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Michael Thomas Plumblee

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Effects of irrigation scheduling using soil moisture sensors, irrigation termination, and simulated damage on plant development and yield on cotton (*Gossypium hirsutum* L.) in the Mid-South

By

Michael Thomas Plumblee

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Effects of irrigation scheduling using soil moisture sensors, irrigation termination, and simulated damage on plant development and yield on cotton (*Gossypium hirsutum* L.) in the Mid-South

By

Michael Thomas Plumblee

Approved:

Darrin M. Dodds
(Co-Major Professor)

L. Jason Krutz
(Co-Major Professor)

Angus L. Catchot Jr.
(Minor Professor)

J. Trenton Irby
(Committee Member)

Johnie N. Jenkins
(Committee Member)

Michael S. Cox
(Graduate Coordinator)

J. Mike Phillips
(Department Head)

George M. Hopper
Dean
College of Agriculture and Life Sciences

Name: Michael Thomas Plumblee

Date of Degree: May 4, 2018

Institution: Mississippi State University

Major Field: Agronomy

Major Professors: Darrin M. Dodds and L. Jason Krutz

Title of Study: Effects of irrigation scheduling using soil moisture sensors, irrigation termination, and simulated damage on plant development and yield on cotton (*Gossypium hirsutum* L.) in the Mid-South

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Candidate for Degree of Doctor of Philosophy

Through proper irrigation scheduling and management of damaged cotton, sustainable agricultural withdrawal from the Mississippi River Valley Alluvial Aquifer can be achieved while maximizing net returns. This research was conducted to 1) develop a sensor based irrigation strategy that maximized cotton lint yield and quality, irrigation, and water use efficiency (IWUE) and 2) quantify the effects of timing of damage, intensity, and foliar N on cotton growth and development. Lint yield, fiber quality, and IWUE were optimized using a season-long irrigation threshold of -90 kPa and irrigation terminated 2-weeks before cracked boll. Regardless of cotton variety (early- or late-maturing) or timing of damage, plant height, number of nodes, and lint yield were negatively correlated with the intensity of damage. Moreover, the application of foliar nitrogen to damaged cotton had no effect on plant growth, lint yield, or fiber quality, regardless of N application timing. These data indicate that lint yield, and fiber quality are optimized when cotton varieties are selected based on yield potential, irrigated at -90 kPa threshold, and irrigations are terminated two weeks before cracked boll.

DEDICATION

I would like to dedicate this dissertation to my loving wife, Allison Plumblee. Through your support, encouragement, understanding, help, and love you made getting through this degree possible. Without you this would have been an unimaginable feat to accomplish. I am looking forward to spending the rest of my life with you, and I am excited as we begin a new chapter in our lives.

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CHAPTER I

DETERMINING OPTIMUM IRRIGATION SCHEDULE USING SOIL MOISTURE SENSORS IN FURROW IRRIGATED COTTON

1.1 Abstract

Sensor based irrigation thresholds for Mid-South crops could reduce agricultural withdrawal from the Mississippi River Valley Alluvial Aquifer. This research was conducted to develop a sensor based irrigation threshold for cotton (*Gossypium hirsutum* L.) that maximizes lint yield, fiber quality, and irrigation water use efficiency (IWUE). The effects of irrigation based on growth stage (full season, emergence to first bloom, first bloom to peak bloom, and peak bloom to first cracked boll) and irrigation threshold (non-irrigated, -50 kPa, -90 kPa, and -130 kPa) on plant growth parameters and lint yield, fiber quality, and IWUE were evaluated on a Leeper silty clay loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts) from 2015 through 2017 at the R.R. Foil Plant Science Research Center, Starkville, MS. Neither irrigation threshold ($p \geq 0.3014$), cotton growth stage ($p \geq 0.1557$), nor the threshold by growth stage interaction ($p \geq 0.2203$) had any effect on plant height at bloom, nodes at bloom, nodes above white flower, cotton height at cracked boll, total nodes at cracked boll, nodes above cracked boll, lint turnout, or fiber quality.

Irrigation threshold based on cotton growth stage did not affect lint yield ($p = 0.2231$). Furrow irrigation applied at a weighted -90 kPa threshold throughout the

growing season in 2016 resulted in a 25 and 26% increase in lint yield compared to -50 kPa and non-irrigated thresholds, respectively. Irrigation water use efficiency was affected by irrigation threshold when managed throughout the season in 2015 and 2016. In 2015 and 2016, irrigation threshold values of -90 kPa had 45 and 72% greater IWUE, respectively, than threshold values of -50 kPa. The interaction of irrigation threshold by cotton growth stage impacted IWUE when data were pooled across year. When irrigation threshold was managed by growth stage, IWUE increased 41 to 42% where no irrigation was applied from emergence to first bloom compared to IWUE when thresholds of -130 and -90 kPa were used, respectively. Cotton managed throughout the season based on a soil moisture sensor threshold of -90 kPa provided the greatest lint yield and IWUE. Additionally, to maximize IWUE, irrigation should only be applied prior to first bloom for special circumstances such as extreme drought.

1.2 Introduction

The Mid-South region of the United States (U.S.), consisting of western Tennessee, southeast Missouri, Mississippi, Arkansas, and Louisiana, obtains a majority of irrigation water from groundwater reserves. In the Mid-South, the Mississippi River Valley Alluvial Aquifer spans nearly 86,000 sq. km (33,000 sq. miles), from Louisiana to Missouri. Wells are tapped into the alluvial aquifer for agricultural irrigation. An estimated 96% of water removed from the alluvial aquifer is used by agriculture (Reba *et al*., 2014). Since the early 1900's, the volume of water withdrawn from this aquifer has increased. The Arkansas Natural Resources Commission reported a withdrawal and recharge rate of 8,036 Mgal/day and 3,374 Mgal/day, respectively, in 2012; thus withdrawal exceeds recharge resulting in declining aquifer levels, annually (Swaim *et al*., 2016).

Cotton (*Gossypium hirsutum* L.) is a major commodity produced in Mississippi, grown on an average of 214,000 hectares (528,500 acres) annually from 2007–2017. Mississippi ranked 4th in cotton production in the U.S. in 2017 (NASS, 2018). From 2011–2014, 44% of the cotton planted in Mississippi was irrigated (NASS, 2016). Approximately 70% of the irrigated cotton in Mississippi is furrow irrigated, the least efficient delivery method currently practiced (FAO, 2018). The remaining 30% of irrigated cotton in Mississippi is applied through overhead sprinkler irrigation (USDA, 2016).

Cotton is categorized as a drought tolerant crop due to its deep taproot, indeterminate growth habit, and semi-tropical and tropical origin; however, cotton may use up to 38 L (10 gallons) of water per plant to maximize yield (Bednarz *et al*., 2003). Water use and demand in cotton is relatively low (< 2.54 mm of water per day) until reproductive growth begins, where it increases until peak bloom and is maximized at 7.1 mm (0.28 inches) of water per day (Fisher and Udeigwe, 2012).

Currently in the U.S. and other parts of the world, various irrigation scheduling methods are utilized to maximize yield while minimizing water use. Though irrigation scheduling methods for cotton exist, not all producers are irrigating using a scheduling method. According to the 2012 Census of Agriculture, only 17% of Mississippi irrigators use a scientific scheduling tool. Of these producers, only 11% schedule irrigation with soil moisture sensors (USDA, 2016). Soil moisture sensors are excellent tools for determining the soil water content in a particular area of a field; however, soils within a field can be variable which may necessitate the use of multiple sensors to accurately schedule irrigation (Vories *et al*., 2015). Field operations and high initial cost are detriments to the use of soil moisture sensors. However, the incorporation of soil moisture sensors into irrigation decision making, allows producers to monitor and determine plant available water in the soil, thus providing a specific threshold value in which irrigation should be initiated (Lieb and Perry, 2012). Previous research exists regarding irrigation scheduling; however, due to crop physiology, growth, and development of cotton, many irrigation scheduling questions remain. Numerous studies have been conducted on cotton water stress, primarily in arid regions of the U.S., where irrigation is essential for crop growth (Vories *et al*., 2015). Limited research has been conducted on irrigation scheduling in cotton in the Mid-South using furrow irrigation and soil moisture sensors.

Timely irrigation, may reduce cost and maximize profit (Vories *et al*., 1991). Eliminating excessive irrigation reduces production cost and conserves water resources (Loka *et al*., 2011). Garrott *et al*. (1988) observed that maximum cotton yields were associated with the lowest levels of water stress. Constable and Hearn (1981), Cull *et al*. (1981), and Turner *et al*. (1986) observed that water stress during flowering and boll development had detrimental effects on yield. However, other research indicates that the most critical period of cotton irrigation is unclear (Loka *et al*., 2011). In regions of the U.S. where supplemental water through irrigation is not necessary for total crop growth, yields fluctuate from year to year even when irrigation is used; therefore, continued irrigation research in cotton is essential (Vories *et al*., 2015).

In order to responsibly utilize the alluvial aquifer to irrigate cotton in Mississippi and throughout the Mid-South, research to develop a sensor based irrigation threshold for cotton that optimizes lint yield, fiber quality, and irrigation water use efficiency (IWUE) is needed. Therefore, the objectives of this research were to evaluate the use of Watermark® soil moisture sensors to determine an optimum irrigation threshold in cotton, to establish threshold values for cotton grown in Mississippi, and to determine if irrigation at specific growth stages had any effect on cotton growth and development, lint yield, IWUE, or fiber quality.

1.3 Materials and Methods

Research was conducted at the R.R. Foil Plant Science Research Center near Starkville, MS (33.473795° N, 88.769147° W) on a Leeper silty clay loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts) from 2015 through 2017. Stoneville 4946 GLB2 (Bayer CropScience, Research Triangle Park, NC) cotton was planted at 111,150 seeds/ha and a depth of 2.5 cm (Table 1.1). Plots consisted of 4 – 96-cm rows that were 12.2-m in length. Four Watermark® 200SS soil moisture sensors (The Irrometer Co., Inc., Riverside, CA) were installed in the second replication of the study in each treatment at depths of 15, 30, 60, and 90 cm. Furrow irrigation was applied when the weighted average of the soil water potential over the 90-cm depth was at threshold. Furrow irrigation was applied with 38-cm by 9-mil lay-flat polyethylene tubing (Delta Plastics, Little Rock, AR), with delivery optimized with the Pipe Hold and Universal Crown Evaluation Tool (PHAUCET version 8.2.20, USDA-NRCS, Washington, DC) (Kebede *et al*., 2014; Bryant *et al*., 2017). Flow rate at the field inlet was determined with a McCrometer flow tube with attached McPropeller bolt-on saddle flowmeter

(McCrometer Inc., Hemet, California). Treatments were in a split-plot arrangement within a randomized complete block design with four replications. The main-plot factor was cotton growth stage, which consisted of emergence to first bloom, first bloom to peak bloom, and peak bloom to first cracked boll. The sub-plot factor was kilopascal (kPa) thresholds including -90, -130, and non-irrigated. In addition, a season long non-irrigated, -50, -90, and -130 kPa threshold were included as controls. Insect control, fertility, plant growth regulator, weed control, and harvest aids were applied based on Mississippi State University Extension recommendations (Bond *et al.*, 2017; Catchot *et al.*, 2017; Dodds, 2017; Dodds *et al.*, 2017a). Data collection consisted of plant height, number of nodes, and nodes above white flower (NAWF) at first bloom, plant height and number of nodes at first cracked boll, nodes above cracked boll (NACB), lint turnout, lint yield, fiber quality, and total water use. Irrigation water use efficiency was calculated using Equation 1.1. Cotton was harvested using a spindle picker modified for small plot research (Table 1.1). Lint turnout was determined by harvesting a 25-boll hand sample by hand and ginning on a 10 saw laboratory cotton gin (Continental Eagle Corp., Prattville, AL). Seed and lint were weighed and lint turnout was calculated by dividing the weight of lint by the total weight of seed plus lint. Fiber quality was determined using a High Volume Instrument (HVI$^{®}$) at the Fiber and Biopolymer Research Institute, Lubbock, TX. Statistical analyses were conducted using PROC GLM procedure in SAS v.9.4 (SAS Institute, Cary, NC). Data were analyzed using analysis of variance (ANOVA) and means were separated using Fisher's Protected LSD at the 0.05 level of significance. Random effects consisted of year and replication and fixed effects consisted of threshold value and growth stage.

1.4 Results and Discussion

Rainfall fluctuated by year throughout the course of this research when compared to the 10 year average rainfall for Starkville, MS (Table 1.2). In 2015, June, August, and September received 31, 57, and 67% less rainfall than the 10 year average, respectively (Table 1.2). These weather conditions resulted in reductions in soil moisture during critical reproductive growth stages in cotton, thus resulting in an increase in irrigation frequency. Early in 2015, adequate soil moisture was provided by rainfall, therefore; irrigation thresholds were not met in 2015 from emergence to first bloom (Table 1.3). Additionally, the 2016 growing season received 15, 14, 24, and 40% less rainfall than the 10 year average during June, July, August, and September, respectively (Table 1.2). Similar to 2015, the 2016 growing season experienced reduced rainfall during critical reproductive growth stages albeit the duration of reduced rainfall was greater in 2016 where reduced rainfall was also experienced in July. Though rainfall was limited during first bloom to peak bloom, increased rainfall from peak bloom to first cracked boll coupled with reduced water use resulted in no irrigation thresholds being met from peak bloom to first cracked boll (Table 1.4). In contrast, the 2017 growing season received 51, 41, and 6% greater rainfall in June, August, and September compared to the 10 year average, respectively (Table 1.2). Therefore in 2017, the frequency of supplemental irrigation was reduced considerably when compared to 2015 and 2016, where irrigation thresholds were not met from emergence to first bloom or from peak bloom to first cracked boll (Table 1.5).

Full season soil moisture sensor thresholds did not affect cotton height at first bloom, node counts at first bloom, nodes above white flower at first bloom, plant height at cracked boll, nodes above cracked boll, lint turnout, micronaire, fiber length, fiber strength, fiber uniformity, or fiber elongation in any year; therefore, data were pooled across year ($p \geq 0.2721$) (Table 1.6). Average values for plant growth parameters and fiber quality are reported in Table 1.7. Previous research has shown contrasting results where fiber quality parameters were affected by irrigation levels in cotton (Dagdelen *et al*., 2009); however, these findings were from an arid environment where irrigation was necessary for cotton production. Furthermore, vegetative growth has been observed to increase where irrigation frequency increases (Stockton, *et al*., 1961). Similar effects were not observed in this research which may suggest that variety selection and consistent rainfall may have influenced overall vegetative growth parameters. Stoneville 4946 GLB2 is a variety that can perform well under irrigated or non-irrigated conditions (Dodds *et al*., 2017b). Furthermore, plant growth regulator applications were only needed in 2015 to control excessive vegetative growth, where an application of mepiquat chloride at a rate of 36.8 g-ai/ha was warranted at first bloom. In addition, irrigation did not have a direct effect on overall plant growth and development.

Full season soil moisture sensor threshold did affect lint yield in 2016 ($p = 0.0495$) and IWUE in 2015–2016 ($p \leq 0.0002$) (Table 1.8). In 2016, irrigation applied when soil moisture deficit reached -90 kPa resulted in lint yield that was 25 and 26% greater than a threshold of -50 kPa and non-irrigated treatments, respectively, resulting in 510 to 536 kg/ha lint yield reductions (Table 1.9). While a season long sensor threshold was only significant in one year of the study, these data suggest that a threshold value of -50 kPa for cotton grown in Mississippi may be too aggressive thus, overwatering cotton and reducing lint yield. These data also suggest that utilizing a threshold of -130 kPa would be more beneficial in terms of lint yield than utilizing -50 kPa when compared to -90 kPa (Table 1.9). Previous research by Hagan *et al*. (1967) reported similar results where a threshold value recommendation of -90 kPa for loam and clay soil textures was optimum. Irrigation water use efficiency was influenced by full season irrigation triggered by soil moisture sensor thresholds in 2015 and 2016 ($p \leq 0.0002$) (Table 1.8). In 2015, IWUE was 45% greater when a threshold of -90 kPa was utilized compared to a threshold of -50 kPa, thus an increase of 27 kg-lint/cm of irrigation water applied resulted (Table 1.10). In 2015, soil moisture deficit for irrigation managed season long did not reach -130 kPa. In 2016, IWUE was 36% greater when a threshold of -90 kPa was utilized compared to -130 kPa and 72% greater when compared to -50 kPa (Table 1.10). When irrigation thresholds of -130 kPa were utilized, IWUE was 57% greater than irrigation using a threshold at -50 kPa (Table 1.10). Therefore, in 2016 a -90 kPa threshold provided an increase of 21 to 42 kg-lint/cm of irrigation water applied compared to -130 and -50 kPa, respectively. In 2017, no differences in IWUE were observed. These observations are likely a result of treatments with a threshold value of -130 kPa not being irrigated due to excessive rainfall. Additionally, only one irrigation event occurred during the 2017 growing season ($p = 0.8264$) (Table 1.5 and 1.10). Based on these results, a threshold of -90 kPa provided the greatest IWUE compared to -50 kPa or -130 kPa therefore, suggesting that -50 kPa is too aggressive and -130 kPa is not supplying enough water to maximize lint yield.

The interaction of growth stage by irrigation threshold did not affect plant height at bloom, number of nodes at bloom, nodes above white flower, plant height at cracked boll, nodes above cracked boll, lint turnout, lint yield, micronaire, fiber length, fiber uniformity, fiber strength, or fiber elongation in any year. Therefore, data were pooled across years ($p \geq 0.2203$) (Table 1.11). However, the interaction of growth stage by threshold did influence IWUE ($p = 0.0231$). Where cotton was not irrigated from emergence to first bloom an increase of 41 and 42% in IWUE was observed, equating to an increase of 30 kg-lint/cm of irrigation water applied compared to treatments irrigated based on -130 and -90 kPa thresholds, respectively (Table 1.12). Additionally, non-irrigated cotton and irrigation applied at -90 kPa thresholds from first bloom to peak bloom resulted in 83 and 86% greater IWUE compared to -130 kPa threshold (Table 1.12). Furthermore, IWUE was 35% greater where no irrigation was utilized from peak bloom to first cracked boll compared to -90 kPa thresholds (Table 1.12). Based on these data, no benefit other than increased IWUE was observed by varying irrigation threshold by cotton growth stage (Table 1.11). Plant growth, lint yield, and fiber quality means for the interaction of soil moisture sensor threshold by cotton growth stage are reported in Table 1.13. These results agree with Loka *et al*., 2011 who found the most critical period of growth for cotton irrigation is unclear. However, these results disagree with Constable and Hearn (1981), Cull *et al*. (1981), and Turner *et al*. (1986) who observed that water stress during flowering and boll development have detrimental effects on yield. Results observed from this research may have been due to the rainfall received throughout the growing season given that previous research was conducted in arid regions. The amount of irrigation water applied in a single furrow irrigation event may have also contributed to an adequate level of soil moisture throughout multiple growth stages. Although lint yield differences due to growth stage by threshold interaction were not observed, IWUE differences reinforce current recommendations for irrigation initiation. In Mississippi, irrigation prior to first bloom is rarely needed due to low cotton water demand and early seasonal rainfall; therefore, irrigation prior to first bloom is rarely recommended except for special circumstances such as extreme drought. From this research, when irrigation was not applied from emergence to first bloom, lint yield was similar as treatments that received irrigation at thresholds of -90 and -130 kPa, but with reduced early season water use.

1.5 Conclusion

It is concluded that by utilizing a weighted soil moisture threshold of -90 kPa for the full growing season, lint yield and IWUE is maximized when compared to a -50 kPa threshold. Furthermore, varying soil moisture sensor threshold values throughout the growing season did not provide any benefit with respect to cotton lint yield, fiber quality, or plant growth and development parameters; however, IWUE increased where irrigation was not applied until first bloom. Overall, Watermark® soil moisture sensors are an excellent tool for scheduling irrigation in cotton in Mississippi. Coupled with a season long soil moisture weighted threshold of -90 kPa and irrigating before first bloom only in drought conditions or specific circumstances, proper irrigation scheduling for cotton planted in Mississippi on silty clay loam soil textures can be achieved.

Table 1.1 Planting and harvest dates for Starkville, MS, 2015 – 2017

	Year		
	—2015—	—2016—	—2017—
Planting	May 8	May 7	May 7
Harvest	Oct. 4	Oct. 10	Oct. 25

Table 1.2 Rainfall amounts for trial location in Starkville, MS

Month	2015 Rainfall (cm)	2016 Rainfall (cm)	2017 Rainfall (cm)	10 Year Average (cm)
May	12.9	8.2	15.4	12.8
June	7.9	9.8	23.3	11.5
July	10.3	9.0	9.6	10.5
August	5.0	8.8	19.6	11.6
September	3.8	7.0	12.3	11.6
October	6.3	0.1	5.6	8.3
Total	46.2	42.9	85.8	66.3

Table 1.3 Irrigation water applied (ha-cm) at specific growth stages for 2015

	Growth Stage			
Treatment	Emergence to First Bloom (G1)	First Bloom to Peak Bloom (G2)	Peak Bloom to First Cracked Boll (G3)	Total
Non-Irrig. – G1	0.00	19.13	34.00	53.13
-90 kPa – G1	0.00	0.00	83.69	83.69
-130 kPa – G1	0.00	19.13	58.85	77.98
Non-Irrig. – G2	0.00	0.00	34.00	34.00
-90 kPa – G2	0.00	16.56	34.00	50.56
-130 kPa – G2	0.00	0.00	0.00	0.00
Non-Irrig. – G3	0.00	19.13	0.00	19.13
-90 kPa – G3	0.00	19.13	34.00	53.13
-130 kPa – G3	0.00	19.13	0.00	19.13
Non-Irrig. – Full Season	0.00	0.00	0.00	0.00
-50 kPa – Full Season	0.00	35.70	24.84	60.54
-90 kPa – Full Season	0.00	35.70	0.00	35.70
-130 kPa – Full Season	0.00	0.00	0.00	0.00

Table 1.4 Irrigation water applied (ha-cm) at specific growth stages for 2016

	Growth Stage			
Treatment	Emergence to First Bloom (G1)	First Bloom to Peak Bloom (G2)	Peak Bloom to First Cracked Boll (G3)	Total
Non-Irrig. – G1	0.00	14.87	0.00	14.87
-90 kPa – G1	21.90	25.85	0.00	47.75
-130 kPa – G1	0.00	40.03	0.00	40.03
Non-Irrig. – G2	28.84	0.00	0.00	28.84
-90 kPa – G2	9.98	14.93	0.00	28.84
-130 kPa – G2	44.23	28.84	0.00	73.07
Non-Irrig. – G3	31.81	13.92	0.00	45.73
-90 kPa – G3	44.23	14.93	0.00	59.16
-130 kPa – G3	9.98	40.03	0.00	50.01
Non-Irrig. – Full Season	0.00	0.00	0.00	0.00
-50 kPa – Full Season	31.81	65.87	0.00	97.68
-90 kPa – Full Season	9.98	25.85	0.00	35.83
-130 kPa – Full Season	9.98	40.03	0.00	50.01

Table 1.5 Irrigation water applied (ha-cm) at specific growth stages for 2017

	Growth Stage			
Treatment	Emergence to First Bloom (G1)	First Bloom to Peak Bloom (G2)	Peak Bloom to First Cracked Boll (G3)	Total
Non-Irrig. – G1	0.00	19.32	0.00	19.32
-90 kPa – G1	0.00	19.32	0.00	19.32
-130 kPa – G1	0.00	19.32	0.00	19.32
Non-Irrig. – G2	0.00	0.00	0.00	0.00
-90 kPa – G2	0.00	19.32	0.00	19.32
-130 kPa – G2	0.00	0.00	0.00	0.00
Non-Irrig. – G3	0.00	19.32	0.00	19.32
-90 kPa – G3	0.00	19.32	0.00	19.32
-130 kPa – G3	0.00	19.32	0.00	19.32
Non-Irrig. – Full Season	0.00	0.00	0.00	0.00
-50 kPa – Full Season	0.00	19.32	0.00	19.32
-90 kPa – Full Season	0.00	19.32	0.00	19.32
-130 kPa – Full Season	0.00	0.00	0.00	0.00

Table 1.6 Analysis of variance probability values for full season management of soil moisture sensor threshold values for plant growth parameters and fiber quality 2015–2017.

	Ht. at Blm.[b]	Nodes at Blm.[c]	NAWF[d]	Ht. at Cracked Boll[e]	NACB[f]	Turnout	Mic.[g]	Leng.[h]	Unif.[i]	Stren.[j]	Elon.[k]
	p-values[a]										
Threshold	0.9974	0.9862	0.2721	0.9869	0.7689	0.2911	0.3003	0.5930	0.9748	0.9190	0.7854

[a] Data was pooled across years 2015–2017.
[b] Plant height at bloom.
[c] Total plant nodes at bloom.
[d] Nodes above white flower.
[e] Plant height at cracked boll.
[f] Nodes above cracked boll.
[g] Micronaire.
[h] Fiber length.
[i] Fiber uniformity.
[j] Fiber strength.
[k] Fiber elongation.

Table 1.7 Means for plant growth parameters and fiber quality values for soil moisture sensor threshold values for full season management 2015–2017.

Threshold[a]	Ht. at Blm.[b]	Nodes at Blm.[c]	NAWF[d]	Ht. at Cracked Boll[e]	NACB[f]	Turnout	Mic.[g]	Leng.[h]	Unif.[i]	Stren.[j]	Elon.[k]
	–cm–	——number——		–cm–	–number–	–%–	–mic–	–mm–	–%–	–gram/tex–	–%–
Non-Irrigated	71	13.5	7.4	92.1	6.7	40.7	4.6	29.7	84.2	33.5	7.3
-50 kPa[l]	74	13.6	7.6	94.2	6.1	40.4	4.5	30.2	84.0	33.4	7.2
-90 kPa	75	13.7	7.6	97.1	6.6	41.3	4.8	30.0	84.2	33.5	7.3
-130 kPa	74	13.6	7.3	91.6	5.7	40.9	4.6	29.7	83.9	33.9	7.3

[a] Data was pooled across years 2015–2017.
[b] Plant height at bloom.
[c] Total plant nodes at bloom.
[d] Nodes above white flower.
[e] Plant height at cracked boll.
[f] Nodes above cracked boll.
[g] Micronaire.
[h] Fiber length.
[i] Fiber uniformity.
[j] Fiber strength.
[k] Fiber elongation.
[l] Kilopascals.

Table 1.8 Analysis of variance probability values for full season management of soil moisture sensor threshold values for cotton lint yield (kg/ha) and irrigation water use efficiency (kg lint/ha-cm) 2015–2017.

	——2015——		——2016——		——2017——	
	Lint Yield	IWUE[a]	Lint Yield	IWUE	Lint Yield	IWUE
	p-values					
Threshold	0.5070	0.0002	0.0495	<0.0001	0.7804	0.8264

[a] Irrigation water use efficiency.

Table 1.9 Soil moisture sensor threshold effect on cotton lint yield (kg/ha) 2015–2017.

	—2015—	—2016—	—2017—
Threshold	Lint Yield		
	—kg/ha[a]—		
Non-Irrigated	2040 a	1542 b	1247 a
-50 kPa[b]	2003 a	1568 b	1253 a
-90 kPa	2176 a	2078 a	1232 a
-130 kPa	2188 a	1752 ab	1173 a

[a] Means within a column followed by same lowercase letter are not significantly different according to pairwise t-tests at p = 0.05.

[b] Kilopascals.

Table 1.10 Soil moisture sensor threshold effect on irrigation water use efficiency (kg lint/ha-cm) for full season management 2015–2017.

	—2015—	—2016—	—2017—
Threshold[a]	Irrigation Water Use Efficiency		
	—kg lint/ha-cm—		
-50 kPa[b]	33.02 b	16.06 c	64.88 a
-90 kPa	60.83 a	58.08 a	63.81 a
-130 kPa	--	37.32 b	--

[a] Means within a column followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

[b] Kilopascals

Table 1.11 Analysis of variance probability values for soil moisture sensor threshold value by growth stage 2015–2017.

	Ht. at Blm.[b]	Nodes at Blm.[c]	NAWF[d]	Ht. at Cracked Boll[e]	NACB[f]	Turnout	Lint Yield	Mic.[g]	Leng.[h]	Unif.[i]	Stren.[j]	Elon.[k]	IWUE[l]
	p-values[a]												
Threshold	0.9126	0.9371	0.8398	0.3153	0.6705	0.9274	0.1240	0.9071	0.9000	0.3014	0.6396	0.8733	0.0002
Growth Stage	0.9683	0.6903	0.2200	0.9550	0.6498	0.8995	0.1557	0.3720	0.6837	0.9923	0.2746	0.9124	0.0038
Thres[m]*GS[n]	0.9915	0.9915	0.2203	0.6283	0.9921	0.7385	0.2231	0.8592	0.8062	0.7144	0.8087	0.2805	0.0231

[a] Data was pooled across years 2015-2017.
[b] Plant height at bloom.
[c] Total plant nodes at bloom.
[d] Nodes above white flower.
[e] Plant height at cracked boll.
[f] Nodes above cracked boll.
[g] Micronaire.
[h] Fiber length.
[i] Fiber uniformity.
[j] Fiber strength.
[k] Fiber elongation.
[l] Irrigation water use efficiency.
[m] Threshold.
[n] Growth Stage.

Table 1.12 Soil moisture sensor threshold by growth stage effect on irrigation water use efficiency (kg lint/ha-cm) 2015–2017.

Growth Stage	Sensor Threshold	IWUE
		–kg lint/ha-cm–
Emergence to Bloom	Non-Irrigated	71.35 a
Emergence to Bloom	-90 kPa	41.27 c
Emergence to Bloom	-130 kPa	41.85 c
Bloom to Peak Bloom	Non-Irrigated	41.25 c
Bloom to Peak Bloom	-90 kPa	50.95 abc
Bloom to Peak Bloom	-130 kPa	7.16 d
Peak Bloom to Cracked Boll	Non-Irrigated	69.59 ab
Peak Bloom to Cracked Boll	-90 kPa	45.13 c
Peak Bloom to Cracked Boll	-130 kPa	47.82 bc

[a] Irrigation water use efficiency.
[b] Kilopascals.

Table 1.13 Mean values for soil moisture sensor threshold value by growth stage 2015–2017

Treatment Comb.[a]		Ht. at Blm.[b]	Nodes at Blm.[c]	NAWF[d]	Ht. at Cracked Boll[e]	NACB[f]	Turnout	Lint Yield	Mic.[g]	Leng.[h]	Unif.[i]	Stren.[j]	Elon.[k]
		–cm–	——number——		–cm–	-number-	–%–	–kg/ha–	–mic–	–mm–	–%–	–gram/tex–	–%–
GS[l] – 1	-90kPa	72	13.2	7.4	92.5	6.0	40.8	1797	4.7	30.2	83.9	33.3	7.5
GS – 1	-130 kPa	74	13.4	7.1	96.0	6.3	42.2	1826	4.7	30.0	83.9	33.8	7.3
GS – 1	Non-Irri.	70	13.4	7.0	90.4	6.5	41.2	1709	4.7	29.7	84.2	33.4	7.4
GS – 2	-90kPa	70	13.3	7.3	90.9	6.2	40.9	1614	4.7	30.2	84.1	33.5	7.4
GS – 2	-130 kPa	75	13.6	7.7	94.5	6.5	41.1	1695	4.7	29.7	84.2	33.8	7.2
GS – 2	Non-Irri.	72	13.5	7.8	91.7	5.6	41.1	1726	4.6	29.5	83.8	33.4	7.4
GS – 3	-90kPa	72	13.7	7.9	94.0	6.5	41.0	1845	4.7	30.0	83.9	34.0	7.3
GS – 3	-130 kPa	73	13.6	7.6	92.0	6.1	41.0	1789	4.6	30.0	83.8	32.9	7.3
GS – 3	Non-Irri.	74	13.7	7.8	91.9	6.2	40.8	1756	4.7	30.0	83.3	33.5	7.3

[a] Data was pooled across years 2015–2017.
[b] Plant height at bloom.
[c] Total plant nodes at bloom.
[d] Nodes above white flower.
[e] Plant height at cracked boll.
[f] Nodes above cracked boll.
[g] Micronaire.
[h] Fiber length.
[i] Fiber uniformity.
[j] Fiber strength.
[k] Fiber elongation.
[l] Growth Stage (1 – emergence to 1st bloom; 2 – 1st bloom to peak bloom; 3 – peak bloom to 1st cracked boll).

$$IWUE = \frac{Y}{IWA} \tag{1.1}$$

Irrigation water use efficiency (IWUE) was calculated as described by Vories *et al.* (2005), where IWUE (kg lint/hectare-cm), Y is cotton lint yield (kg/ha), and IWA is irrigation water applied (hectare-cm).

CHAPTER II

DETERMINING OPTIMUM IRRIGATION TERMINATION TIMING USING FURROW IRRIGATION IN COTTON

2.1 Abstract

Properly terminating furrow irrigation in mid-southern U.S. crops could reduce irrigation costs, the likelihood of adverse harvest conditions, and agricultural withdrawal from the Mississippi River Valley Alluvial Aquifer. Research was conducted to develop an irrigation termination recommendation for furrow irrigated cotton (*Gossypium hirsutum* L.) that optimizes lint yield and fiber quality, while reducing late season irrigation cost. The effects of terminating irrigation (two weeks prior to first cracked boll, one week prior to first cracked boll, at first cracked boll, and one, two, and three weeks after first cracked boll) were evaluated on plant growth parameters, lint yield, and fiber quality. Studies were conducted on a Leeper silty clay loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts) and on a Dundee silty clay (fine-silty, mixed, active, Typic Endoaqualfs) from 2015 through 2017 at the R.R. Foil Plant Science Research Center, Starkville, MS and the Delta Research and Experiment Station, Stoneville, MS, respectively. Time at which irrigation was terminated did not affect ($p \geq 0.6107$) plant height or number of nodes at harvest, lint turnout, lint yield, or fiber quality. Results agree with the currently recommended time to terminate irrigation at first cracked boll. Terminating at this time was adequate to maximizing plant growth parameters, lint yield,

and fiber quality. Furthermore, this research illustrates that it may be possible to terminate irrigation earlier than first cracked boll, especially in years with adequate rainfall, thus reducing late season irrigation cost and reducing water withdrawal from the alluvial aquifer.

2.2 Introduction

The Mid-South region of the United States (U.S.), consisting of western Tennessee, southeast Missouri, Mississippi, Arkansas, and Louisiana, obtains a majority of irrigation water from groundwater reserves. In the Mid-South, the Mississippi River Valley Alluvial Aquifer [Alluvial Aquifer] spans nearly 86,000 sq. km (33,000 sq. miles), from Louisiana to Missouri. Wells are tapped into the alluvial aquifer for agricultural irrigation. An estimated 96% of water removed from the alluvial aquifer is pumped for agriculture (Reba *et al*., 2014). Since the early 1900's, the volume of water being pumped from the alluvial aquifer has increased. The Arkansas Natural Resources Commission reported a withdrawal and recharge rate of 8,036 Mgal/day and 3,374 Mgal/day, respectively, in 2012; thus withdrawal exceeds the recharge resulting in declining aquifer levels, annually (Swaim *et al*., 2016).

Cotton (*Gossypium hirsutum* L.) is a major commodity produced in Mississippi, grown on an average of 214,000 hectares (528,500 acres) annually from 2007–2017. Mississippi ranked 4th in cotton production in the United States (U.S.) in 2017 (NASS, 2018). From 2011–2014, 44% of the cotton planted in Mississippi was irrigated (NASS, 2016). Approximately 70% of the irrigated cotton grown in Mississippi is irrigated through furrow irrigation systems, the least efficient method of irrigation currently practiced. The remaining 30% of irrigated cotton in Mississippi is applied through overhead sprinkler irrigation systems (USDA, 2016).

Cotton is a perennial shrub that originates from tropical and subtropical climates (Fryxell, 1986). Cotton has the ability to tolerate hot and dry weather better than other major row crops due to its indeterminate grown habit. Although cotton has the ability to survive in adverse environmental conditions, water is a key factor in maximizing production (Jordan, 1986). Cotton water use is often illustrated by measuring evapotranspiration (ET), which is a combination of water lost from evaporation and transpiration of the plant (Sassenrath and Schmidt, 2012). The cotton water use curve developed by Supak and Metzer (1977) and later re-evaluated by Vories, Oosterhuis, and Bourland (1991) found that cotton water demand is relatively low until reproductive growth initiates where it increases to a peak of 7.1 mm (0.28 inches) of water needed per day (Vories *et al*., 2003; Fisher and Udeigwe, 2012). Water use remains high until open bolls begin to appear on the plant after which cotton water use decreases (Fisher and Udeigwe, 2012). Adequate water to the plant either through rainfall or supplemental irrigation at the appropriate timing is crucial; however, irrigation termination timing is not well defined (Vories *et al*., 2011).

Proper irrigation termination should not affect lint yield or result in delayed crop maturity, poor fiber quality, and unfavorable field conditions at harvest (Vories *et al*., 2011). The added expense of irrigating should also be considered when determining when to terminate irrigation (Vories *et al*., 2011). Terminating furrow irrigation in cotton has been determined by calendar date, plant growth stage, use of growing degree days (GDDs) and plant monitoring. Silvertooth *et al*. (1996) suggested that furrow irrigation be terminated using GDDs, where the final irrigation application should not occur past 333 GDDs post-anthesis of harvestable bolls. Research from Bourland *et al*. (1992) and Vories *et al*. (2001) was based on monitoring the number of nodes above the upper most first-position white flower (NAWF) on plants to base decisions for irrigation termination. The current recommendation in Mississippi for terminating furrow irrigation is terminating at first cracked boll and 7 to 10 days after first cracked boll for sprinkler irrigation (Dodds, 2014). The differentiation in termination timing for the two application methods is due to the volume of water applied through each system per irrigation event (Dodds, 2014). The University of Arkansas suggests using a combination of heat unit accumulation (GDDs) and crop development monitoring (NAWF). Irrigation termination is recommended when cotton reaches 350 GDDs past cutout (NAWF = 5) in northern Arkansas and 500 GDDs past cutout in southern Arkansas (Reba, *et al*., 2012). Published research on furrow irrigation termination in the Mid-South is limited and additional data is needed regarding irrigation termination using furrow irrigation in the Mid-South.

The objectives of this study were 1) to determine the optimum irrigation termination timing for furrow irrigated cotton in the Mid-South that maximizes plant growth parameters, lint turnout, lint yield, and fiber quality and 2) to determine a irrigation termination timing that reduces irrigation costs and water withdrawal from the alluvial aquifer.

2.3 Materials and Methods

Research was conducted at the R.R. Foil Plant Science Research Center near Starkville, MS (33.475396° N, 88.769066°W) on a Leeper silty clay loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts) and at the Delta Research and Education

Center near Stoneville, MS (33.436551° N, 90.910929° W) on a Dundee silty clay (fine-silty, mixed, active, thermic Typic Endoaqualfs) from 2015 through 2017. Cotton was planted at 111,150 seeds/ha and a depth of 2.5 cm (Table 2.1). Plots consisted of 8 – 96-cm rows that were 12.2-m in length in Starkville, and 4 – 102-cm rows that were 12.2-m in length in Stoneville. Furrow irrigation was applied using 38-cm by 9-mil lay-flat polyethylene tubing (Delta Plastics, Little Rock, AR), with delivery optimized with the Pipe Hold and Universal Crown Evaluation Tool (PHAUCET version 8.2.20, USDA-NRCS, Washington, DC) (Kebede *et al*., 2014; Bryant *et al*., 2017). Flow rate at the field inlet was determined with a McCrometer flow tube with attached McPropeller bolt-on saddle flowmeter (McCrometer Inc., Hemet, California). Treatments were arranged in a randomized complete block design with four replications. Cotton was irrigated throughout the growing season based on current extension recommendations (Allen *et al*., 1998) until two weeks prior to first cracked boll which was based off of growing degree unit accumulation (2150 DD_{60}) and overall crop condition (115 days after planting) (Ritchie *et al*., 2004). At two weeks prior to first cracked boll, all plots were irrigated. On a weekly basis after the initial blanket irrigation, irrigation was terminated each week until three weeks after first cracked boll. Irrigation was therefore terminated at two weeks prior to first cracked boll, one week prior to first cracked boll, at first cracked boll and one, two, and three weeks after first cracked boll. Insect control, fertility, plant growth regulators, weed control, and harvest aids were applied based on Mississippi State University Extension recommendations (Bond *et al*., 2017; Catchot *et al*., 2017; Dodds, 2017; Dodds *et al*., 2017a). Data collection consisted of plant height and number of nodes at harvest, lint turnout, lint yield, and fiber quality. Cotton was harvested using a spindle picker modified for small plot research (Table 2.1). Lint turnout was determined by harvesting a 25-boll hand samples by hand and ginning on a 10 saw laboratory cotton gin (Continental Eagle Corp., Prattville, AL). Seed and lint were weighed and lint turnout was calculated by dividing the weight of lint by the total weight of seed plus lint. Fiber quality was determined using a High Volume Instrument (HVI®) at the Fiber and Biopolymer Research Institute, Lubbock, TX. Statistical analyses were conducted using PROC GLM procedure in SAS v.9.4 (SAS Institute, Cary, NC). Data were analyzed using analysis of variance (ANOVA) and means were separated using Fisher's Protected LSD at the 0.05 level of significance. Random effects consisted of location and year and fixed effects were irrigation termination timing.

2.3 Results and Discussion

Rainfall fluctuated by year throughout the time in which irrigation was terminated when compared to the 10 year average rainfall for Starkville and Stoneville, MS (Table 2.2). In Starkville in 2015 and 2016, rainfall in August and September was between 24 and 67% less than the 10 year average, respectively (Table 2.2). However, in 2017 rainfall in Starkville during August and September was 41 and 6% greater than the 10 year average, respectively (Table 2.2). In Stoneville in 2015, August and September received 73 and 78% less rainfall than the 10 year average, respectively (Table 2.2). In 2016 and 2017, rainfall during August was 48 and 74% greater than the 10 year average, but September had 90 and 55% less rainfall, respectively (Table 2.2). Based on these weather conditions, less than average rainfall during the boll maturation and initial irrigation termination periods were observed in August and September in 2015 and 2016 in Starkville and 2015 in Stoneville.

Irrigation termination timing did not impact cotton height at harvest, number of nodes at harvest, lint turnout, lint yield, micronaire, fiber length, fiber uniformity, fiber strength, or fiber elongation in any year or location; therefore, data were pooled across year and location ($p \geq 0.6107$) (Table 2.3). Average values for plant height and number of nodes, lint turnout, lint yield, and fiber quality parameters are reported in Table 2.4. Previous research conducted by Vories *et al*. (2002) agrees with the findings of this research, where differences in lint yield for extended irrigation applications were variable and not reliable. Porter *et al*. (2014) found that neither lint yield or lint turnout was affected by irrigation termination timing. In addition, research conducted by Vories *et al*. (2011) reported that no differences in fiber quality were observed due to varying irrigation termination timings. Vories *et al*. (2011) also reported that no consistent trend relating fiber quality to final irrigation was observed (Table 2.6). However, Silvertooth *et al*. (2006) found that lint yield and micronaire values consistently increased with later irrigation termination dates. These results were derived from Arizona where supplemental irrigation is necessary to produce cotton and rainfall is limited. Silvertooth *et al*. (2006) did note that irrigation termination after cutout provided the greatest lint yield and optimum micronaire, suggesting that current recommendations of irrigation termination in Mississippi may be near optimum.

Though irrigation termination timing did not have an effect on plant growth parameters, lint turnout, lint yield, or fiber quality, these results suggest that when adequate rainfall in the Mid-South region has occurred there is no additional benefit to irrigating beyond the current irrigation termination recommendation of first cracked boll. Furthermore, these results suggest that irrigation could be terminated two weeks prior to first cracked boll without observing a negative effect on plant growth, lint turnout, lint yield, or fiber quality. Typical furrow irrigation events apply between 5 and 10 cm/ha of water. Irrigation costs associated with furrow irrigation in cotton are estimated at approximately $6.30 per ha-cm. Therefore, by reducing one irrigation event at the end of the growing season, cost savings between $31.60 to $63.21 per hectare could occur (Falconer *et al*., 2017). With this said, earlier irrigation termination may assist in the reduction of water withdrawal from the alluvial aquifer and reduce the likelihood of creating unfavorable harvest conditions while maintaining plant growth, lint yield, and fiber quality.

2.4 Conclusion

Terminating irrigation two weeks prior to first cracked boll when adequate soil moisture or rainfall is present maximized plant growth parameters, lint turnout, lint yield, and fiber quality. In this study, there was no benefit from terminating irrigation after two weeks prior to first cracked boll. Overall, irrigation termination timing should be based on specific environmental conditions, where factors such as soil moisture content and rainfall should be considered prior to irrigation termination timing. However, reductions in irrigation costs and reducing the likelihood of creating an environment favorable for adverse conditions may be observed with earlier irrigation termination timings.

Table 2.1 Planting and Harvest Dates for Starkville and Stoneville, MS 2015–2017.

	———Starkville———			———Stoneville———		
	–2015–	–2016–	–2017–	–2015–	–2016–	–2017–
Planting	May 8	May 7	May 7	May 5	May 10	May 8
Variety	ST 4946[a]	ST 4946	ST 4946	PHY 499[b]	DP 1639[c]	ST 4946
Harvest	Oct. 5	Oct. 24	Oct. 25	Sept. 30	Oct. 5	Oct. 3

[a] Stoneville 4946 GLB2
[b] Phytogen 499 WRF
[c] Deltapine 1639 B2XF

Table 2.2 Rainfall amounts for trial location in Starkville, MS and Stoneville, MS.

	Starkville				Stoneville			
Month	2015 Rainfall (cm)	2016 Rainfall (cm)	2017 Rainfall (cm)	10 Year Average (cm)	2015 Rainfall (cm)	2016 Rainfall (cm)	2017 Rainfall (cm)	10 Year Average (cm)
May	12.9	8.2	15.4	12.8	17.7	8.3	12.4	13.1
June	7.9	9.8	23.3	11.5	6.5	12.9	19.3	7.5
July	10.3	9.0	9.6	10.5	8.1	16.6	10.9	10.3
August	5.0	8.8	19.6	11.6	1.9	13.9	27.3	7.1
September	3.8	7.0	12.3	11.6	2.0	0.9	4.3	9.5
October	6.3	0.1	5.6	8.3	13.9	0.5	0.6	13.5
November	21.2	8.8	2.9	9.8	15.3	11.4	2.4	9.8
Total	67.4	51.7	88.7	76.1	65.4	64.5	77.2	70.8

Table 2.3 Analysis of variance probability values for irrigation termination timing for Starkville and Stoneville, MS 2015-2017.

	Ht. at Harvest[b]	Nodes at Harvest[c]	Turnout	Lint Yield	Mic[d]	Leng.[e]	Unif.[f]	Stren.[g]	Elon.[h]
	p-values[a]								
Timing	0.9945	0.9197	0.9755	0.7583	0.8178	0.9103	0.6107	0.7611	0.8406

[a] Data pooled across year and location.
[b] Plant height at harvest.
[c] Total plant nodes at harvest.
[d] Micronaire.
[e] Fiber length.
[f] Fiber uniformity.
[g] Fiber strength.
[h] Fiber elongation.

Table 2.4 Means for plant growth parameters, lint turnout, lint yield, and fiber quality for irrigation termination timing in Starkville, MS and Stoneville, MS 2015–2017.

Timing[a]	Ht. at Harvest[b].	Nodes at Harvest[c].	Turnout	Lint Yield	Mic.[d]	Leng.[e]	Unif.[f]	Stren.[g]	Elon.[h]
	–cm–	–number–	–%–	–kg/ha–	–mic–	–mm–	–%–	-gram/tex-	–%–
2 Wk before CB	103	19.8	42.0	1459	4.7	29.2	83.6	33.2	7.5
1 Wk before CB	103	19.5	42.1	1426	4.8	29.2	83.9	32.7	7.4
Cracked Boll	102	19.5	42.3	1367	4.7	29.2	83.4	33.3	7.6
1 Wk after CB	100	19.3	42.4	1426	4.8	29.2	83.8	33.3	7.5
2 Wk after CB	102	19.5	42.4	1480	4.8	29.2	83.7	33.1	7.5
3 Wk after CB	100	20.0	42.2	1498	4.7	29.2	83.5	33.1	7.6

[a] Data pooled across year and location.
[b] Plant height at harvest.
[c] Total plant nodes at harvest.
[d] Micronaire.
[e] Fiber length.
[f] Fiber uniformity.
[g] Fiber strength.
[h] Fiber elongation.

CHAPTER III

EFFECT OF TIMING AND INTENSITY OF PHYSICAL DAMAGE TO EARLY- AND LATE-MATURING COTTON VARIETIES

3.1 Abstract

Determining the effects of time and intensity of physical damage in cotton (*Gossypium hirsutum* L.) grown in the Mid-South could improve management decisions and insurance adjustments after weather or wildlife related crop damage has occurred. Research was conducted to quantify the effects of time of damage and intensity or amount of damage on early- and late-maturing cotton varieties in the Mid-South. The effects of time of damage (4-leaf, pinhead square, first bloom, and first bloom + four weeks) and amount or degree of damage (0, 2, 4, 6, and 8 node removal) on plant height and number of nodes, lint turnout, lint yield, and fiber quality were evaluated on cotton planted in a Marietta fine sandy loam (Fine-loamy, siliceous, active, thermic, Fluvaquentic Eutrudepts) at the R.R. Foil Plant Science Research Center, Starkville, MS, in a Brooksville silty clay (Fine, smectitic, thermic Aquic Hapluderts) at the Black Belt Experiment Station, Brooksville, MS, in a Collins silt loam (Coarse-silty, mixed, active, acid, thermic Aquic Udifluvents) at the West Tennessee AgResearch and Education Center, Jackson, TN, and in a Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs) at the Fisher Delta Research Center, Portageville, MO from 2015 through 2017. The interaction of variety by damage intensity nested in timing had no effect on

plant height, number of nodes, lint turnout, lint yield, micronaire, fiber length, fiber uniformity, fiber strength, or fiber elongation ($p \geq 0.0824$). Variety affected plant height at first bloom, first bloom + four weeks, and harvest ($p \leq 0.0008$), and number of nodes at first bloom + four weeks and harvest ($p \leq 0.0372$). Varieties differed in lint turnout, lint yield, micronaire, fiber uniformity, fiber strength, and fiber elongation ($p \leq 0.0152$). However, these varietal differences were expected when we selected PHY 222 WRF and PHY 499 WRF for this research. The interaction of intensity of damage by time of damage had an effect on plant height and number of nodes at pinhead square, first bloom, first bloom + four weeks, and at harvest ($p \leq 0.0001$), where reductions in plant height ranged from 20 to 57% and the number of nodes were reduced by 12 to 64% when compared to the untreated check. Damage intensity by time of damage interaction had an effect on lint turnout, lint yield, micronaire, fiber length, and fiber strength ($p \leq 0.0391$). Reductions in lint yield (11 to 70%), lint turnout (2 to 6%), and micronaire (3 to 8%) were observed. Increases of 3 and 2% in fiber length and fiber strength, respectively were also observed depending on timing of damage and intensity. Overall, plant heights and the number of nodes were reduced as the intensity of damage increased at each stage of plant growth (time of damage) throughout the growing season. Furthermore, as the intensity of damage increased during any growth stage lint yield was reduced significantly.

3.2 Introduction

Cotton (*Gossypium hirsutum* L.) is a major crop grown in the southern United States (U.S.) and across the Mid-South region (Arkansas, Louisiana, Mississippi, Missouri, and Tennessee). From 2011-2015 approximately 4.6 million hectares (11.4

million acres) of cotton were planted per year across the U.S., with approximately 14% of production taking place in the Mid-South (NASS, 2016). In Mississippi, cotton contributed $370 million to the economy annually from 2011-2015 (NASS, 2015). Cotton is a high input crop compared to those grown in rotation with cotton. With seed costs and technology fees exceeding $247 per hectare, input costs associated with production, initial input costs for cotton are substantial (MSU, 2016).

Optimum yield must be attained to maximize profits in cotton production. Environmental factors such as rainfall are unpredictable and typically lead to variations in productivity from year to year (Wang, 2011). Crop damage from hail storms and wildlife cause an estimated $5.5 billion in crop and property damages annually in the U.S. (Conover, 2002; NWC, 2015). Approximately 14% of U.S. crop failures are due to hail and wildlife damage (RHIS, 2015).

Determining potential yield loss in cotton due to physical damage inflicted on the plant is important for replanting and management decisions throughout the growing season (Wang, 2011). The National Crop Insurance Services [NCIS] utilizes a specific procedure to estimate yield loss due to crop damage that was developed in conjunction with the United States Department of Agriculture – Federal Crop Insurance Corporation [USDA-FCIC] (USDA-FCIC, 2003; NCIS, 2006; Wang, 2011). While this procedure is good for estimating yield loss due to damage, it primarily focuses on early season damage and making replant decisions. If crop damage occurs early in the growing season the option to replant is still possible; however, if damage occurs later in the growing season, such as during reproductive growth, replanting is not an option (Wang, 2011).

Late season damage may destroy apical meristems, fruiting branches, and/or bolls making yield loss estimations extremely complex (Wang, 2011).

The indeterminate growth habit of cotton results in varying degrees of recoverability from physical damage. This variation is greatly influenced by the growth stage or timing at which the damage occurs as well as the severity or intensity of the damage itself (Smith and Varvil, 1981; MSU, 2014). Lane (1959), Smith and Varvil (1981), and Peacock and Hawkins (1974) all attempted to quantify yield loss due to crop damage. Several environmental factors affected final cotton yield after physical damage occurred. Delayed maturity is often associated with cotton damage from weather events or wildlife damage. Delayed maturity can lead to increased insect damage, potential exposure to unfavorable weather, and increased production costs (MSU, 2014).

In the Mid-South, growing early maturing cotton varieties has become popular in recent years due to high pest pressure from tarnished plant bugs (*Lygus lineolaris*) (Bagwell *et al*., 2008). Delayed maturity may increase the risk of reduced plant development due to lack of heat unit accumulation (Raper and Gwathmey, 2015). Thus, early-maturing cotton varieties may recover from crop damage better than later maturing varieties. Little data exists, however, regarding the effect of varietal maturity and potential recoverability from simulated damage. In addition, damage from hail or wildlife feeding is unpredictable and the severity can vary greatly within a small geographic region.

The objective of this research, therefore, was to quantify the effects of time and intensity of damage on early- and late-maturing cotton varieties in the Mid-South to better quantify expected plant growth parameters, as well as, reductions in lint yield and fiber quality caused by hail and/or wildlife damage so that accurate management decisions and insurance adjustments can be implemented.

3.3 Materials and Methods

Research was conducted from 2015 through 2017 in cotton plots planted at the R.R. Foil Plant Science Research Center near Starkville, MS (33.474342°N, 88.776028°W) on a Leeper silty clay loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts), at the Black Belt Branch Experiment Station near Brooksville, MS (33.258162°N, 88.559379°W) on a Brooksville silty clay (fine, smectitic, thermic Aquic Hapluderts), and at the Fisher Delta Research Center near Portageville, MO (36.415065°N, 89.698921°W) on a Dubbs silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs). Moreover, research, was conducted at the University of Tennessee, West Tennessee AgResearch and Education Center near Jackson, TN (35.621263°N, 88.843162°W) on a Collins silt loam (Coarse-silty, mixed, active, acid, thermic Aquic Udifluvents) in 2015 and 2016. Phytogen 222 WRF (early-maturity) and Phytogen 499 WRF (late-maturity) (Dow AgroSciences, Indianapolis, IN) cotton was planted 2.5 cm deep at 111,150 seeds/ha (Table 3.1). Plots consisted of 2 – 96-cm rows that were 12.2, 12.2, 9.1 and 9.1-m in length in Starkville, Brooksville, Jackson, and Portageville, respectively. Plots were arranged in a 4X5 nested factorial arrangement within a randomized complete block design with four replications. Damage type differed by location where damage was inflicted by the mechanical removal of plant nodes using scissors in Starkville, MS, Brooksville, MS, and Jackson, TN. However, in Portageville, MO, damage was inflicted by physically removing leaves, squares, and bolls from the plant. In both scenarios the apical meristem of the plant was removed. Time of damage included the 4-leaf stage, pinhead square (8-10 nodes), first bloom (12-14 nodes), and first bloom + 4 weeks (18-22 nodes). The intensity of damage differed at the 4-leaf growth stage and consisted of the removal of the top 0, 2, and 4 nodes. The intensity of damage at all other growth stages (pinhead square, first bloom, and first bloom + four weeks) consisted of removing the top 0, 2, 4, 6, or 8 nodes from plants. An untreated check for both varieties was included where 0 nodes were removed from the plants. Insect control, fertility, and weed control were applied based on Mississippi State University Extension recommendations (Bond *et al*., 2017; Catchot *et al*., 2017). No plant growth regulators were applied during the growing season. Furrow irrigation was applied in Starkville, MS, 2015–2017. Blanket applications of harvest aids were timed based on the condition of plots that were not artificially damaged (Dodds *et al*., 2017a). Data collection consisted of plant height and number of nodes at each time the plants were artificially damaged and at the end of the season. In addition, lint turnout, lint yield, and fiber quality data were collected. Cotton was harvested using a spindle picker modified for small plot research (Table 3.1). Lint turnout was determined by harvesting a 25-boll sample by hand and ginning on a 10 saw laboratory cotton gin (Continental Eagle Corp., Prattville, AL). Seed and lint were weighed and lint turnout was calculated by dividing the weight of lint by the total weight of seed plus lint. Fiber quality was determined using a High Volume Instrument (HVI®) at the Fiber and Biopolymer Research Institute, Lubbock, TX. Statistical analyses were conducted using PROC GLIMMIX procedure in SAS v.9.4 (SAS Institute, Cary, NC). Data were analyzed using analysis of variance (ANOVA) and means were separated using multiple pairwise t-tests at the 0.05 level of significance. Random effects consisted of location and year. Fixed effects consisted of variety, node removal nested in growth stage, and variety by node removal nested in growth stage.

3.4 Results and Discussion

Location and year influenced plant height at pinhead square, first bloom, first bloom + four weeks, and harvest as well as number of nodes at first bloom, first bloom + four weeks, and harvest, lint turnout, lint yield, fiber length, fiber uniformity, fiber strength, and fiber elongation ($p < 0.0001$) (Table 3.2 and 3.3). Micronaire was only affected by location ($p < 0.0001$) (Table 3.3). Even though location and year affected the majority of the measured response variables, data were pooled over year and location to determine if treatment combinations of damage intensity and damage timing had effects on cotton.

The interaction of variety by intensity of damage nested in time of damage was analyzed to determine if either variety (early- or late-maturing) responded different to intensity or time of damage treatment combinations in terms of plant height and number of nodes, lint turnout, lint yield, and fiber quality. Our data indicate that there is no interaction effect of variety by intensity of damage nested in time of damage on plant height or number of nodes, lint turnout, lint yield, or fiber quality ($p \geq 0.0824$) (Tables 3.2 and 3.3).

Cotton variety influenced plant height at first bloom, first bloom + four weeks, and harvest as well as number of nodes at first bloom + four weeks and harvest ($p \leq 0.0372$) (Table 3.2). Variety also affected lint turnout, lint yield, micronaire, fiber uniformity, fiber strength, and fiber elongation ($p \leq 0.0152$) (Table 3.3). These results agree with previous research conducted by Dodds *et al*. (2015) that PHY 499 WRF and PHY 222 WRF have different growth habits, maturity, and yield potential characteristics.

The interaction of variety by intensity of damage nested in time of damage did not influence plant height, the number of nodes, lint turnout, lint yield, or fiber quality ($p \geq 0.0824$), data were pooled across variety, locations, and years allowing the treatment combination of intensity of damage nested in time of damage to be analyzed (Tables 3.2 and 3.3).

When data was pooled across locations, years, and variety, intensity of damage nested in time of damage affected plant height and number of nodes at pinhead square, first bloom, first bloom + four weeks, and harvest ($p \leq 0.0002$) (Table 3.2). At pinhead square, plants that were damaged at the 4-leaf growth stage resulted in 10 and 22% reduction in plant height, as well as a 13 and 22% reduction in number of nodes where two and four nodes were removed compared to the untreated, respectively (Table 3.4).

At first bloom, reductions in plant height and number of nodes persisted where plants were damaged at the 4-leaf growth stage, where 26 and 57% reductions in plant height and 27 and 64% reductions in the number of nodes where two and four nodes were removed compared to the untreated, respectively (Table 3.5). Furthermore, plant heights at pinhead square resulted in a 13 and 15% reduction in plant height where eight nodes were removed compared to the untreated and four node removal, respectively (Table 3.5). In addition, the number of nodes at pinhead square resulted in a 10 and 16% reduction where six and eight nodes were removed compared to the untreated, respectively (Table 3.5).

At first bloom + four weeks, reductions in plant height and the number of nodes were still apparent in plants that were damaged at the 4-leaf and pinhead square growth stages. Plants that were damaged at the 4-leaf growth stage had a 10 and 40% reduction in plant height and a 17 and 36% reduction in the number of nodes where two and four nodes were removed, respectively (Table 3.6). Plants that were damaged at the pinhead square growth stage had 14, 16, 27, and 50% reductions in plant height where two, four, six, and eight nodes were removed compared to the untreated, respectively (Table 3.6). Additionally, the number of nodes were reduced by 20, 18, 26, and 41% where two, four, six, and eight nodes were removed, respectively (Table 3.6). Furthermore, plants that were damaged at first bloom had 13 and 22% reductions in height where six and eight nodes were removed compared to the untreated, respectively (Table 3.6). The number of nodes were also reduced by 7, 7, 15, and 26% where two, four, six, and eight nodes were removed compared to the untreated, respectively (Table 3.6).

At harvest differences in plant height and the number of nodes were present; however, differences where early season damage occurred were not as apparent at harvest. No difference in plant height at harvest were observed where plants were damaged at the 4-leaf growth stage (Table 3.7). However, the number of nodes measured were reduced by 12 and 14% where four nodes were removed compared to the untreated and two node removal at the 4-leaf growth stage, respectively (Table 3.7). At harvest, plants that received two and six node removal at pinhead growth stage differed by 11% with removal of two nodes less than removal of six nodes (Table 3.7). Total nodes measured at harvest, where damage occurred at pinhead square, were reduced 10% where eight nodes were removed compared to the untreated (Table 3.7). Plant heights measured at harvest, where damage occurred at first bloom, were reduced 14% where four nodes were removed compared to the untreated (Table 3.7). Differences in the number of nodes at harvest, where damage occurred at first bloom, were reduced 12, 11, 14, and 10% where two, four, six, and eight nodes were removed compared to the untreated, respectively (Table 3.7). Furthermore, differences in plant height and number of nodes measured at harvest were observed where damage occurred at first bloom + four weeks. Plant heights were reduced by 14 and 20% where six and eight nodes were removed compared to the untreated, respectively (Table 3.7). Number of nodes were reduced by 12, 14, 19, and 24% where two, four, six, and eight nodes were removed compared to the untreated, respectively (Table 3.7).

Overall, as damage intensity increased during each damage timing plant height and number of nodes were reduced. However, plants that were damaged early in the growing season (4-leaf and pinhead square) had similar plant heights and number of nodes when measured at harvest compared to the untreated. Similarities in cotton height and number of nodes where early season damage occurred compared to the untreated could be contributed to the number of days remaining in the growing season after the physical damage occurred thus allowing damaged plants to compensate by harvest. Similar findings were reported by Smith and Varvil (1981) who found that the time in which damage occurs within the growing season reflects a point in time in the development of the crop and therefore the amount of time remaining in the growing season, can greatly influence observed outcomes. Furthermore, previous research conducted on damage simulation in cotton provides a limited base of information on plant height and node recoverability after damage occurs, but primarily focused on lint yield, lint turnout, and fiber quality parameters in response to damage occurring.

The intensity of damage nested in time of damage affected lint turnout, lint yield, micronaire, fiber length, and fiber strength when pooled across locations, years, and variety ($p \leq 0.0391$) (Table 3.3). Differences in lint yield were observed when damage occurred at the 4-leaf growth stage where yield reductions of 13 and 42% were observed when two and four nodes were removed compared to the untreated, respectively (Table 3.8). When damage occurred at pinhead square, yield reductions of 12, 20, 38, and 70% were observed where two, four, six, and eight nodes were removed compared to untreated, respectively (Table 3.8). When damage occurred at first bloom, yield reductions of 19, 33, 56% were observed where four, six, and eight nodes were removed compared to untreated, respectively (Table 3.8). When damage occurred at first bloom + four weeks yield reductions of 26 and 33% were observed where six and eight nodes were removed compared to untreated, respectively (Table 3.8). Overall, these results suggest that as damage occurs later in the growing season cotton is able to withstand greater damage intensities without suffering yield reductions. These observations agree with Smith and Varvil (1981) that as the severity of damage increased, the degree of recoverability decreased. However, Smith and Varvil (1981) also observed that when the same severity of damage occurred in older plants, decreased recoverability also occurred which coincides with the findings of this research. Furthermore, research conducted by Yang *et al*. (2016) found that yield loss due to main stem node removal was compensated by increased boll number on vegetative branches, thus resulting in no difference in yield response to main stem node removal. Those data coincide with the results from this research due to four node removal being the greatest intensity of damage.

Differences in lint turnout were only observed when damage occurred at the 4-leaf and pinhead square growth stages. When damage occurred at the 4-leaf growth stage, there was a 3% reduction in lint turnout where four nodes were removed compared to the untreated (Table 3.9). When damage occurred at the pinhead square growth stage, lint turnout was reduced 2, 4, and 6% where four, six, and eight nodes were removed compared to the untreated, respectively (Table 3.9). Lint turnout was affected when damage occurred at greater intensity at early season timings. These results agree with the findings of Peacock and Hawkins (1974), who found that plants severely injured early in the season had less lint turnout than plants with no injury or moderate injury. However, research conducted by Smith and Varvil (1981) did not observe any differences in lint turnout regardless of damage.

Differences in fiber quality parameters were observed only in micronaire, fiber length, and fiber strength ($p \leq 0.0391$) (Table 3.3). Similar to lint turnout, differences in micronaire were only observed when damage occurred at the 4-leaf and pinhead square damage timings. When damage occurred at the 4-leaf growth stage there was a 6% reduction in micronaire where four nodes were removed compared to the untreated (Table 3.10). When damage occurred at the pinhead square growth stage, micronaire was reduced by 3, 7, and 8% where four, six, and eight nodes were removed compared to the untreated, respectively (Table 3.10). No differences in micronaire were observed when damage occurred at first bloom or first bloom + four weeks regardless of damage intensity. Similar findings were reported by Peacock and Hawkins (1974) as well as

Smith and Varvil (1981) who found micronaire decreased as damage intensity increased. However, while differences in micronaire were observed, they did not affect price discount. Differences in micronaire could be attributed to the lack of fiber wall development indicating immaturity of lint fibers rather than mature fibers with low micronaire. An in-depth explanation of this observation is described by Peacock and Hawkins (1974).

Differences in fiber length were only observed when damage occurred at first bloom where there was a 2% increase in fiber length, where eight nodes were removed compared to the untreated (Table 3.11). Furthermore, differences in fiber strength were only observed when damage occurred at the pinhead square growth stage where there was a 3% increase in fiber strength when eight nodes were removed compared to the untreated (Table 3.12). Previous research from Smith and Varvil (1981) and Peacock and Hawkins (1974) reported damage intensity or damage timing resulted in no differences with fiber length and fiber strength parameters. Differences in this research due to the increased delay in maturity that was observed where eight nodes were removed at both pinhead square and first bloom.

3.5 Conclusion

No differences in how cotton responds to type and time of damage were found between the two varieties. Variety selection should be based on geographic region, yield potential, and the grower’s management style to optimize detrimental effects of crop damage such as hail damage or deer feeding. Cotton has the ability to better compensate for early season damage (4-leaf, pinhead square, and first bloom) in terms of plant growth parameters compared to late season damage. Additionally, lint yield reductions were greatest where cotton was damaged at pinhead square and first bloom with eight nodes removed. Damage later in the season had less adverse effects than early season damage. Lint turnout and micronaire were affected when damage occurred early in the growing season at the 4-leaf and pinhead square growth stages however, fiber strength and fiber length were only affected when eight nodes were removed from pinhead square and first bloom, respectively.

Overall, if damage occurs in cotton, the time and intensity of the damage will dictate the effects. If cotton is damaged early in the season (4-leaf, pinhead square, first bloom) but the option to replant is not available, managing for earliness should include limiting N, use of PGRs, and reducing late-season irrigation. If cotton is damaged late in the season (first bloom + four weeks) and lower first position bolls are undamaged, minimal yield loss should result from normal management of the crop the remainder of the season.

Table 3.1 Planting and Harvest Dates for Starkville, MS, Brooksville, MS, and Portageville, MO 2015–2017 and Jackson, TN 2015–2016.

	———Starkville———			———Brooksville———			——Jackson——		———Portageville———		
	–2015–	–2016–	–2017–	–2015–	–2016–	–2017–	–2015–	–2016–	–2015–	–2016–	–2017–
Planting	May 8	June 1	May 8	May 21	June 2	May 8	May 22	May 31	May 23	May 26	May 17
Harvest	Oct. 12	Oct. 24	Oct. 25	Oct. 19	Oct. 27	Nov. 10	Oct. 30	Oct. 12	Oct. 7	Oct. 24	Nov. 7

Table 3.2 Analysis of variance probability values for location, year, variety, damage intensity nested in damage timing, and the interaction of variety by damage intensity nested in damage timing for plant growth parameters.

	Height at Pinhead Square	Node at Pinhead Square	Height at Bloom	Node at Bloom	Height at Bloom + 4 wk	Node at Bloom + 4 wk	Height at Harvest	Node at Harvest
	p-values							
Location	<0.0001	0.0689	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year	<0.0001	0.2145	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Variety	0.0994	0.2275	0.0008	0.1152	<0.0001	0.0372	<0.0001	<0.0001
Intensity(Timing)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001
Var.[a]*Intensity(Timing)	0.9484	0.8156	0.9952	0.9903	0.9942	0.9160	0.8158	0.0824

[a] Variety.

Table 3.3 Analysis of variance probability values for location, year, variety, damage intensity nested in damage timing, and the interaction of variety by damage intensity nested in damage timing for lint turnout, lint yield, and fiber quality.

	Lint Turnout	Lint Yield	Mic[a]	Leng.[b]	Unif.[c]	Stren.[d]	Elon.[e]
	p-values						
Location	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year	<0.0001	<0.0001	0.1161	<0.0001	<0.0001	<0.0001	<0.0001
Variety	<0.0001	0.0005	0.0125	0.1884	0.0152	<0.0001	0.0002
Intensity(Timing)	<0.0001	<0.0001	<0.0001	0.0391	0.1247	0.0266	0.7867
Var.[f]*Intensity(Timing)	0.2757	0.1364	0.8809	0.9003	0.9877	0.9189	0.2080

[a] Micronaire.
[b] Fiber length.
[c] Fiber uniformity.
[d] Fiber Strength.
[e] Fiber elongation.
[f] Variety.

Table 3.4 Damage intensity nested in damage timing effect on plant height (cm) and plant nodes (number) measured at pinhead square pooled across location, variety, and year.

	Damage Intensity									
	-0 Nodes-	-2 Nodes-	-4 Nodes-	-6 Nodes-	-8 Nodes-	-0 Nodes-	-2 Nodes-	-4 Nodes-	-6 Nodes-	-8 Nodes-
Damage Timing	Plant Height					Plant Nodes				
	cm[a]					number[a]				
4-leaf	21.4 a	19.2 b	16.7 c	--	--	4.8 a	4.2 b	3.8 c	--	--
Pinhead Square	21.4 a	21.0 a	21.0 a	21.1 a	21.3 a	4.8 a	4.7 a	4.9 a	4.8 a	4.9 a
1st Bloom	21.4 a	20.3 a	20.4 a	20.7 a	20.1 a	4.8 a	4.8 a	4.9 a	4.7 a	4.7 a
1st Bloom + 4 Wks.	21.4 a	21.3 a	20.7 a	20.6 a	21.4 a	4.8 a	4.9 a	4.7 a	4.8 a	5.0 a

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

Table 3.5 Damage intensity nested in damage timing effect on plant height (cm) and plant nodes (number) measured at 1st bloom pooled across location, variety, and year.

	Damage Intensity									
	-0 Nodes-	-2 Nodes-	-4 Nodes-	-6 Nodes-	-8 Nodes-	-0 Nodes-	-2 Nodes-	-4 Nodes-	-6 Nodes-	-8 Nodes-
Damage Timing	Plant Height					Plant Nodes				
	cm[a]					number[a]				
4-leaf	33.2 a	24.5 b	14.1 c	--	--	7.4 a	5.3 b	2.7 c	--	--
Pinhead Square	33.2 a	31.6 ab	33.9 a	31.4 ab	28.9 b	7.4 a	6.8 ab	6.9 ab	6.6 b	6.2 b
1st Bloom	33.2 a	33.3 a	33.8 a	32.8 a	32.3 a	7.4 a	7.4 a	7.5 a	7.4 a	7.1 a
1st Bloom + 4 Wks.	33.2 a	34.5 a	34.7 a	33.7 a	35.1 a	7.4 a	7.9 a	7.7 a	7.1 a	7.8 a

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at p = 0.05.

Table 3.6 Damage intensity nested in damage timing effect on plant height (cm) and plant nodes (number) measured at 1^{st} bloom + 4 weeks pooled across location, variety, and year.

	Damage Intensity									
	-0 Nodes-	-2 Nodes-	-4 Nodes-	-6 Nodes-	-8 Nodes-	-0 Nodes-	-2 Nodes-	-4 Nodes-	-6 Nodes-	-8 Nodes-
Damage Timing	Plant Height					Plant Nodes				
	cm[a]					number[a]				
4-leaf	69.4 a	62.6 b	41.7 c	--	--	12.3 a	10.2 b	7.9 c	--	--
Pinhead Square	69.4 a	59.4 b	58.4 b	50.7 c	34.9 d	12.3 a	9.9 bc	10.1 b	9.1 c	7.2 d
1st Bloom	69.4 a	63.8 ab	64.9 ab	60.4 b	53.9 c	12.3 a	11.5 b	11.4 b	10.5 c	9.1 d
1st Bloom + 4 Wks.	69.4 a	68.1 a	68.2 a	65.5 a	68.5 a	12.3 a	12.5 a	12.5 a	12.1 a	12.5 a

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

Table 3.7 Damage intensity nested in damage timing effect on plant height (cm) and plant nodes (number) measured at harvest pooled across location, variety, and year.

	Damage Intensity									
	-0 Nodes-	-2 Nodes-	-4 Nodes-	-6 Nodes-	-8 Nodes-	-0 Nodes-	-2 Nodes-	-4 Nodes-	-6 Nodes-	-8 Nodes-
Damage Timing	Plant Height					Plant Nodes				
	cm[a]					number[a]				
4-leaf	97.0 a	96.0 a	90.1 a	--	--	18.4 a	19.0 a	16.2 b	--	--
Pinhead Square	97.0 ab	91.5 b	92.7 ab	103.3 a	101.9 ab	18.4 a	17.2 ab	17.1 ab	17.2 ab	16.5 b
1st Bloom	97.0 a	85.8 ab	83.0 b	85.5 ab	86.6 ab	18.4 a	16.2 b	16.4 b	15.8 b	16.5 b
1st Bloom + 4 Wks.	97.0 a	91.3 ab	87.1 abc	83.0 bc	77.4 c	18.4 a	16.1 b	15.8 b	14.8 bc	14.0 c

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

Table 3.8 Damage intensity nested in damage timing effect on cotton lint yield (kg/ha) pooled across location, year, and variety.

	Damage Intensity				
Damage Timing	0 Nodes	2 Nodes	4 Nodes	6 Nodes	8 Nodes
	kg/ha[a]				
4-leaf	1259 a	1092 b	735 c	--	--
Pinhead Square	1259 a	1114 b	1006 c	779 d	377 e
1st Bloom	1259 a	1174 a	1056 b	846 c	555 d
1st Bloom + 4 Wks.	1259 a	1180 a	1171 a	1001 b	844 c

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

Table 3.9 Damage intensity nested in damage timing effect on lint turnout (%) pooled across location, variety, and year.

	Damage Intensity				
Damage Timing	0 Nodes	2 Nodes	4 Nodes	6 Nodes	8 Nodes
	% turnout[a]				
4-leaf	41.1 a	41.1 a	39.7 b	--	--
Pinhead Square	41.1 a	40.7 ab	40.3 bc	39.6 c	38.7 d
1st Bloom	41.1 a	41.0 a	40.8 a	40.7 a	40.2 a
1st Bloom + 4 Wks.	41.1 a	41.0 a	40.9 a	40.8 a	40.8 a

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

Table 3.10 Damage intensity nested in damage timing effect on micronaire (mic) pooled across location, variety, and year.

	Damage Intensity				
Damage Timing	0 Nodes	2 Nodes	4 Nodes	6 Nodes	8 Nodes
	micronaire[a]				
4-leaf	4.7 a	4.7 a	4.5 b	--	--
Pinhead Square	4.7 ab	4.8 a	4.6 b	4.4 c	4.4 c
1st Bloom	4.7 a	4.8 a	4.8 a	4.8 a	4.7 a
1st Bloom + 4 Wks.	4.7 a	4.7 a	4.8 a	4.8 a	4.9 a

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at p = 0.05.

Table 3.11 Damage intensity nested in damage timing effect on fiber length (mm) pooled across location, variety, and year.

	Damage Intensity				
Damage Timing	0 Nodes	2 Nodes	4 Nodes	6 Nodes	8 Nodes
	mm[a]				
4-leaf	29.2 a	29.5 a	29.5 a	--	--
Pinhead Square	29.2 a	29.2 a	29.2 a	29.5 a	29.7 a
1st Bloom	29.2 b	29.2 b	29.5 ab	29.5 ab	29.7 a
1st Bloom + 4 Wks.	29.2 a	29.5 a	29.5 a	29.2 a	29.5 a

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

Table 3.12 Damage intensity nested in damage timing effect on fiber strength (grams/tex) pooled across location, variety, and year.

	Damage Intensity				
Damage Timing	0 Nodes	2 Nodes	4 Nodes	6 Nodes	8 Nodes
	grams/tex[a]				
4-leaf	32.7 a	32.9 a	32.9 a	--	--
Pinhead Square	32.7 b	33.0 b	32.7 b	32.7 b	33.5 a
1st Bloom	32.7 a	32.6 a	33.0 a	33.1 a	33.3 a
1st Bloom + 4 Wks.	32.7 a	33.0 a	33.1 a	32.8 a	33.2 a

[a] Data pooled over location, year, and variety. Means within a row followed by same lowercase letter are not significantly different according to pairwise t-tests at p = 0.05.

CHAPTER IV

EFFECT OF FOLIAR APPLIED NITROGEN TO DAMAGED COTTON

4.1 Abstract

Economic crop management decisions are needed for producers in the mid-southern U.S. who experience adverse weather or other types of damage to cotton at a time where replanting is not an option. This research was conducted to determine if the addition, timing, or sequence of foliar nitrogen fertilizer applications had an effect on plant height, number of nodes, lint yield, lint turnout, or fiber quality in cotton that was artificially damaged in specific ways. The effect of foliar nitrogen (no foliar N, foliar N applied at the time of damage, one week after damage occurred, two weeks after occurred, at the time of damage + one week after damage occurred, at the time of damage + two weeks after damage occurred, one week after + two weeks after damage occurred, and at the time of damage + one week after + two weeks after damage occurred) were evaluated on Phytogen 499 WRF planted in a Leeper silty clay loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts) at the R.R. Foil Plant Science Research Center, Starkville, MS and in a Brooksville silty clay (fine, smectitic, thermic Aquic Hapluderts) at the Black Belt Experiment Station, Brooksville, MS in 2016 and 2017. Plant growth stage when damage occurred affected plant height at harvest, lint yield, and micronaire ($p \leq 0.0342$). The time when foliar nitrogen was applied had an effect on total number of nodes, lint turnout, lint yield, micronaire, and fiber strength ($p \leq 0.0127$). The interaction

of time when foliar N was applied and time of damage did not affect plant height or number of nodes at harvest, lint turnout, lint yield, or fiber quality ($p \geq 0.2713$).

Plant height was reduced by 6% where damage occurred at pinhead square compared to first bloom. However, lint yield and micronaire were 39 and 5% greater where damage occurred at pinhead square compared to first bloom, respectively. The number of nodes was reduced 4 to 7% where foliar nitrogen applications were made at the time of damage, at the time of damage and one week after, at the time of damage and two weeks after, one week and two weeks after damage, and at the time of damage, one, and two weeks after damage, when compared to the untreated check. No differences in lint yield were observed between any time of application combinations; however, lint yield was reduced 63 to 72% compared to the untreated check. Micronaire was reduced for each treatment except where foliar nitrogen was applied one week after damage, when compared to the untreated check. Fiber strength was different where cotton was damaged compared to the untreated check; however, time of N application did not affect strength.

4.2 Introduction

Cotton (*Gossypium hirsutum* L.) is a major crop grown in the southern United States (U.S.) and across the Mid-South region (Arkansas, Louisiana, Mississippi, Missouri, and Tennessee). From 2011-2015 approximately 4.6 million hectares (11.4 million acres) of cotton were planted per year across the U.S., with approximately 14% of production taking place in the Mid-South (NASS, 2016). In Mississippi, cotton contributed $370 million to the economy annually from 2011-2015 (NASS, 2015). Cotton is often considered a high input crop when compared to other crops grown in rotation with cotton. With seed costs and technology fees exceeding $247 per hectare and several other input costs associated with production, initial input costs can be substantial in cotton (MSU, 2016). In order for growers to maximize profit in cotton, optimum yield must be attained. Environmental factors such as rainfall are unpredictable and typically lead to variations in productivity from year to year (Wang, 2011). Crop damage from hail storms and wildlife cause an estimated $5.5 billion in crop and property damages annually in the U.S. (Conover, 2002; NWC, 2015). Approximately 14% of U.S. crop failures were due to hail and wildlife damage (RHIS, 2015). Often when crop failures due to hail or wildlife damage are experienced, the option to replant is not available. Therefore, the decision of whether to terminate the crop or continue to manage the crop must be made. After damage has occurred, any economic tactic to alleviate plant stress, promote plant growth, and reduce delays in maturity may be warranted. The typical producer response to stunted cotton is to apply additional nitrogen in an effort to overcome adverse environmental effects (Peacock and Hawkins, 1974). Although additional nitrogen can lead to excessive vegetative growth in cotton, applying more nitrogen could lead to increasing the likelihood of nitrogen pollution into water sources as well as increasing production costs and ultimately reducing profit potential. Applications of foliar nitrogen have recently become more popular due to the increased need for efficient nutrient utilization that is observed with early maturing high-yielding cotton varieties that are currently grown (Oosterhuis and Weir, 2010).

Previous research evaluating applications of foliar nitrogen in cotton has shown some benefit, where foliar applied nitrogen is utilized to supplement soil applied nitrogen during reproductive growth (Snyder *et al*., 1998; Oosterhuis *et al*., 1989; Oosterhuis and Bondada, 2001). However, applications of foliar nitrogen have not consistently increased lint yields (Anderson and Walmsley, 1984; McConnell *et al*., 1998; Oosterhuis and Bondada, 2001; Roberts *et al*., 2006). Research conducted by McConnell *et al*. (1998) and Snyder *et al*. (1998) concluded that lack of yield response from applications of foliar nitrogen may be due to nitrogen rate applied to the soil as well as foliar nitrogen applications being made to cotton that does not have critically deficient nitrogen levels.

While previous research evaluating foliar nitrogen applications in cotton has been conducted, limited research on foliar nitrogen applications made during vegetative growth stages and to damaged cotton is available. Therefore, the objectives of this research were to determine if foliar applied nitrogen or nitrogen application timing had an effect plant growth, lint turnout, lint yield, or fiber quality.

4.3 Materials and Methods

Research was conducted at the R.R. Foil Plant Science Research Center near Starkville, MS (33.474670°N, 88.788238°W) on a Leeper silty clay loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts) and at the Black Belt Experiment Station near Brooksville, MS (33.257110°N, 88.559723°W) on a Brooksville silty clay (fine, smectitic, thermic Aquic Hapluderts) in 2016 and 2017. Phytogen 499 WRF (Dow AgroSciences, Indianapolis, IN) cotton was planted at 111,150 seeds/ha and a depth of 2.5 cm (Table 4.1). Plots consisted of 2–96 cm rows that were 9.1 m in length in 2016 and 12.2-m in 2017. Damage was simulated by mechanically removing eight main stem nodes from the plant including the apical meristem with the use of scissors at different timings which included pinhead square and first bloom. Unpublished data from research conducted by Plumblee *et al*. (2015) suggested that eight node removal at pinhead square and first bloom had the greatest affect on lint yield. After damage occurred, foliar nitrogen was applied at different timings which included at the time of damage, one week after damage, two weeks after damage, at the time of damage and one week after, at the time of damage and two weeks after, one week and two weeks after damage occurred, at the time of damage, one week, and two weeks after. Plots where cotton was damaged but no foliar nitrogen was applied were included as well as an undamaged untreated check for comparison purposes. Treatments were arranged within a randomized complete block design with three replications in 2016 and four replications in 2017. All foliar applied nitrogen treatments were applied with a CO_2 backpack sprayer calibrated to deliver a spray volume of 187 L/ha at a pressure of approximately 317 kPa at a speed of 4.8 km/h using a 2-row boom with AI11002-VS nozzles (TeeJet, Springfield, IL). Controlled-Release Nitrogen (CoRoN, Helena Holding Co. Collierville, TN) (25-0-0) was applied at a rate of 2.78 kg N/ha at each application timing. All applications were made at or near sunset per label instructions to reduce risk for crop injury. Insect control, fertility, weed control, and harvest aids were applied based on Mississippi State University Extension recommendations (Bond *et al*., 2017; Catchot *et al*., 2017; Dodds *et al*., 2017a). Data collection consisted of plant height and number of nodes at harvest, lint turnout, lint yield, and fiber quality. Cotton was harvested using a spindle picker modified for small plot research (Table 4.1). Lint turnout was determined by harvesting a 25-boll hand sample by hand and ginning on a 10 saw laboratory cotton gin (Continental Eagle Corp., Prattville, AL). Seed and lint were weighed and lint turnout was calculated by dividing the weight of lint by the total weight of seed plus lint. Fiber quality was determined by a High Volume Instrument (HVI®) at the Fiber and Biopolymer Research Institute, Lubbock, TX. Statistical analyses were conducted using PROC GLM procedure in SAS v.9.4 (SAS Institute, Cary, NC). Data were analyzed using analysis of variance (ANOVA) and means were separated using Fisher's Protected LSD at the 0.05 level of significance. Random effects consisted of location and year. Fixed effects consisted of foliar nitrogen application timing, growth stage at the time of damage, and foliar nitrogen application timing by growth stage.

4.4 Results and Discussion

The interaction of growth stage at which time damage occurred by foliar nitrogen application timing did not influence plant height or number of nodes at harvest, lint turnout, lint yield, or fiber quality ($p \geq 0.2713$) (Table 4.2). Growth stage at the time in which damage occurred influenced plant height at harvest, lint yield, and micronaire ($p \leq 0.0342$) when pooled across locations and years (Table 4.2). Plant heights at harvest were reduced by 6% where plants were damaged at pinhead square compared to first bloom (Table 4.3). Although height differences were observed between growth stages at the time in which damage occurred, plant height did not affect lint yield as plants damaged at first bloom had a 39% reduction in lint yield compared to plants damaged at pinhead square (Table 4.3). Reductions in lint yield could be attributed to the reduced number of days remaining in the growing season following the time at which cotton was damaged. Similar findings from Smith and Varvil (1981) reported that the time at which damage occurs within the growing season reflects a point in the development of the crop, therefore, the amount of time remaining in the growing season can greatly influence observed outcomes. Additionally, Smith and Varvil (1981) found that when the same severity of damage occurred in older plants, a decrease in recoverability was observed which agrees with this research. Similarly to lint yield, a 5% reduction in micronaire was observed where plants were damaged at first bloom compared to pinhead square (Table 4.3).

Foliar nitrogen application timing had an affect on number of nodes at harvest, lint turnout, lint yield, micronaire, and fiber strength ($p \leq 0.0127$) when pooled across locations and years (Table 4.2). The number of nodes at harvest were reduced by 5, 6, 4, 5, and 7% where foliar nitrogen applications were made at the time of damage, at the time of damage + one week, at the time of damage + two weeks, one week after + two weeks after, and at the time of damage + one week after + two weeks after compared to the untreated check, respectively (Table 4.4). Based on these data, four out of five application timings that reduced the number of nodes were applied at the time in which the damage occurred. Therefore, it can be hypothesized that foliar nitrogen applied at the time of damage may increase crop injury to remaining leaves. No differences in lint yield due to application timing were observed where cotton had been damaged (Table 4.4). However, lint yield reductions between 63 and 72% were observed between the untreated check and all damaged plots regardless of foliar nitrogen application timing (Table 4.4). Foliar nitrogen applied one week after damage occurred resulted in 13% greater micronaire compared to foliar nitrogen applied at the time of damage + one week after (Table 4.4). Furthermore, when compared to the untreated check, all damaged cotton except where foliar nitrogen was applied one week after damage, resulted in micronaire reductions ranging between 12 and 19% (Table 4.4). Overall, micronaire reduction where cotton was damaged could be due to damaged plants having delayed maturity, and though defoliation was delayed as late as possible, lint fibers may have still been immature at the time harvest aids were applied. Other than micronaire, fiber strength was the only fiber quality parameter that was affected by foliar nitrogen application. Where foliar nitrogen was applied at the time of damage + two weeks after, fiber strength was not different compared to the untreated check. However, all other damage treatments, regardless of foliar nitrogen application, had between 3 and 6% greater fiber strength than the untreated check (Table 4.4). Based on the findings from Peacock and Hawkins (1974), secondary wall thickness within the boll heavily influences fiber strength. Though day length and temperature influences secondary wall formation, the delay in maturity experienced with damaged cotton in this research did not appear to adversely effect fiber strength as fiber strength was improved.

4.5 Conclusion

Foliar nitrogen applied to physically damaged cotton did not increase plant height, number of nodes, lint turnout, lint yield, or fiber quality. Furthermore, foliar nitrogen application timing and whether individual or sequential applications were utilized, did not have an affect on plant height, lint turnout, lint yield, or fiber quality. Reductions in the number of nodes where foliar nitrogen applications were made at the time of damage + one week after damage + two weeks after damage, compared to where no foliar nitrogen application was made to damaged cotton were observed. Overall, if damage occurs in cotton, management strategies other than the use of foliar applied nitrogen should be evaluated for positive responses in plant growth, lint yield, and fiber quality.

Table 4.1 Planting and harvest dates for Starkville and Brooksville, MS 2016-2017.

	———Starkville———		———Brooksville———	
	–2016–	–2017–	–2016–	–2017–
Planting	May 7	May 7	May 10	May 8
Harvest	Oct. 24	Nov. 10	Oct. 11	Oct. 31

Table 4.2 Analysis of variance probability values for damage timing (growth stage), application timing, and the interaction of application timing by growth stage for plant growth parameters, lint turnout, lint yield, and fiber quality.

	Plant Height at Harvest	Plant Node at Harvest	Lint Turnout	Lint Yield	Micronaire	Fiber Length	Fiber Uniformity	Fiber Strength	Fiber Elongation
	p-values[a]								
Growth Stage	0.0147	0.0734	0.0516	<0.0001	0.0342	0.5306	0.3022	0.1818	0.1101
Application Timing	0.4569	0.0127	<0.0001	<0.0001	0.0002	0.9798	0.8339	0.0079	0.7178
Timing*GS[b]	0.9818	0.9509	0.5935	0.7183	0.2713	0.7898	0.9233	0.6473	0.7623

[a] Data was pooled across year and location.

[b] Growth stage.

Table 4.3 Damage timing (growth stage) effects on plant height (cm), plant nodes (number), lint turnout (%), lint yield (kg/ha), micronaire (mic), fiber length (mm), fiber uniformity (%), fiber strength (grams/tex), and fiber elongation (%).

Application Timing[a]	Plant Height	Plant Nodes	Lint Turnout	Lint Yield	Micronaire	Fiber Length	Fiber Uniformity	Fiber Strength	Fiber Elongation
	–cm-	-number-	–%–	–kg/ha–	–mic–	–mm–	–%–	-grams/tex-	–%–
Pinhead Square	95 b	16.7 a	40.96 a	589 a	4.2 a	28.7 a	83.7 a	33.1 a	7.3 a
First Bloom	101 a	17.0 a	40.19 a	360 b	4.0 b	28.7 a	83.6 a	33.4 a	7.5 a

[a] Data pooled over location, year, and foliar N application timing. Means within a column followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

Table 4.4 Foliar nitrogen application timing effects on plant height (cm), plant nodes (number), lint turnout (%), lint yield (kg/ha), micronaire (mic), fiber length (mm), fiber uniformity (%), fiber strength (grams/tex), and fiber elongation (%).

Application Timing[a]	Plant Height	Plant Nodes	Lint Turnout	Lint Yield	Micronaire	Fiber Length	Fiber Uniformity	Fiber Strength	Fiber Elongation
	–cm-	-number-	–%–	–kg/ha–	–mic–	–mm–	–%–	-grams/tex-	–%–
Untreated	91 a	17.5 a	43.85 a	1261 a	4.7 a	28.7 a	83.6 a	31.9 b	7.2 a
No App.	102 a	17.0 abc	40.29 b	427 b	4.0 bc	29.0 a	83.5 a	33.7 a	7.4 a
At Clipping	99 a	16.6 bcd	39.96 b	420 b	4.1 bc	28.7 a	83.8 a	33.5 a	7.4 a
1 Wk. After Clip.	102 a	17.0 abc	40.47 b	462 b	4.3 ab	28.7 a	83.8 a	33.1 a	7.5 a
2 Wks. After Clip..	102 a	17.2 ab	40.34 b	434 b	4.0 bc	29.0 a	83.8 a	33.4 a	7.3 a
At Clip. + 1 Wk.	100 a	16.4 cd	39.46 b	352 b	3.8 c	29.0 a	83.6 a	33.0 a	7.3 a
At Clip. + 2 Wks.	102 a	16.8 bcd	40.69 b	429 b	4.0 bc	28.7 a	83.6 a	32.9 ab	7.4 a
1 Wk. + 2 Wks. After	98 a	16.6 bcd	40.29 b	367 b	4.1 bc	28.7 a	83.8 a	33.5 a	7.4 a
At Clip. + 1 Wk. + 2 Wks. After	99 a	16.3 d	39.83 b	443 b	4.1 bc	28.5 a	83.2 a	34.0 a	7.4 a

[a] Data pooled over location, year, and damage timing (growth stage). Means within a column followed by same lowercase letter are not significantly different according to pairwise t-tests at $p = 0.05$.

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