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AGRONOMY AND SOILS

Cotton Development and Yield Response to Irrigation, Planting Date, and Cultivar in North Carolina

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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 nonuniform shape of most North Carolina fields are not conducive for a center pivot system. However, benefits to yield due to irrigation in North Carolina have been reported, specifically in years receiving below average or sporadic rainfall. 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 more than 750 mm of rainfall and no differences were observed for any parameters between irrigated and non-irrigated plots. Total rainfall in 2015 and 2016 was lower with several extended periods without rain events. There was a greater plant height increase and dry weight accumulation throughout the growing season in response to SDI. Cotton yields were increased by SDI in 2015 and 2016. Cultivar only influenced lint yield in 2016 with the earlier-maturing 'PHY 333 WRF' having greater lint yield than 'PHY 499 WRF'. Planting date did not influence yield under irrigated conditions, and the timing of rainfall played a role similar to previous reports in North Carolina. Irrigation applied via SDI will increase cotton plant stature, fruit retention, and yield in response to deficit moisture conditions, independent of planting date or cultivar.

North Carolina receives between 1 and 1.4 m yr^{-1} of rainfall east of the mountain region. Although this amount might provide enough total rainfall to satisfy the seasonal water requirements of most crops, the timing and distribution of rainfall can be yield limiting factors. Irrigation is an important tool to mitigate periods of limited water availability (Jordan et al., 2014; Nuti et al., 2012; Sorenson et al., 2011; USDA-NASS, 2014).

Recent studies conducted across the southeastern Cotton Belt have shown that irrigation has the potential to stabilize or increase cotton yields in regions with uncertain rainfall patterns. 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) in Tennessee (Gwathmey et al., 2011). Using historical weather data from the area, it was determined this rainfall pattern occurred in 60% of the years with available data. Whitaker et al. (2008) reported increased yields with irrigation in two of three years with 60 to 70 cm of total water (rainfall and irrigation) per season being optimal in Georgia. Pettigrew (2004) and Balkcom et al. (2006) also reported increased yields with irrigation in two of four years and in two of three years in Mississippi and Alabama, respectively.

Several studies also have 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 North Carolina have shown increases in cotton yield in six of 11 years from 2001 through 2013 versus non-irrigated cotton (Jordan et al., 2014; Nuti et al., 2006, 2012). Rainfall totals of 45 cm or greater, from May to August were adequate and erased the effect of irrigation on fiber yield. 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, 2012). It has been reported, both in peanut (Lanier et al., 2004) and cotton (Nuti et al., 2006; Whitaker et al., 2008), that yield did not differ between SDI and overhead sprinkler irrigation (OSI), but irrigation increased yield compared to non-irrigated systems. Ritchie et al. (2009) found that irrigated cotton grown in SDI systems in contrast to OSI had increased boll retention between nodes six and 10, effectively reduc-

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ing the number of bolls from nodes 14 through 18. This increased boll retention also caused plants to be more compact and reduced in height, although yield did not differ between irrigation systems (Ritchie et al., 2009). SDI systems are similar in investment costs to pivot OSI but are more economical in fields of 25 ha or less, given a system with a lifespan of at least 10 years (O'Brien et al., 1998).

Along with increasing yield, proper irrigation regimes should maximize water-use efficiency of the cropping system while 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 using SDI when compared to OSI, increasing water-use efficiency by as much as 23%. Lamb et al. (2015) addressed both the agronomic and economic effects of irrigation rate in cotton produced in the humid southeastern U.S. in Georgia. Yield 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 yield 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 an SDI system was at 75% plant water-use replacement with drip lines buried in every other row.

Planting dates in North Carolina range from late April through early June. Planting date will often dictate which cultivars are selected based on maturation rating (Edmisten and Collins, 2016). Nuti et al. (2012) found that the effects of SDI were independent of planting date and cultivar in eastern North Carolina. Though seasonal environmental conditions can influence cotton response to planting date, data from five years indicated 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, however, limited research exists on the interactions these factors have on cotton growth and development throughout the season.

Even with the potential benefits of irrigation in cotton, irrigated cotton hectares in North Carolina has remained at approximately 2.7% of the total hectares planted since 2002 (USDA-NASS, 2014). Subsurface drip irrigation systems are similar in investment costs to pivot OSI but are more economical in fields of 25 ha or less (O'Brien et al., 1998). Much of this lack of adoption of irrigation in North Carolina is due to a mean field size of 4.25 ha and the irregular field shapes more common in North Carolina than in many other cotton producing regions. These factors render large OSI systems unsuitable, whereas SDI could fit such a niche. This study is part of a long-term study on the feasibility of SDI as a viable irrigation strategy in North Carolina. In addition to establishing fiber yield, influences of planting date and cultivar on season-long growth and development were determined.

MATERIALS AND METHODS

Research 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) during the 2014 to 2016 seasons. 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 consisting of four rows (91-cm row spacing) by 12 m in length and 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 to 10 May for the early planting, 20 to 24 May for the mid-planting, and 3 to 8 June for the late planting (Table 1).

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 June	17 June
2015	6 May	21 May	8 June	17 June
2016	10 May	24 May	8 June	20 June

Cotton (*Gossypium hirsutum* L.) cultivar Phytogen (PHY) 333 WRF and PHY 499 WRF (Dow AgroScience, Indianapolis, IN) were chosen to represent early and late maturing cultivars, respectively. Phytogen 333 WRF is described as an early maturing cultivar with the average first fruiting node of six. Phytogen 499 WRF is described as a mid-maturing cultivar with the average first fruiting node of 7.9. The maturity description from Phytogen is based on maturity data across the Cotton Belt. Although PHY 499 WRF is listed as mid-maturing, it is representative of a late maturing cultivar in North Carolina, due to the shorter growing season compared to other regions of the U.S. 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 applied at planting. Cotton was maintained using North Carolina extension recommendations regarding all pest management and harvest decisions (NCCES, 2016).

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 (single or concurrent days) of 18 mm or greater, irrigation was terminated for 3 d and reinitiated on the 4th d. 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. This period was selected because no irrigation treatment occurred prior to June for any treatment combination. In addition, the last effective date of anthesis in North Carolina is 20 to 25 August (NCCES, 2016) and approximately 65% of the maturation interval for the last boll will occur by 30 September.

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**

Daily values for maximum temperature, minimum temperature, and rainfall were obtained from the State Climate Office of North Carolina located at North Carolina State University. Daily heat units were calculated in each year using the following equation:

$$\text{Heat Units (HU)} = [(T_{max} + T_{min})/2] - 15.5\ °C,$$

where T_{max} and T_{min} were the maximum and minimum daily temperatures in °C, respectively and 15.5 °C was the threshold temperature for growth.

Plant populations were determined from plant counts of a randomly selected 3.1 m of on the two center rows at 2 wks after emergence. Plant heights were measured weekly on five random plants from the center two rows from the soil level to the uppermost terminal. In 2015 and 2016, plant samples were taken at four growth stages for each planting date by cutting plants from 0.5 m at the soil surface from the two center rows. Samples were taken from each planting date at pinhead square (PHS), first bloom, first open boll (open boll), and at the day of defoliation. Three plants were separated into leaves, stems, and squares, flowers, and bolls. All samples were then dried at 70 °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. In 2016, following the same procedures, a fifth sample was also taken at the 3rd wk of bloom. 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, NE).

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 three replicates in plots planted to variety PHY499 WRF in 2015 and all plots of three replicates. 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 two center rows of each plot were machine harvested on 29 October. In 2015, due to concerns of inclement weather affecting cotton yield and quality, 1 m from each of the two center rows was hand harvested when each planting date was deemed ready. 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 weather concerns the second and third planting dates 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. The retained 50 boll samples were ginned with a Continental 12-saw tabletop gin without lint cleaners to obtain 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, NC) 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 also were influenced by cultivar in 2016 and were converted to lint yield based on the average lint percentages of 45 and 43% for PHY333 WRF and PHY499 WRF, 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

Environmental Conditions. *Water Availability*. 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, 2012). Rainfall accumulation varied widely from season to season for the period of June to September. (Table 2 and Fig.1A). Rainfall received from June to September was 769, 488, and 813 mm in 2014, 2015, and 2016, respectively (Table 2). Rainfall events (single or concurrent days) of the magnitude required to terminate irrigation for the allotted 3 d was 15, 10, and 14 in 2014, 2015, and 2016, respectively (Fig. 2).

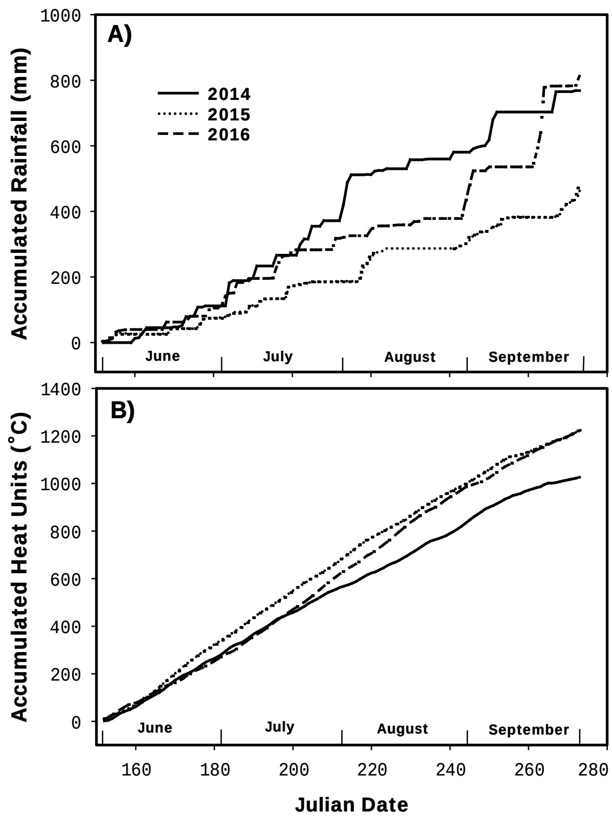

Figure 1. Cumulative rainfall (A) and heat units (B) from 1 May through 31 September in 2014, 2015, and 2016.

In 2016, 235 mm of precipitation fell between the 2 wks prior to and 2 wks following the early planting date, with only 10 of 28 d not receiving any measurable rainfall (Fig. 2). Total rainfall during the reported period was the greatest in 2016, although more than 50% of this rainfall fell during the month of September (Fig 1A.). The remnants of Hurricane Hermine delivered 146 mm of rainfall between 1 and 3 September, followed by Tropical Storm Julia that accounted for 246 mm of rainfall from 19 to 22 September (Figs. 1A and 2). The remnants of Hurricane Matthew in early October then delivered another 269 mm of rainfall (Fig. 2). The rainfall received in October was not accounted for as seasonal rainfall, as most of the cotton was more thsn 60% open bolls. This late rainfall also resulted in delayed defoliation and harvest of all planting dates.

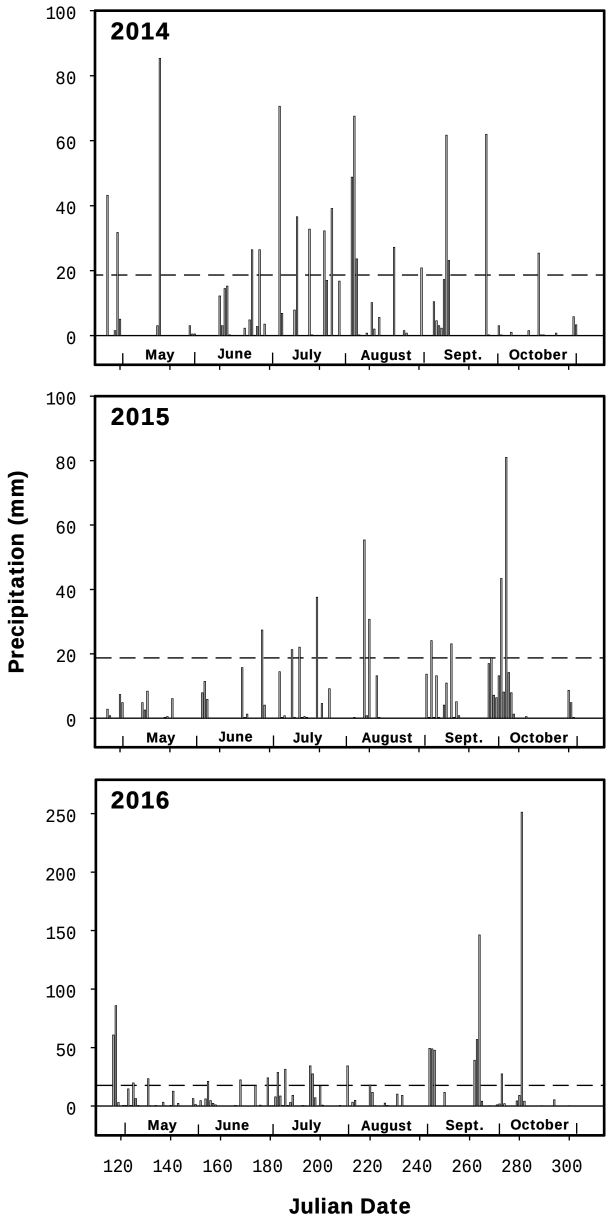

Figure 2. Rainfall amounts from 25 April to 31 October in 2014 (a), 2015 (b), and 2016 (c). Horizontal dashed lines represent the 18 mm threshold at which irrigation was terminated for three days. Notice the y-axis scale difference in 2016.

Due to the evenly distributed and high total rainfall throughout the growing season, no differences were observed between irrigated and non-irrigated cotton in 2014 for fiber yield (Table 3) or any growth parameters measured during the season, including plant heights and partitioned and total biomass (data not shown). Lack of response to SDI was similar to previous findings where rainfall totals were greater than 45 cm from May through August (Jordan et al., 2014; Nuti et al., 2006, 2012).

Table 3. 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^z	1029 a
Non-Irrigated	1299	330 b	459 b
LSD	ns	138	61
Planting Date			
Early	1254	int^y	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

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

^{y} Main effect means omitted due to a significant two-way interaction between SDI and planting date.

Temperature Patterns. Total accumulated heat units (HU) through September was greatest for 2015 and 2016 with ending values of about 1225 HU (Fig. 1B). The lowest HU value was seen in 2014 with a total of 1026 HU. This value is 83.8 % of the latter 2 yrs.

The importance of the first 40 DAP in determining the growth and yield potential of a cotton crop has been reported (Banks, 2006). With this concept in mind, the HU available for each planting date and year combination was determined over the 40-d post-planting period (Fig. 3). Heat units for early planting dates during 2014, 2015, and 2016 were 71.5, 67.3, and 67.0 %, respectively when compared to the late planting date. These values for the mid-planting date were 86.1, 83.7, and 90.4 % for the same respective years. All HU from all planting dates increased linearly with the exception of the early date in 2016 when cool conditions during the first two weeks caused delayed HU accumulation.

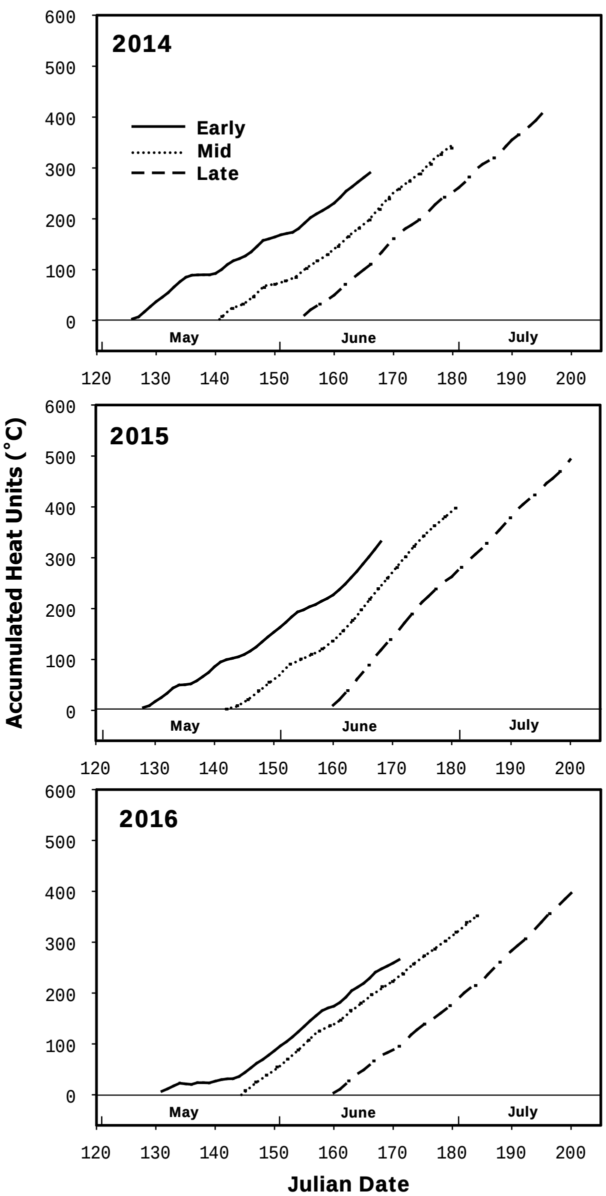

Figure 3. Heat units measured during the first 40 days after early-, mid- and late-plantings for the years 2014, 2015, and 2016.

Fiber Yield. Of the 3 yrs of the study, only 2014 did not show significant responses to irrigation (Table 3). In 2015 and 2016 the two-way interaction between SDI and planting date was significant. Irrigation applied through subsurface drip 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} compared to the non-irrigated treatment (Table 3). These responses are associated to the both the total rainfall and the seasonal pattern of rain events (Figs. 1, 2). In turn, greater stored soil water throughout the growing season in both 2015 and 2016 was found in response to 64 and 43 irrigation applications, respectively (data not shown). This study is part of a long-term examination of the effects of SDI on yield in various crops including cotton (Jordan et al., 2014; Nuti et al., 2006, 2012). With the present study included, positive yield responses to SDI have been observed in 8 of 14 yrs (cotton response to SDI was not studied in 2009 and 2010). In the 8 yrs yield responses were observed, the mean increase due to SDI was 481.4 kg ha^{-1} greater lint yield, which represented an 82.9% increase over the non-irrigated plots.

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 3). 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 attained greater reproductive maturity. 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}. This reversal toward increased yield in earlier versus the late planting date was likely due to sparse rainfall that fell in August (60 mm) 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 PHY 333 WRF having greater lint yield than PHY 499 WRF (Table 3).

Previous research has shown that the dry weight of individual fruiting structures is reduced under water stress conditions (Grimes and Yamada, 1982; McMichael and Hesketh, 1982; Turner at al., 1986; Zhao and Oosterhuis, 1997). In this study, individual boll weights did not respond to SDI (data not shown), thus indicating yield responses to SDI was solely associated with increased boll number.

Attainment of Plant Stature. *Plant Height.* Plant heights responded positively to SDI in both 2015 and 2016 (Fig. 4), which is similar to the report by Pace et al. (1999). The plant height response to SDI was earlier and of greater magnitude in 2015 than in 2016. The first significant plant height differences in the early-, mid- and late-planted cotton occurred at 56, 41, and 36 DAP, respectively in 2015. In 2016, the first differences were observed at 79, 44, and 40 DAP, for the same respective planting dates. Maximal plant heights were attained in 2015 at 86, 76, and 65 DAP for the early-, mid-, and late-planted cotton, respectively. For the same respective planting dates in 2016, maximal plant heights were attained at 94, 70, and 63 DAP. The differences in maximal plant height in 2015 for the early-, mid- and late-planted cotton were 25, 30, and 21 cm, respectively. The differences in 2016 for the same respective dates were 12, 14, and 19 cm. The early-planted cotton in 2016 experienced reduced heat unit accumulation over the initial 2 wk period with only 43.7 HU as compared to approximately 130 HU for the two later planting dates. Late-planted cotton had the greatest plant heights in all measurements, followed by the mid-planted and then early-planted cotton. The effects of planting dates on plant height suggest that the heat units available in the first 40 d after planting (Fig. 3) were important in creating the foundation for subsequent growth. The vegetative development rate of late-planted cotton was increased due to increased temperatures and more optimum growing conditions during germination and early development (Table 4; Fig. 3). Wells and Meredith (1984a) found that vegetative dry matter produced in response to a late-April planting was less than 80% of that produced by a mid-May planting date.

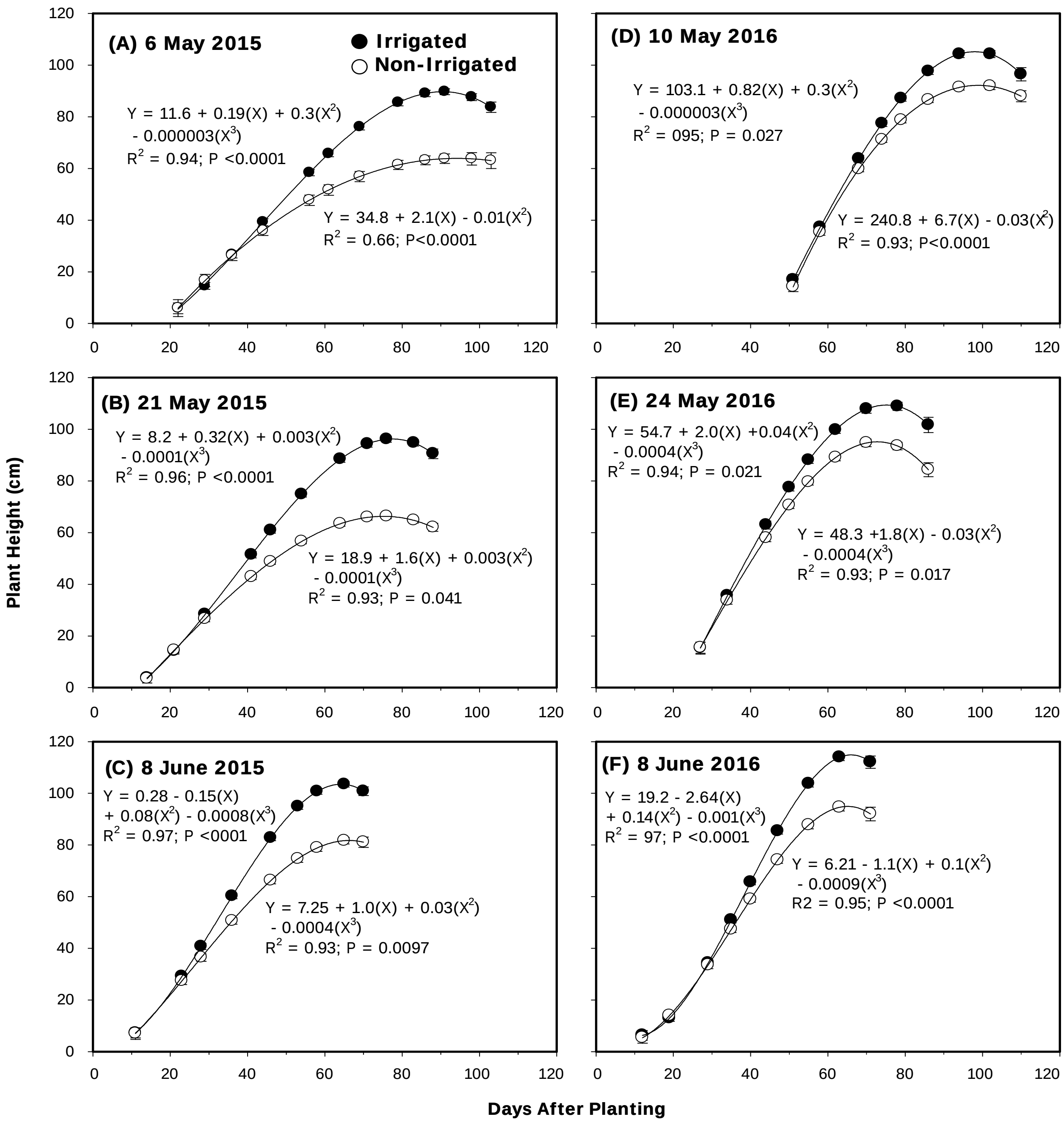

Figure 4. Plant height as a function of days after planting for irrigated and non-irrigated cotton and for early-, mid-, and late-planted cotton in 2015 and 2016. Error bars represent ± 1 standard error.

Table 4. 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	10.0 b[z]	15.2 c	21.3 c	34.3 c	54.3 c	62.7 c	68.6 c	74.6 c
Mid	10.3 b	21.4 b	48.4 b	58.5 b	70.8 b	76.9 b	77.2 b	79.0 b
Late	26.4 a	33.7 a	59.2 a	80.6 a	84.1 a	87.4 a	95.5 a	97.3 a
LSD	1.1	1.6	2.4	3.7	3.4	4.3	4.0	3.7
Cultivar								
PHY333WRF	15.2	22.7 b	42.0	57.3	69.0	74.8	79.0	81.4 b
PHY499WRF	16.0	24.1 a	43.9	58.3	70.4	76.5	81.9	85.8 a
LSD	ns	1.3	ns	ns	ns	ns	ns	3.0
2016								
Planting Date								
Early	-	-	-	19.5 c	30.1 c	59.4 b	78.9	-
Mid	-	-	-	77.0 b	85.7 b	96.3 a	99.9 b	-
Late	-	-	-	84.1 a	95.6 a	99.0 a	106.3 a	-
LSD	-	-	-	4.8	3.6	4.0	16.4	-
Cultivar								
PHY333WRF	-	-	-	59.0	68.1 b	82.7 b	90.0 b	-
PHY499WRF	-	-	-	61.4	72.8 a	87.0 a	96.3 a	-
LSD	-	-	-	ns	2.9	3.2	4.0	-

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

Cultivar PHY499WRF had greater plant height in both 2015 and 2016. This observation of cultivar height difference was expected as PHY 499 WRF is described by Phytogen as a tall variety, compared to the PHY 333 WRF description of medium-tall. The differences in maximal height were approximately 4 to 6 cm.

Leaf Area Indices. Subsurface drip irrigation increased leaf area index (LAI) starting first bloom and continuing through first open boll in 2016 (Table 5). The LAI values for the non-irrigated treatments were 79, 73, and 64% of the irrigated values found in 2016 at first bloom, bloom plus 3 wks, and first open boll, respectively. This pattern was also evident in 2015 (data not shown). 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) suggested, however, the reduction of leaf area is due to a reduction in individual leaf size and not the number of leaves. Regardless of the reason for reduced LAI values in non-irrigated cotton, smaller plant canopies will be less able to intercept available sunlight and canopy photosynthetic rates will be diminished (Pettigrew and Meredith, 2012).

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 5). The greatest LAI values in 2016 were observed in the early- and mid-planting dates with values of approximately 3.0. Zhang et al. (2016) reported that maximum LAI occurred during early boll setting under saturation or regular irrigation, whereas deficit irrigation showed maximum LAI coincided with peak boll setting.

Although cultivar PHY 333 WRF had a greater LAI in some instances in 2015 (data not shown), overall, the response of LAI to cultivar was relatively minor when compared to the responses to irrigation and planting date (Table 5).

Reproductive Dry Matter. In 2015 and 2016, differences between the dry weight of fruiting structures of irrigated and non-irrigated cotton were insignificant through first bloom (Fig. 5). 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 vulnerable to abscission in response to water stress within the 1st wk they are visible (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 (Guinn and Mauney, 1984), though neither scenario was observed in this study.

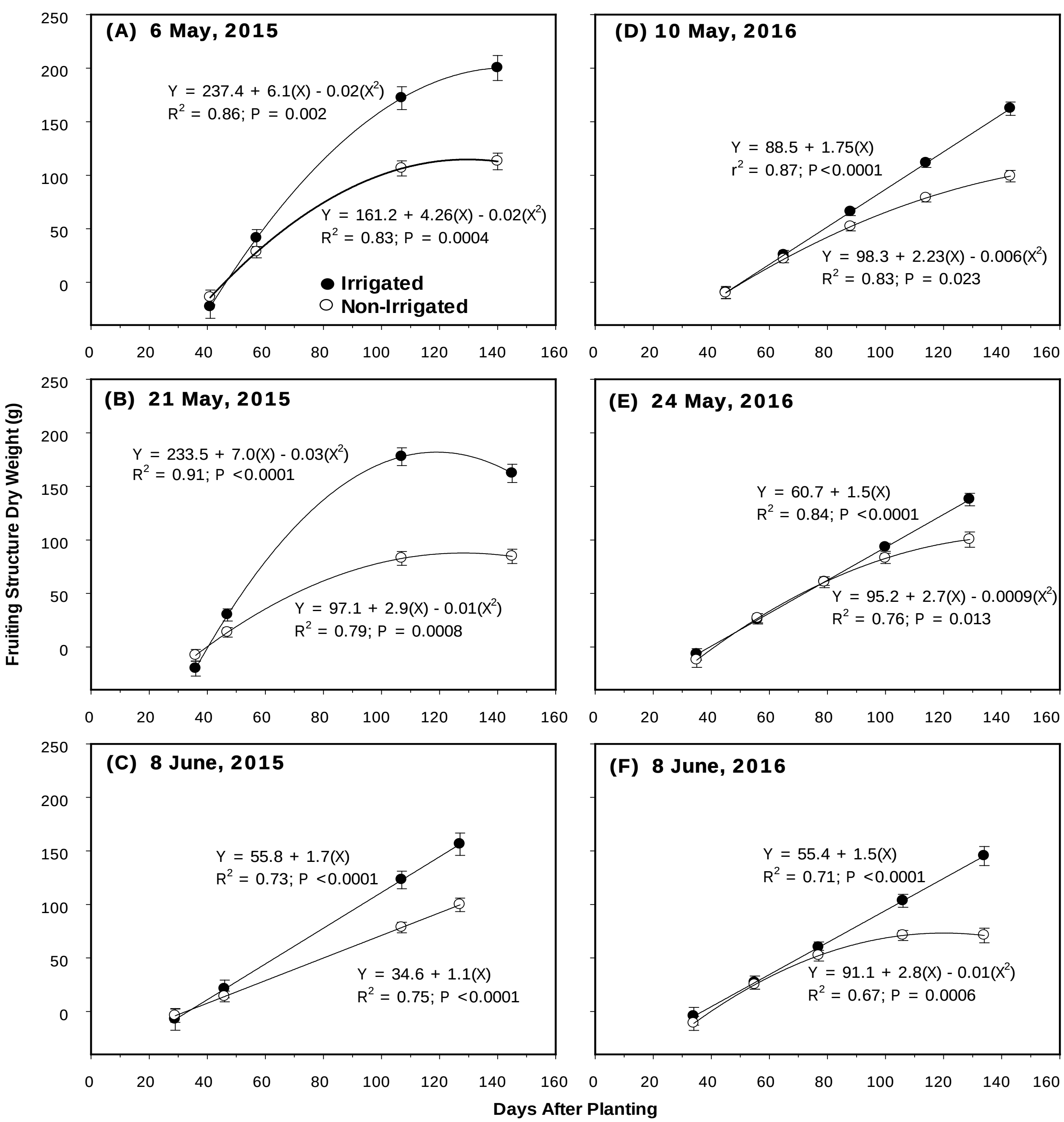

Figure 5. Fruit dry weight as a function of days after planting for irrigated and non-irrigated cotton and for early-, mid-, and late-planted cotton in 2015 and 2016. Error bars represent ± 1 standard error.

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	0.48	2.71 a[z]	3.26 a	1.90 a	0.75
Non-Irrigated	0.45	2.15 b	2.37 b	1.21 b	0.77
LSD	ns	0.14	0.11	0.21	ns
Planting Date					
Early	0.30 c	1.97 b	2.90 a	1.43	0.81 a
Mid	0.43 b	2.61 a	3.14 a	1.63	0.99 a
Late	0.65 a	2.71 a	2.39 b	1.60	0.48 b
LSD	0.06	0.456	0.35	ns	0.18
Cultivar					
PHY333WRF	0.48	2.40	2.80	1.59	0.75
PHY499WRF	0.45	2.46	2.83	1.52	0.78
LSD	ns	ns	ns	ns	ns

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

Beyond first bloom, the response of fruiting structure dry weights to irrigation increased greatly in 2015 (Fig. 5). Differences observed in 2016, however, they were not observed until after the 3rd wk of bloom and were smaller than those observed in 2015 at first open boll and defoliation. 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. Soil water in the top 30 cm of nonirrigated plots declined sharply in late July, whereas SDI maintained greater soil water (data not shown). 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 in response to concomitant vegetative growth.

Irrigation, cultivar and planting date all had large influences on the proportion of dry matter found in reproductive versus vegetative tissues at the time of defoliation (Table 6). Irrigation in 2015 resulted in 57.6% of biomass in fruit as compared with 47.3% in the non-irrigated cotton. These same respective values in 2016 were 54.0 and 49.1%. The same increase in reproductive partitioning in response to irrigation is evident in the reproductive-to-vegetative ratios (RVR) with irrigated and non-irrigated values of 1.50 and 1.22, respectively, in 2015. In 2016, RVR values were 1.22 and 1.03 ($p = 0.068$) for the irrigated and non-irrigated treatments, respectively. Cultivar differences were also observed in both years with PHY 333 WRF having both greater percentage fruit and RVR than PHY 499 WRF. The effects of planting date were also significant with regard to percentage fruit and RVR. The early-planted cotton had greater percentage fruit and RVR than the mid- and late-planted crops.

Greater RVR has been reported to be associated with newer cultivars when compared with obsolete cultivars (Wells and Meredith, 1984b). In a subsequent study designed to determine if continued progress through conventional breeding for yield was plausible, data suggested that yield increases realized through selection for further partitioning from vegetative to reproductive structures were likely to continue after 1990 (Meredith and Wells, 1989). In the present study, increases in percentage fruit biomass and RVR were associated with moisture availability, cultivar earliness, and earlier planting date indicating that a shift towards earlier maturity generates positive yield changes.

Table 6. Influence of irrigation, planting date, and cultivar on biomass partitioning of stem, leaf and fruit as a percentage of the total biomass and reproductive-to-vegetative dry matter ratio (RVR) at defoliation in 2015 and 2016

	2015				2016			
	Stem	Leaf	Fruit	RVR	Stem	Leaf	Fruit	RVR
	---------- % ----------				---------- % ----------			
Irrigation								
Irrigated	36.6	6.8 b[z]	57.6 a	1.50 a	39.1	6.9	54.0 a	1.22
Non-Irrigated	37.4	15.3 a	47.3 b	1.22 b	40.9	10.0	49.1 b	1.03
LSD	y	2.0	4.8	0.21	ns	y	4.7	x
Planting Date								
Early	29.5	11.2	59.3 a	1.63 a	36.3 b	7.9	55.8 a	1.31 a
Mid	39.1	11.7	49.2 b	1.03 b	39.2 b	9.8	51.0 b	1.09 b
Late	40.9	10.2	48.9 b	1.03 b	44.4 a	7.7	47.9 b	0.97 b
LSD	y	ns	4.9	0.33	3.7	y	4.7	0.20
Cultivar								
PHY333WRF	33.6	10.2 b	56.2 a	1.42 a	36.9 b	8.2	54.9 a	1.26 a
PHY499WRF	39.4	11.9 a	48.7 b	1.04 b	43.1 a	8.7	48.2 b	0.99 b
LSD	y	1.7	4.0	0.28	3.0	ns	3.8	0.17

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

[y] Main effect mean significance difference omitted due to a significant three-way interaction between the main effects of subsurface drip irrigation, cultivar, and planting date.

[x] Significantly different at $p = 0.068$.

CONCLUSIONS

The major conclusions from the study herein were: (1) of the main effects studied in this investigation, SDI was most important in explaining an enhancement in observed fiber yields. In 2015 and 2016, irrigation increased yields 170 and 124%, respectively. The magnitude and the likelihood of these responses agrees with earlier reported yield differences found in this long-term study. (2) The criteria for a response to SDI are that rainfall fall below some undefined threshold total and/or the pattern rainfall events are poorly distributed, resulting in rain limitations during critical stages of growth. (3) Plant growth as measured as plant height, LAI, and reproductive dry weight was important in explaining the observed yield differences in response to irrigation. Irrigation resulted in taller plants that could support greater leaf growth and plant stature and hence greater reproductive production. (4) Later planting dates resulted in increased vegetative growth as observed in enhanced plant height and stem dry weight. This observation was related to greater available heat units observed in the latter two planting dates during early development. This enhanced vegetative growth also contributed to the reduced fruit percentages of total biomass and RVR at defoliation. (5) Overall, irrigation appears to have promise as a production input in North Carolina and SDI is a viable option. More than half the years (57%) in the long-term SDI study have resulted in substantial (82.9%) yield increases.

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DISCLAIMER

Mention of a trademark, warranty, proprietary product or vendor does not constitute a guarantee by North Carolina State University and does not imply approval or recommendation of the product to the exclusion of others that may be suitable.

REFERENCES

Banks, J.C. 2006. Best management practices–One. p. 2337–2342. *In* Proc. Beltwide Cotton Conf. San Antonio, TX. 3-6 Jan. 2006. Natl. Cotton Counc. Am., Memphis, TN.

Balkcom, K.S., D.W. Reeves, J.N. Shaw, C.H. Burmester, and L.M. Curtis. 2006. Cotton yield and fiber quality from irrigated tillage systems in the Tennessee Valley. Agron. J. 98:596–602.

Cahoon, C.W., A.C. York, D.L. Jordan, W.J. Everman, R.W. Seagroves, L.R. Braswell, et al. 2015. Weed control in cotton by combinations of microencapsulated acetochlor and various residual herbicides applied preemergence. Weed Tech. 29:740–750.

Carmer, S.G., W.E. Nyquist, and W.M. Walker. 1989. Least significant differences for combined analyses of experiments with two- or three-factor treatment designs. Agron. J. 81:665–672.

Edmisten, K.L., and G.D. Collins. 2016. Planting Decisions. p. 19–22 *In* K. Edmisten (Ed.), 2016 Cotton Information. North Carolina Coop. Ext. Serv. Publ. AG-417. Raleigh, NC.

Fisher, K., and T. Udeigwe. 2012. Cotton water requirements. p. 14–16 *In* C. Perry and E. Barnes (Eds.), Cotton Irrigation Management for Humid Regions. Cotton Inc., Cary, NC.

Grabow, G.L., R.L. Huffman, R.O. Evans, D.L. Jordan, and R.C. Nuti. 2006. Water distribution from a subsurface drip irrigation system and dripline spacing effect on cotton yield and water use efficiency in a coastal plain soil. Trans. ASABE. 49:1823–1835.

Grimes, D.W., and H. Yamada. 1982. Relation of cotton growth and yield to minimum leaf water potential. Crop Sci. 22:134–139.

Guinn, G., and J.R. Mauney. 1984. Fruiting of cotton I. Effects of moisture status on flowering. Agron. J. 76:90–94.

Gwathmey, C.O., B.G. Leib, and C.L. Main. 2011. Lint yield and crop maturity response to irrigation in a short-season environment. J. Cotton Sci. 15:1–10.

Jordan, D.L., P.D. Johnson, G.L. Grabow, and T. Corbett. 2014. Corn, cotton, and peanut response to tillage and subsurface drip irrigation in North Carolina. Agron. J. 106:962–967.

Krieg, D.R., and J.F.M. Sung. 1986. Source-sink relations as affected by water stress during boll development. p. 73–77 *In* J.R. Mauney and J.M. Stewart (Eds.), Cotton Physiology. The Cotton Foundation, Memphis, TN.

Lamb, M.C., R.B. Sorenson, R.C. Nuti, and C.L. Butts. 2015. Agronomic and economic effect of irrigation rate in cotton. Crop, Forage, Turfgrass Manag. 1:1–7. Doi: 10.2134/cftm2014.0061.

Lanier, J.E., D.L. Jordan, J.S. Barnes, J. Matthews, G.L. Grabow, W.J. Griffin, Jr., J.E. Bailey, P.D. Johnson, J.F. Spears, and R. Wells. 2004. Disease management in overhead sprinkler and subsurface drip irrigation systems for peanut. Agron. J. 96:1058–1065.

McMichael, B.L., and J.D. Hesketh. 1982. Field investigations of the response of cotton to water deficits. Field Crops Res. 5:319–333.

Meredith, W.R., Jr., and R. Wells. 1989. Potential for increasing cotton yields through enhanced partitioning to reproductive structures. Crop Sci. 29:636–639.

Moore, K.J., and P.M. Dixon. 2015. Analysis of combined experiments revisited. Agron. J. 107:763–771.

North Carolina Cooperative Extension Service [NCCES]. 2016. Cotton Information. AG- 417. North Carolina Coop. Ext. Serv., Raleigh, NC.

Nuti, R.C., G.D. Collins, D.L. Jordan, T. Corbett, J.E. Lanier, K.L. Edmisten, R. Wells, and G.L. Grabow. 2012. Cotton response to subsurface drip irrigation, planting date, cultivar, and mepiquat chloride. J. Crop Manage. 112:319. doi: 10.1094/CM-2012- 0319-01RS.

Nuti, R.C., S.N. Casteel, R.P. Viator, J.E. Lanier, K.L. Edmisten, D.L. Jordan, G.L. Grabow, J.S. Barnes, J.W. Matthews, and R. Wells. 2006. Management of cotton grown under overhead sprinkle and subsurface drip irrigation. J. Cotton Sci. 10:76–88.

O'Brien, D.M., D.H. Rogers, F.R. Lamm, and G.A. Clark. 1998. An economic comparison of subsurface drip and center pivot sprinkler irrigation systems. Appl. Eng. Agric., 14:391–398.

Pace, P.F., H.T. Cralle, S.H.M. El-Halawany, J.T. Cothren, and S.A. Senseman. 1999. Drought-induced changes in shoot and root growth of young cotton plants. J. Cotton Sci. 3:183–187.

Pettigrew, W.T. 2004. Moisture deficit effects on cotton lint yield, yield components, and boll distribution. Agron J. 96:377–383.

Pettigrew, W.T., and W.R. Meredith, Jr. 2012. Genotypic variation in physiological strategies for attaining cotton lint yield production. J. Cotton Sci. 16:179–189.

Ritchie, G.L., J.R. Whitaker, C.W. Bednarz, and J.E. Hook. 2009. Subsurface drip and overhead irrigation: A comparison of plant boll distribution in upland cotton. Agron. J. 101:1336–1344.

Sorensen, R.B., C.L. Butts, and R.C. Nuti. 2011. Deep subsurface drip irrigation for cotton in the southeast. J. Cotton Sci. 15:233–242.

Turner, N.C., A.B. Hearn, J.E. Begg, and G.A. Constable. 1986. Cotton (*Gossypium hirsutum* L.): Physiological and morphological responses to water deficits and their relationship to yield. Field Crops Res. 14:153–170.

Ungar, E.D., E. Kletter, and A. Genizi. 1989. Early season development of floral buds in cotton. Agron. J. 81:643-649.

United States Department of Agriculture-National Agricultural Statistics Service [USDA-NASS]. 2014. 2012 Census of agriculture: North Carolina state and county data. http://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_State_Level/North_Carolina/st37_1_037_37.pdf. (verified 17 Jun 2019).

Wells, R., and W.R. Meredith, Jr. 1984a. Comparative growth of obsolete and modern cotton cultivars: I. Vegetative dry matter partitioning. Crop Sci. 24:858–862.

Wells, R., and W.R. Meredith, Jr. 1984b. Comparative growth of obsolete and modern cotton cultivars: II. Reproductive dry matter partitioning. Crop Sci. 24:863–868.

Whitaker, J.R., G.L. Ritchie, C.W. Bednarz, and C.I. Mills. 2008. Cotton subsurface drip and overhead irrigation efficiency, maturity, yield, and quality. Agron. J. 100:1763–1768.

Zhang, D., Z. Luo, S. Liu, W. Li, W. Tang, and H. Dong. 2016. Effects of deficit irrigation and plant density on the growth, yield and fiber quality of irrigated cotton. Field Crops Res. 197:1–9.

Zhao, D., and D. Oosterhuis. 1997. Physiological response of growth chamber-grown cotton plants to the plant growth regulator PGR-IV under water-deficit stress. Environ. Exp. Bot. 38:7–14.