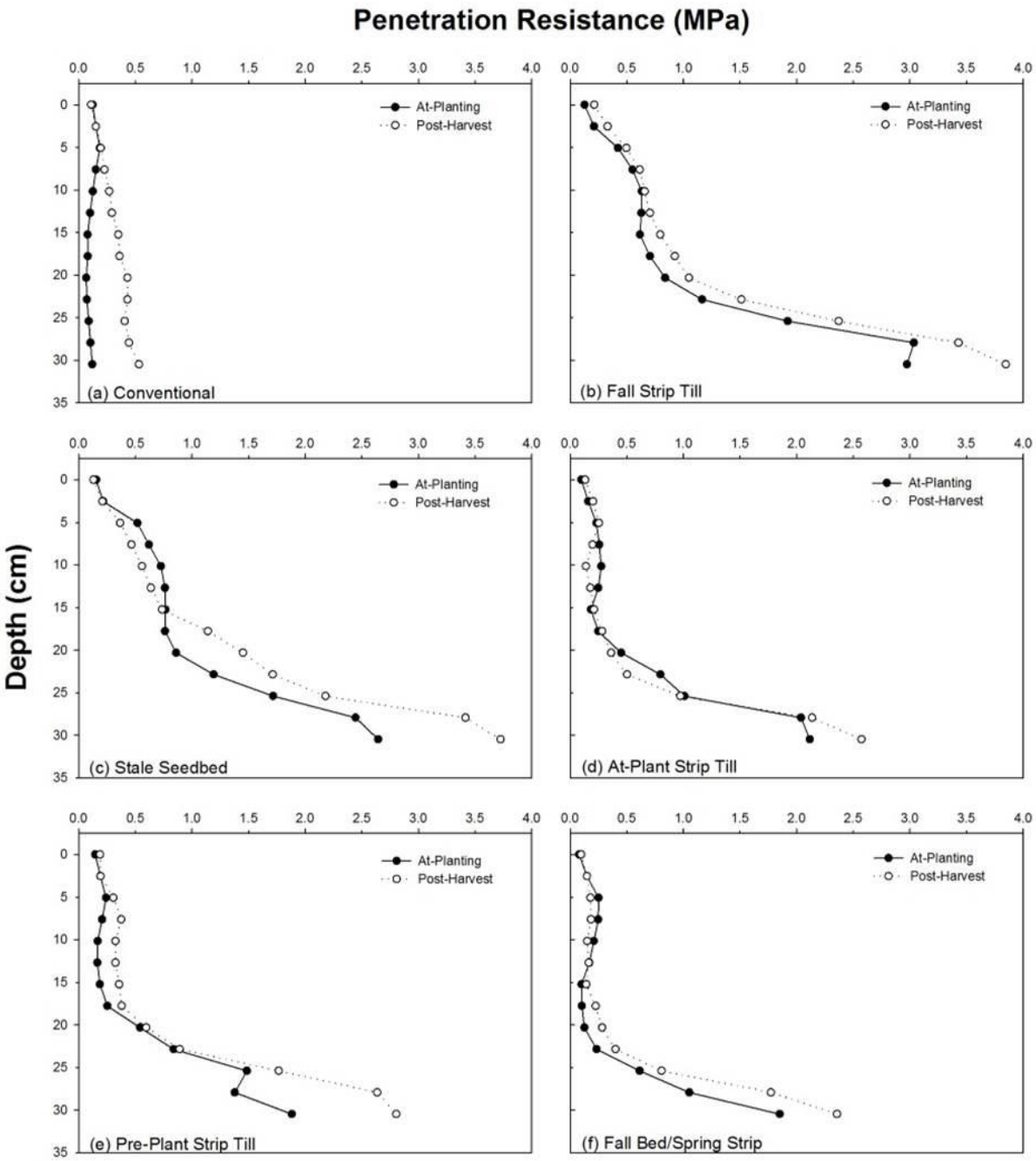

Figure 3. Observed penetration resistance (PR) plotted against soil depth per tillage system at planting and post-harvest at the Peanut Belt Research Station. Soil water contents were different at planting and post-harvest and PR is not directly comparable

UPLAND COTTON GROWTH AND YIELD RESPONSE TO INCREASED INPUTS AND PLANTING DATE ACROSS THE MID-SOUTH AND SOUTHEAST COTTON BELT

ABSTRACT

Along with the increasing cost of cotton seed and chemicals required to control pests in cotton, growers are often pressured to incur additional expenses in the name of plant health. The objectives of this study were to evaluate several representative inputs used in cotton production systems on cotton growth and development compared to current extension recommendations and to determine the yield and economic gain from the use of these inputs. The inputs chosen for this study included a 150% soil fertility program, in-furrow fungicide, in-furrow insecticide, early season foliar fungicide, and late season foliar potassium fertilization. Each of the inputs was included as an individual treatment and in a high-input treatment consisting of all five inputs together along with a control treatment based on the local extension recommendations of each state participating in the trial. Each treatment was included at both an early and late planting date from 2014 through 2016 in Missouri, Mississippi, North Carolina, and Virginia. Plant populations and plant heights at 5 weeks after planting (WAP) were not influenced by inputs except for a reduction in plant population of the 150% fertility treatment when compared to local extension recommendations in 2016. Thrips injury rating at 3 WAP was reduced by treatments including the in-furrow insecticide compared to the control in two of three years in both North Carolina and Virginia. This reduction in thrips injury was not observed in Missouri or Mississippi however, due to the resistance of tobacco thrips (*Frankliniella fusca*) to the neonicotinoid class of insecticides that has been found in the Mid-South. Although none of the inputs increased cotton lint yield, plant date did influence most parameters with late planted cotton having greater plant heights and lower thrips injury. Late planted cotton however, had reduced yields in seven of the 11 environments. Due to the lack of a yield increase, the cost of any of the additional inputs was not recovered, with the greatest economic loss being that of the high-input treatment. Each of the additional inputs included in this study is an extension recommended treatment for use under specific circumstances or thresholds and should not be used as a blanket agronomic treatment in the name of plant health.

INTRODUCTION

The cost of cotton production has been steadily increasing since 1995. Chemical costs have increased 11% since 2005 and 35% since 1995 (USDA-ERS, 2016a). Fertilizer costs have increased 120% since 2005 and 93% since 1995 (USDA-ERS, 2016a). The greatest increase however is seed cost, increasing by 91% since 2005 and 551% since 1995 (USDA-ERS, 2016a). The total cost of inputs since 2005 has increased 44% while the total gross value of cotton fiber and cottonseed has increased only 22% (USDA-ERS, 2016a).

Much advancement in cotton production has led to this increased cost of production. Genetic enhancements to improve yield and ease of maintenance have occurred through breeding efforts. Such breeding efforts have increased cotton yields while reducing plant size and increasing earliness in modern cultivars (Wells, 2016; Wells and Meredith, 1984; Wells and Meredith, 2012). Modern cultivars show a reduction in the vegetative to reproductive structure ratio, leading to increased fruiting structure biomass and improved yields (Wells, 2016; Wells and Meredith, 1984; Wells and Meredith, 2012).

The introduction of new technology, including plant incorporated protectants and herbicide tolerance in the 1990s, has also increased ease of production while continuing the trend of increasing seed cost (Culpepper and York, 1998; Nida et al., 1996; USDA-ARS, 2000). Since 1996, the adoption rate for Bt (*Bacillus thuringiensis*) cotton and herbicide-tolerant cotton has steadily increased to 84% and approximately 90% of planted hectares, respectively (USDA-ERS, 2016b). Although initially simplifying the management of the cotton bollworm (tobacco budworm, *Heliothis virescens* F., and cotton bollworm, *Helicoverpa zea* B.) and weed complexes, these technologies have shown recent downfalls including the selection for Bt-resistant bollworms in sweet corn with similar Cry toxins to those used in cotton cultivars, as well as several herbicide-resistant weed species (Culpepper, 2006; Dively et al., 2016; Norsworthy et al., 2012). Due to the diminishing control of cotton bollworm, the presence of herbicide resistant weeds, and the threat of selecting for future herbicide-resistance, growers are forced to include more costly chemical control options than were needed in previous years (Collins and Reisig, 2016; Norsworthy et al., 2012).

Along with the increasing costs of seed and chemicals (USDA-ERS, 2016a), which are largely out of the control of the producer, growers are often pressured to include additional inputs by many sectors of the cotton industry. These additional inputs are often extension-recommended practices under certain environmental conditions or when specific symptoms are observed. The inputs are presented to growers as vague ways to promote plant health even when the recommended conditions and symptoms are not present. Therefore, research was conducted to include several representative inputs, regardless of present environmental conditions or plant symptoms, to determine the effect on cotton growth and yield compared to current local extension recommendations.

MATERIALS AND METHODS

Experiments were conducted at Lee Farm at the Fisher Delta Research Center in Portageville, MO; the Upper Coastal Plain Research Station in Rocky Mount, NC; and the Tidewater Agriculture Research and Extension Center in Suffolk, VA from 2014 through 2016; the R.R. Foil Plant Science Research Station in Starkville, MS in 2015; and the Black Belt Experiment Station in Brooksville, MS in 2016. Cultivar Phytogen 499WRF (Dow AgroScience, Indianapolis, IN) was seeded at a rate of 8.09 seed m^{-1} row (106,447seed ha^{-1}) in Missouri on 76 cm row spacing; 10.7 seed m^{-1} row (111,458 seed ha^{-1}) on 96 cm row spacing in Mississippi; 9.8 seed m^{-1} row (108,160 seed ha^{-1}) on 91 cm row spacing in North Carolina; and 11.2 seed m^{-1} row (121,939 seed ha^{-1}) on 91 cm row spacing in Virginia. Plots at all locations were 12.2 m in length, four rows wide.

A total of seven treatments were included in this study with a control treatment of base extension recommendations from the local state in regards to all aspects of production including fertility and pest management (Table 1) (Dodds, 2017; Edmisten, 2016; Frame et al., 2016; Univ. of Missouri, 2017). Five fertilizer and chemical inputs were chosen to include in this study to represent the varying options that are presented to growers as practices to improve plant health, including a 150% soil fertility program, in-furrow fungicide, in-furrow insecticide, early season foliar fungicide, and late season foliar potassium fertilization (Table 1).

The base extension recommendations, used as the control to which all additional inputs were compared, consisted of each states local extension recommendations for cotton production including fertility only at soil-test-recommended rates and disease and pest control only when threshold levels were reached (Dodds, 2017; Edmisten, 2016; Frame et al., 2016; Univ. of Missouri, 2017). All treatments were managed with these base recommendations with the exception of the additional input in question. The soil fertility input, 150% soil fertility, consisted of 150% of the soil-test-recommended rates of nitrogen (N), phosphorus (P), and potassium (K). The additional 50% of N, P, and K was applied to the surface of the soil prior to planting each spring. The in-furrow fungicide input, mefenoxam (Ridomil Gold SL, Syngenta Crop Protection, Greensboro, NC), was applied at planting at a rate of 106 ml ha^{-1}. When recommended (due to a field history of seedling disease, use of low quality seed, planting into reduced tillage or no-till systems, or unfavorable weather conditions for germination) an in-furrow fungicide provides added protection against the cotton seedling disease complex above what is already achieved with the fungicide seed treatment that is present on the overwhelming majority of planted acres (Keonning and Collins, 2016). Imidacloprid (Admire Pro, Bayer Crop Science, Research Triangle Park, NC), the in-furrow insecticide, was applied at planting at a rate of 672 ml ha^{-1}. Using imidacloprid in-furrow on top of insecticidal seed treatments has been recommended to improve and prolong the management of early season thrips populations in upland cotton in the southeastern US Cotton Belt (Reisig, 2016). Although the use of imidacloprid in-furrow is currently an extension-recommended practice for cotton planted in the southeast United States, the input was chosen for inclusion in this study based on resistance of tobacco thrips (*Frankliniella fusca*) to the neonicotinoid class of insecticides in the Mid-South, and the declining efficacy of the neonicotinoids on tobacco thrips in the Southeast (Huseth et al., 2016). A foliar fungicide, azoxystrobin (Quadris, Syngenta Crop Protection, Greensboro, NC), was applied at a rate of 438 ml ha^{-1} at the 3 to 4 leaf stage and again at a rate of 584 ml ha^{-1} at matchhead square. According to the label, the application of azoxystrobin is intended to prevent leaf spots and boll rots caused by fungal pathogens in conditions conducive to disease development (Syngenta Crop Protection, 2017). The final input consisted of a series

of weekly potassium nitrate (KNO_3, 13-0-44) applications of 11.2 kg ha^{-1} (4.9 kg K ha^{-1}) each during the first five weeks of bloom for a total of 56 kg ha^{-1} (24.6 kg K ha^{-1}). Potassium is utilized by cotton throughout the growing season, impacting plant-water relations, photosynthesis, and assimilate transport (Pettigrew, 2008). The majority of K utilization however, occurs during boll development, when K plays a vital role in cotton fiber elongation (Pettigrew, 2008; Snider and Oosterhuis, 2015). It is recommended that K fertilization be completed prior to planting, as foliar K applications have shown inconsistent yield responses and can reduce yields when adequate K is already available (Crozier and Hardy, 2016; Howard et al., 1998). Each of the five additional inputs was included as an individual treatment and in a high-input treatment consisting of all five inputs together, treated at the same rate and timing as each of the individual treatments.

Each treatment was included at two planting dates each year. Early planting ranged from 27 April to 8 May in Missouri, 9 May to 11 May in Mississippi, 9 May to 15 May in North Carolina, and from 9 May to 24 May in Virginia. Late planting ranged from 24 May to 30 May in Missouri, 7 June to 8 June in Mississippi, 25 May to 2 June in North Carolina, and 23 May to 10 June in Virginia.

Plant populations were determined in all locations except Missouri 2014. Plant populations were determined by counting individual plants from 3 m from each of the two center rows in Missouri, North Carolina, and Virginia and from 4 m from each of the two center rows in Mississippi. Visual thrips injury ratings were assigned to each plot at three weeks after planting (WAP). Thrips injury ratings were based on a one to five scale in which a rating of one indicates no visible injury and a rating of five indicates severe injury or plant death (Faircloth et al., 2001). Plant heights were also measured for five plants in each plot at 5 WAP across all locations with the exception of Missouri 2014. Five plants from the center two rows were measured from the soil surface to the terminal bud (Grimes and Yamada, 1982). The two center rows of each plot were machine harvested from late October through early November in each season and seed cotton samples from each plot were ginned to determine turnout lint percentage, with the exception of locations in Mississippi.

Data were analyzed as a split block design blocked by plant date, with early and late planting date corresponding to separate sections of the field. Within each plant date, input treatments were arranged as a randomized complete block design with a total of seven treatments and 4 replications in Mississippi, North Carolina, and Virginia, and three replications in Missouri. Treatments were randomized independently within each block for each location and year. Plant date and input treatments were considered fixed effects and location, year, and replications were considered random effects. Data were subjected to analysis of variance using the PROC GLM in SAS 9.4 (SAS Institute Inc., Cary, North Carolina) with corrected error terms for fixed and random effects and means were separated using Dunnett's Procedure ($\alpha = 0.05$) for a pairwise comparison of each input with the local extension recommendations (Carmer et al, 1989; Moore and Dixon, 2015).

Effects of year, location, and plant date on lint percentage of cotton were significant although the lint percentage between inputs did not differ. Therefore, seedcotton yield was converted to lint yield based on the gin turnout from each individual plot, ranging from 35 to 45% in Missouri, 41 to 50% in North Carolina, and 40 to 48% in Virginia. Seedcotton yield in Mississippi was converted to lint yield based on a lint turnout of 40%.

RESULTS AND DISCUSSION

The three-way interaction of year, plant date, and input was significant for plant populations. When analyzed by year however, the two-way interaction of main effects plant date and input was not significant in any year. At the time plant populations were calculated, only the 150% soil fertility, in-furrow fungicide, in-furrow insecticide had been applied. When pooled across all locations, plant populations of any treatment did not differ when compared to local extension recommendations in 2014 and 2015 (Table 2). In 2016, plant populations were lower in plots treated with 150% soil fertility. Plant date only influenced plant populations in 2014 (Table 2). The increased populations of late-planted cotton are most likely due to increased soil and air temperatures at planting, providing more optimal germination conditions.

When pooled across all locations and years, plant heights measured at 5 WAP did not differ due to input (Table 2). Plant date did, however, influence plant heights as late planted cotton had greater plant heights at 5 WAP than did early planted cotton. The increased plant heights observed in late planted cotton are most likely related to an increased rate of vegetative development due to increased temperatures and more optimum growing conditions during germination and early development.

The three-way interaction of location, year, and plant date was significant for visual thrips injury so that data were not pooled across location for analysis. Visual thrips injury ratings were taken in Missouri in only 2016 and no differences were observed by input or by plant date (Table 3). In Mississippi, the two-way interaction of year and plant date was significant. No differences were observed by input for either early or late planted cotton, with the exception of late planted cotton in 2015, for which the in-furrow fungicide reduced visual thrips injury rating compared to local extension recommendations. There is unlikely to be any biological reason for the reduction of thrips injury due to the use of an in-furrow fungicide. It is more probable that a slight vigor response to the in-furrow fungicide was observed, resulting in a lower visual injury rating. All injury ratings of the late planted cotton were low and the reduction of injury rating due to the use of an in-furrow fungicide was minor. The lack of a response to the in-furrow insecticide was not unexpected due to the presence of neonicotinoid-resistant tobacco thrips populations in the Mid-South (Huseth et al., 2016).

In the southeastern United States however, populations of tobacco thrips range in susceptibility to neonicotinoid insecticides and the practice of using a neonicotinoid in-furrow insecticide over a neonicotinoid insecticidal seed treatment is still efficacious in most areas (Huseth et al., 2016; Reisig, 2016). In early-planted cotton in North Carolina, the in-furrow insecticide reduced visual thrips injury compared to the local extension recommendations, though the high-input treatment, which includes the in-furrow insecticide along with all of the additional inputs, did not (Table 3). In 2014 and 2016, late planted cotton in North Carolina saw a reduction in thrips injury rating of the high-input treatment compared to the local extension recommendations, while the in-furrow insecticide alone did

not show a reduction. In 2015, no differences in visual thrips injury rating were observed in late planted cotton. In 2014 and 2016 in Virginia, both the in-furrow insecticide alone and the high-input treatment reduced visual thrips injury compared to the local extension recommendations, though no differences were observed in 2015 (Table 3). Visual thrips injury ratings in Virginia were only taken for early planted cotton.

Though no differences were observed due to planting date in Missouri and all other locations were analyzed by planting date due to interactions, late-planted cotton tended to have lower visual thrips injury than early-planted cotton. Planting date has previously been shown to have a significant effect on thrips abundance in cotton with late-planted cotton often infested with fewer thrips than a timely-planted crop, possibly due to the number of alternate hosts available at the time of emergence (Parajulee et al., 2006; Parrella and Lewis, 1997).

The two-way interaction of year and plant date within location was significant for cotton lint yield so that each location was analyzed separately. With the exception of Virginia, all years within each location were analyzed alone. In Missouri and North Carolina, plant date did not influence cotton lint yields in 2016 (Table 4). For all remaining locations and years, early-planted cotton had greater yields compared to late-planted cotton by at least 244 kg ha^{-1} and as much as 1090 kg ha^{-1}. It is possible that this reduction in yield for late-planted cotton occurred due to a reduction in season length and observed heat units for late-planted cotton compared to early-planted cotton as was previously observed by O'Berry et al. (2008). O'Berry et al. (2008) however, only observed yield differences due to planting date in the Mid-South and observed no differences in yield in North Carolina and Virginia.

With no significant interactions concerning the main effect of inputs, lint yields were pooled across all locations and years. Neither individual inputs nor the high-input treatment increased cotton lint yield compared to the local extension recommendations, with a range of cotton lint yield means between inputs of only 59 kg ha^{-1} (Table 5). This lack of differences due to input was expected as the circumstances under which each of these inputs would have been warranted were never encountered during this study.

The cost of each input, including the high-input treatment, along with the increase in lint yield needed to cover the cost of each treatment is presented in Table 5. The cost for each input ranged from less than 20 $ ha^{-1} for the in-furrow fungicide to almost 120 $ ha^{-1} for the 150% soil fertility, totaling to greater than 300 $ ha^{-1} for the high-input treatment. As neither the individual inputs nor the high-input treatment increased lint yields compared to local extension recommendations, none of the treatments would have covered the cost of the inputs under the circumstances encountered during this study.

As previously discussed, each of the inputs included in this study are extension-recommended practices under certain environmental conditions or pest thresholds. Based on the outcomes of this study and the economic considerations of each input however, it is not recommended that producers use these inputs as plant health treatments under circumstances not specifically recommended by extension service recommendations. Although the logistics of a field study makes it impossible to evaluate every non-extension-based recommendation presented to producers, it is imperative that producers consider each recommendation based on sound data to prevent an unnecessary reduction of net returns in the name of plant health.

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Table 1. Treatments and inputs used in experiments in Missouri, Mississippi, North Carolina, and Virginia from 2014-2016.

Treatment	Product	Trade Name	Rate	Application Timing	Manufacturer
Base Ext. Rec.	-	-	-	-	-
Base+ 150% Soil Fertility	N, P, K	-	1.5x soil test	Preplant	-
Base+ In-Furrow Fungicide	mefenoxam	Ridomil Gold SL	106 ml ha^{-1}	At-Planting	Syngenta Crop Protection
Base+ In-Furrow Insecticide	imidacloprid	Admire Pro	672 ml ha^{-1}	At-Planting	Bayer Crop Science
Base+ Foliar Fungicide	azoxystrobin	Quadris	438 ml ha^{-1}	3-4 Leaf Stage	Syngenta Crop Protection
			584 ml ha^{-1}	MHS	
Base+ Foliar Fertilizer	KNO_3	-	11.2 kg ha^{-1} (56 kg ha^{-1})	Weeks of Bloom 1-5	-
Base+ High Input	Inputs 2-6	-	-	-	-

Table 2. Influence of input treatments and cotton planting date on plant populations and plant heights measured at 5 weeks after planting in Missouri, Mississippi, North Carolina, and Virginia from 2014 to 2016.

	Plant Populations			Plant Height
	2014	2015	2016	
	---------- plants ha^{-1} ----------			----- cm -----
Input				
Base Ext. Rec.	92662	108722	100452	22.95
Base+ 150% Soil Fertility	92687	109251	89930*	23.45
Base+ In-Furrow Fungicide	87757	112086	94095	23.09
Base+ In-Furrow Insecticide	100756	111977	96182	23.81
Base+ Foliar Fungicide	95137	110784	98378	23.23
Base+ Foliar Fertilizer	90222	114633	95942	22.84
Base+ High Input	86075	112108	99437	23.15
MSD	ns	ns	7472	ns
Plant Date				
Early	75386 b†	109357	93154	21.19 b
Late	108983 a	113373	99536	25.86 a
LSD	6111	ns	ns	0.49

*Comparison of input means to base extension recommendations is significant according to Dunnett's procedure at α=0.05.
† Means followed by the same letter within each column and effect are not significantly different according to Fisher's Protected LSD at p ≤ 0.05.

Table 3. Influence of input treatments and cotton planting date on visual thrips injury rating at 3 weeks after planting in Missouri, Mississippi, North Carolina, and Virginia from 2014 to 2016.

	Missouri	Mississippi			North Carolina			Virginia	
		Early	Late		Early	Late			
	2014-2016	2014-2016	2015	2016	2014-2016	2014	2015-2016	2014,2016	2015
	---------- Thrips Injury Rating (1-5) ----------								
Input									
Base Ext. Rec.	2.00	2.56	2.00	2.00	2.46	2.25	1.50	2.10	1.40
Base+ 150% Soil Fertility	2.33	2.50	2.00	1.50	2.88	2.50	1.88	1.95	1.50
Base+ In-Furrow Fungicide	2.67	2.63	1.00*	2.00	2.21	2.75	1.50	1.78	1.50
Base+ In-Furrow Insecticide	2.33	2.50	1.75	1.00	1.29*	1.50	1.63	1.30*	1.50
Base+ Foliar Fungicide	2.50	2.19	1.75	1.50	2.50	2.50	1.38	1.85	1.50
Base+ Foliar Fertilizer	2.33	2.38	1.25	1.25	2.67	2.25	1.50	1.83	1.40
Base+ High Input	2.50	2.31	1.25	1.50	1.92	1.38*	1.75	1.23*	1.55
MSD	ns	ns	0.77	ns	0.581	0.86	ns	0.329	ns
Plant Date									
Early	2.81								
Late	1.95								
LSD	ns								

*Comparison of input means to base extension recommendations is significant according to Dunnett's procedure at α=0.05.

Table 4. Influence of cotton planting date on lint yield in Missouri, Mississippi, North Carolina, and Virginia from 2014 to 2016.

	Missouri			Mississippi		North Carolina			Virginia
Plant Date	2014	2015	2016	2015	2016	2014	2015	2016	2014-2016
	---------- lint yield (kg ha^{-1}) ----------								
Early	1270 a†	1531 a	1530	2490 a	1511 a	2047 a	1148 a	772	1401 a
Late	510 b	1098 b	1318	1400 b	812 b	1340 b	904 b	715	1026 b
LSD	116	115	ns	199	119	231	89	ns	47

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 5. Cotton lint yield response to additional inputs along with cost of each input treatment and the lint yield gain above base extension recommendations required to cover the cost of each input (breakeven lint gain).

Input	Lint Yield	Input Cost[†]	Breakeven Lint Gain[‡]
	kg ha^{-1}	$ ha^{-1}	kg ha^{-1}
Base Ext. Rec.	1238	-	-
Base+ 150% Soil Fertility	1283	119.93	78
Base+ In-Furrow Fungicide	1242	17.93	12
Base+ In-Furrow Insecticide	1252	29.54	19
Base+ Foliar Fungicide	1251	105.30	68
Base+ Foliar Fertilizer	1263	65.16	42
Base+ High Input	1297	337.90	219
MSD	ns	-	-

[†]Cost of inputs are based on prices obtained January 2016 in North Carolina. The cost of each input does not include application cost.
[‡]Breakeven lint gain based on cotton lint price of \$1.54 kg^{-1} (\$0.70 lb^{-1}).

COTTON DEVELOPMENT AND YIELD RESPONSE TO IRRIGATION, PLANTING DATE, AND CULTIVAR IN NORTH CAROLINA

ABSTRACT

In 2012, only 2.7% of North Carolina's cotton (*Gossypium hirsutum* L.) was irrigated compared to the national average of 39%. The small size and non-uniform shape of most North Carolina fields, that would not be feasible for a center pivot system, are the main cause for the lack of irrigated acres. Prior research however, has shown irrigation can increase, or stabilize, cotton yields in years receiving below average or sporadic rainfall in North Carolina. The objective of this research was to investigate the impact of subsurface drip irrigation (SDI) on growth and yield of early- and late-maturing cotton cultivars at varying planting dates in eastern North Carolina. In 2014, the site received over 750 mm of rainfall and no differences were observed for any parameters between irrigated and non-irrigated plots. In 2015 and 2016, however, rainfall totals were lower with several multiple week periods without rainfall. There was a greater rate of plant height increase and dry weight accumulation throughout the growing season as influenced by SDI. Cotton yields were not affected by SDI, planting date, or cultivar in 2014, while they were increased by SDI in 2015 and 2016, planting date in 2015, and cultivar in 2016. Planting date did not influence yield under irrigated conditions, and the effect of planting date was highly dependent on rainfall amount and distribution when under non-irrigated conditions. The results from this study are similar to previous findings in that, in years with reduced or poorly distributed rainfall, SDI will increase cotton development, fruit retention, and yield in North Carolina, independent of planting date and cultivar.

INTRODUCTION

Average daily water requirements of cotton range from approximately 2 mm, through the seedling stage, to almost 8 mm during peak bloom (Fisher and Udeigwe, 2012). Though North Carolina's cotton growing season may provide enough total rainfall to satisfy the seasonal water requirement, it is the distribution of this rainfall throughout the growing season that can limit cotton growth and yield. Irrigation can be used to supplement rainfall and protect the crop during those inevitable times during the growing season when there is not enough water for plant uptake (Jordan et al., 2014; Nuti et al., 2012; Sorenson et al., 2011). Even with the potential benefits of irrigation in cotton, irrigated cotton hectares in North Carolina has remained constant since 2002 at approximately 2.7% of the total hectares planted, while the national irrigated cotton average has increased to 39% (USDA-NASS, 2014).

Water is required for cell expansion and even moderate water stress can reduce stem elongation, stem and leaf dry weights, total nodes, and leaf area (Loka et al., 2011; McMichael and Hesketh, 1982; Pace et al., 1999; Turner et al., 1986). Severe water stress reduces vegetative growth but can also lead to the destruction of present tissue. Abscission of leaves and destruction of chloroplasts and mitochondria are also associated with severe water stress (Berlin et al, 1982; Bondada and Oosterhuis, 2002; McMichael et al., 1972).

Studies have yielded conflicting answers as to which growth stage of cotton is most sensitive to water stress; early bloom, peak bloom, or boll development after bloom (Loka et al., 2011; Loka and Oosterhuis, 2012; Orgaz et al., 1992; Radin et al., 1992). Guinn and Mauney (1984a) determined that regardless of the most sensitive growth stage of cotton, the cause for a reduction in cotton yield is the reduction in the number of flowers that occur three weeks after severe water stress. This reduction in flowers is due to a decrease in vegetative growth, a lack of production of new fruiting sites, and increased square abortion (Guinn and Mauney, 1984a; Mauney, 1986). In addition to the reduction in flowers three weeks following severe water stress, there is a reduction of ovules per boll. The number of ovules in a boll directly influences fiber production and the number of ovules is determined two to three weeks before anthesis (Loka and Oosterhuis, 2012; Mauney, 1986). This time frame

would suggest that one of the most sensitive stages of cotton to water stress is three weeks prior to peak bloom.

Recent studies conducted across the southeast cotton belt have shown that irrigation has the potential to stabilize or increase cotton yields in humid regions with uncertain rainfall patterns. In Jackson, TN, research has shown an increase in cotton yield could be expected in years when less than 28 cm of rainfall was received between 40 and 120 days after planting (DAP) (Gwathmey et al., 2011). Using historical weather data from the area, Gwathmey et al. (2011) determined this rainfall pattern occurred in 60% of the years with available data. Whitaker et al. (2008) in Georgia reported increased yields with irrigation in 2 of 3 years with 60 to 70 cm of total water per season being optimal. Pettigrew (2004) in Mississippi and Balkcom et al. (2006) in Alabama also reported increased yields with irrigation in 2 of 4 years and in 2 of 3 years, respectively.

Several studies have also been conducted in the Southeast to determine the influence of type of irrigation system on cotton yield. Studies conducted utilizing subsurface drip irrigation (SDI) in eastern NC have shown an increase in cotton yield by SDI in 6 of 11 years from 2001 through 2013 (Jordan et al., 2014; Nuti et al., 2006; Nuti et al., 2012). Rainfall totals of 45 cm or greater, from May to August, mitigated the effect of irrigation on fiber yields. Alternatively, when less than 35 cm of rainfall was received cotton yields were increased due to irrigation (Jordan et al., 2014; Nuti et al., 2006; Nuti et al., 2012). It has been reported, both in peanut (Lanier et al., 2004) and cotton (Nuti et al., 2006; Whitaker et al., 2008), that yields did not differ between SDI and overhead sprinkler irrigation, but irrigation increased yields compared to non-irrigated systems. Ritchie et al. (2009) found that irrigated cotton grown in SDI systems had increased boll retention between nodes 6 and 10, effectively reducing the number of bolls from nodes 14 through 18, when compared to cotton grown under overhead sprinkler irrigation. This increased boll retention also caused plants to be more compact with reduced plant heights when irrigated by SDI systems, although yields did not differ compared to overhead sprinkler irrigation (Ritchie et al., 2009). Subsurface drip irrigation systems are similar in investment costs to overhead center pivot

irrigation but are more economical in fields of 25 ha or less, given a system with a life of at least 10 years (O'Brien et al., 1998).

Along with increasing yield, proper irrigation regimes must maximize the water use efficiency of the cropping system while also maximizing profit. Maximizing water use efficiency can be accomplished by using irrigation scheduling programs, soil moisture measurements, or simple plant water budgets. Whitaker et al. (2008) showed that water use efficiency can be improved through the use of SDI when compared to overhead sprinkler irrigation, increasing water use efficiency by as much as 23%. Lamb et al. (2015) in Georgia addressed both the agronomic and economic effects of irrigation rate in cotton produced in the humid southeast United States. Yields were increased compared to non-irrigated treatments by utilizing a 100% plant water use replacement irrigation strategy. However, a 66% plant water use replacement strategy increased yields compared to the non-irrigated treatments, while maximizing both water use efficiency and net return to irrigation (Lamb et al., 2015). In Georgia, Sorenson et al. (2011) determined the best irrigation strategy to maximize cotton water use efficiency using a SDI system was at 75% plant water use replacement with drip lines buried in every other row.

Nuti et al. (2012), in eastern North Carolina, found that the effects of SDI were independent of planting date and cultivar. Planting dates in North Carolina range from late April through early June and this timing will often factor into cultivar choice based on maturation rating (Edmisten and Collins, 2016). Though seasonal environmental conditions can have a large influence on cotton response to planting date, data from over 5 years indicates that late-planted cotton yields do not begin to fall below early-planted yields until after 10 June (Edmisten and Collins, 2016). Research has been conducted on cotton yield response to the interactions of SDI, planting date, and cultivar in North Carolina, while limited research exists on the influence these interactions have on cotton growth and development throughout the season. This study was conducted to determine the impact of SDI, planting date, and cultivar on cotton growth, development, and final lint yield in eastern North Carolina.

MATERIALS AND METHODS

The study was conducted at the Peanut Belt Research Station (PBRS) located near Lewiston-Woodville, NC (36.07 N, -77.11W) on a Norfolk sandy loam (fine-loamy, kaolinitic, thermic Typic Paleudults). Treatments were arranged in a split plot design with irrigation serving as whole plot units and a factorial of cultivar and cotton planting date serving as subplot units. Each combination of irrigation, cultivar, and planting date was assigned to plots of four rows (91-cm row spacing) by 12 m in length, with each combination replicated five times. The planting dates used in this study were chosen to represent early, mid, and late planted cotton in eastern North Carolina and ranged from 5 May to 10 May for the early planting, 20 May to 24 May for the mid-planting, and 3 June to 8 June for the late planting (Table 1).

Cotton cultivar Phytogen (PHY) 333WRF and PHY499WRF (Dow AgroScience, Indianapolis, IN) were chosen to represent early and late maturing cultivars, respectively. Phytogen 333WRF is described as an early maturing variety with the average first fruiting node of six (Dow Agroscience, 2017a). Phytogen 499WRF is described as a mid-maturing variety with the average first fruiting node of 7.9 (Dow Agroscience, 2017b). The maturity description from Phytogen is based on maturity data across the cotton belt and although PHY 499 WRF is listed as mid-maturing, it is representative of a late maturing variety in North Carolina, due to our shorter growing season as compared to other regions of the US cotton belt. Both cultivars were planted at a rate of 9.8 seed m^{-1} row (108,160 seed ha^{-1}) with 112 kg ha^{-1} of 18-46-0 fertilizer. Cotton was maintained using North Carolina extension recommendations in regards to all pest management, fertility, and harvest decisions (NCCES, 2016).

Whole plots were either irrigated or rainfed. Irrigation was supplied via an SDI system, originally installed in February 2001 as described by Lanier et al. (2004), Grabow et al. (2006), Nuti et al. (2006;2012), and Jordan et al. (2014). In April 2014, the system was updated by installing new drip lines (NetaFim DripNet PC Drip Tape, Netafim, Tel Aviv, Israel) buried at 30-cm depth using an in-row subsoiling unit. The drip lines were equipped with emitters spaced at 30 cm, each delivering 1.6 L h^{-1}. Also included in this update were a

centrifugal water pump (Munro LP100B 1hp, Munro Products and Solutions, Grand Junction, CO), flow meters (iPERL 25mm meter, SENSUS Products, Raleigh, NC), and remote control with UniPro PC software and UniPro Communicator (SENSUS Products, Raleigh, NC). Irrigation was applied daily, Monday through Friday, at 5 mm d^{-1}. After a rainfall event of 18 mm or greater, irrigation was terminated for three days and reinitiated on the fourth day. This irrigation strategy did not use any form of plant or soil water content indicators and was set to prevent water stress at any point throughout the growing season. Irrigation, rainfall, and irrigation plus rainfall totals, along with the number of days in which irrigation was applied for June through September are presented in Table 2.

Plant populations were determined at two weeks after emergence and plant heights were measured weekly throughout each season. In 2015 and 2016, plant samples were taken at four growth stages throughout the season for each planting date by cutting plants at the soil surface from 0.5 meter of row from each of the two center rows. Samples were taken from each planting date at pinhead square (PHS), first bloom, first open boll (open boll), and at defoliation. Three plants were separated into leaves, stems, and fruit before drying to determine the response of partitioning effects to the main effects of SDI, planting date, and cultivar. Separated fruit consisted of any fruiting structure on the plant including squares, flowers, and bolls. All samples were then dried at 100° C for 48 h, at which point a sample would be weighed and returned to the drier. This same sample would be weighed every 24 h until a constant weight was reached. After a constant weight was reached in the sample, all plant samples were weighed to determine the dry weight of plant material. In 2016, following the same procedures, a fifth sample was also taken at the third week of bloom. These data, along with plant heights measured weekly, were subjected to regression procedures testing for linear, quadratic, and cubic functions for dry weight or plant height against days after planting (DAP). Leaf area was also measured prior to drying and leaf area index (LAI) was calculated from the three separated plants using a LI-COR LI-3100 Leaf Area Meter (LI-COR, Inc., Lincoln, Nebraska).

Soil water content was measured weekly beginning in August 2015 with a PR2/6 profile probe (Delta-T Devices, Cambridge, United Kingdom) with readings at 10-, 20-, 30-,

40-, 60-, and 100-cm depths. Access tubes for the PR2/6 profile probe were installed in reps two, three, and four in plots planted to variety PHY499WRF in 2015 and all plots in reps two, three, and four in 2016. From the volumetric water content output, the depth of soil water stored in the top 30 cm of the profile was calculated for each plot.

In 2014, the harvest season was such that all plots were able to mature before harvest without the threat of reduced yield or quality to early-planted cotton, so the two center rows of each plot were machine harvested on 29 October. In 2015 however, one meter from each of the two center rows was hand harvested when each planting date was deemed ready due to concerns of inclement weather affecting cotton yield and quality. During the hand harvesting process, the first 50 bolls were kept separate to determine individual boll weight before being included in the total harvest weight. The first planting date was harvested on 9 October and due to further weather concerns the second and third planting date were hand harvested together on 29 October. In 2016, due to heavy rainfall events in September and October, all planting dates were hand harvested on 3 November following the same hand harvest procedure as described in 2015. Seed cotton samples from each plot were ginned to determine turnout lint percentage.

Data were analyzed as a split plot design and subjected to analysis of variance using PROC GLM in SAS 9.4 (SAS Institute Inc., Cary, North Carolina) with corrected error terms for fixed and random effects (Carmer et al., 1989; Moore and Dixon, 2015). Means were separated using Fisher's Protected LSD test at $P \leq 0.05$, with the exception of soil moisture content which was tested at $P \leq 0.10$ (Carmer et al., 1989). Lint percentage of each sample was analyzed as described, and it was determined that lint percentage did not differ due to main effects in 2014, so seed cotton yields were converted to lint yield with the average lint percentage of 46%. Similar to Pettigrew (2004), lint percentage was influenced by SDI in 2015 and 2016. Therefore, seed cotton yields for irrigated plots of both varieties were converted to lint yield based on the average lint percentage of 46%. Non-irrigated seed cotton yields in 2015 were converted to lint yield by the average lint percentage of 45%. Non-irrigated seed cotton yields were also influenced by cultivar in 2016 and were converted

to lint yield based on the average lint percentages of 45% and 43% for PHY333WRF and PHY499WRF, respectively.

Due to differences in rainfall patterns across seasons, data were analyzed by year unless otherwise specified. Various two-way interactions were significant for the parameters measured. If the *F* values associated with the main effects were at least 10 times greater than the *F* values associated with the interaction, then data were pooled (Cahoon et al., 2015).

RESULTS AND DISCUSSION

Rainfall patterns throughout a growing season strongly dictate the influence of irrigation on cotton growth and yield response (Gwathmey et al., 2011; Jordan et al., 2014; Nuti et al., 2006; Nuti et al., 2012). Rainfall accumulation varied widely from season to season for the period of June to September and ranged from 488 mm to 813 mm (Table 2) (CRONOS, 2016). Total rainfall received from June to September was the lowest in 2015. The station received only 10 events of the magnitude required to terminate irrigation for the allotted three days compared to 15 and 14 events in 2014 and 2016, respectively.

In 2016, 235 mm of precipitation fell between the two weeks prior to and the two weeks following the early planting date, with only 10 of 28 days not receiving any measurable rainfall. Rainfall total during the growing season was the greatest in 2016, although more than 50% of this rainfall fell during the month of September. The remnants of Hurricane Hermine delivered 146 mm of rainfall between 1 Sep and 3 Sep, followed by Tropical Storm Julia that accounted for 246 mm of rainfall from 19 Sep to 22 Sep (Figure 1). The remnants of Hurricane Matthew in early October then delivered another 269 mm of rainfall. The rainfall received in October was not accounted for as seasonal rainfall, as the majority of the cotton was already mature. This late rainfall did however disrupt the harvest season, delaying defoliation and harvest of all planting dates.

Due to the evenly distributed, high rainfall total throughout the growing season, no differences were observed between irrigated and non-irrigated cotton in 2014 for any growth parameters measured during the season, including plant heights, partitioned and total biomass. This lack of a response to SDI was similar to previous findings in which a response

to SDI was not observed at this site when rainfall totals were greater than 45 cm from May through August (Jordan et al., 2014; Nuti et al., 2006; Nuti et al., 2012).

Irrigation was not initiated until after plant populations were calculated and was therefore not utilized as an effect in the analysis of plant population. Plant population was not influenced by either planting date or cultivar (data not shown).

Total soil water in the top 30 cm of the soil profile ranged from 1.7 to 7.3 cm in August and September in 2015 and from 2.3 to 7.0 cm from June through August in 2016 (Figure 2). In 2015, soil water was similar between irrigated and non-irrigated plots for early- and mid-planted cotton throughout August with irrigated plots maintaining greater soil water in September. Irrigated plots with late-planted cotton maintained greater soil water than non-irrigated at all measurements with the exception of 12 Aug in which a rainfall event of 13 mm occurred within the three days leading up to the measurement. In 2016, irrigated plots maintained greater soil water storage through all measurements once irrigation was initiated in late June for all planting dates (Figure 2).

Similar to findings by Pace et al. (1999), plant heights, measured from 3 to 11 weeks after planting (WAP), were increased by SDI from 5 WAP through the end of the season, with the exception of early-planted cotton in 2016 (Figure 3). An increase in plant heights due to SDI was not observed until 7 WAP in 2016 due to excess rainfall, and associated weather, that occurred in early May. Differences in plant height between irrigated and non-irrigated cotton were greater in 2015 than in 2016, most likely due to lower rainfall totals in 2015. Plant heights were also influenced by planting date in all measurements and by cultivar at 4 and 11 WAP in 2015 and 8, 9, and 10 WAP in 2016, all independent of SDI (Table 3). Late-planted cotton had the greatest plant heights in all measurements, followed by the mid-planted and then early-planted cotton. The vegetative development rate of late-planted cotton was increased due to increased temperatures and more optimum growing conditions during germination and early development. Cultivar PHY499WRF had greater plant heights for all measurements when differences were observed (Table 3). This observation of cultivar height difference was expected as PHY499WRF is described by

Phytogen as a tall variety, compared to the PHY333WRF description of medium-tall (Dow Agroscience, 2017a; Dow Agroscience, 2017b).

Subsurface drip irrigation also increased LAI at all sample timings with the exception of those taken at PHS and defoliation in 2015 (Table 4) and 2016 (Table 5). The explanations for the reduction in leaf area due to water stress are conflicting. Kreig and Sung (1986) reported a reduction in leaf area due to water stress by reducing the production of new leaves both on sympodial branches and on the main stem, though the main stem is less affected. Pettigrew (2004) suggests however, the reduction of leaf area is due to a reduction in individual leaf size and not the number of leaves. The current study is limited in explaining the reduction of LAI in that neither leaf counts nor measurements of individual leaf size were conducted. In 2015, irrigated cotton had a lower LAI at defoliation, most likely due to increased earliness under SDI. In 2016, samples taken at defoliation were not timely due to extreme rainfall events, as previously discussed, and differences in LAI were not observed.

When LAI was influenced by planting date at or before first bloom, late-planted cotton had the greatest LAI, attributable to increased temperatures and more optimum growing conditions during germination and early season development for late-planted cotton (Table 4,5). Cultivar PHY333WRF had a greater LAI at PHS, and at first open boll when irrigated, and at defoliation in 2015 (Table 4) though cultivar did not influence LAI in 2016 (Table 5).

In 2015 and 2016, differences between the dry weight of fruiting structures of irrigated and rainfed cotton were insignificant through first bloom (Figure 4). This is likely due to ample available water for plant uptake prior to bloom, as well as a lower daily plant water requirement prior to bloom as squares require less water than developing bolls. Water stress occurring before bloom can reduce the number of flowers, as squares are the most sensitive to water stress within the first week they are visible, with the response to water-deficit stress being abscission (Ungar et al., 1989). Some studies have shown an increase in flowering with minor water stress before bloom due to an inhibition of excess vegetative growth, though neither scenario was observed in this study (Guinn and Mauney, 1984a).

Beyond first bloom, the response of fruiting structure dry weights to irrigation increased greatly in 2015 (Figure 4). Differences observed in 2016 however, were not observed until after the third week of bloom and were smaller than those observed in 2015 at first open boll and defoliation (Figure 4). Although irrigated plots maintained increased soil water in 2016 compared to non-irrigated plots, early season rainfall events minimized dry weight differences between irrigated and non-irrigated plots. As indicated in Figure 2 however, soil water in the top 30 cm of non-irrigated plots declined sharply in late July while SDI maintained increased soil water. The dry weight differences observed in 2016 between irrigated and non-irrigated cotton first occurred during this period of water stress for non-irrigated cotton and continued throughout the remainder of the season. Increased dry weight of fruiting structures associated with SDI in this study was most likely due to increased fruit retention and increased fruiting sites with additional vegetative growth, though previous studies have shown the dry weight of individual fruiting structures is also reduced under water stress conditions (Grimes and Yamada, 1982; McMichael and Hesketh, 1982; Turner at al., 1986; Zhao and Oosterhuis, 1997).

Independent of SDI, cultivar and planting date also influenced the dry weight of fruiting structures in 2015 and 2016 (Table 6). In 2015, early-planted cotton had the greatest fruiting structure dry weights on all sample dates. In 2016, early-planted cotton had the greatest dry weights only at defoliation, possibly due to the poor planting and early season conditions previously discussed. Cultivar influenced dry weight of fruiting structures only at first bloom in 2015, and first bloom, third week of bloom, and defoliation in 2016 (Table 6). Cultivar PHY333WRF had greater dry weights for all samples when differences were observed. A two-way interaction of planting date and cultivar was significant at the third week of bloom in 2016. Planting date only differed in regards to dry weight of fruit with cultivar PHY333WRF, with mid-planted cotton having the greatest dry weight.

Biomass partitioning was determined by calculating the individual percent of stem, leaves, or fruit biomass of the total sample biomass. Partitioning of biomass shifted throughout the season being dominated by leaf biomass at PHS, with a consistent decline to less than 10% of the total biomass at defoliation (Table 7,8,9). Stem biomass, as a percent of

the total, remained fairly steady throughout the season at 30 to 45%. Fruit biomass was negligible at PHS and was not considered as part of the total biomass. The proportion of fruit biomass increased from less than 10% of the total at first bloom to about 50% at open boll and defoliation.

A three-way interaction of the main effects SDI, cultivar, and planting date was significant for the proportion of stem biomass to total biomass at defoliation in 2015. Subsurface drip irrigation influenced the proportion of stem biomass for only two of nine sample dates, increasing percent stem biomass at first bloom in 2015 and at third week of bloom in 2016 (Table 7).

Cultivar had a more consistent influence on stem biomass as a percentage of total biomass (Table 8). With the exception of PHS in 2015, PHY499WRF had an increased proportion of stem biomass compared to PHY333WRF for all samples. This is not unexpected as PHY499WRF also had increased plant heights compared to PHY333WRF. Planting date influenced the proportion of stem biomass for all measurements with the exception of PHS in 2016 (Table 9). Where differences were observed, early-planted cotton had the lowest percentage of stem biomass except at PHS and for the non-irrigated PHY333WRF at defoliation in 2015. With the exception of the PHS samples in 2015 and 2016, late-planted cotton had the greatest percentage of stem biomass, attributable to an increased vegetative development rate due to increased temperatures and more optimum growing conditions during germination and early development.

A two-way interaction between main effects SDI and planting date was significant for the proportion of leaf biomass to total biomass at the open boll and defoliation samples in 2016. Proportion of leaf biomass was reduced by SDI in all samples in 2015 except for PHS (Table 7). Leaf biomass as a percentage of the total was also reduced by SDI for the third planting date in 2016 at defoliation. Subsurface drip irrigation only increased percentage of leaf biomass at the second planting date of the first open boll sample in 2016. Cultivar influenced the partitioning to leaf biomass on only three of nine sample dates (Table 8). Cultivar PHY333WRF had an increased proportion of leaf biomass at PHS in 2016, while PHY499WRF increased proportion of leaf biomass at defoliation in 2015 and third week of

bloom in 2016. On the remaining six sample dates, cultivar did not influence the percentage of leaf biomass. Early-planted cotton had the greatest proportion of leaf biomass for the seven samples in which differences were observed with the exception of PHS in 2015 and under irrigated conditions for the first open boll and defoliation samples in 2016 (Table 9). Late-planted cotton had the lowest proportion of leaf biomass for all samples in which differences were observed, except for PHS in 2015.

Two-way interactions between main effects SDI and planting date were significant for the proportion of fruit biomass to total biomass at open boll sample in 2015, and at first bloom and defoliation in 2016 (Table 7). The proportion of fruit biomass was not increased by SDI until first open boll in 2015 and until defoliation in 2016. Irrigated cotton had a lower percentage of fruit biomass compared to non-irrigated cotton at first bloom in 2015, at first bloom in 2016 for late-planted cotton, and the third week of bloom in 2016 for all planting dates. The reduction in proportion of fruit biomass may have been due to the observed decrease in vegetative growth in non-irrigated cotton and not to an increase in fruiting structures. As the season progressed, irrigated cotton had a greater percentage of fruit biomass at open boll in 2015 and at defoliation in both 2015 and 2016. This increased fruit biomass late in the season was most likely caused by an increase in fruiting sites associated with increased plant heights and vegetative growth and with increased boll retention without water stress (Guinn and Mauney, 1984a; Guinn and Mauney, 1984b; Jordan, 1986; Mauney, 1986).

Unlike the percentage of leaf biomass, cultivar influenced the percentage of fruit biomass for all sampling dates with the early cultivar PHY333WRF having a greater percentage of fruit biomass than the late cultivar PHY499WRF (Table 8). With the exception of the first bloom sample for both irrigated and non-irrigated treatmets, and the open boll sample for non-irrigated cotton in 2016, early-planted cotton had a greater proportion of fruit biomass compared to mid- and late-planted (Table 9).

Lint yield in 2014, as with all parameters measured, was not influenced by any of the main effects of SDI, planting date, and cultivar, due to above-average, well-distributed rainfall throughout the growing season (Table 10). In 2015 and 2016 the two-way interaction

between SDI and planting date was significant. The *F* value associated with SDI was at least 10 times greater than the *F* value associated with the interaction, so the interaction was ignored for the main effect of SDI (Cahoon et al., 2015). Subsurface drip irrigation increased lint yield in 2015 and 2016 by at least 500 kg ha^{-1}, with the exception of the last planting date in 2015 which yield was only increased by 200 kg ha^{-1} (Table 10). This increase in yield due to SDI was not unexpected as irrigated plots consistently maintained greater stored soil water throughout the growing season (Figure 2).

Planting date only influenced lint yield under non-irrigated conditions. In 2015, late-planted cotton had greater yields than early- and mid-planted cotton by at least 250 kg ha^{-1} (Table 10). This increase in yield by late-planted cotton was due to several well-timed, late-season rainfall events that affected late-planted cotton but occurred after the early- and mid-planted cotton had reached cutout. The opposite occurred in 2016, in that late-planted cotton had lower lint yields than early and mid-planted cotton by as much as 200 kg ha^{-1}. Rainfall patterns were also drastically different in August of 2016 compared to 2015. In 2016, 60 mm of rainfall fell in August compared to 210 mm and 430 mm in July and September, respectively. This likely caused an increase in fruit abortion in the late-planted cotton, effectively reducing lint yield. Cultivar only influenced lint yield in 2016 with the earlier-maturing PHY333WRF having greater lint yield than PHY499WRF (Table 10).

Yield response to SDI was solely associated with increased boll number as indicated by the lack of a response of individual boll weight to SDI. Previous research, however, has shown that the dry weight of individual fruiting structures is reduced under water stress conditions though it was not observed in this study (Grimes and Yamada, 1982; McMichael and Hesketh, 1982; Turner at al., 1986; Zhao and Oosterhuis, 1997). Individual boll weight was influenced by planting date in 2014 and by cultivar in 2015 and 2016. Late-planted cotton had a greater boll weight than early- and mid-planted cotton in 2014, and the early-maturing PHY333WRF had a greater boll weight than the late-maturing PHY499WRF in both 2015 and 2016 (Table 11).

CONCLUSIONS

Due to above-average total rainfall, SDI did not influence any parameter measured in 2014. The only measured parameter to differ among treatments in 2014 was individual boll weight as influenced by planting date. The effects of planting date were inconsistent in many of the parameters measured, though under irrigated conditions, did not influence yield. Similar to previous research, without irrigation, planting date influence on final yield was dependent upon the amount and distribution of rainfall throughout the growing season (Edmisten and Collins, 2016; Nuti et al., 2012). The influence of cultivar was also inconsistent and only affected yield in 2016, with the early-maturing cultivar increasing lint yield compared to the late-maturing cultivar. The early-maturing cultivar had higher individual boll weights, fruit dry weight, and proportion of fruit biomass throughout the season compared to the late-maturing cultivar. While increasing most reproductive parameters, the early-maturing cotton was shorter, had reduced LAI, and a reduced proportion of stem and leaf biomass throughout the season compared to the late-maturing cultivar.

In 2015 and 2016, however, SDI did increase plant heights, LAI during early fruiting and boll development, late season fruit biomass, and final lint yield independent of planting date and cultivar. The results of this study indicate that in years with reduced or poorly distributed rainfall, SDI will increase cotton yield in North Carolina. The data presented suggest that this increase in yield is due to increased fruiting structures due to increased boll retention and increased fruiting sites, as individual boll weight did not differ between irrigated and non-irrigated cotton.

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LIST OF FIGURES

Table 1. Early, mid-, and late planting dates and date of first irrigation from 2014 to 2016.

	Early Plant	Mid-Plant	Late Plant	First Irrigation
2014	5 May	20 May	3 Jun	17 Jun
2015	6 May	21 May	8 Jun	17 Jun
2016	10 May	24 May	8 Jun	20 Jun

Table 2. Seasonal rainfall, irrigation, and combined totals from June through September, along with the number of days in which irrigation was applied for 2014 through 2016.

	Rainfall	Irrigation	Total Water	Irrigation Events
	---------- mm ----------			
2014	769	171	940	36
2015	488	319	807	64
2016	813	215	1028	43

Table 3. Influence of planting date and cultivar on plant height from 3 to 11 weeks after planting (WAP) in 2015 and 2016.

	3 WAP	4 WAP	5 WAP	7 WAP	8 WAP	9 WAP	10 WAP	11 WAP
	---------- Plant Height (cm) ----------							
2015								
Planting Date								
Early	10.03 b†	15.16 c	21.27 c	34.30 c	54.31 c	62.65 c	68.63 c	74.57 c
Mid	10.29 b	21.37 b	48.35 b	58.53 b	70.77 b	76.9 b	77.2 b	78.95 b
Late	26.42 a	33.71 a	59.15 a	80.62 a	84.1 a	87.36 a	95.53 a	97.32 a
LSD	1.08	1.56	2.39	3.65	3.38	4.32	4.01	3.69
Cultivar								
PHY333WRF	15.2	22.71 b	41.95	57.27	69.03	74.78	79.01	81.44 b
PHY499WRF	15.95	24.11 a	43.9	58.34	70.42	76.5	81.89	85.80 a
LSD	ns	1.28	ns	ns	ns	ns	ns	3.01
2016								
Planting Date								
Early	-	-	-	19.54 c	30.07 c	59.4 b	78.55 c	-
Mid	-	-	-	77 b	85.7 b	96.25 a	99.85 b	-
Late	-	-	-	84.1 a	95.6 a	98.95 a	106.33 a	-
LSD	-	-	-	4.8	3.55	3.97	16.36	-
Cultivar								
PHY333WRF	-	-	-	59.02	68.07 b	82.73 b	90.04 b	-
PHY499WRF	-	-	-	61.41	72.84 a	87 a	96.27 a	-
LSD	-	-	-	ns	2.9	3.24	4.01	-

†Means followed by the same letter within each column and effect are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 4. Influence of subsurface drip irrigation (SDI), planting date, and cultivar on leaf area index (LAI) in 2015 at pinhead square (PHS), first bloom, first open boll, and defoliation.

	PHS	First Bloom	First Open Boll		Defoliation
			Irrigated	Non-Irrigated	
	---------- LAI ----------				
SDI					
Irrigated	0.500	1.447 a†	-‡	-	0.581 b
Non-Irrigated	0.439	1.129 b	-	-	0.948 a
LSD	ns	0.196	-	-	0.105
Planting Date					
Early	-	0.875 c	1.876	1.081 b	0.838
Mid	0.476	1.215 b	1.726	1.348 b	0.741
Late	0.463	1.773 a	1.521	1.721 a	0.728
LSD	ns	0.177	ns	0.340	ns
Cultivar					
PHY333WRF	0.433 b	1.237	1.523 b	1.264	0.673 b
PHY499WRF	0.507 a	1.339	1.893 a	1.514	0.865 a
LSD	0.051	ns	0.247	ns	0.124

†Means followed by the same letter within each column and effect are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.
‡A three-way interaction of irrigation, plant date, and cultivar was significant for the first open boll sample. When analyzed by irrigation, the two-way interaction of plant date and cultivar was not significant and is presented as such.

Table 5. Influence of subsurface drip irrigation (SDI), planting date, and cultivar on leaf area index (LAI) in 2016 at pinhead square (PHS), first bloom, third week of bloom (Bloom+3W), first open boll, and defoliation.

	PHS	First Bloom	Bloom+3W	First Open Boll	Defoliation
	---------- LAI ----------				
SDI					
Irrigated	0.476	2.709 a†	3.255 a	1.896 a	0.753
Non-Irrigated	0.447	2.153 b	2.371 b	1.210 b	0.773
LSD	ns	0.141	0.115	0.209	ns
Planting Date					
Early	0.302 c	1.966 b	2.903 a	1.433	0.813 a
Mid	0.432 b	2.613 a	3.143 a	1.632	0.994 a
Late	0.650 a	2.714 a	2.394 b	1.595	0.482 b
LSD	0.062	0.456	0.349	ns	0.182
Cultivar					
PHY333WRF	0.476	2.402	2.799	1.588	0.748
PHY499WRF	0.446	2.460	2.828	1.519	0.778
LSD	ns	ns	ns	ns	ns

†Means followed by the same letter within each column and effect are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 6. Influence of planting date and cultivar on fruit dry weight in 2015 and 2016 at pinhead square, first bloom, third week of bloom (Bloom+3W), first open boll, and defoliation.

	First Bloom	Bloom+3W	First Open Boll	Defoliation
	---------- Fruit dry weight (g) ----------			
2015				
Planting Date				
Early	4.06 a†	-‡	157.89 a	149.05 a
Mid	2.40 c	-	138.00 b	120.30 b
Late	3.24 b	-	128.75 b	108.10 b
LSD	0.54	-	17.83	19.77
Cultivar				
PHY333WRF	3.94 a	-	146.77	132.33
PHY499WRF	2.52 b	-	136.32	119.30
LSD	0.44	-	ns	ns
2016				
Planting Date				
Early	3.19 b	int§	117.03	119.49 a
Mid	4.08 b		115.53	107.39 ab
Late	6.45 a		111.48	92.10 b
LSD	0.96		ns	16.10
Cultivar				
PHY333WRF	5.67 a	int	120.92	113.03 a
PHY499WRF	3.48 b		108.37	99.62 b
LSD	0.78		ns	13.15
Interaction				
PHY333 - Early	ns	62.26 b	ns	ns
PHY333 - Mid		73.56 a		
PHY333 - Late		60.37 b		
LSD		10.47		
PHY499 - Early	ns	55.26	ns	ns
PHY499 - Mid		48.88		
PHY499 - Late		50.84		
LSD		ns		

†Means followed by the same letter within each column and effect are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.
‡Third week of bloom samples were not collected in 2015.
§Main effect means omitted due to a significant two-way interaction between cultivar and planting date.

Table 7. Influence of subsurface drip irrigation (SDI) on biomass partitioning of stem and leaf as a percentage of the total biomass at pinhead square and biomass partitioning of stem, leaf, and fruit as a percentage of the total biomass at first bloom, third week of bloom (Bloom+3W), first open boll, and defoliation in 2015 and 2016.

	2015			2016		
	Stem	Leaf	Fruit	Stem	Leaf	Fruit
	Percent					
Pinhead Square						
Irrigated	31.2	70.6	-	31.7	68.3	-
Non-Irrigated	29.4	68.8	-	32.3	67.7	-
LSD	ns	ns	-	ns	ns	-
First Bloom						
Irrigated	46.1 a†	49.0 b	4.9 b	49.9	46.4	int‡
Non-Irrigated	42.8 b	51.8 a	6.5 a	48.9	46.2	
LSD	1.5	1.3	0.6	ns	ns	
Bloom+3W						
Irrigated	-§	-	-	45.7 a	28.8	25.5 b
Non-Irrigated	-	-	-	40.8 b	28.9	30.3 a
LSD	-	-	-	3.4	ns	2.9
First Open Boll						
Irrigated	32.9	13.7 b	int	35.3	int	49.0
Non-Irrigated	31.6	19.4 a		36.7		49.5
LSD	ns	1.3		ns		ns
Defoliation						
Irrigated	int	6.8 b	57.6 a	39.1	int	54.0 a
Non-Irrigated		15.3 a	47.3 b	40.9		49.1 b
LSD		2.0	4.8	ns		4.7

†Means followed by the same letter within each column and sample timing are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

‡Main effect means omitted due to either a significant two-way interaction between irrigation and planting date or a three-way interaction between the main effects of SDI, cultivar, and planting date.

§Third week of bloom samples were not collected in 2015.

Table 8. Influence of cultivar on biomass partitioning of stem and leaf as a percentage of the total biomass at pinhead square and biomass partitioning of stem, leaf, and fruit as a percentage of the total biomass at first bloom, third week of bloom (Bloom+3W), first open boll, and defoliation in 2015 and 2016.

	2015			2016		
	Stem	Leaf	Fruit	Stem	Leaf	Fruit
	---------- percent of total biomass ----------					
Pinhead Square						
PHY333WRF	30.0	70.0	-	31.0 b†	69.0 a	-
PHY499WRF	30.6	69.4	-	33.0 a	67.0 b	-
LSD	ns	ns	-	1.9	1.9	-
First Bloom						
PHY333WRF	43.0 b	50.1	6.8 a	48.3 b	46.3	5.3 a
PHY499WRF	45.9 a	49.6	4.6 b	50.4 a	46.3	3.2 b
LSD	1.1	ns	0.4	1.1	ns	0.5
Bloom+3W						
PHY333WRF	-‡	-	-	40.6 b	28.3 b	31.1 a
PHY499WRF	-	-	-	45.9 a	29.4 a	24.7 b
LSD	-	-	-	1.4	1.0	2.0
First Open Boll						
PHY333WRF	29.6 b	16.3	54.1 a	32.8 b	15.0	52.3 a
PHY499WRF	34.9 a	16.7	48.4 b	39.2 a	14.5	46.3 b
LSD	2.3	ns	3.2	2.0	ns	2.4
Defoliation						
PHY333WRF	int§	10.2 b	56.2 a	36.9 b	8.2	54.9 a
PHY499WRF		11.9 a	48.7 b	43.1 a	8.7	48.2 b
LSD		1.7	4.0	3.0	ns	3.8

†Means followed by the same letter within each column and sample timing are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

‡Third week of bloom samples were not collected in 2015

§Main effect means omitted due to a significant three-way interaction between the main effects of subsurface drip irrigation, cultivar, and planting date.

Table 9. Influence of planting date on biomass partitioning of stem and leaf as a percentage of the total biomass at pinhead square and biomass partitioning of stem, leaf, and fruit as a percentage of the total biomass at first bloom, third week of bloom (Bloom+3W), first open boll, and defoliation in 2015 and 2016.

	2015			2016		
	Stem	Leaf	Fruit	Stem	Leaf	Fruit
	Percent					
Pinhead Square						
Early	30.9 b†	69.1 b	-	31.0	69.0	-
Mid	36.3 a	63.7 c	-	31.4	68.6	-
Late	23.8 c	76.2 a	-	33.6	66.4	-
LSD	2.5	2.5	-	ns	ns	-
First Bloom						
Early	40.3 c	50.9 a	8.8 a	48.0 b	48.4 a	int‡
Mid	44.7 b	50.8 a	4.5 b	50.3 a	46.0 b	
Late	48.4 a	47.8 b	3.8 c	49.8 a	44.6 b	
LSD	1.3	1.3	0.5	1.4	1.4	
Bloom+3W						
Early	-§	-	-	41.5 b	30.9 a	27.6
Mid	-	-	-	44.0 a	28.1 b	27.9
Late	-	-	-	44.3 a	27.6 b	28.1
LSD	-	-	-	1.8	1.3	ns
First Open Boll						
Early	24.8 b	17.5 a	int	33.5 b	int	int
Mid	35.5 a	15.6 b		35.1 b		
Late	36.4 a	16.5 ab		39.4 a		
LSD	2.8	1.6		2.5		
Defoliation						
Early	int	11.2	59.3 a	36.3 b	int	55.8 a
Mid		11.7	49.2 b	39.2 b		51.0 b
Late		10.2	48.9 b	44.4 a		47.9 b
LSD		ns	4.9	3.7		4.7

Table 9. Continued.
†Means followed by the same letter within each column and sample timing are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.
‡Main effect means omitted due to either a significant two-way interaction between irrigation and planting date or a three-way interaction between the main effects of subsurface drip irrigation, cultivar, and planting date.
§Third week of bloom samples were not collected in 2015.

Table 10. Influence of subsurface drip irrigation (SDI), planting date, and cultivar on final lint yield from 2014 to 2016.

	2014	2015	2016
	---------- Lint Yield (kg ha^{-1}) ----------		
SDI			
Irrigated	1236	892 a†	1029 a
Non-Irrigated	1299	330 b	459 b
LSD	ns	138	61
Planting Date			
Early	1254	int‡	int
Mid	1274		
Late	1276		
LSD	ns		
Cultivar			
PHY333WRF	1272	630	779 a
PHY499WRF	1265	592	710 b
LSD	ns	ns	51
Interaction			
Irrigated Planting Date			
Early	ns	902	1099
Mid		981	1014
Late		793	973
LSD		ns	ns
Non-Irrigated Planting Date			
Early	ns	250 b	508 a
Mid		226 b	534 a
Late		514 a	336 b
LSD		71	61

†Means followed by the same letter within each column and effect are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.
‡Main effect means omitted due to a significant two-way interaction between SDI and planting date.

Table 11. Influence of subsurface drip irrigation (SDI), planting date, and cultivar on individual boll weight from 2014 to 2016.

	2014	2015	2016
	---------- Boll Weight (g boll^{-1}) ----------		
SDI			
Irrigated	5.54	4.69	4.62
Non-Irrigated	5.63	4.12	4.32
LSD	ns	ns	ns
Planting Date			
Early	5.43 b†	4.25	4.58
Mid	5.48 b	4.35	4.43
Late	5.86 a	4.52	4.39
LSD	0.23	ns	ns
Cultivar			
PHY333WRF	5.62	4.52 a	4.62 a
PHY499WRF	5.56	4.29 b	4.31 b
LSD	ns	0.21	0.20

†Means followed by the same letter within each column and effect are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

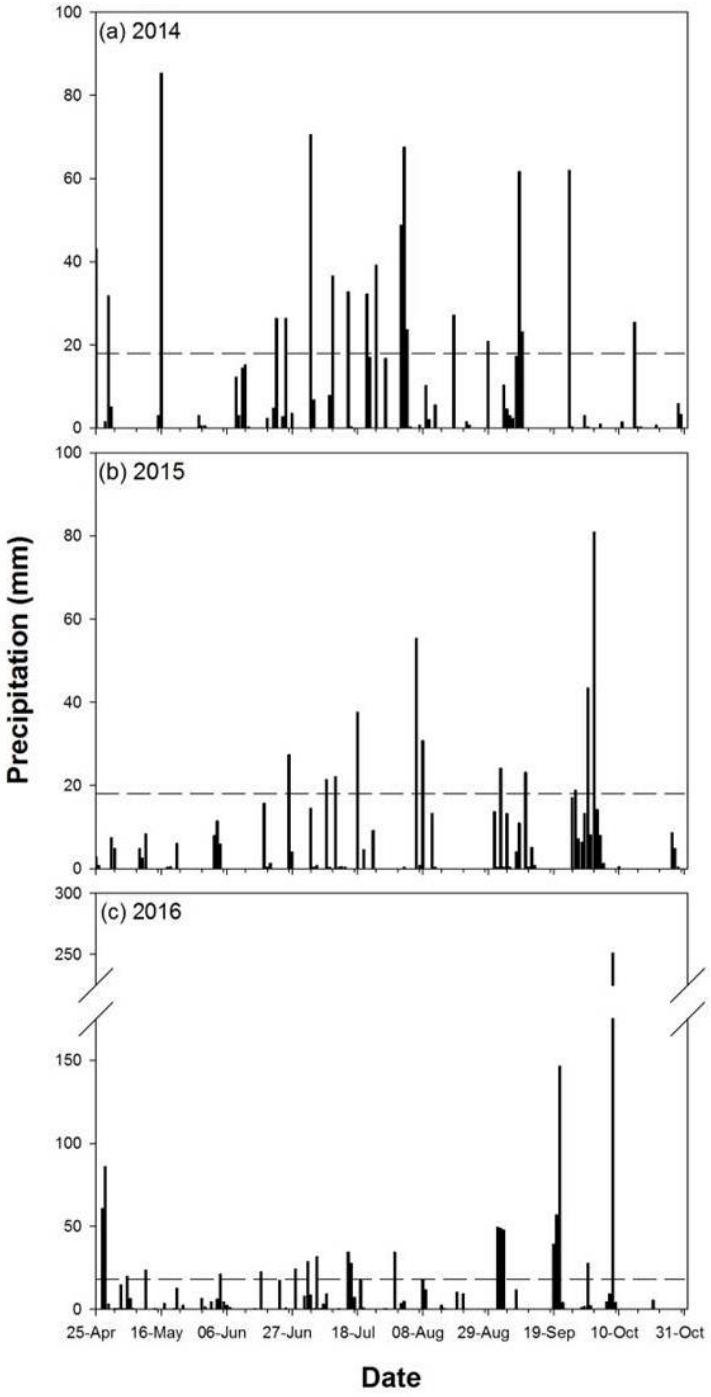

Figure 1. Rainfall amounts from 25 April to 31 October in 2014 (a), 2015 (b), and 2016 (c). Horizontal dashed lines represent the 18 mm threshold at which irrigation was terminated for three days.

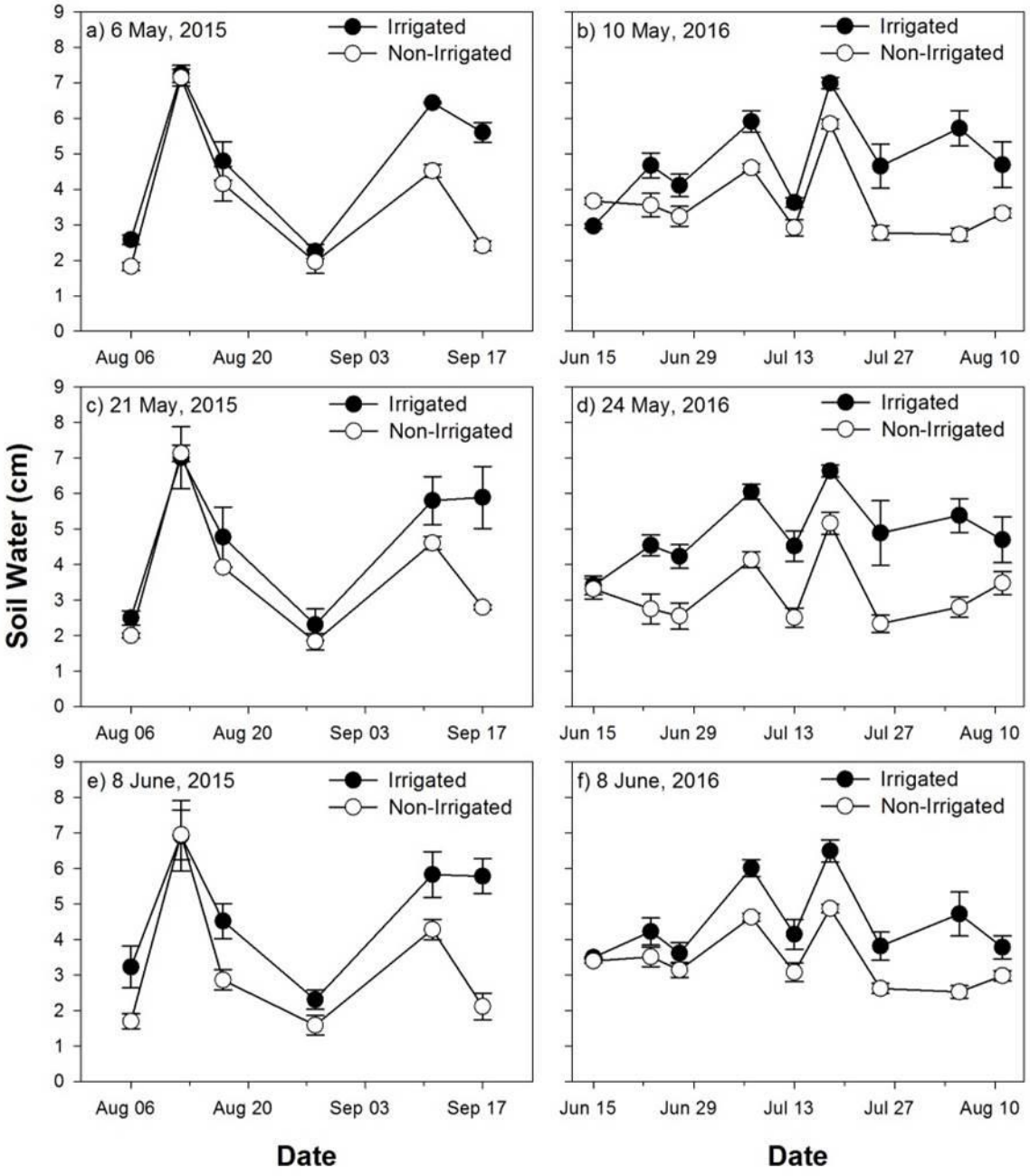

Figure 2. Amount of water stored in a 30-cm soil profile in irrigated and non-irrigated plots of early-, mid-, and late-planted cotton in August and September of 2015 and from June to August of 2016. Error bars represent $\pm$ 1 standard error.

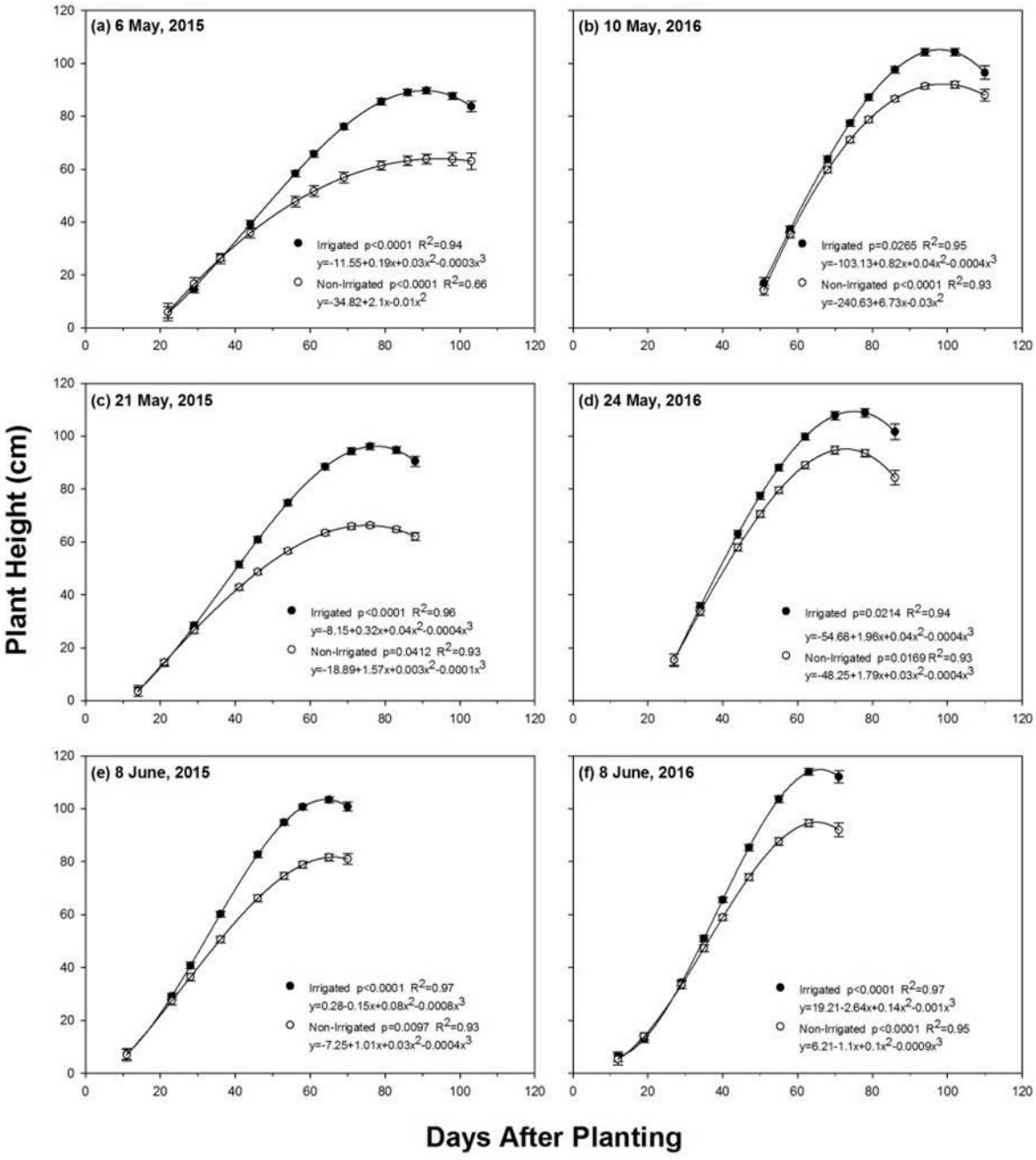

Figure 3. Plant height as a function of days after planting for irrigated and non-irrigated cotton and for early-, mid-, and late-planted cotton in 2015 and 2016. Error bars represent $\pm$ 1 standard error.

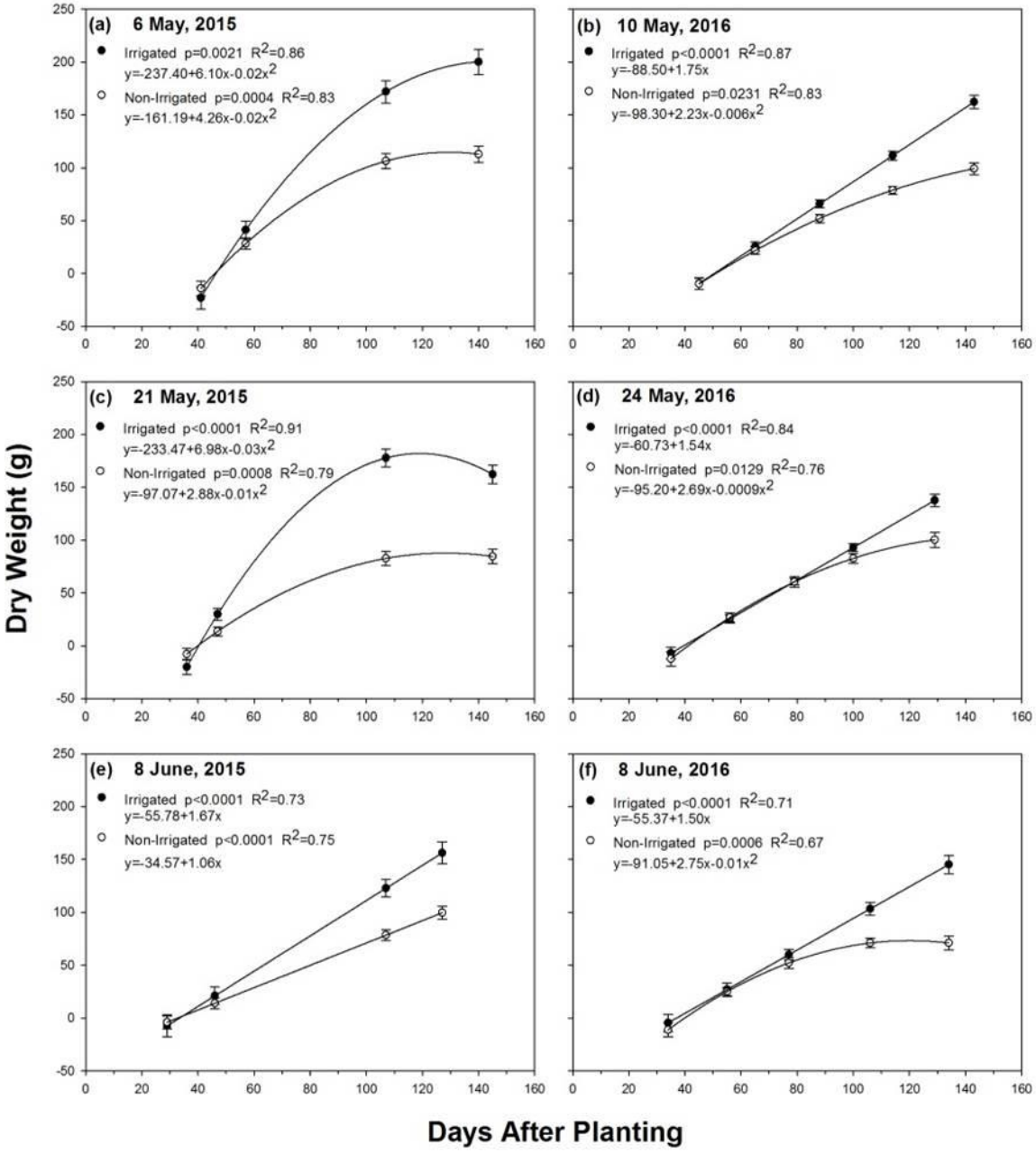

Figure 4. Fruit dry weight as a function of days after planting for irrigated and non-irrigated cotton and for early-, mid-, and late-planted cotton in 2015 and 2016. Samples means appear in the order of pinhead square, first bloom, first open boll, and defoliation in 2015 and pinhead square, first bloom, third week of bloom, first open boll, and defoliation in 2016. Error bars represent $\pm$ 1 standard error.

USE OF THE CSM-CROPGRO-COTTON MODEL TO DETERMINE THE AGRONOMIC AND ECONOMIC VALUE OF IRRIGATION TO UPLAND COTTON PRODUCTION IN NORTH CAROLINA

ABSTRACT

Although prior research has shown that irrigation can increase or stabilize cotton lint yields in North Carolina, only 2.7% of North Carolina's planted hectares are irrigated compared to the national average of 39%. Economic analysis of irrigation use in cotton is difficult however, due to widely varying weather patterns that occur from year to year. Most often, field-based studies are not suited for determining the effects of these weather patterns on the economics of irrigation on a long-term scale. The objectives of this study were to evaluate both the agronomic and economic value of irrigation to upland cotton production using the CSM-CROPGRO-Cotton simulation model with long-term historical weather data for 11 cotton producing counties in North Carolina. Long-term simulations were based on eight irrigation levels, including non-irrigated, triggered when the plant available water reached a maximum allowable depletion of 50%. The economic analysis made use of the Cotton Incorporated: Cotton Irrigation Decision Aid to determine the economic feasibility of irrigation using investment analysis tools such as cash flow, payback period, and net present value (NPV). The agronomic and economic responses to irrigation were both strongly dependent on seasonal rainfall. Lint yield of non-irrigated cotton was reduced by more than 10% of fully-irrigated cotton yield in more than 80% of the site-years simulated. The irrigation level required to maximize yield and that required to maximize cash flow and NPV, however, were not always the same. The results of the long term simulations and subsequent economic analysis suggest that irrigation is a feasible investment for cotton producers in North Carolina, as positive cash flows and NPVs were observed for all 11 counties.

INTRODUCTION

With an average daily water requirement ranging from 2 mm to 8 mm from the seedling stage through peak bloom, the total amount and distribution of rainfall throughout the growing season in North Carolina strongly influences the growth and yield of cotton (*Gossypium hirsutum* L.) (Fisher and Udeigwe, 2012). Irrigation is used by many growers in the humid southeast United States as a tool to protect the cotton crop during those times throughout the growing season when there is not enough available water for plant uptake and utilization.

Previous studies conducted in North Carolina have shown that irrigation can be used to increase, and possibly more importantly, to stabilize cotton yields in years with below average or poorly distributed rainfall. Conducted under the same subsurface drip irrigation system in eastern NC, three studies from 2001 through 2013 have shown an increase in cotton yield by irrigation in 6 of 11 years (Jordan et al., 2014; Nuti et al., 2006; Nuti et al., 2012). Rainfall patterns during these studies indicate that cotton yields in years receiving 45 cm of rainfall or greater, from May to August, are not affected by irrigation and that cotton yields are increased by irrigation when less than 35 cm of rainfall is received (Jordan et al., 2014; Nuti et al., 2006; Nuti et al., 2012).

Other recent studies conducted across the southeast cotton belt have also shown this trend of improved cotton yields with irrigation. Lamb et al. (2015) addressed the effects, both agronomic and economic, of irrigation rate on cotton produced in the humid Southeast US. Though yields were increased compared to non-irrigated treatments by a 100% replacement irrigation treatment, the 66% treatment increased yields compared to the non-irrigated treatments, while maximizing water use efficiency and net return to irrigation (Lamb et al., 2015). A study conducted in Jackson, TN showed a positive response in cotton yield due to irrigation could be expected in years when rainfall received between 40 and 120 days after planting (DAP) was less than 28 cm (Gwathmey et al., 2011). Using historical weather data from the area, Gwathmey et al. (2011) determined this deficient rainfall pattern occurred in 60% of the years with available data. Whitaker et al. (2008) in Georgia, Pettigrew (2004) in Mississippi, and Balkcom et al. (2006) in Alabama, also reported

increased yields with irrigation in 2 of 3 years, 2 of 4 years, and 2 of 3 years, respectively. Even with the potential benefits of irrigation in cotton presented from North Carolina and across the Southeast, irrigated cotton acreage in North Carolina has remained constant since 2002 at approximately 2.7% of the total acres planted while the national average has increased to 39% (USDA-NASS, 2014).

Crop Simulation Models

By the mid-1980's, complex models were being developed to aid researchers and farm managers in making crop management decisions, such as irrigation and pest management practices. The use of these models also allowed for increased accuracy of yield forecasts based on these crop management decisions across varying environments. SOYGRO (Wilkerson et al., 1983), PNUTGRO (Boote et al., 1992), CERES-Maize (Jones and Kiniry, 1986), and CERES-Wheat (Ritchie and Otter, 1985) were four of the new models developed to incorporate varying weather patterns, plant biotic and abiotic stresses, and farm specific cultivar characteristics, production practices, and location data for better pre- and in-season management decisions. One major disadvantage of these models was that each had differing requirements of input parameters and different modes of operation (Jones et al., 2003).

The Decision Support System for Agrotechnology Transfer (DSSAT), the most widely used crop modeling system by researchers today, was developed to give researchers the ability to make better decisions about adapting production technology to new locations, with differing soils and climate patterns when field experiments may be time or cost prohibitive (Hoogenboom et al., 2015; Jones et al., 2003; Uehara and Tsuji, 1998). The development of DSSAT made it possible to bring together many of the various existing crop models to standardize parameter input and operation of each model. DSSAT has been continuously modified since its development and is currently comprised of a modular platform that allows users to simulate development and yield of a crop or cropping system based on read-in or simulated management practices in response to changing climatic conditions and cultivar-specific characteristics (Gijsman et al., 2002; Jones et al., 2003;

Modala et al., 2015). Because of its modular format, researchers can more easily modify the model to fit location- and crop-specific parameters without risk of negatively affecting the model as a whole. The current DSSAT cropping system model (CSM) incorporates each of the current 28 crop models as individual modules that can be used alone or in congruence with each other for simulating multiple crops on a single soil model for single season or multi-season crop rotation simulations (Jones et al., 2001; Jones et al., 2003; Modala et al., 2015). Under the CSM module are two main cropping modules: CROPGRO, a generic grain legume model developed by integrating SOYGRO, PNUTGRO, and BEANGRO; and CERES, a model for several grass and grain crops (Boote et al, 1992; Hoogenboom et al., 1992; Jones et al., 2003; Thorp et al., 2014b).

A minimum data set of site characteristics, daily weather values, soil characteristics and initial conditions, and grower management practices for operation of the model are described by Jones et al. (2003) and Thorp et al. (2014a). Required site specific characteristics include latitude and longitude, average annual temperature and amplitude of temperature range, major obstructions to sunlight, and any artificial drainage. Thorp et al. (2014a) describes the minimum daily weather inputs as solar radiation, minimum and maximum temperatures, and precipitation. If using the FAO-56 Penman-Monteith (Allen et al., 1998) estimation of ET, average wind speed and dew point data are also needed, but if unavailable, wind speed is estimated at 86.4 km day^{-1} and dew point is set to minimum daily temperature. Soil classification by the USDA-NRCS taxonomic systems, profile and layer characteristics, water retention values, and initial carbon, nitrogen, and water conditions are some of the parameters required for local soils (Jones et al., 2003; Thorp 2014a). Required crop management values include specific cultivar coefficients, planting data, irrigation management, fertilizer applications, tillage practices, and harvest data (Jones et al., 2003).

DSSAT Irrigation Simulations

Because large variations in total rainfall and weather patterns exist both within and between cotton growing seasons, field irrigation studies are limited in the amount of information that can be obtained in a short amount of time. The DSSAT cropping models

have thus been used to simulate irrigation studies for various crops in many instances when field experiments have not been feasible for varying reasons. Using historical weather data, crop simulation models can be used to determine the effects of varying irrigation strategies in a region over extended periods of time. Steele et al. (2000) used the CSM-CERES-Maize to simulate irrigation scheduling on the corn crop in North Dakota. Researchers used CERES-Maize, simulating evapotranspiration (ET) as a water balance checkbook model to schedule irrigation. Model simulations showed a reduction of irrigation amounts of 30% while maintaining a 5% increase in yield compared to typical grower practices in the area. DeJonge et al. (2012) also used the CERES-Maize model to simulate an irrigation strategy to increase water productivity by 15%. Model simulations showed that by reducing vegetative growth stage irrigation from 20mm to 2.5mm per week, ET could be reduced while maintaining high yields (DeJonge et al., 2012). Kisekka et al. (2015) used CERES-Maize to determine that with a maximum allowable depletion (MAD) of plant available water (PAW) of 50%, terminating irrigation at 90 to 95 DAP resulted in the least soil water available after harvest while not reducing yield. Termination of irrigation any later than 90 to 95 DAP, while not reducing yield, resulted in excess soil water after harvest in an area relying on an already diminishing aquifer (Kisekka et al., 2015). Using the BEANGRO growth model for dry beans in Brazil, Faria et al. (1997) determined the optimal irrigation threshold to trigger an irrigation event, was at a MAD threshold of 60%. Simulations showed that using this threshold, growers could maximize yield and net return by maintaining soil moisture while reducing the number of irrigation events and total irrigation amount. Similar work was conducted using CERES-Maize in India to determine the depth of soil water that should be managed along with the MAD threshold to maximize corn yields based on a simulation of corn grown under varying irrigation trigger thresholds in a water limited environment (Panda et al., 2004).

Cammarano et al. (2012) used the DSSAT cotton crop model, CSM-CROPGRO-Cotton (Messina et al., 2004; Pathak et al., 2007; Zamora et al., 2009), to evaluate agronomic and economic response to various irrigation strategies across ten cotton growing locations in Australia. Simulations included 12 irrigation regimes of varying depths of irrigation, all

triggered at a MAD threshold of 50% PAW. The authors observed from the long-term simulations that the irrigation strategy that maximized yields did not always maximize profits. Agronomic practices and varying input costs and commodity prices can change the irrigation strategy that results in the highest net return (Cammarano et al., 2012). Also using CSM-CROPGRO-Cotton, Modala et al. (2015) simulated several irrigation strategies and the subsequent effect on final seed cotton yield. As observed from model simulations during seasons with normal rainfall conditions, reducing the irrigation level from 100% ET replacement to 66% ET replacement only reduced seed cotton yield by 5.3%. Under dry conditions, however, simulated yield was reduced by 17.5% when irrigation was reduced from 100% ET replacement to 70% ET replacement (Modala et al., 2015).

Though research has been presented from both field-based and model-based experiments showing the response of cotton lint yield to irrigation, a lack of long-term information is available on this response in North Carolina. This study is intended to determine the response of cotton lint yield to irrigation based on long-term historical weather data as well as the economic outcomes of investing in an irrigation system for use in North Carolina.

MATERIALS AND METHODS

Long-term crop simulations for the purpose of the agronomic and economic evaluation of the use of irrigation in North Carolina cotton were performed using the CSM-CROPGRO-Cotton model of DSSAT 4.6.1 (Hoogenboom et al., 2015; Jones et al., 2003). Though the calibration and validation of the CSM-CROPGRO-Cotton model for use in North Carolina were conducted previously by Wilkerson (unpublished data, 2017) and are beyond the scope of this chapter, materials and methods of the calibration and validation that are relevant to this study's long-term simulations are presented.

The CSM-CROPGRO-Cotton model was calibrated and validated for use in eastern North Carolina with data from a field-based irrigation experiment conducted in 2015 and 2016 at the Peanut Belt Research Station located near Lewiston-Woodville, NC (36.07 N, -77.11W) on a Norfolk sandy loam (fine-loamy, kaolinitic, thermic Typic Paleudults) as

discussed in Chapter 3 (Wilkerson, unpublished data, 2017). The field study included a factorial of three planting dates and two cultivars, each grown under both fully-irrigated and rainfed conditions. Irrigation to plots was supplied via a subsurface drip irrigation system with irrigation applied daily, Monday through Friday, at 5 mm d^{-1}. After a rainfall event of 18 mm or greater, irrigation was terminated for three days and reinitiated on the fourth day. This irrigation strategy was expected to be representative of cotton production under no-water stress conditions. Soil profile parameters were determined based on the data available from the Natural Resource Conservation Service for the soils in question (USDA-NRCS, 2017). The model was calibrated using data from both the irrigated and rainfed plots of cultivar Phytogen (PHY) 333WRF (Dow AgroScience, Indianapolis, IN) by adjusting model cultivar coefficients based on measurements of vegetative and reproductive biomass and leaf area taken at four developmental stages, along with final crop yield from the 2015 growing season. The model was then validated against the same biomass, leaf area, and yield data observed during the 2016 growing season.

Further calibration and validation was conducted using historical county yield data from 11 counties across North Carolina (Table 1) (USDA-NASS, 2016). These counties were chosen based on cotton acreage and yields and the availability of a long-term weather record. Weather data were obtained from a single Cooperative Observer Program network station in each county, compiled by the Center for Oceanic-Atmosphere Prediction Studies (COAPS) through the Southeast Climate Consortium (SECC). Simulations were made using weather data from 1979 to 2015, cultivar PHY333WRF, three planting dates (1 May, 15 May, and 29 May), no irrigation, a row spacing of 91 cm, a planting density of 12 plants m^{-2}, and assuming no nutrient or pest stress throughout the season (Wilkerson, unpublished data, 2017). Soil parameters, including maximum rooting depth, maximum drainage rate, Soil Conservation Service (SCS) runoff curve number, and the soil fertility factor were manually adjusted and simulated yields for each site-year were compared to observed county average yields. Maximum rooting depth varied greatly between counties and ranged from 25- to 75-cm depths (Table 1). This range of rooting depths across eastern North Carolina is not uncommon as naturally occurring hardpans, high soil strength layers, are often associated

with structureless soils, low in organic matter, and occur in over 50% of coastal plain soils (Busscher et al., 2006).

For each county, the soil profile for which simulated yield best matched county average yield over the 37-year period was chosen to use for the simulation study reported here. The fit of the model was evaluated using the root mean square error (RMSE), mean bias error (MBE), and coefficient of determination (R^2), calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \quad (1)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(S_i - O_i) \quad (2)$$

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})}{\left[\sum_{i=1}^{n}(O_i - \overline{O})^2\right]^{0.5}\left[\sum_{i=1}^{n}(S_i - \overline{S})^2\right]^{0.5}} \right\}^2 \quad (3)$$

where i is year (1-37), O_i is the observed value, S_i is the simulated value, and *n* is the number of pairs of observed and simulated values (Legates and McCabe, 1999). The calibrated model was able to adequately simulate the effect of drought on cotton growth and yield in North Carolina, explaining 59% of the year to year variability in county average yields with an MBE of -4 kg ha^{-1} and an RMSE of 335, even though simulations used only one weather station, soil profile, and cotton cultivar per county, and assumed no nutrient or pest stresses (Wilkerson, unpublished data, 2017).

Long-Term Simulations

To explore the potential agronomic and economic value of irrigation to cotton producers in North Carolina, model simulations were run using the calibrated CSM-CROPGRO-Cotton for each of the 11 North Carolina counties used during the validation of the model. For each county, the soil profile was set to the profile of best fit as previously described and weather files were created using historical weather from each of the weather

stations used during the model validation (Table 1). Weather files from each county included historical data from 1950 to 2015 with the exception of Bertie and Hertford Counties which used only historical weather data from 1954 to 2015 and 1975 to 2015, respectively. Cotton cultivar PHY333WRF was simulated as planted on 1 May, 15 May, and 29 May with 91 cm row spacing at a density of 12 plants m^{-2}. To eliminate the impact of increasing CO^2 levels over this time period on crop growth and yield, CO_2 levels were assumed to be at the 2015 level of 400 ppm for all weather years and locations (Dlugokencky and Tans, 2017). Simulated seed cotton yields were converted to lint yield assuming a moisture content of 6% for seed cotton and a lint turnout percentage of 45%, the North Carolina state average in 2015 (USDA-NASS, 2016).

Simulated irrigation strategies were triggered at a MAD threshold of 50% PAW for a soil water management depth of 18 cm. When this threshold was met, one of seven irrigation depths was applied, resulting in a total of eight irrigation strategies including a non-irrigated strategy. The seven irrigation strategies applied irrigation of fixed depths of 1, 2, 3, 4, 8, and 12 mm as well as a strategy in which the model would refill the profile completely. An irrigation efficiency of 0.75 was used to convert simulated irrigation totals to corrected seasonal irrigation totals.

Simulated yields and seasonal irrigation were used to determine the net water use efficiency of irrigation (WUE_i, kg ha^{-1} mm^{-1}) for each irrigation strategy, calculated as:

$$WUE_i = \frac{(Y_i - Y_o)}{IA_i} \quad (4)$$

where Y_i is the yield from the given level of irrigation within a location (kg ha^{-1}), Y_o is the non-irrigated yield within the same location (kg ha^{-1}), and IA_i is the total irrigation water applied by the given level of irrigation within the location (mm) (Fan et al., 2005; Lamb et al., 2015).

Economic Analysis

The economic analysis made use of the Cotton Incorporated: Cotton Irrigation Decision Aid (Paxton, 2011). This decision aid calculates the feasibility of investing in furrow, center pivot, or subsurface-drip irrigation systems based upon initial and annual ownership costs, variable costs dependent on the amount of irrigation applied, and the return on irrigated lint yield compared to non-irrigated lint yield with options to include financing costs as well. Although it is recommended that the user customize the input values in the decision aid, default values are provided for all required parameters (Table 2). Calculated output of the decision aid includes annual cash flow of a given level of irrigation (CF_i, \$), the payback period (yr) required to cover the initial cost of investment, and net present value (NPV, \$) of the system based on the provided discount rate using the following equations:

$$CF_i = hectares * \{[(Y_i - Y_o) * P_c] - IC_i\} \quad (5)$$

$$Payback_{years} = \frac{PC}{CF_i} \quad (6)$$

$$NPV = \sum_{z=1}^{x} \frac{(CF_i)_z}{(1+d)^z} \quad (7)$$

where P_c is the price of cotton lint assumed to be \$1.54 kg^{-1}; IC_i is the total, annual ownership cost of irrigation including both fixed and variable costs (\$ ha^{-1}); PC is the total purchasing cost of the system (\$); x is the total number of years included in the NPV calculation; z is the individual year in question; and d is the assumed discount rate of 5% (Paxton, 2011). The NPV calculation used during this study assumed a planning horizon of 15 years so that the value of z would fall between 0 and 15. Though the payback period and NPV are both often used in investment analysis, NPV, unlike the payback period, also considers the time value of money and accounts for cash flow over time compared in present value terms (Paxton, 2011). Cash on hand at the present time is assumed to be more valuable than future cash due to the potential earning value of the present cash. Although an

acceptable payback period may vary between users, the NPV output is more definitive in that a positive NPV represents a feasible investment.

The economic analysis conducted in this study was based on the default values provided in the decision aid for a standard center pivot irrigation system covering 53 hectares including the initial and annual fixed cost estimates and annual variable ownership costs with the exception of those costs associated with varying amounts of applied irrigation. Input parameters including total irrigation applied, expected yield for irrigated cotton, and expected yield for dryland cotton were gathered directly from the simulations for each location and year.

RESULTS AND DISCUSSION

Mean rainfall totals were similar for all counties across the historical record with mean seasonal totals ranging from 575 to 687 mm of rainfall although total rainfall across all years ranged from a minimum of 222 to 1235 mm (Table 1). Due to the wide range of seasonal rainfall totals across years and locations and the varying irrigation strategies, simulated irrigation totals varied greatly as well, ranging from 4 to 652 mm of total irrigation with irrigation strategy means at each location ranging from 45 to 451 mm (Table 3).

For all counties, simulated lint yields increased with increasing levels of irrigation until either the 8 or 12 mm irrigation strategy at which point yields plateaued, as shown in Figure 1 for Bertie, Pitt, and Robeson Counties representing a low, medium, and high irrigation environment, respectively. Similar to Bertie and Robeson Counties, as shown in Figure 1, simulated yields under the 4 mm irrigation strategy were within 1% of the maximum for all counties with the exception of Pitt and Wilson Counties, in which simulated yields of the 4 mm strategy were within 2 and 3% of the maximum, respectively (data not shown). Once simulated yields were maximized at either the 8 or 12 mm irrigation strategy, yields were no longer increased with additional irrigation. Although the irrigation required to maximize yield varied by county, the increase in lint yield due to irrigation was consistent as non-irrigated lint yield was reduced by more than 10% compared to fully-irrigated cotton in

over 80% of simulated site-years and was reduced by more than 40% in almost 50% of site-years (Figure 2).

The response of simulated lint yield to irrigation was closely related to total rainfall received during the season. Low rainfall years, receiving lower than one standard deviation below the mean rainfall, required over 230 mm of irrigation to maximize simulated lint yields in Bertie County (Figure 3). High rainfall years, receiving greater than one standard deviation above mean rainfall, required only 53 mm of additional irrigation to maximize simulated lint yields. Dryland cotton yields in high rainfall years were greater than in low rainfall years and the difference in simulated lint yields between non- and fully-irrigated yields was greater than 850 kg ha^{-1} in low rainfall years compared to just 85 kg ha^{-1} in high rainfall years.

The difference of simulated lint yield between rainfed and the irrigation strategy that maximized lint yield varied greatly across counties, ranging from an increase of 312 kg ha^{-1} in Sampson County to 772 kg ha^{-1} in Robeson County (Table 4). The variation of yield response to the fully-irrigated strategies is due to differences in both rainfall and county soil profile parameters used in the model. Regardless of the differences observed or assumed between counties, the average increase in lint yield between rainfed and fully-irrigated cotton was greater than 1 bale ha^{-1} (226 kg ha^{-1}) in all counties.

In some regions or years, access to irrigation water may be limited and the goal of maximizing yield through irrigation may not be feasible. To this end, a producer should also strive to maximize WUE_i as well as yield. Though either the 8 or 12 mm irrigation strategies maximized lint yields in all counties, the greatest WUE_i was observed in either the 3 or 4 mm irrigation strategies in each county (Table 4). Net water use efficiency for all irrigation strategies ranged from 1.16 to 3.62 kg ha^{-1} mm^{-1}. With simulated yields within 3% of the maximum in all counties, and greater WUE_i compared to the 8 and 12 mm strategies, the 4 mm irrigation strategy would be the optimum strategy for producers when access to irrigation water is limited.

Along with maximizing yield through irrigation, growers must determine if the investment of installing irrigation is feasible based on criteria specific to their operations.

Similar to findings by Cammarano et al. (2012), however, the irrigation strategy required to maximize yields did not always maximize CF_i (Table 5). Cash flow of simulated irrigation levels typically increased with increasing irrigation up to the 4 or 8 mm irrigation depths, above which CF_i began to decrease with additional irrigation (Figure 4). Similar to the law of diminishing returns, the returns from increased yields with additional irrigation was not enough to cover the cost of the additional irrigation.

The average payback period associated with the irrigation strategy required to maximize profit ranges from less than two years to greater than eight years (Table 5). In all counties, the average payback period is less than the assumed 15 year life of a new irrigation system, suggesting that the investment would be feasible when utilizing the irrigation strategy that maximizes profit.

Where the payback period falls short as an investment analysis tool is with the time value of money. Cash on hand at the present time is assumed to be more valuable than future cash due to the potential earning value of the present cash. The NPV output of the decision aid considers this time value of money and is a better analysis tool for investment decisions (Paxton, 2011). Net present value trends followed the exact trends of CF_i, and irrigation strategies that maximized CF_i also maximized NPV (Table 5). Net present values increased with increasing irrigation to the 4 or 8 mm irrigation depths and then decreased slightly with additional irrigation (Figure 4).

Although CF_i and NPV were both maximized at either the 4 or 8 mm irrigation level, both calculations yielded positive values for all irrigation levels of 4 mm or greater in all counties and were positive for irrigation levels as low as 2 mm in five counties (Data not shown). The positive NPV associated with the varying irrigation strategies suggests that irrigation is a feasible investment for cotton producers in eastern North Carolina. Using the irrigation strategies of applying 4 or 8 mm of irrigation at a MAD of 50% will maximize CF_i compared to the remaining strategies considered in this study.

It is possible that profitability of irrigation could be underestimated as the soil fertility factor used in the long-term simulations was assumed to be equal across both rainfed and irrigated simulations. As described by Vick (2016) using the CSM-CERES-Maize model,

the trend of increasing simulated yields with increasing irrigation did not differ, but rather the magnitude of increase in simulated yields with increasing irrigation was greater when the soil fertility factor was set to reflect increased soil fertility under irrigated conditions. In cotton, Pettigrew and Zeng (2014) reported that lint yield response to irrigation was reduced when nitrogen (N) fertility was limiting. However, the interactions between N fertility and irrigation practices are complex and not well defined and further research is warranted in North Carolina to determine the impact of these interactions on irrigated cotton production.

This study is limited however, in that while the data presented would suggest a feasible investment for cotton producers, many cotton fields in North Carolina are small and irregularly shaped. The economic analysis conducted as a part of this study was based on the assumption of investment in a standard center-pivot irrigation system covering 53 ha and the application of this information should be limited to similar irrigation systems in size and design. Further economic analysis should be conducted to determine the feasibility of investment in various irrigation system designs that have the ability to be customized to small or irregularly shaped fields.

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Table 1. Field and soil profile parameters and historical weather data used for the model validation and long-term simulations for 11 counties in eastern North Carolina including latitude and longitude, soil type, rooting depth, mean daily minimum and maximum temperature, and mean seasonal rainfall.

County	Latitude	Longitude	Soil Type	Rooting Depth	Mean Daily Minimum Temp	Mean Daily Maximum Temp	Mean Seasonal Rainfall
	---------- (°) ----------			(cm)	------- (°C) -------		(mm)
Bertie	36.132	-77.171	Rains fine sandy loam	65	17.21	29.97	613
Edgecombe	35.885	-77.539	Rains fine sandy loam	25	17.98	30.17	580
Halifax	36.478	-77.672	Wedowee sandy loam	48	17.20	29.61	575
Hertford	36.452	-77.080	Craven fine sandy loam	32	16.74	29.02	613
Lenoir	35.197	-77.543	Rains fine sandy loam	28	17.85	30.11	687
Martin	35.853	-77.031	Rains fine sandy loam	25	18.24	29.83	652
Northampton	36.397	-77.424	Norfolk sandy loam	75	17.23	29.73	583
Pitt	35.640	-77.398	Rains fine sandy loam	25	18.38	30.20	641
Robeson	34.627	-79.025	Rains fine sandy loam	25	18.20	30.41	612
Sampson	35.025	-78.276	Rains fine sandy loam	50	18.36	30.20	630
Wilson	35.694	-77.946	Rains fine sandy loam	50	18.04	30.22	596

Table 2. Default values provided and assumptions used by the Cotton Incorporated: Cotton Irrigation Decision Aid for the irrigation investment analysis.

	Unit	Unit Value	Price or Cost
Initial Investment *(Well, Pump, Power Unit, Center Pivot)*	$		74,390.00
Annual Fixed Ownership Costs *(Depreciation, Property Tax, Insurance, Interest)*	$ $year^{-1}$		8,544.67
Annual System Repairs and Maintenance	$ $year^{-1}$		1,264.63
Labor	hr $12.5mm^{-1}$	1	
	$ hr^{-1}	8.50	
	$ $12.5mm^{-1}$		8.50
Diesel Fuel	gal $12.5mm^{-1}$	1	
	$ gal^{-1}	3.00	
	$ $12.5mm^{-1}$		3.00
Additional Costs Associated with Irrigation *(Insect and Disease Management)*	$ ha^{-1}		49.40
Net Present Value Discount Rate	%	5.0	
Cotton Lint	$ kg^{-1}		1.54

Table 3. Seasonal irrigation means for simulated irrigation strategies triggered at a maximum allowable depletion (MAD) of 50% of plant available water in 11 counties in eastern North Carolina. Irrigation strategies range from applied irrigation of 1 to 12 mm depths when triggered as well as a strategy to refill the soil profile (Profile) when triggered at a 50% MAD.

County	1 mm	2 mm	3 mm	4 mm	8 mm	12 mm	Profile
	---------- mm ----------						
Bertie	49	87	112	122	131	134	150
Edgecombe	82	155	218	257	290	315	429
Halifax	61	112	148	165	176	183	210
Hertford	65	121	164	181	194	206	233
Lenoir	75	142	200	239	272	305	416
Martin	78	150	212	252	286	313	427
Northampton	54	101	135	152	167	182	207
Pitt	67	127	180	211	236	253	294
Robeson	81	154	219	262	301	331	451
Sampson	45	82	108	121	128	133	152
Wilson	51	94	127	146	161	169	190
Mean	64	120	166	192	213	229	287

Table 4. Simulated irrigation strategy required to maximize lint yield and to maximize net water use efficiency of irrigation (WUE_i), along with the increase in lint yield (ΔYield) compared to the non-irrigated strategy and WUE_i for 11 counties in eastern North Carolina.

County	Irrigation Strategy Max Yield	ΔYield	Irrigation Strategy Max WUE_i	WUE_i
		(kg ha^{-1})		(kg ha^{-1} mm^{-1})
Bertie	8 mm	374	4 mm	2.95
Edgecombe	8 mm	771	4 mm	2.94
Halifax	8 mm	427	4 mm	2.57
Hertford	12 mm	673	4 mm	3.62
Lenoir	8 mm	636	3 mm	2.68
Martin	8 mm	721	3 mm	2.84
Northampton	12 mm	373	4 mm	2.34
Pitt	12 mm	591	4 mm	2.67
Robeson	12 mm	775	3 mm	2.89
Sampson	12 mm	313	4 mm	2.47
Wilson	12 mm	501	4 mm	3.14
Mean		560		2.83

Table 5. Difference in simulated irrigation (ΔIrrigation) and yield (ΔYield) between the non-irrigation and irrigation level for which the cash flow (CF_i) and net present value (NPV) were maximized and the net water use efficiency of irrigation (WUE_i), CF_i, average payback period, and NPV associated with the maximizing irrigation level for 11 counties in eastern North Carolina using standard center-pivot irrigation covering 53 ha.

County	Irrigation Strategy Max CF_i	ΔIrrigation	ΔYield	WUE_i	CF_i	Payback Period	NPV
		(mm)	(kg ha^{-1})	(kg ha^{-1} mm^{-1})	($)	(years)	($)
Bertie	8 mm	130	374	2.88	13,993	5.32	67,479
Edgecombe	8 mm	290	771	2.66	41,328	1.80	337,699
Halifax	4 mm	165	424	2.57	16,922	4.40	96,429
Hertford	8 mm	194	672	3.46	36,337	2.05	288,363
Lenoir	8 mm	272	636	2.34	30,897	2.41	234,579
Martin	4 mm	252	709	2.81	37,471	1.99	299,567
Northampton	8 mm	167	372	2.23	12,651	5.88	54,215
Pitt	8 mm	236	590	2.50	28,257	2.63	208,485
Robeson	8 mm	301	774	2.57	41,264	1.80	337,068
Sampson	8 mm	128	312	2.44	8,983	8.28	17,952
Wilson	8 mm	161	499	3.10	23,243	3.20	158,923
Mean		209	558	2.69	26,486	3.61	190,978

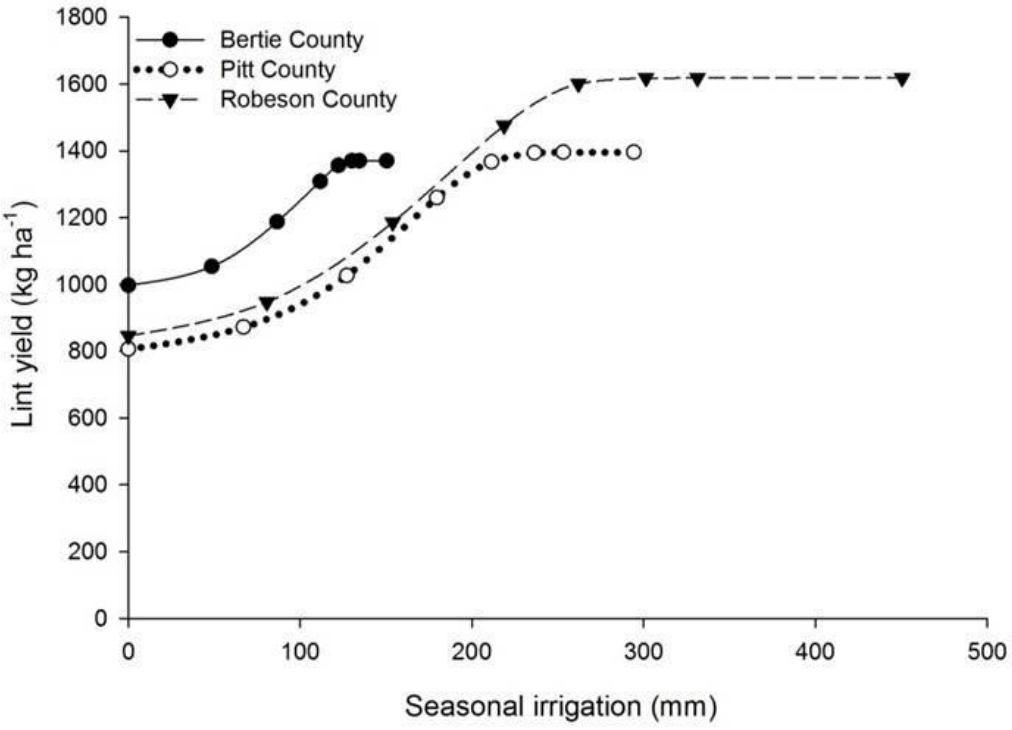

Figure 1. Simulated yield response of cotton to eight irrigation strategies, including non-irrigated, for Bertie, Pitt, and Robeson Counties representing a low, medium, and high irrigation environment, respectively. Each line represents the average of 66 years of simulations with the exception of Bertie County representing only 62 years of simulations.

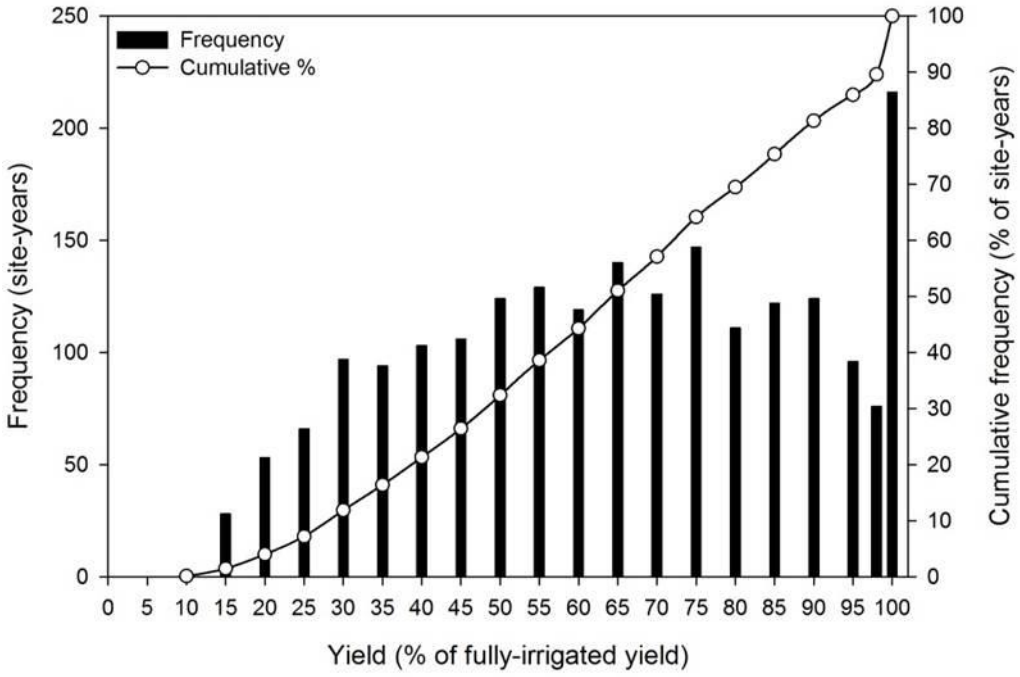

Figure 2. Frequency of occurrence and cumulative distribution of non-irrigated yield as a percentage of fully-irrigated yield across all counties and weather years, representing a total of 2079 site-years.

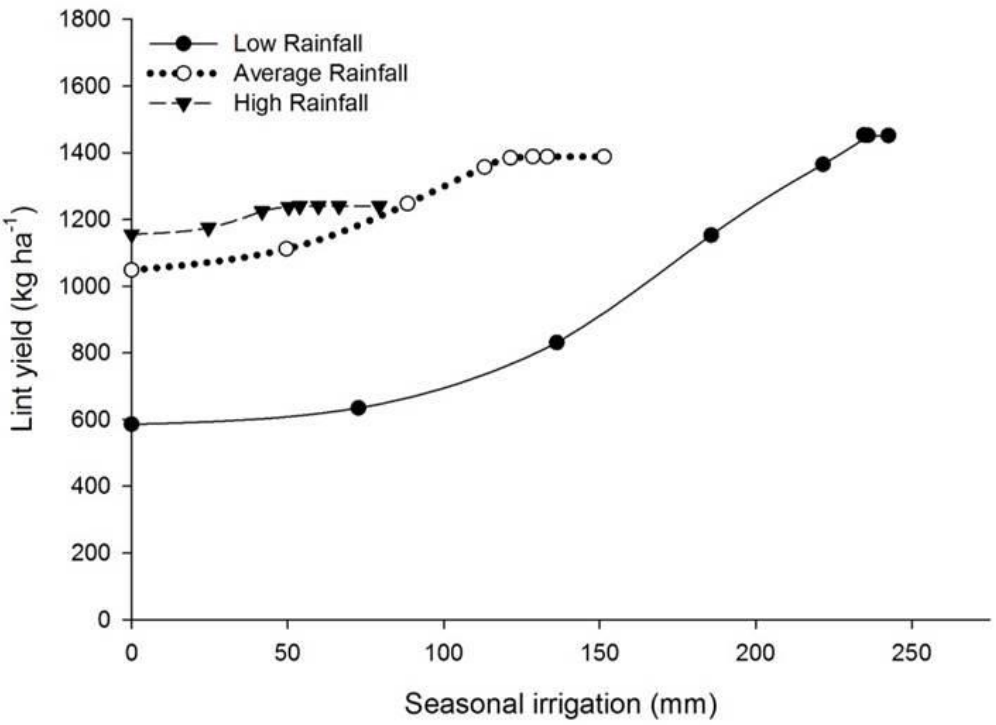

Figure 3. Simulated yield response of cotton to eight irrigation strategies, including non-irrigated, in Bertie County for years with low, average, and high seasonal rainfall totals. Low rainfall years received less than 444 mm of rainfall, one standard deviation less than the mean, and high rainfall years received greater than 782 mm of rainfall, one standard deviation greater than the mean. Average rainfall years received rainfall totals within the range of one standard deviation below and above the mean. Each line represents the average of 62 years of simulations.

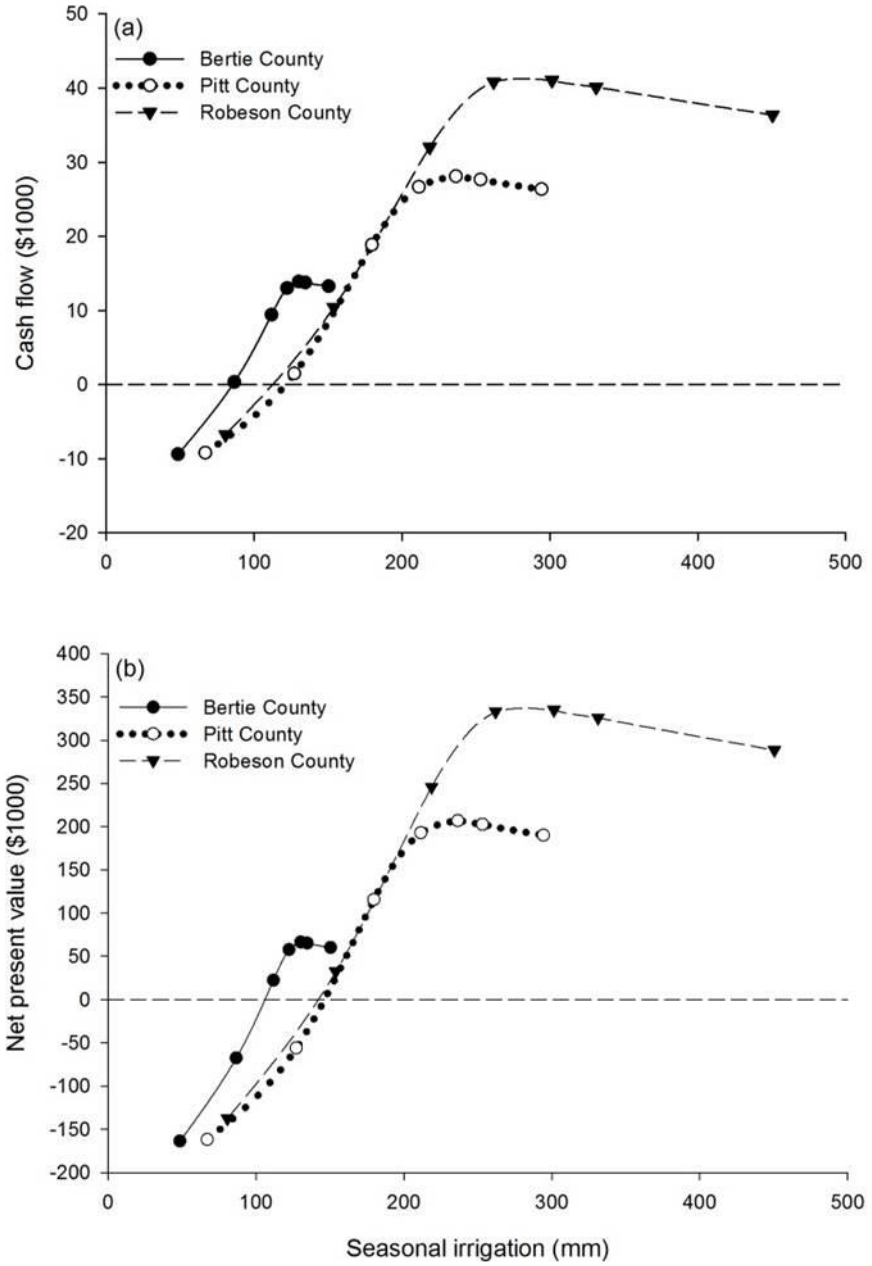

Figure 4. Cash flow (a) and net present value (NPV) (b) of seven irrigation strategies for Bertie, Pitt, and Robeson Counties. Each line represents the average of 66 years of simulations with the exception of Bertie County representing only 62 years of simulations. Horizontal dashed lines represent the breakeven point of $0, above which a positive NPV represents a feasible investment.