EFFICACY OF RECOVERY SPRAYS TO SYNTHETIC AUXIN INJURED COTTON AND COMPARISON OF MULTIPLE AND SINGLE PASS HARVEST SYSTEMS EFFECT ON COTTON YIELD AND FIBER QUALITY

A Dissertation

By

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
In partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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December 2020

Major Subject: Agronomy

ABSTRACT

The latest major technology advancement for cotton producers (*Gossypium sp.*) is arguably auxin-resistant cultivars, but this technology has created issues with auxin injury from off-site movement, requiring the use of coarse nozzles for herbicide application. To address these issues, studies were conducted to address defoliation with coarse nozzle tips and the ability to promote recovery of cotton plants from auxin injury.

The study of nozzle types and carrier volumes revealed higher carrier volumes are more successful at defoliating and opening bolls than lower carrier volumes. Water volumes of 47 L ha^{-1} should be avoided when making cotton harvest aid applications, as all defoliation, open boll, and regrowth values were consistently reduced at the lowest carrier volume. Various nozzle types had less impact on harvest aid efficacy than carrier volume.

In 2017, three recovery products (mepiquat chloride, N-Demand + Advantigro, and Radiate) used on dicamba-injured cotton resulted in similar yields to untreated cotton. These findings were not present for 2018 or 2019, as none of the recovery treatments produced yields comparable to the untreated check. For all three years of the 2,4-D trial, all the recovery treatments were comparable in yield and none of treatments improved yields, although in 2017, the auxin-only treatment resulted in similar lint yields to the untreated check.

Another major concern for cotton producers is seed cotton removal from fields due to weather delays. A study was conducted to measure the benefits of early removal of seed cotton through a multiple picking process compared to the traditional single-pass harvest method. Over the seven site-years, for both picker- and stripper-harvested varieties, similar trends were observed for both yield, fiber quality, and gross revenue. These results indicated that multiple harvests provided comparable value for short-season and mid-late season cotton varieties. For lint yields, this research indicated there is more benefit to timely harvest for cotton grown in high-yielding and picker-harvested environments than non-irrigated, low-yielding, and stripper-harvested cotton. Furthermore, multiple harvesting provides a significant value and provides an economic justification for robotic harvesting to be developed for the cotton industry.

DEDICATION

This dissertation is dedicated in loving memory of my grandfather and longtime cotton farmer, William A. Warner, who instilled a love of agriculture in me. My early childhood memories of riding in a tractor or chopping cotton will always be something in which I take great pride. Thank you for giving me something in life that brings such immense joy and passion.

I would also like to thank my mother, Anne, and father, Gil, for being enormously helpful and supportive throughout the entire doctorate process. There were challenging days, but you made them a lot easier.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank Dr. Gaylon Morgan for giving me the opportunity to pursue my PhD at Texas A&M University in the Cotton Extension Program. I sincerely could not have asked for a better advisor, for whom I have the utmost respect. I also appreciate the opportunity to learn and receive guidance from other excellent professors such as Drs. David Kerns, Muthu Bagavathiannan, Amir Ibrahim, Emi Kimura, Glenn Ritchie, Robert Hardin, Scott Nolte, Eric Hequet, and many others. This dissertation and the research presented within would not have been possible without the assistance from Program Specialist Dale Mott, and fellow students Jenny Dudak, Justin Jackson, Brady Arthur, and many others, for them and their friendships I am extremely grateful.

In part of my appreciation, I would like to thank other university professors that replicated or assisted in my studies, Drs. Seth Byrd, Alan Dabney, Darrin Dodds, Randy Norton, Andrea Jones, Guy Collins, Trey Cutts, Keith Edmisten, John Snider, Tyson Raper, John Wanjura, and Emi Kimura. Their addition to my projects greatly benefitted the research. Finally, I would like to thank Dr. Ed Barnes with Cotton Incorporated for his amazing leadership through an incredibly intensive project and for the sponsorship of the “robotics” project as well as my fellowship.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Assistant Professor Robert Hardin and Professor Gaylon Morgan, co-advisors from the Biological and Agricultural Engineering and Soil and Crop Sciences Department, respectively, and Assistant Professor Emi Kimura, from the Soil and Crop Department at Texas A&M University and Professor Glen Ritchie, Texas Tech University.

Funding Sources

Graduate study was supported by fellowships from Cotton Incorporated and Texas A&M AgriLife. This work was also made possible by Cotton Incorporated project number 18-732TX. The contents of this dissertation are solely the responsibility of the authors and do not necessarily represent the views of the Cotton Incorporated.

NOMENCLATURE

AFIS	Advanced fiber information system
ANOVA	Analysis of variance
DAA	Days after application
DPA	Days past anthesis
GPS	Global positioning system
HVI	High Volume Instrument
LPH	Liters per hectare
LSD	Least significant difference
KPH	Kilometers per hour
NASS	National Agricultural Statistics Service
SAS	Statistical Analysis System
USDA	United States Department of Agriculture
UTC	Untreated check

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CHAPTER I

INTRODUCTION

Cotton (*Gossypium sp.*) producers require diverse knowledge and management skills for managing equipment, financing, marketing, and complex crop production systems. Producers are constantly searching for approaches to remain profitable. They do this by increasing revenues through greater yields or improved fiber quality, or decreasing expenditures by reducing farm inputs, maximizing labor and equipment efficiency and often both. As President John F. Kennedy once famously stated, "The farmer is the only man in our economy who buys everything retail, sells everything at wholesale, and pays the freight both ways." This economic system has minimal margin of error for producer decision making but does encourage innovation and adoption of new technology, such as herbicide and insecticide technology, more efficient machinery, and current knowledge of best agricultural practices.

The pace of revolutionary technological discoveries in agriculture across the world has accelerated in the last century. With the advent of pesticides, industrially produced bulk fertilizers, hybridization of crops, introgression of transgenic traits, GPS sensing, and automation, farmers now have the potential to produce higher yields every year (Adapted: NCCA, 2019) as seen in Figure 1.1.

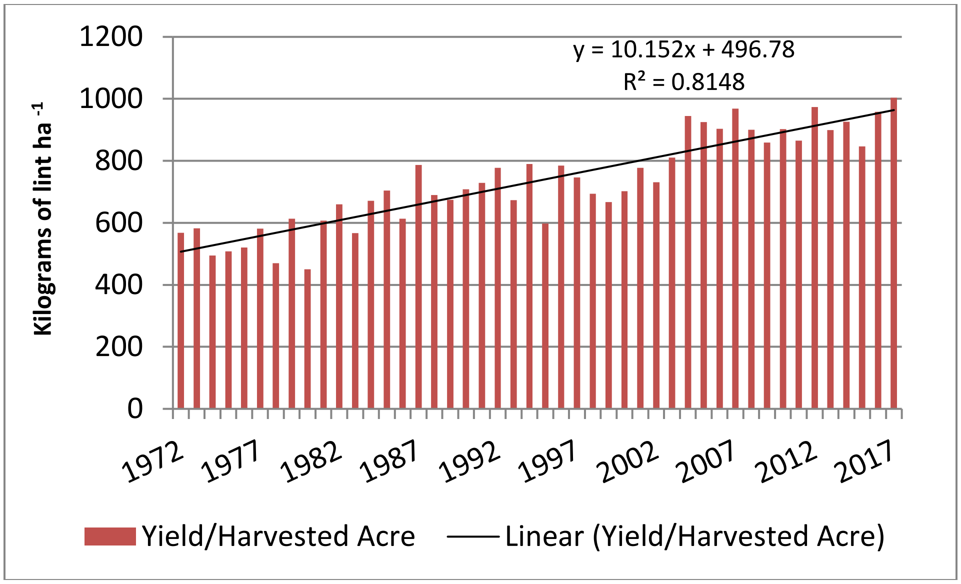


Figure 1.1. Historical United States lint cotton yields from 1972 to 2018 and trend line showing improved annual yields (kg ha^{-1})(Adapted from USDA-ERS, 2019).

The United States (U.S.) is the third largest producer and number one exporter of cotton in the world (USDA, 2019). The U.S. cotton industry creates $21 billion in products and services along with 125,000 jobs (USDA-ERS, 2019). In 2018, the U.S. planted 5,497,519 ha (13,584,665 acres) of upland cotton in 17 states; Texas was the leading state with 3,074,453 hectares (7,597,138 acres) (USDA-FSA, 2019). In 2017, the harvested area of cotton was 4,391,000 ha with 20,223,000 total bales (480 pound bales) produced in the U.S. resulting in an average yield of 1,003 kg ha^{-1} of cotton lint (Figure 1) (NCCA, 2019).

Studies have shown the effectiveness of harvest aids is highly influenced by environmental conditions, harvest aid type (hormonal or contact), and their usage rates (Gwathmey and Hayes, 1997; Eder et al. 2018). Furthermore, the deposition volume and type of nozzles used during application (Griffin et al. 2020) also affect harvest aid application success. Higher carrier volumes typically resulted in greater levels of defoliation and boll opening than lower carrier volumes, whereas defoliation, open boll, and regrowth values were consistently reduced at the lowest carrier volume. Subsequently, water volumes of 47 L ha^{-1} should be avoided when making cotton harvest aid applications. Although additional research evaluating differences in nozzle types and carrier volume with desiccants is warranted, these studies suggest larger droplet size nozzles could be used for harvest aid applications at carrier volumes in excess of 93 L ha^{-1}.

The increase in cotton acreage, as observed in 2017 and 2018, and poor harvest conditions, as occurred in 2018, causes an amplified strain on harvest equipment leading to more mechanical failures, and delay of timely harvest. Even without harvest delays, the lower-positioned mature cotton bolls are exposed to weathering for over 45 days while waiting for the upper position and vegetative bolls to mature, crop defoliation, and harvest to begin. In traditional production systems in the US, cotton harvest aids are recommended to be applied when 60% of cotton bolls are open, and harvesting occurs approximately 1-2 weeks later in the best of scenarios (Kerby et al., 2000). Multiple harvests earlier in the season would allow for a more efficiently timed seed cotton harvest while preserving yield and fiber quality and ultimately, boosting profitability. With recent developments in autonomous equipment, cost-effective computing capacity, image processing, and battery innovation, autonomous robotic harvesters are being developed and may have a viable fit within cotton.

Rapid adoption of synthetic auxin-resistant crops, which now have over 75% market share across the US (USDA, 2018), has created a significant increase in off-site movement cases (Bradley, 2019). This is a major concern for cotton growers across the Cotton Belt due to tank contamination, bulk container contamination, and off-target movement of herbicides into cotton and other susceptible crops. A diligent and proactive approach is being implemented by local, state, and federal agencies to reduce the amount of off-site cases, but incidents continue to occur (Vann and Cahoon, 2019). Farm-level questions about the source of the injury arise once symptomology of off-target synthetic auxin application has been observed in a field. Previous research has been published on the impacts of various synthetic auxin rates and timing on soybean and cotton yield and quality. In cotton, auxin injury can cause up to 70% yield reduction when damaged by 2,4-D at first square (Everitt et al. 2009; Byrd et al. 2016). However, little information is present on the impact of various commercially available products, such as plant growth regulators or nutritional and hormonal products, on aiding the cotton plants in recovering from auxin injury. A study was established to answer these questions.

Literature Review

Water Volume and Deposition Effects on Harvest aid Efficacy

Cotton (*Gossypium hirsutum* L.) is an indeterminate perennial shrub that is grown as an annual row crop. Producers rely on harvest aids to achieve optimal lint yield and fiber quality and prepare plants for efficient and timely mechanical harvesting (Chen and Dong, 2016). Harvest aid is a broad term that includes products that serve as defoliants, desiccants, regrowth inhibitors, and boll openers, with some products having activity in more than one of these areas. The effectiveness of harvest aids is greatly influenced by weather conditions and plant condition, including immature fruit load, plant size, residual soil nitrogen, and varietal differences (Gwathmey et al., 1986; Oosterhuis et al., 1991; Snipes and Evans, 2001; Supak and Snipes, 2001). Weather conditions at the time of application, but also before and after application, affect harvest aid efficacy (Gwathmey et al., 2004).

Defoliants allow more efficient harvest as these products remove unwanted plant material, such as leaves, petioles, and bracts and potentially reduce the amount of regrowth a plant will exhibit (Supak and Snipes, 2001). Plants that are naturally mature, nutrient-limited, and have higher leaf-moisture content tend to defoliate more readily. Higher temperatures and humidity levels also increase the efficacy of some defoliant products (Cathey, 1986). The removal of vegetative plant material helps preserve fiber quality by reducing lint staining, moisture within modules, and leaf and petiole material that must be removed in the gin. The reduction of vegetative material in harvested cotton delivered to the gin reduces lint cleaning requirements and thereby reduces ginning costs (Bechere et al., 2011). Additionally, excessive cleaning at the gin increases fiber breakage, which decreases fiber length and increases short fiber content, which can lead to additional fiber quality discounts (Larson et al., 2002).

Defoliants are generally separated into two categories: hormonal and herbicidal. Hormonal defoliants (thidiazuron and ethephon) increase the ethylene concentration in the leaf, limiting auxin transport, which in turns initiates the abscission process at the base of the petiole and allows the leaf to separate from the stem or branch (Morgan and Durham, 1975). Herbicidal defoliants (e.g., carfentrazonethyl, fluthiacet-methyl, pyraflufen ethyl, saflufenacil, and tribufos) injure the leaf, which stimulates ethylene production and leads to the initiation of the abscission process. If herbicidal defoliant rates are too high for the crop condition, the injury will increase leaf desiccation causing leaf tissue to die too rapidly and preventing the abscission layer from developing. This leads to desiccated leaves remaining attached to the plant and increases leaf material entering the harvester and module.

Harvest aids also include boll openers that promote mature bolls to open more rapidly by weakening the boll sutures. Boll openers are not systemic and are not translocated from the leaves to the bolls (Gwathmey and Hayes, 1997). As a result, coverage is crucial; boll openers must reach and adequately cover unopened bolls to obtain effective boll opening. Cooler temperatures (highs below 24° C) require rates twice has high compared to warmer temperatures (highs above 29° C) (Gwathmey et al., 1986). Properly timed boll openers expedite cotton harvest to avoid inclement weather and minimize cellular degradation, staining, rotting, and hard locking (Logan and Gwathmey, 2002).

Sprayer nozzles are designed to deliver various droplet sizes and volume output capabilities depending on the needed coverage, product (systemic or non-systemic), application speed, and chemical properties of the products being applied. The spray volume output is regulated by the exit orifice size and pressure with increasing orifice size and/or pressures delivering higher spray volume. Application speed impacts carrier volume with faster speeds lowering application rates and possibly detrimentally influencing deposition in other ways (Heidary et al., 2014).

There are numerous sprayer nozzles manufactured by various companies with various designs, but most are a variation of flat fan or hollow-cone nozzle (TeeJet Technologies, 2017). Nozzles are designed to create or change different spray droplet sizes and patterns based on desired applications. In 1985, extended-range nozzles that allow for greater variation with pressure were brought to the marketplace and allow producers more flexibility in spray droplet size without having to change nozzles frequently.

Due to the 2016 release of auxin-resistant cotton seed and their associated auxin herbicides, applicators were required by federal law to apply auxin herbicides with extremely coarse to ultra-coarse nozzles to create large spray droplets and with minimal, driftable fine droplets (Monsanto Company, 2018). Larger droplet sizes reduce the potential for off-site movement by physical drift and/or temperature inversions. However, larger droplets decrease coverage on the leaf surface. For example, a 500-micron water droplet is equal to eight 250-micron (categorized as medium droplet size) water droplets in volume (Kruger et al., 2013). The reduction in coverage resulting from large droplet size can be partially compensated for by increasing the carrier volume. However, increasing carrier volume is not preferred by growers due to added expenses from hauling and time spent refilling nurse and spray tanks. Furthermore, growers would prefer to minimize costs of their farming operation by reducing the number of nozzle types needed to be purchased. Hence, the desired reduction of expenditures would likely persuade them to use the required coarse to ultra-coarse tips for harvest aids.

For maximum canopy penetration of harvest aids, 47 to 93 L ha^{-1} should be used for aerial application and 93 to 187 L ha^{-1} for ground applications to significantly increase defoliation (Siebert et al., 2006). Siebert et al. (2006), using three different nozzles: flat fan, hollow cone, and air induction, demonstrated that higher carrier volumes provided greater efficacy and were recommended to obtain adequate canopy coverage and penetration in cotton with rank or excessive growth. Harvest aid labels for products containing the active ingredients of tribufos (Amvac Chemical Corporation, 2019), thidiazuron (Loveland Products, 2019b), or ethephon (Loveland Products, 2019a) make the same general recommendations on their labels for high spray volumes, but with no mention of nozzle selection. The objective of this research study was to determine the most effective spray volumes for proper defoliation, boll opening, and minimizing leaf grades.

Comparison of Multiple and Single Pass Harvest Methods Effect on Cotton Yield and Fiber Quality

Understanding the variability of cotton fiber within a single plant, individual bale, or an entire field requires multifaceted knowledge. Factors affecting fiber quality and yield include genetics of the cultivar planted; physiological development of the cotton plant and fiber; environmental factors and management decisions, including defoliation timing, which contributes to boll and fiber development; harvesting system; and ginning processes. These intertwined factors play a major role in influencing fiber quality characteristics and complicate isolation of individual factors of significance in research projects. Wanjura et. al (2019) found significant differences between harvest methods and cultivars based on High Volume Instrument (HVI). The treatments produced differences among color and leaf grades, uniformity, strength, and, ultimately, loan value for ginning method by cultivar. The standardized cotton fiber quality parameters are outlined by the USDA-AMS Classing Offices and drive premiums and discounts that influence revenues for U.S. cotton producers (USDA-AMS, 2018).

A cotton plant is an indeterminate perennial shrub that is managed as an annual crop and is harvested once in the U.S. The plant usually constructs at least fourteen and possibly upwards of thirty-five nodes within a growing season. The number of nodes is influenced by the length of growing season, water availability, nutrient availability, the indeterminacy of cultivar, and seeding rates. The node of the first sympodial branch is consistent for a given cultivar, but plant populations and the environmental conditions also impact the initiation of first sympodial branch. In most current varieties, the first sympodial branch will start around the seventh node and sympodial branches continue to develop vertically up the plant, leading to seven to potentially 28 sympodial nodes, depending on the factors mentioned above. On each of these nodes, each branch has the potential for three to four fruiting sites with typical plant populations, starting at the main stem and moving outward (Mauney, 1986). A greater number of bolls per plant with comparable plant populations will increase lint yield (Heitholt, 1993). Conversely, cotton boll positioning on the plant affects fiber quality, as first position bolls on nodes 5 to 7 were found to have less intraplant photosynthate competition leading to creating greater strength and longer fibers (Davidonis et al., 2014).

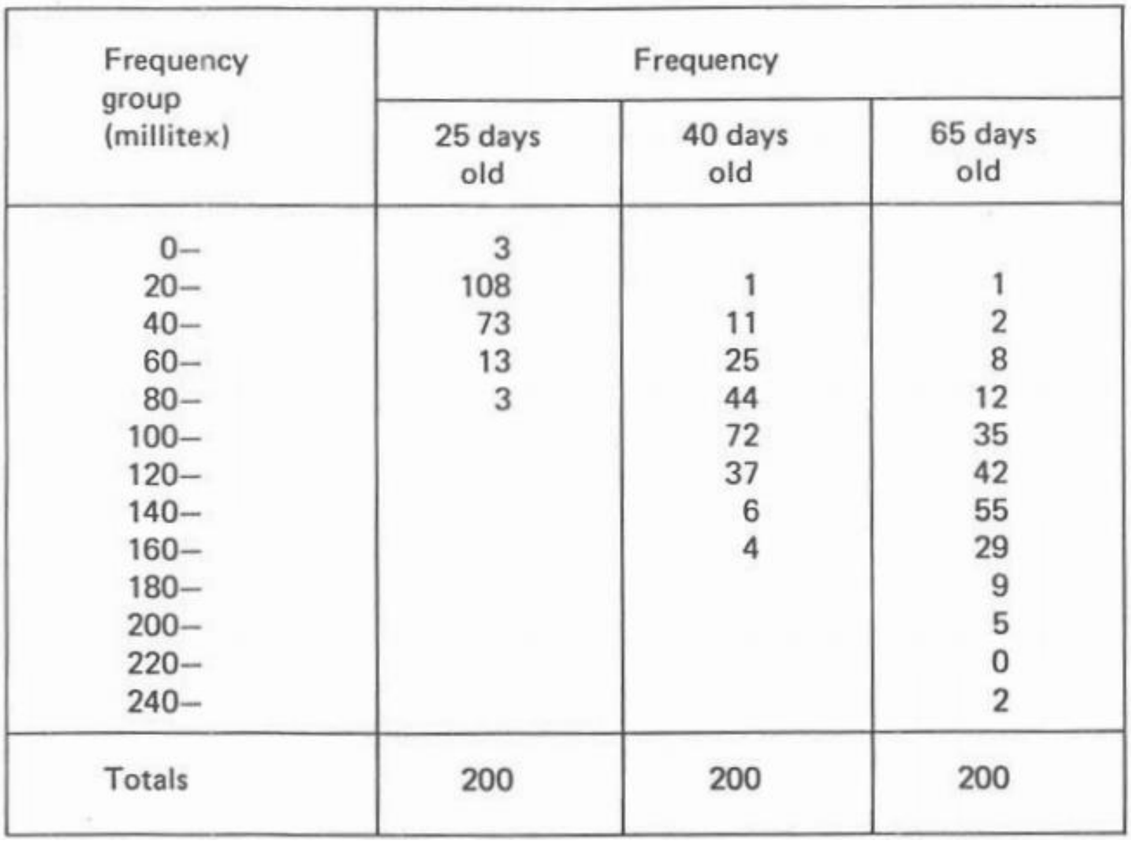
Intraplant variability of fiber quality characteristics is influenced by fruiting positions on sympodial branches, vertical hierarchy, and varietal selection (Kothari et al., 2015). Intraplant cotton fiber quality variability has been shown to be partially due to plant phenological genetic composition. Ayele et al. (2017) concluded that differences existed between cultivars in fiber quality parameters, such as micronaire, uniformity, strength, and length, from plant sympodial branch hierarchy, but the environment was a larger source of intraplant variability in fiber characteristics. Lower-positioned bolls had higher micronaire, strength, and length than higher-positioned bolls. The amount of variation between lower- and higher-positioned sympodial branches was dependent upon the cultivar, but weather events also affected the amount of variation in fiber characteristics. Extremes in temperature and rainfall caused greater disparity in intraplant fiber characteristics than when weather was closer to normal (Ayele, et al, 2017).

Previous research by Elms et al. (2001) in Lubbock, TX, reported vertical retention of fruiting sites affects overall micronaire. Yield and the total number of fruiting sites exhibited the greatest amount of variability, while lint quality was more consistent across the field. Inconsistent yields affected gross revenue more so than fiber quality parameters. The study also reported a negative correlation between micronaire and yield, fruiting sites, and length indicating that higher, less mature boll positions decrease fiber quality parameters, although the harvested immature bolls increased lint yield. In the lowest yielding year, the number of fruiting sites and upper bolls was lower, leading to a more mature crop, with higher micronaire, length, and strength.

Kothari et al. (2015) quantified the intraplant variability of cotton fiber in College Station, TX. Lower-position bolls had higher micronaire, and greater strength, length, and uniformity, as opposed to higher-position bolls. Some varieties expressed a greater amount of disparity in micronaire, strength, length and uniformity than between the lower and higher sympodial branches, but all six genotypes tested expressed different fiber properties based on sympodial hierarchy placement.

Fruiting positions start at different times throughout the season, which leads to exposure to different external weather conditions throughout the plant's reproductive development. Even within a boll, fibers begin growth at staggered intervals from different seeds located within the locule. On the day of anthesis, numerous fibers initially develop at the chalazal end of the ovule, progressing to the micropyle. Fiber diameter is determined as early as 3 or 4 days past anthesis (DPA). A secondary cellulose layer starts inside the primary layer at approximately one micrometer diameter until about 22 DPA, about the same time as fiber elongation ceases, and the fiber begins to thicken. Cellulose then begins to accumulate in the secondary layer, spiraling in different directions along the length of the fiber (Cotton Incorporated, 2017). The layers are much like rings on a tree with each ring having different characteristics depending on environmental conditions. The number and thickness of secondary layers has a large impact on fiber strength. This process continues until boll opening when the fiber diameter reaches approximately 18 micrometers. This entire process continues over approximately two months, depending on climate and heat unit accumulation as shown in Table 1.1. If the process is shortened due to poor environmental conditions or limited resources due to peak fruit load on the plant, the fiber will not reach full maturity and could be as thin as one micrometer (Reprinted: Table 1.1). A fiber having a smaller theta, or secondary wall thickness, has lower strength. These immature fibers are more likely to break during harvesting, lint cleaning, and ginning, resulting in shorter length, less uniformity, and higher short fiber content.

Table 1.1 Linear density of single cotton fibers (Reprinted from Lord and Heap, 1981)



Frequency group (millitex)	Frequency		
	25 days old	40 days old	65 days old
0–	3		
20–	108	1	1
40–	73	11	2
60–	13	25	8
80–	3	44	12
100–		72	35
120–		37	42
140–		6	55
160–		4	29
180–			9
200–			5
220–			0
240–			2
Totals	200	200	200

Entire field or macro-environmental considerations, such as weather, cultivar selection, planting date, density, percent fruit retention, and row spacing have effects on fiber quality (Davidonis et al., 2014; Echer et al., 2015; Raper et al., 2018). The negative effects of many macro-environmental factors, including moisture availability, extreme temperatures, and pest populations, may not be fully mitigated by the producer. Macro-environments that can be manipulated by the farmer include planting date, row spacing configurations and uniformity, and seeding rates. Seeding rates range from 50,000 to 180,000 plants ha^{-1}, depending on expected moisture availability and yield goals (Quisenberry, 1986; Adams et al., 2018). Appropriate planting dates and timely irrigation, if available, can mitigate detrimental weather events including heat and moisture stress. Temperatures below 22 and above 16^{o}C slow cellulose accumulation in cotton fiber cell walls, requiring longer for complete fiber development. Accumulating secondary wall cellulose in regions with shorter growing seasons at higher latitudes, including the High Plains, upper Mid-South, and Upper Atlantic cotton production regions can be a challenge. High day (above 35ºC) and night (above 27ºC) temperatures increase respiration rates within the plant, and stress is compounded by limited plant available water. In turn, the cotton plant expends valuable photosynthates for survival, instead of reproductive development of seed and fiber, thus lowering strength, maturity, and length (Ehlig, 1986). Planting within an optimum planting date window is a management strategy that can impact cotton fiber qualities (Davidonis, 2003). When planting dates were delayed beyond the optimum timing, fiber maturity was decreased, and short fiber content increased. Cultivar selection also affects fiber quality, although yield has been shown to be more highly correlated to environment (Raper et al., 2018; Snider et al., 2013).

Research utilizing three deficit irrigation strategies, maintaining 75±5, 60±5, or 45 ± 5% of field capacity, demonstrated that fiber length and strength from higher-position bolls were adversely affected by drought conditions more than lower fruiting position bolls. This research illustrates that cotton plants prioritize resources to lower position bolls over upper position bolls. Additionally, drought stress was shown to shorten the fruit maturity period, which in turn prohibited formation of new fruiting sites (Wang et al., 2016). Drought conditions induce a shift in phytohormones, namely ethylene and abscisic acid, which impact both the leaf and fruit abscission zone and increase fruit shedding. In most cotton growing regions, drought conditions are not prolonged, but periodically occur. As a result, once the cotton plant regains adequate moisture, the reproductive process will restart, resulting in fruiting gaps on a plant and increasing the variability of fiber quality characteristics (Jordan, 1986).

Cotton in the US is grown as far north as Kansas and Virginia, where there is a high risk of not reaching adequate heat unit accumulation during the growing season to maximize yields and fully mature the upper canopy bolls. Along with drought and late planting dates, cooler temperatures at the final stages of cotton fiber development hinder cellulose development and result in reduced strength of cotton fibers. At temperatures at or below 22ºC, cellulose synthesis becomes limited and at 15ºC entirely eliminated (Haigler et al., 1991). Wang et al. (2009) reported a strong correlation between fiber strength and peak cellulose accumulation, which is related to higher temperatures during the rapid cellulose-increasing stage, roughly 3 to 21 days past anthesis.

Within a field, there can be great variability in soil (texture, depth, and nutrient levels), surface drainage, and pest pressure, which can affect fiber qualities (Johnson et al. 2002). The authors reported that soil pH, phosphorous and organic matter were shown to significantly affect yield and fiber properties, including maturity. Based on HVI results, micronaire, length, uniformity strength and elongation were significantly affected by soil phosphorous levels. Length, strength and elongation percentage were significantly affected by pH levels. Soil pH (6.5-7.5) and organic matter (2-3) also had a positive correlation with yield, fiber length, immature fiber fraction, and theta (Johnson et al., 2002).

Kerby and Buxton (1981) reported that first fruiting positions receive more nutrient resources than second positions and that abortion of either position favors assimilate movement to the remaining position(s). Conversely, first position losses can be offset, if favorable conditions occur by the second positions, as subtending leaves will reallocate photosynthates and water to the next fruiting position on the same sympodial branch. Kerby and Buxton (1981) found that low seeding densities increased the likelihood of positions to be retained, although this result was not statistically different from the higher seeding density. However, seeding densities did not affect retention of first position bolls. In both years of the study, the majority of boll positions were on nodes 10-15, regardless of treatment levels of irrigation or planting densities. In a study conducted at the LSU Northeast Research Center, fruiting position retention was affected by nitrogen rates but not by the sympodial node on the cotton plant. Intrasympodial competition of retained fruiting position affected boll weights; conversely, various applied nitrogen rates did not (Kerby and Buxton, 1981).

In addition to the genetic component, nutrient and pest management, environmental conditions (Kerby et. al, 2000), harvest aid application timing and product (Gwathmey, 1986), and processing (Byler et al, 2014) can impact cotton fiber quality. In mechanically harvested cotton, harvest aid products are generally applied to decrease plant material, leaves and small limbs, in the harvested seed cotton and improve harvest efficiency. Gormus et al. (2017) demonstrated that premature application of the harvest aids thidiazuron, diuron, and ethephon led to higher leaf grades and trash content in classed cotton. The study also found a yield reduction when harvest aids were applied at 40 and 80% open bolls due to immature fibers and inclement weather, respectfully (Gormus, 2017). The aggressiveness of defoliation strategies ultimately affects defoliation efficacy in most locations (Byrd et al., 2016; Eder et al., 2017). Finally, the effectiveness of harvest aids is highly influenced by environmental conditions, harvest aid type (hormonal or contact), and their usage rates (Gwathmey and Hayes, 1997; Eder et al. 2017). Larson et al. (2002) found that 528 degree units with a base temperature of 15.6°C (950 degree units with a base temperature of 60°F) post cut-out maximized profitability of harvest aid application timing, although this study did not account for the risk of potentially harmful weather events during prolonged application of harvest aids. Furthermore, delaying harvest aid applications could potentially increase the average micronaire in many southern production regions of the Cotton Belt as more time is given for upper bolls to further mature leading to micronaire over 5.0 and causing discounts.

Once harvest aids are applied, harvest method and timing can also affect fiber quality. Seed cotton harvested and stored for three months at or above 12% moisture had a negative effect on fiber quality in Australia, namely color (van der Sluijs and Long, 2016). A study evaluating cotton harvest and storage methods effect on seed and fiber quality reported that moisture content when stored in a conventional module had the greatest impact on color, namely yellowing. The yellowing drastically occurs at moistures above 12%. Prolonged module storage, beyond ten days, and increased module and ambient temperatures increased the yellowing effect (Curley et al., 1988). The higher moisture cotton had a slightly higher leaf grade, 3 compared to 2, and a higher micronaire. Although the cotton harvested at higher moisture had a greater micronaire, there were no significant differences for the fiber strength and length grades. Another challenge for the US cotton industry is cotton acres have increased in 2016 and

2017 while the number of operating gins continues to decline (Figure 1.2) (Adapted: USDA-ERS, Cotton Ginning Surveys, 2019). This trend has led to harvested seed cotton stored longer in fields and at gin yards.

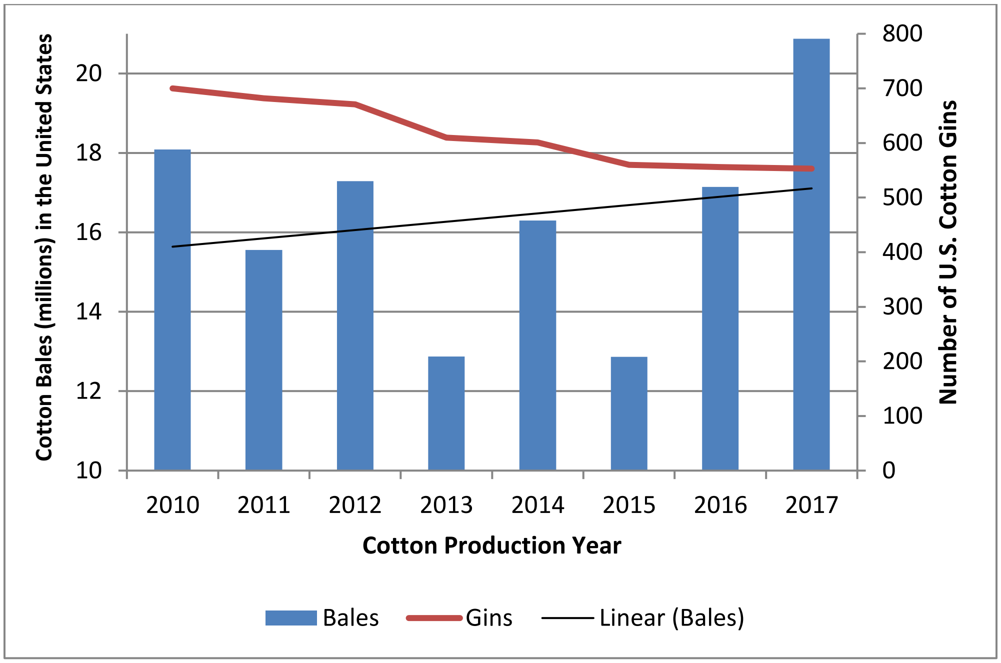


Figure 1.2. Number of Cotton Bales produced and the number of operating gins in the US from 2010-2017 (Adapted from USDA-ERS, Cotton Ginning Surveys, 2019).

All US cotton is harvested by stripper harvesters and spindle-picker harvesters, but hand picking remains common in many parts of the world. Post-harvest processing varies depending on harvest method. Stripper harvesters collect more additional plant material, including burs, small stems, and leaf material, and may pull more weeds, if present, into the harvester as well. This creates a greater need for aggressive lint-cleaning during the ginning process, which increases the potential for fiber breakage, shorter staple lengths, and higher short fiber content (Telgemeier, 1965; Porter, 2013). Cotton strippers also harvest more of the immature bolls with immature fiber present at the top of the plant or on vegetative branches causing lower micronaire, strength, uniformity, and length (Telgemeier, 1965; Porter, 2013). Spindle pickers do a better job of separating the seed cotton from the vegetation and pull less foreign plant material into the harvester, which generally allows for less aggressive ginning to separate lint from seed and trash (Faulkner et al., 2007). Hand-picking requires the least cleaning during ginning, because hand harvesting removes only the seed cotton with very few contaminants (Hedges, 1950). Handpicking can still introduce some foreign matter, such as animal and human hair, yarn and cloth pieces, and other fibrous cotton-like containments, which are extremely difficult, if not impossible, to remove during the ginning process (Sharma, 2014).

Efficacy of Recovery Sprays to Cotton Injured by Synthetic Auxins

The first organic herbicides, namely synthetic auxins, were discovered during World War II. Previous chemical mixtures for controlling weeds included common salt, sodium nitrate and iron sulfate. The usage of these inorganic weed killers caused undesirable foliar burn on row crops. Moreover, these solutions were costly and required extraordinary use rates. The creation of 2,4-D (2,4-dichlorophenoxyacetic acid) started the chemical weed control revolution (Peterson, 1967).

Charles Darwin's discovery of phototropism began the pursuit of understanding phytohormones. Zimmerman and Hitchcock (1942) confirmed that phenoxyacetic acids and benzoic acids have effects on several broadleaf plants. Of the chemicals tested at that time, 2,4-D displayed the strongest reactions when administered to tomato plants, and John F. Lontz (1943) received for a patent for 2,4-D. Researchers often described injury of plant tissues, and even necrosis of plants, when higher rates where applied. E.J. Kraus envisioned use of these synthetic auxins for weed control in row crops (Hamner, 1944). Kraus noted that 2,4-D actively translocated throughout plants and into root systems, even when small amounts of active ingredients where placed on a plant's foliage. In the first public report of a selective weed control application of 2,4-D, Marth, Mitchell (1944), described 80% control of white clover, while the treated golf course bluegrass demonstrated no herbicide injury (Mitchell, 1944). The American Water Works Association listed 35 weed species killed by 2,4-D in 1946. The active ingredient 2,4-D initially cost $12.50 per pound ($5.67 per kilogram), but merely six years later the cost was $0.50 per pound due to mass production (Peterson, 1967).

Synthetic auxins are a Weed Science Society of America Group 4 herbicide and Herbicide Resistant Action Committee Group O. There are three other chemical families of synthetic auxins: Pyridine carboxylic acid, Quinolone carboxylic acids and a newly added group, Arylpicolinates (Dow AgroSciences, 2017; WSSA, 2018). Dicamba (3,6-dichloro-o-methoxybenzoic acid) is in the Benzoic acid chemical family due to the benzoic ring molecule structure. The family of Phenoxy-carboxylic acid, also called phenoxys, includes 2,4-D (2,4-Dichlorophenoxyacetic acid), due to the phenoxycarboxylic ring in its molecule.

Natural auxins, such as indole-3-acetic acid (IAA), facilitate plant growth and new tissue development. Application of synthetic auxins, such as dicamba and 2,4-D, overstimulate receptors, causing malfunction of plant tissue and at elevated rates, necrosis (Grossmann, 2010). The transport inhibitor response 1 (TIR1) protein has been shown to be a target site of synthetic auxins (Dharmasiri, 2005a; Dharmasiri, 2005b). The deregulation of this TIR1 protein begins a series of events that leads to unrestrained manufacturing of ethylene and abscisic acid. The subsequent injury symptoms are leaf tissue swelling and epinasty, stem curling, stunted growth, chlorosis, and potentially senescence (Grossmann, 2007).

Most synthetic auxins are classified as safe to humans, especially dicamba and 2,4-D (Bunch et al., 2012). Dicamba (3,6-dichloro-o-methoxybenzoic acid) first became commercially available in 1962 (Timmons, 1970). In 2017, dicamba was the second most used herbicide in cotton production systems, only behind glyphosate, at 1,388,446 kilograms of active ingredient used on 45% of all total row crop planted acres in 2017. Also, 453,592 kilograms of 2,4-D active ingredient were used in cotton production systems on 12% of total planted acres (NASS-USDA, 2017).

Palmer amaranth (*Amaranthus palmeri*) and tall waterhemp (*A. tuberculatus*) are two weeds that have developed resistance to multiple herbicides (Riar et al., 2013). Control of these *Amaranthus* species should be performed before the weeds reach 10 cm in height (Norsworthy et al., 2012). The only control mechanism beyond this height is usually mechanical removal. Effective weed management options are decreasing with the discovery of Protoporphyrinogen oxidase (PPO) inhibitor resistance (Salas et al., 2016) preceded by the discovery of glyphosate resistance in 2006 and Acetolactate synthase (ALS) inhibitor resistance in 1992 (Gaeddert et al. 1997; Culpepper et al., 2006). Resistance of *A. tuberculatus* (tall waterhemp) to synthetic auxins has already been identified in Illinois and Nebraska (Heap, 2019) More recently, waterhemp has been reported to be resistant to long-chain Fatty Acid (LCFA) inhibitors (Group 15 herbicides), namely S-metolachlor, in Illinois (Smith, 2019). As additional weeds develop resistance to more herbicide sites of action, researchers, producers, consultants, and agriculture chemical manufacturers are increasingly concerned with the diminishing efficacy of synthetic auxins. Norsworthy et al. (2012) outlined 12 herbicide best management practices for the preservation of herbicide modes of action including methods to reduce field seedbanks, correct herbicide application, and other methods of field weed control.

Despite the broad-spectrum broadleaf weed control of synthetic auxins, such as dicamba and 2-4-D, off-site movement is a major concern because of the high susceptibility to very low rates. Herbicides move off-site by three primary mechanisms: volatility, physical drift, and temperature inversions. Volatility occurs when an herbicide lands on the intended target as a spray solution but changes to a gaseous state then moves off-site. Physical spray-particle drift occurs when the carrier droplet sizes are typically less than 200 microns, and pushed by wind to an undesired location (Al-Khatib, 2019). Application of herbicides at lower wind speeds reduces the occurrence of physical drift (Carlsen et al., 2006). Furthermore, lower application pressures, slower applicator speeds, and appropriate nozzle selection reduce the quantity of fine droplets, while still maintaining the same carrier volume. Due to their lighter physical weight, small droplets take longer to fall to the target, and are more easily moved by lower wind speeds. Lower boom heights also assist in minimizing off-site movement due to decreasing the travel distance prior to reaching the target site; therefore, less drift occurs. The third primary mechanism of off-target movement is temperature inversions. Temperature inversions develop in the troposphere when warmer air is layered between cooler air layers. These layers create boundaries that restrict upward movement and disbursement of smaller carrier droplets that can then be blown horizontally onto undesired target areas at greater concentrations. Wind speeds above 4.8 kph (3 MPH) allow air layers, through convection, to properly mix, reducing the concentration of the herbicide. Increased herbicide carrier volumes have shown a reduction in off-site physical drift injury due to decreased herbicide carrier concentrations (Banks and Schroeder, 2002;Ellis, Griffin, and Jones, 2016).

Compounding the off-site movement concern is the sensitivity of cotton to 2,4-D and dicamba compared to other herbicides. Rates of 2,4-D amine and dicamba dimethylamine salt formulations as low as 0.14 and 0.28 g ai ha^{-1} , respectively, cause herbicide injury to cotton plants (Everitt and Keeling, 2009). Cotton injury at higher rates of 2,4-D and earlier in the cotton plant's life cycle increases yield loss (Miller et al., 1963). Byrd et al. (2016) posed two interesting question regarding dynamics of 2,4-D injury on cotton plants that have yet to be researched: does increased water stress magnify injury and does a cotton cultivar's maturity affect lint yield, where later-maturing varieties have more opportunity to compensate following early-season injury? An Egan et al. (2014) meta-analysis found a dicamba tank contamination application of 56 g ha^{-1} and a particle drift equating to 5.6 g ha^{-1} will cause yield reductions of 64.2% and 54.5%, respectively, when the cotton is at the flowering stage. However, capturing exact acreage affected by auxin drift is extremely challenging. Incidents of drift, either residential or agricultural, often go unreported through the regulatory channels. A meta-analysis from Egan et al. (2014) surmised visual herbicide injury from dicamba (r^2=0.001) does not correlate to actual yield, regardless of growth stage on cotton plants.

On the contrary, visual injury from 2,4-D has a stronger correlation to yield loss for cotton plants (r^2=0.32) but is still poorly correlated. The correlation of yield to either auxin visual injury was less for cotton than soybean. Marple et al., (2007) demonstrated that 2,4-D caused the greatest visual injury and yield loss of cotton of the seven synthetic auxin herbicides tested.

The Association of American Pesticide Control Officials (AAPCO) reported that 1,086 of 1,778 (61%) drift complaints in 21 states across the Midwest, Southeast, and Mid-South were synthetic auxin-related in 2018. Of the 1,086 reports, 1,010 were specific to dicamba, an increase from 763 in 2017 (AAPCO, 2019). Steps have been taken to minimize off-site movement of herbicides. Products containing dicamba diglycolamine or dimethylamine salts, designed for lower volatility and in-season use, became restricted-use pesticides in 2019. An applicator must complete restricted-use pesticide and synthetic auxin training; keep records on wind speeds, application timing, and tank cleanout events; and document crops surrounding the application site. Dicamba-containing products, such as Engenia® (BASF, 2019), FeXapan® (Corteva, 2019) and, Xtendimax® (Bayer Ag, 2019), may only be applied twice over-the-top, between one hour after sunrise and two hours before sunset, up to sixty days after planting cotton. The application of synthetic auxins must have a minimum spray volume of at least 142 liters per hectare (15 GPA), use a sprayer speed above 24 kilometers per hour (15 MPH), be made between wind speeds of 4.8 and 16 kilometers per hour (3 and 10 MPH), and be applied with approved nozzles and tank-mix partners (Bayer Ag, 2019).

These strict label regulations make timely application of synthetic auxins to small weeds difficult. Hartzler (2017) demonstrated that only half of the days in the last week of May in Iowa meet the label requirements of synthetic auxins due to rainfall or wind speed. Two weeks later, in mid-June, wind and field conditions improved, but average daily temperatures were elevated. Higher temperatures or lower relative humidity, which is seen throughout much of the cotton belt, increases the chances for volatility (Behrens and Lueschen, 1979). Further complicating the application timing are unexpected temperature inversions (Grant and Mangan, 2019), which occur throughtout agriculture landscapes worldwide.

From realizing the challenges farmers face attempting to apply auxin chemistries within weather-generated time restraints, cotton’s sensitivity to auxins, and the proven fact off-site movement will occur, research was needed to identify the potential to remediate cotton plants injured from 2,4-D or dicamba. Furthermore, farmers have and will likely continue to attempt to use products to remediate auxin injury to their cotton. The potential of commercially available treatments to improve cotton recovery and increase lint yield following injury from dicamba or 2,4-D has not been evaluated.

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CHAPTER II

WATER VOLUME AND DEPOSITION EFFECTS ON HARVEST AID EFFICACY[1]

Harvest aids provide cotton farmers with the ability to harvest in an efficient and timely manner. Harvest aids also assist in preserving overall fiber quality by reducing fiber degradation and discoloration from exposure to weather and by the reduction of foreign matter. Many harvest aid active ingredients do not translocate within the plant, thus adequate spray coverage is recommended to improve efficacy of these products. The widespread and rapid adoption of auxin-tolerant cotton varieties has increased the use of larger droplet size nozzles that are required for use with auxin herbicides. Subsequently, the use of larger droplet size nozzles for harvest aid applications will likely increase. The objective of this study was to determine the impact of droplet size and carrier volume on defoliation, desiccation, boll opening, terminal and basal regrowth, and cotton leaf grade. Varying water volumes of 47, 93, 140, and 187 L ha^{-1}, and nozzles that produced fine, medium, and ultra-coarse droplets were evaluated at 14 site-years across the Cotton Belt in 2016 and 2017. Numeric trends indicated higher carrier volumes were more successful at defoliating and opening bolls than lower carrier volumes. Water volumes of 47 L ha^{-1} should be avoided when making cotton harvest aid applications, as all defoliation, open boll, and regrowth values were consistently reduced at the lowest carrier volume. Nozzle types had less impact on harvest aid efficacy than did carrier volume. Site interactions with harvest aids had a greater effect than nozzle type or water volume.

Key words: carrier volume, spray nozzles, harvest aid, cotton

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Introduction

Cotton (*Gossypium hirsutum* L.) is an indeterminate perennial shrub that is grown as an annual row crop. Producers rely on harvest aids to achieve optimal fiber quality and prepare plants for efficient and timely mechanical harvesting (Chen and Dong, 2016). Harvest aid is a broad term that includes products that serve as defoliants, desiccants, regrowth inhibitors, and boll openers, with some products having activity in more than one of these areas. The effectiveness of harvest aids is greatly influenced by weather conditions, plant condition, immature fruit load on the plant, plant size, residual soil nitrogen, and varietal differences (Gwathmey et al., 1986; Oosterhuis et al., 1991; Snipes and Evans, 2001; Supak and Snipes, 2001). Weather conditions at the time of application, but also before and after application, affect harvest aid efficacy (Gwathmey et al., 2004).

Defoliants allow more efficient harvest as these products remove unwanted plant material such as leaves, petioles, and bracts and potentially reduce the amount of regrowth a plant will exhibit (Supak and Snipes, 2001). Plants that are naturally mature, nutrient-limited, and have higher leaf-moisture content tend to defoliate more readily. Higher temperatures and humidity levels also increase the efficacy of some defoliant products (Cathey, 1986). The removal of vegetative plant material helps preserve fiber quality by reducing lint staining, moisture within modules, and leaf and petiole material that must be removed in the gin. The reduction of vegetative material in harvested cotton delivered to the gin reduces lint cleaning requirements and thereby reduces ginning costs (Bechere et al., 2011). Additionally, excessive cleaning at the gin increases fiber breakage, which decreases fiber length and increases short fiber content, which can lead to additional fiber quality discounts (Larson et al., 2002).

Defoliants are generally separated into two categories: hormonal and herbicidal. Hormonal defoliants (thidiazuron and ethephon) increase the ethylene concentration in the leaf, limiting auxin transport, which in turns initiates the abscission process at the base of the petiole and allows the leaf to separate from the stem or branch (Morgan and Durham, 1975). Herbicidal defoliants (e.g., carfentrazonethyl, fluthiacet-methyl, pyraflufen ethyl, saflufenacil, tribufos) injure the leaf, which stimulates ethylene production and leads to the initiation of the abscission process. If herbicidal defoliants rates are too high for the crop condition, the injury will increase leaf desiccation causing leaf tissue to die too rapidly and prevent the abscission layer from developing. This leads to desiccated leaves remaining attached to the plant and increases leaf material entering the harvester and module.

Harvest aids also include boll openers that promote mature bolls to open more rapidly by weakening the boll sutures. Boll openers are not systemic and are not translocated from the leaves to the bolls (Gwathmey and Hayes, 1997). As a result, coverage is crucial; boll openers must reach and adequately cover unopened bolls to obtain effective boll opening. Cooler temperatures (highs below 24° C) require rates twice as high compared to warmer temperatures (highs above 29° C) (Gwathmey et al., 1986). Properly timed boll openers expedite cotton harvest to avoid inclement weather and minimize cellular degradation, staining, rotting, and hard locking (Logan and Gwathmey, 2002).

Sprayer nozzles are designed to deliver various droplet sizes and volume output capabilities depending on the needed coverage, product (systemic or non-systemic), application speed, and chemical properties of the products being applied. The spray volume output is regulated by the exit orifice size and pressure with increasing orifice size and/or pressures delivering higher spray volume. Application speed impacts carrier volume with faster speeds lowering application rates and possibly detrimentally influencing deposition in other ways (Heidary et al., 2014).

There are several sprayer nozzle types manufactured by multiple companies, but most are a variation of flat fan or hollow-cone nozzle (TeeJet Technologies, 2017). Nozzles are designed to create or change different spray droplet sizes and patterns based on desired applications. In 1985, extended-range nozzles that allow for greater variation with pressure were brought to the marketplace and allow producers more flexibility in spray droplet size without having to change nozzles frequently.

Following the 2016 release of auxin-resistant cotton cultivars, applicators are required by federal law to apply auxin herbicides with extremely coarse to ultra-coarse nozzles to create large spray droplets and with minimal, driftable fine droplets (Monsanto Company, 2018). Larger droplet sizes reduce the potential for off-site movement by physical drift and/or temperature inversions. However, larger droplets decrease coverage: a 500-micron water droplet is equal to eight 250-micron (categorized as medium droplet size) water droplets in volume (Kruger et al., 2013). The reduction in coverage resulting from large droplet size can be partially compensated for by increasing the carrier volume. However, increasing carrier volume is not preferred by growers due to added expenses and time refilling nurse and spray tanks.

For maximum canopy penetration, 47 to 93 L ha^{-1} should be used for aerial application and 93 to 187 L ha^{-1} for ground applications to significantly increase defoliation (Siebert et al., 2006). Siebert et al. (2006), using three different nozzles, flat fan, hollow cone, and air induction, demonstrated that higher carrier volumes provided greater efficacy and were recommended to obtain adequate canopy coverage and penetration in cotton with rank or excessive growth (Snipes and Evans, 2001). Harvest aid labels for products containing the active ingredients of tribufos (Amvac Chemical Corporation, 2019), thidiazuron (Loveland Products, 2019b), or ethephon (Loveland Products, 2019a) make the same general recommendations on their labels for high spray volumes, but with no mention of nozzle selection. The objective of this research study was to address which spray volumes are most suitable for proper defoliation, boll opening, and minimizing leaf grades.

Materials and Methods

Research trials were conducted during the 2016 and 2017 growing seasons. In 2016, trials were conducted in six locations across the Cotton Belt, including Starkville, MS; Jackson, TN; Sikeston, MO; College Station and Lubbock, TX; and Solomon, AZ (Table 2.1). In 2017, the trials were repeated at the 2016 locations and two additional locations were added: Raleigh, NC and Brewton, AL. Weather data were compiled from the National Oceanic and Atmosphere Administration’s (NOAA) Global Historical Climatology Network (GHCN) stations (NOAA, 2019). Average daily temperatures, DD15.5 accumulation, and rain amounts for the three rating periods are given for each location by year (Table 1). All locations were planted at the same seeding rate, 120,000 seeds ha^{-1}, with Phytogen® 333 WRF

(Corteva Agrisciences, Indianapolis, IN), which is a semi-smooth leaf cultivar. The trial design was a four replicate, two-way factorial design with plots consisting of four rows 9 m in length. Harvest aid treatments were made to the center two rows and the center two rows were used for collecting visual ratings and harvested cotton for ginning. Applications in Solomon, AZ; Lubbock and College Station, TX; and Raleigh, NC were made with CO_2-pressurized backpack sprayers. Applications in Sikeston, MO; Brewton, AL; Starkville, MS; and Jackson, TN were made with self-propelled ground rigs.

Treatments consisted of applications of four carrier volumes (47, 93, 140, and 187 L ha^{-1}) and three nozzle types: TeeJet hollow cone (XR) (fine droplets), Turbo Teejet® (TT) (medium droplets), and Turbo Teejet Induction® (TTI) (ultra-coarse droplets). A complete list of the 12 nozzle-type-by-carrier-volume treatments is presented in Table 2.2. Orifices, pressure, and ground speeds were adjusted to produce the desired carrier volumes for each individual treatment. An untreated check (UTC) was also included. Plots at all sites were treated with tribufos (Folex®, Amvac Chemical Corporation, Newport Beach, CA) at 0.42 kg a.i. ha^{-1}, ethephon (Superboll®, Nufarm Limited, Alsip, IL) at 1.2 kg a.i. ha^{-1}, and thidiazuron (Freefall®, Nufarm Limited) at 0.06 kg a.i. ha^{-1} (Table 2.2) when the majority of plants in all plots reached four nodes above uppermost, first-position cracked boll or 60% open bolls.

Location/Year		**0 to 7 DAA**			**7 to 14 DAA**			**14 to 21 DAA**		
2017	**Date of App.**[z]	**Avg Temps (ºC)**[y]	**DD15s**[v]	**Rainfall (cm)**[w]	**Avg Temps (ºC)**	**DD15s**	**Rainfall (cm)**	**Avg Temps (ºC)**	**DD15s**	**Rainfall (cm)**
College Station, TX	**8/23**	**26.0**	**73.5**	**46.3**	**27.4**	**83.0**	**0.0**	**23.7**	**57.4**	**0.05**
Raleigh, NC	**9/5**	**19.1**	**25.3**	**1.5**	**22.9**	**51.6**	**1.6**	**23.8**	**58.7**	**0.0**
Brewton, AL	**9/19**	**25.9**	**72.7**	**0.6**	**25.0**	**66.3**	**0.05**	**25.1**	**66.9**	**7.3**
Jackson, TN	**9/23**	**23.9**	**59.1**	**0.0**	**21.0**	**38.3**	**0.0**	**21.1**	**39.1**	**3.6**
Sikeston, MO	**9/27**	**18.5**	**20.8**	**1.01**	**17.6**	**15.0**	**3.5**	**16.4**	**7.4**	**2.0**
Starkville, MS	**9/28**	**22.8**	**50.8**	**0.0**	**22.8**	**51**	**0.18**	**17.9**	**21.0**	**0.08**
Solomon, AZ	**10/2**	**24.1**	**60.5**	**0.0**	**21.5**	**41.9**	**0.0**	**22.4**	**48.6**	**0.0**
Lubbock, TX	**10/11**	**17.9**	**22.4**	**0.0**	**17.0**	**16.9**	**0.03**	**11.1**	**3.4**	**0.18**
2016										
College Station, TX	**8/24**	**26.9**	**79.6**	**2.0**	**27.8**	**86.3**	**1.0**	**27.8**	**86.3**	**0.0**
Solomon, AZ	**9/20**	**25.4**	**69.1**	**0.0**	**24.9**	**66.0**	**1.0**	**25.1**	**67.4**	**2.4**
Jackson, TN	**9/23**	**21.8**	**44.1**	**0.41**	**20.5**	**35.2**	**0.0**	**18.6**	**21.9**	**0.0**
Starkville, MS	**9/23**	**26.1**	**74.1**	**0.0**	**21.6**	**42.7**	**0.0**	**21.1**	**38.9**	**0.0**
Lubbock, TX	**9/27**	**18.7**	**22.2**	**0.0**	**19.6**	**35.5**	**0.0**	**20.3**	**35.4**	**0.0**
Sikeston, MO	**9/28**	**18.7**	**22.2**	**0.0**	**20.6**	**35.5**	**0**	**20.3**	**35.4**	**0.0**

Table 2.1. Weather data including date of harvest aid applications, average temperatures, accumulated DD15s, and rainfall for rating periods from all locations over the 2-year study

[z] Date of harvest aid application

[y] Average temperatures during a 7-d period (0 to 7 days, 7 to 14 days, 14 to 21 days after application)

[x] Degree days 15’s accumulated in a 7-d period (0 to 7 days, 7 to 14 days, 14 to 21 days after application)

[w] Accumulated rainfall in a 7-d period (0 to 7 days, 7 to 14 days, 14 to 21 days after application)

Table 2.2. List of treatments for nozzle type and carrier volume, application details, and spray droplet size category

Treatment abbreviations	Nozzle Type	Carrier Volume (L ha^{-1})	Pressure (kPa)	Speed (km h^{-1})	Spray Droplet Size Category[y]
UTC[z]	Untreated Control				
Fine:47	TXR80053VK	47	276	4.83	Very Fine
Med:47	TT11001	47	207	8.05	Medium
Coarse:47	TTI110015	47	103	8.05	Ultra-Coarse
Fine:93	TXR8001VK	93	276	4.83	Fine
Med:93	TT110015	93	310	8.05	Medium
Coarse:93	TTI110015	93	103	4.83	Ultra-Coarse
Fine:140	TXR80015VK	140	276	4.83	Fine
Med:140	TT110015	140	276	4.83	Medium
Coarse:140	TTI110015	140	276	4.83	Ultra-Coarse
Fine:187	TXR8002VK	187	276	4.83	Fine
Med:187	TT11002	187	276	4.83	Medium
Coarse:187	TTI11002	187	276	4.83	Ultra-Coarse

[z] Untreated Control [y] Micron range of spray droplets; Very fine (60-145), fine (145-225), medium (226-325), and ultra-coarse (>650)

Visual ratings included defoliation (DEF), open boll (OB), desiccation (DES), terminal regrowth (TRG), and basal regrowth (BRG) percentages and were made 7, 14, and 21 days after application (DAA) of the harvest aid treatments. Visual rating observations were made on a 0 to 100 scale with 0 indicating no effect and 100 indicating maximum effect. The three observation ratings were averaged for one value due to the ratings exhibiting a consistent positive linear relationship. The numerical observation rating held rank throughout the three observation timings.

All plots were harvested and a minimum of 2 kg of raw cotton was sent to the University of Tennessee MicroGin to be ginned on a commercial gin, which was cut down to a 20-saw gin. The University of Tennessee MicroGin includes (in order): a Continental Model 511 six-drum inclined cleaner, a Model 601 Continental/Moss-Gordin stick machine, a Continental Model 511 six-drum inclined cleaner, a Model 550 Continental Master Double X feeder, a Model 521 Continental 20-saw 16-in gin, two Moss/Gordin Model 560 Cleanmaster 12-in lint cleaners, and one laboratory-size condenser (Infante et al., 1971). After ginning, approximately 60 g samples were sent to the USDA Agricultural

Marketing Service (AMS) Classing Office in Memphis, TN for fiber analysis by high volume instrumentation (HVI).

Prior to analysis of all locations, all data were normalized to each location's UTC as a preprocessing step aimed at accounting for maturity and environmental variability across locations. An analysis of variance was performed on the averages of the three timing observations (7, 14, and 21 DAA) at individual locations to identify locations with significant treatment effects. For significant effects, Tukey-Kramer's honest significant difference (HSD) test was used with a 0.05 significance level to compare treatment differences (individual location tables or figures not presented).

Normalized data were analyzed using the R statistical software program (R Core Team, Vienna, Austria) and the nlme package for linear and nonlinear mixed-effects models (Pinheiro et al., 2018). Statistical modeling and inference were conducted via linear mixed-effects models. For each defoliation, desiccation, boll opening, terminal and basal regrowth, and cotton leaf grade response variables, linear models were fit with independent variables for water volume, nozzle type, and their interactions, with random effects for location and year. The use of random effects enables all locations and both years to be combined and modeled together while observing differences in response variable variances across the different location-year combinations.

Due to non-normality of the data, classical parametric mixed-effects models were not appropriate. For the purpose of estimating standard errors of model coefficients and computing confidence intervals for their values, bootstrap resampling techniques were employed (Efron and Tibshirani, 1998). The β estimates of each model coefficient were used as an empirical estimate of the coefficient estimate's sampling distribution. Model coefficients were interpreted as average differences between one level of a dependent variable to its respective carrier volume (47 L ha^{-1}), nozzle (Fine), and two-factor (Fine × 47 L ha^{-1}) baseline, holding all other dependent variables constant. Similarly, larger absolute effect sizes along with smaller *p*-values for one dependent variable (or level within one dependent variable) with respect to another dependent variable (or another level of the same dependent variable) were used as indication of greater relative importance of the one dependent level. An example from Table 2.3, under the defoliation column, 93 L ha^{-1} shows a *p*-value of 0.03 compared to 47 L ha^{-1} displaying significance. Along with a positive β coefficient of 4.78, this result indicates a positive significant interaction.

Results and Discussion

Defoliation

Differences were observed in Alabama (2017) with coarse nozzles applying 47 L ha^{-1} (Coarse-47) resulting in the lowest averaged defoliation levels and significantly less than Medium-93, 140, 187, and Coarse-187 (data not shown). Coarse-47 had the highest defoliation levels in the Arizona 2016 study and significantly greater than Medium-93, Fine-47, and Coarse-140. However, in 2017 in Arizona, the results were comparable to previously reported research, where defoliation was significantly greater for the highest carrier volume, Medium and Coarse-187, compared to Fine and Coarse nozzles at the lowest carrier volume (data not shown). At the 2016 Lubbock site, Fine-187 was numerically the best although only significantly greater than Coarse-93. At the same location in 2017, the only treatments that were significantly different were Coarse-187 being the most efficacious and Fine-47 being least effective by 63%.

Both carrier volume and nozzle type had a significant effect on defoliation rating (Table A1). The only statistical treatment differences for defoliation ratings were between the highest carrier volume, 187 L ha^{-1}, with fine nozzles being greater than lowest carrier volume, 47 L ha^{-1}, for both fine and coarse nozzles (Figure 2.1). The general numerical trends suggested increasing carrier volume resulted in increased defoliation ratings and mitigated the impact of the nozzle types. As indicated in the mixed model, water volumes of 140 and 187 L ha^{-1} were significantly better than 47 L ha^{-1}, whereas nozzles did not vary from Fine (Table 2.3). Furthermore, as the water volumes increased in relation to 47 L ha^{-1}, *p*-values became highly significant, demonstrating increased treatment benefit from the higher carrier volumes. Coarse nozzles were not found to be significant, although coarse did have a *p*-value of 0.10.

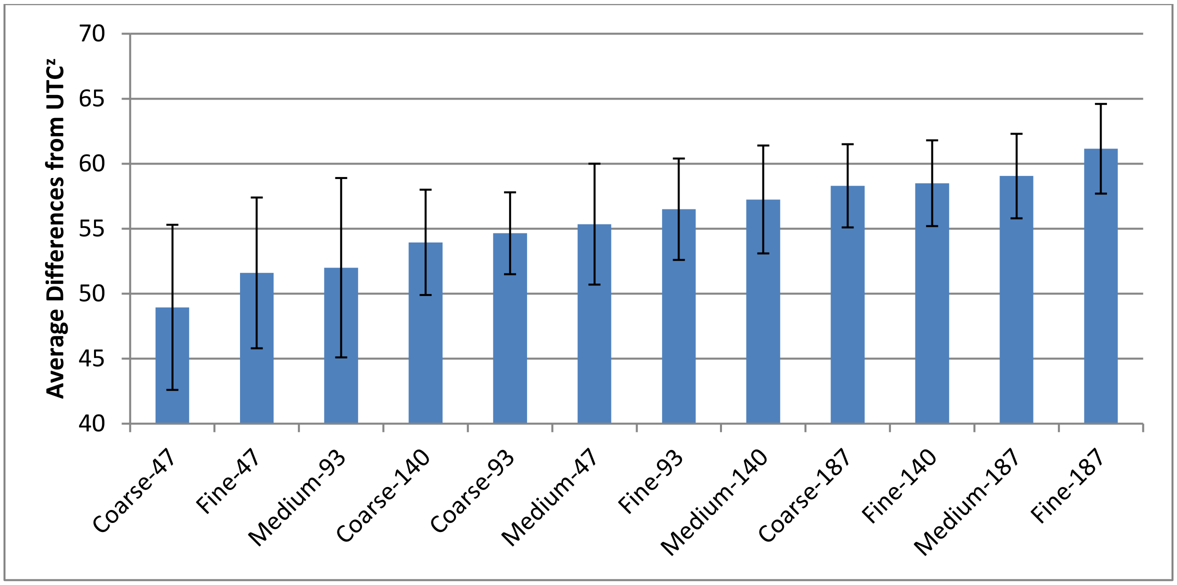

Figure 2.1. Average leaf defoliation percentages for 7, 14, and 21 DAA ratings across 13 locations in 2016 and 2017. Error bars representing 95% Confidence Intervals. ^{Z} Untreated Control

Table 2.3. Treatment effect estimates utilizing a linear mixed model using sites and years as random effects. Beta coefficients (β), standard errors (se), *t*-values (*t*), and *p*-values (*p*) given for each factor.

Factors	Defoliation		Desiccation		Open Bolls		Terminal Regrowth		Basal Regrowth	
Intercept^{v}	β^{z} (SE^{y})	T^{v} (P^{w})	β (SE)	T (P)	β (SE)	T (P)	β (SE)	T (P)	β (SE)	T (P)
Medium	3.58 (2.19)	1.64 (0.10)	1.10 (0.79)	1.40 (0.16)	1.35 (1.41)	0.96 (0.34)	-2.90 (0.97)	-2.99 (0.003)	8.48 (4.05)	-1.08 (0.28)
Coarse	-2.57 (2.18)	-1.18 (0.24)	2.13 (0.79)	2.71 (0.01)	0.50 (1.40)	0.36 (0.70)	-0.32 (0.97)	-0.33 (0.74)	-1.82 (1.69)	0.44 (0.66)
LPH93	4.78 (2.18)	2.20 (0.03)	2.01 (0.79)	2.55 (0.01)	0.72 (1.40)	0.51 (0.61)	-1.98 (0.97)	-2.05 (0.04)	0.73 (1.68)	-1.86 (0.06)
LPH140	6.08 (2.18)	2.79 (0.01)	0.89 (0.79)	1.14 (0.26)	2.10 (1.40)	1.50 (0.13)	-1.24 (0.97)	-1.29 (0.20)	-3.13 (1.68)	-0.76 (0.45)
LPH187	8.67 (2.18)	3.98 (0.0001)	1.80 (0.79)	2.29 (0.02)	1.88 (1.40)	1.35 (0.18)	-1.98 (0.97)	-2.05 (0.04)	-1.28 (1.69)	0.35 (0.73)
Medium : LPH93	-7.92 (3.09)	-2.57 (0.01)	-1.64 (1.11)	-1.48 (0.14)	-1.19 (1.99)	-0.60 (0.55)	2.91 (1.37)	2.12 (0.03)	0.59 (1.68)	1.67 (0.10)
Coarse: LPH93	0.20 (3.09)	0.06 (0.95)	-2.39 (1.10)	-2.17 (0.03)	0.73 (1.98)	0.37 (0.71)	0.72 (1.37)	.053 (0.60)	3.97 (2.38)	-0.09 (0.93)
Medium : LPH140	-4.53 (3.09)	-1.47 (0.14)	-1.69 (1.11)	-1.53 (0.12)	-1.49 (1.99)	-0.75 (0.45)	2.37 (1.37)	1.73 (0.08)	-0.22 (2.37)	0.50 (0.62)
Coarse: LPH140	-1.59 (3.08)	-0.52 (0.61)	-2.17 (1.11)	-1.94 (0.05)	-0.73 (1.98)	-0.37 (0.71)	1.19 (1.37)	0.87 (0.39)	1.20 (2.38)	0.15 (0.88)
Medium : LPH187	-5.43 (3.09)	-1.75 (0.08)	-1.77 (1.11)	-1.60 (0.11)	-0.83 (1.99)	-0.42 (0.68)	2.38 (1.37)	1.74 (0.08)	0.35 (2.38)	-0.48 (0.63)
Coarse: LPH187	-0.18 (3.08)	-0.06 (.95)	-2.96 (1.10)	-2.63 (0.01)	0.57 (1.98)	0.29 (0.77)	0.42 (1.37)	0.31 (0.76)	-1.15 (2.38)	-0.903 (0.37)

[Z] β- Beta coefficients for each parameter

[Y] SE- Standard Error of Beta coefficients in parenthesis

[x] *T*-value of factor and intercept

[w] *P*-value of comparison of Factor and intercept in parenthesis

[v] intercept is representation of Fine, LPH47, and Fine:LPH47 for each grouping

Desiccation

The 2017 Alabama location had higher desiccation levels from both Fine-93 and -187 compared to Fine-47. The Arizona 2016 study rated desiccation Medium-47 and Coarse-93 as the highest two treatments and Coarse-187 and Medium-140 as the lowest and were significantly different from other treatments. Desiccation levels for Lubbock (2017) were the highest for Fine-47, compared to other treatments. North Carolina (2017) study had only Fine-93 rated significantly higher than Fine-47.

When combined across all site-years, no significant differences were observed for desiccation levels for the various treatments, due in part, to relatively low levels of desiccation observed from the chosen harvest aid products (Figure 2.2). Additionally, desiccation was generally more variable across locations, nozzles, and carrier volume than defoliation (Figure 2.1). Siebert et al. (2006) reported comparable findings, whereas defoliation ratings displayed higher significance by nozzle type and carrier volume than the desiccation ratings. Typically, more desiccation would be expected from greater coverage (Snipes and Evans, 2001); however, in this study lower water volumes lead to quicker and more obvious leaf tissue necrosis (Figure 2.2). From the mixed model and combined across carrier volume, coarse nozzles showed more desiccation than fine nozzles, whereas medium nozzles were statistically similar to the fine nozzles. Desiccation with a carrier volume of 93 L ha^{-1} was significantly different than 47 L ha^{-1} (Table 2.3). All treatment combinations with coarse nozzles had significantly lower desiccation than Fine-47.

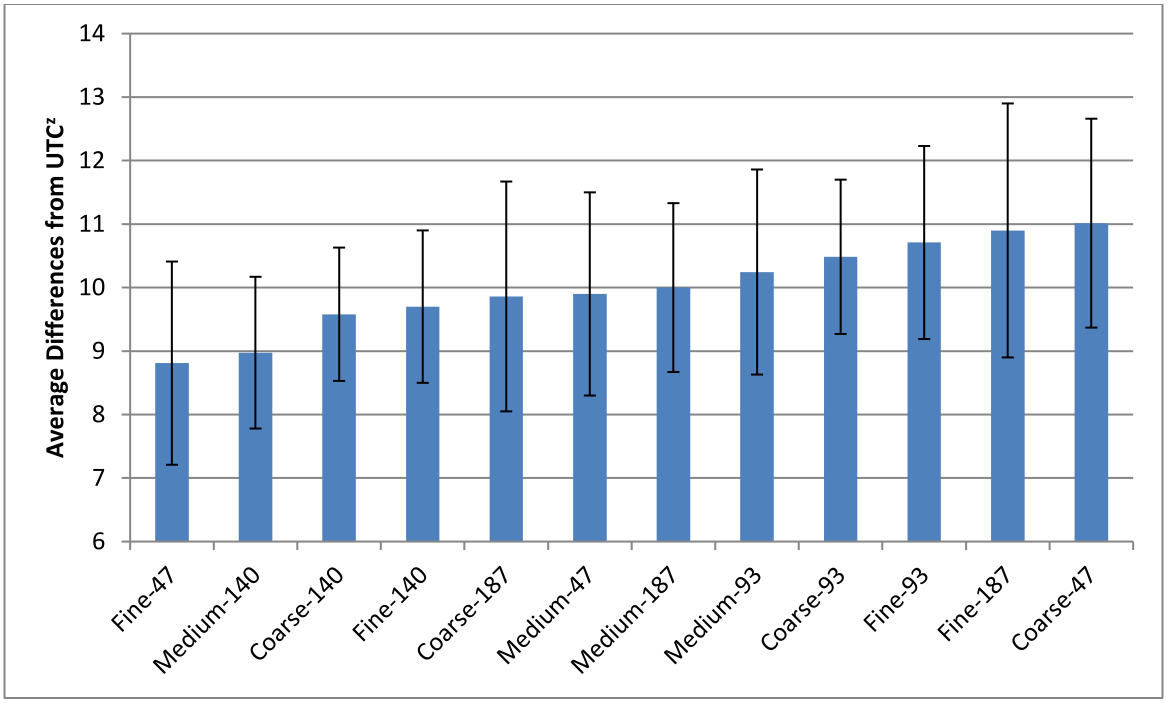

Figure 2.2. Average leaf desiccation percentages across 7, 14, and 21 DAA ratings across 14 locations in 2016 and 2017. Error bars representing 95% Confidence Intervals. ^{Z} Untreated Control

Open Bolls

Arizona in 2017 had the greatest percentage of open bolls from the Fine-140 and Medium-187 and the lowest from Fine-47; however, little consistency existed across carrier volume or nozzles. Lubbock (2016) reported the lowest percent open bolls from Fine-47, but no other differences were significant. In 2017 in Lubbock, Coarse-187 had the highest percentage of open bolls of which Fine-47 was the lowest, but again, little consistency existed for nozzles or carrier volume. The Medium- and Coarse-187 numerically improved the percentage of open bolls in Tennessee (2017), but these treatments were not significantly different than the lowest performer, Fine-47.

Even when compiling across site years, no significant differences were observed for the open boll ratings based on confidence interval comparisons (Figure 2.3) or utilizing the mixed model approach (Table 2.3). Some numerical trends were noted as greater carrier volume increased the open boll rating, where Coarse-187 L ha^{-1}and Medium-187 L ha^{-1} produced the best results (Figure 2.3). However, the aggregated difference in open boll ratings was only 2.65% between the two previously mentioned treatments. Studies have shown boll opening is greatly affected by temperatures and coverage. Under cooler temperatures ethephon takes longer to open bolls (Gwathmey and Hayes, 1997).

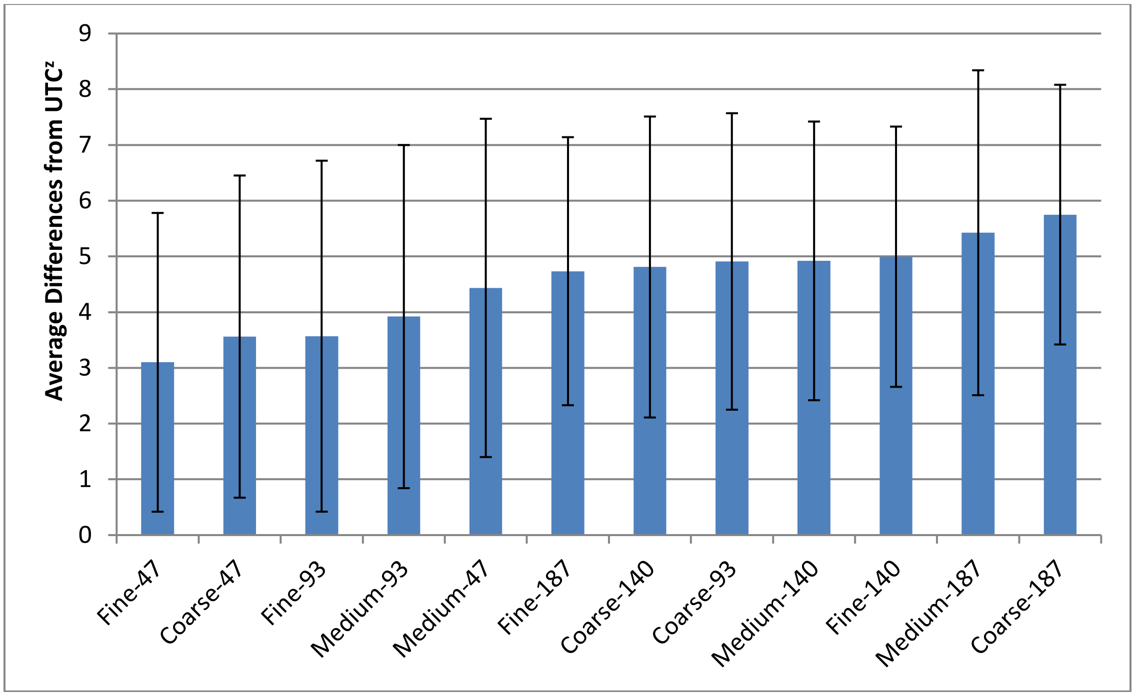

Figure 2.3. Average open boll percentages for 7, 14, and 21 DAA Ratings across 14 locations in 2016 and 2017. Error bars representing 95% Confidence Intervals. ^{Z} Untreated Control

Terminal and Basal Regrowth

Carrier volume, nozzle type, and their interaction had no effect on terminal regrowth (p>0.05) (Table A1). Numerically, the lowest terminal regrowth across all locations occurred with medium nozzles using 47 L ha^{-1} followed by medium nozzles applying 187 L ha^{-1} and Fine-187 L ha^{-1} of water volume (Figure 2.4). These results are consistent with Siebert et al. (2006) who reported carrier volume and nozzle type had significant impact on terminal regrowth at only one of three locations. From the mixed model analysis (Table 2.3) medium nozzles were significantly better than both coarse and fine nozzles. Medium nozzles offered the most consistent results compared to the other two nozzles used in these studies, but no treatments were significantly different (Table 2.3). The mixed model analysis (Table 2.3) showed LPH-187 had significantly worse terminal regrowth ratings than LPH-47. Medium-93 was found to have greater treatment effect than Medium-187 and Coarse-187 at causing terminal regrowth compared to the baseline of Fine-47. No numeric or statistical trends were observed for basal regrowth (Figure 2.5).

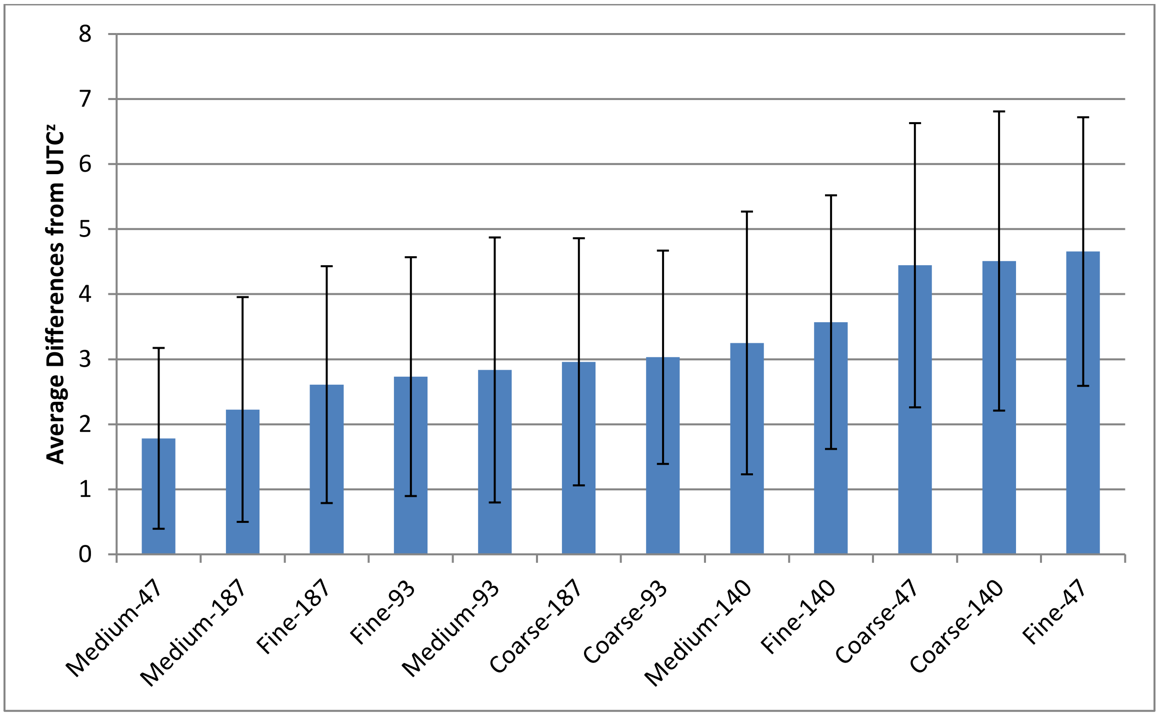

Figure 2.4. Average terminal regrowth percentages for 7, 14, and 21 DAA ratings across 14 locations in 2016 and 2017. Error bars representing 95% Confidence Intervals. Lower numbers represent better efficacy with untreated checks (UTC) regrowth rated as zero for regrowth. ^{Z} Untreated Control

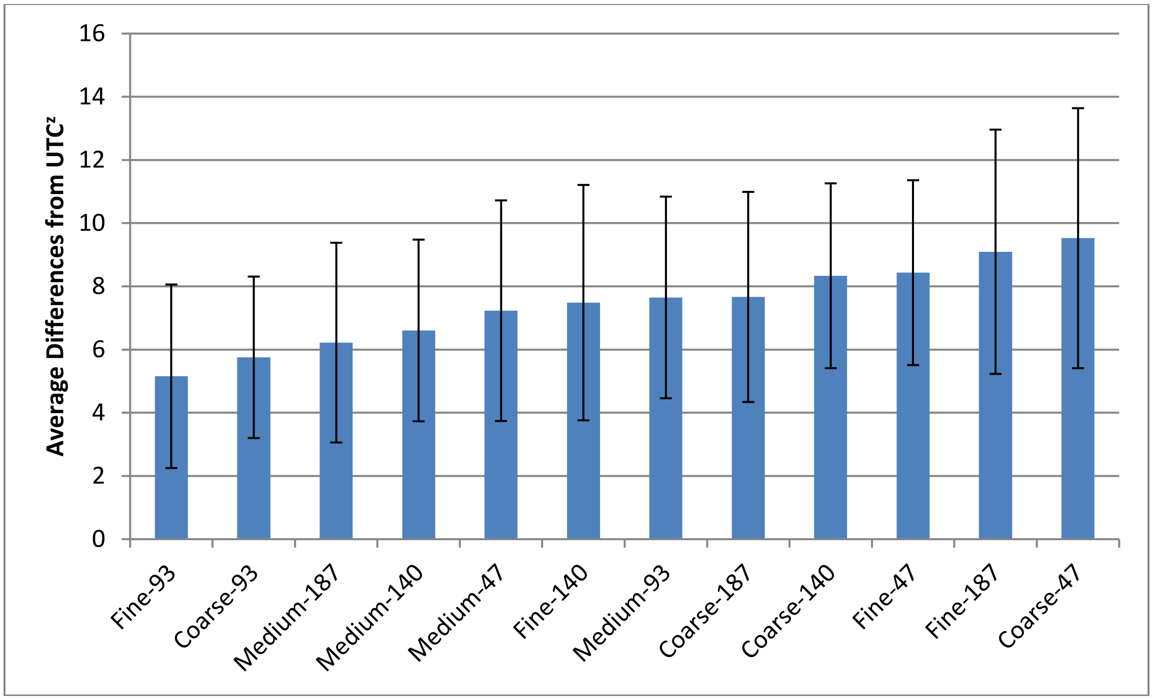

Figure 2.5. Average basal regrowth percentages for 7, 14, and 21 DAA ratings across 14 locations in 2016 and 2017. Error bars representing 95% Confidence Intervals. Lower numbers represent better efficacy with untreated checks (UTC) regrowth numbers rated as zero for regrowth. ^{Z} Untreated Control

Leaf Grade

The ultimate value of increased defoliation and lower desiccation is in decreased cotton leaf grades. However, leaf grade (data not shown) had the highest variance compared to all the other quantification methods for nozzle type and carrier volume performance. Harvest aid product selection and weather previous, during and after application will also affect harvest aid performance (Gwathmey, 1986). Leaf hairiness also tends to have an effect on leaf grades (Eder et al., 2018). With the categorical measurement of leaf grade from HVI, the measurement resolution is low and decreases the potential to identify harvest aid treatment effects. A general trend was that the medium nozzles provided a more consistent response than the other nozzles. These findings were similar to Byrd et al. (2016), Eder et al. (2018), and Gormus et al. (2017) in that defoliation levels did not consistently impact cotton leaf grades.

Discussion

The average leaf defoliation within this trial coincided with findings by Knoche (1994), where efficacy of post-emergence contact herbicides increased as droplets reduced in size with constant carrier volumes. Similarly, in this study the level of defoliation increased as carrier volume increased regardless of nozzle treatment. Much like defoliation within a cotton canopy, the efficacy of boll opener harvest aid products is highly dependent on coverage due to the lack of translocation to or within the boll. As a result, open boll ratings responded similarly to defoliation, where water volume had a greater influence than nozzle type. This research expanded on the carrier volume and droplet size nozzles evaluated by Siebert et al. (2006) to include ultra-coarse nozzles labeled for auxin herbicides in XtendFlex™ and Enlist™ cotton. However, the general conclusions were similar, where increased carrier volume can be used to compensate for ultra-coarse tips.

Regrowth control and desiccation were less consistent than in prior research. These inconsistencies are attributed to the many confounding physiological and environmental factors that influence both regrowth and leaf desiccation (Snipes and Evans, 2001). In this study, an inconsistent response was expected for these parameters and the response was highly variable and inconsistent for both carrier volume and nozzle type. Various state extension publications (Dodds et al., 2018; Kelley et al., 2014) recommend adjusting harvest aid rates depending on forecasted weather, and McCarty (1995) reported weather conditions as being the most critical factor facing efficacy of harvest aids. One major purpose of harvest aid applications is to reduce the amount of plant material harvested to preserve fiber quality. Similar to previous research with a wide range of leaf defoliation levels within their trials (Byrd et al., 2016; Eder et al., 2018; Gormus et al., 2017) only low correlations were observed in the present study between defoliation levels and leaf grade values. Within this trial, insufficient differences in defoliation levels for the carrier volume and nozzles were obtained to expect to observe a significant leaf grade response even with a hairy leaf cultivar.

Conclusions

Our results suggest nozzle type will have less impact on harvest aid efficacy than carrier volume. Higher carrier volumes typically resulted in greater levels of defoliation and boll opening than lower carrier volumes, whereas all defoliation, open boll, and regrowth values were consistently reduced at the lowest carrier volume. Subsequently, water volumes of 47 L ha^{-1} should be avoided when making cotton harvest aid applications. Although additional research evaluating differences in nozzle types and carrier volume with desiccants is warranted, these studies suggest larger droplet size nozzles could be used for harvest aid applications at carrier volumes in excess of 93 L ha^{-1}.

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CHAPTER III.

MULTIPLE-PASS HARVEST COMPARED TO SINGLE PASS HARVEST METHODS ON YIELD AND FIBER QUALITY

Cotton producers annually cope with harvesting seed cotton under wet weather conditions. These conditions prevent field entry and transport of modules to the gin. Other challenges faced by producers are limited harvest capacity and the logistics of moving equipment from field to field. These harvest delaying factors often reduce lint and seed quality and value. To resolve this issue, Cotton Incorporated has launched a research initiative to quantify the potential value of robotic harvesting and develop a prototype robotic cotton harvester. These robotic harvesters will be targeted to perform multiple harvests beginning when the first cotton bolls open. The objective of this study was to compare the economic value of cotton lint, considering yield and quality, from repeated harvesting of seed cotton compared to the traditional single-pass mechanical harvest. The study was conducted in College Station, TX, Tifton, GA, Vernon, TX, and Jackson, TN in 2018-2019. DeltaPine® 1612B2XF and 1646B2XF, an early and mid-full maturity cultivar, respectively, were used in the experiment. Stoneville 4946GLB2, a semi-smooth leaf, early-mid maturity cultivar was used at the Tifton, GA location in 2018.

Multiple hand harvests (mimicking robotic harvesting) occurred twice weekly beginning at first open boll. A spindle picker was used for machine harvesting at all sites except Vernon, TX, where stripper harvester was used. The single-pass machine harvest received two different ginning methods, a ten-saw laboratory gin only or pre-cleaning before ginning on the ten-saw tabletop gin. All other samples were ginned on a ten-saw laboratory gin without cleaning. HVI testing was performed on lint samples.

Over the seven site-years, for both picker- and stripper-harvested cultivars, similar trends were observed for both yield, fiber quality, and lint value. These results indicated that the multiple picking harvest method provides comparable value for short-season and mid-late season cotton cultivars. For lint yields, this research indicated there is more benefit to timely harvest for cotton grown in high-yielding and picker-harvested environments than non-irrigated, low yielding, and stripper-harvested cotton.

Furthermore, multiple harvesting provided significant value. This research provides economic justification for further development of robotic harvesting of cotton.

Introduction

For the 2018 growing season, 17,024,730 upland cotton bales received official USDA classification, with an average leaf grade of 3.49, Rd (reflectance) of 74.8, +b (yellowness) of 8.31, color grade 41-1, strength of 29.95 g tex^{-1}, uniformity index of 81.04, upper half mean length of 2.90 cm (1.142 inches or 36.5 staple) and micronaire of 4.39 (Cotton Incorporated, 2019). The three grades of color, length, and leaf grade are combined to determine a single premium or discount from the base cotton loan value. In 2018, this was the largest premium or discount from base cotton loan value, followed by extraneous matter calls and fiber strength (Figure 3.1) (USDA ERS, 2019). In Texas in 2019, 6,338,419 bales were ginned with a discounts of -$2,667,829 for micronaire, and -$7,597,886 for uniformity and premiums of $38,013,245 for color/leaf/length and $8,069,094 for strength (Cotton Incorporated, 2019)

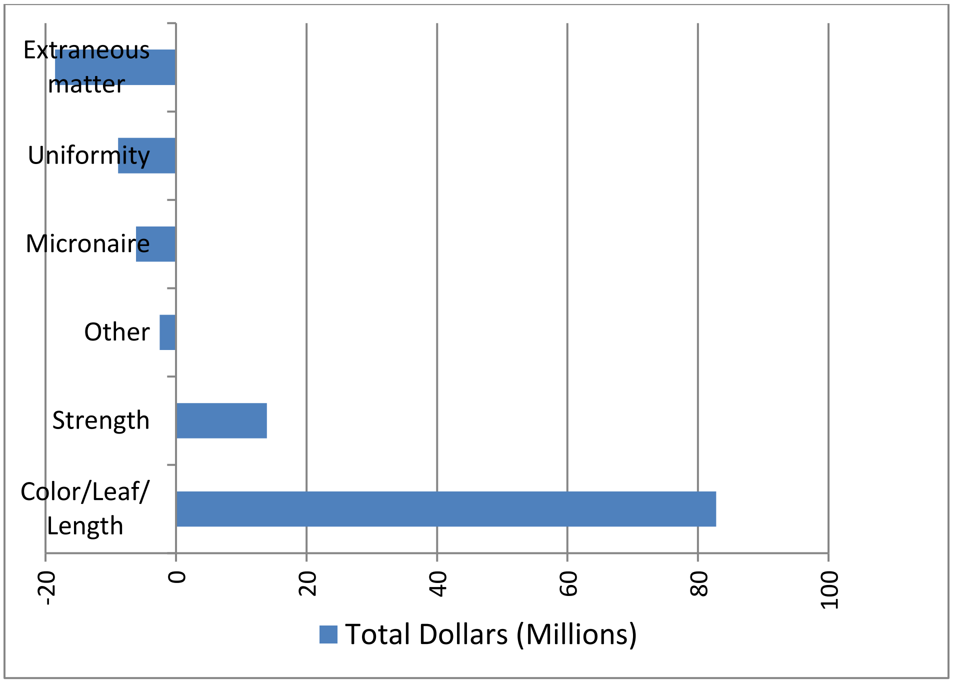
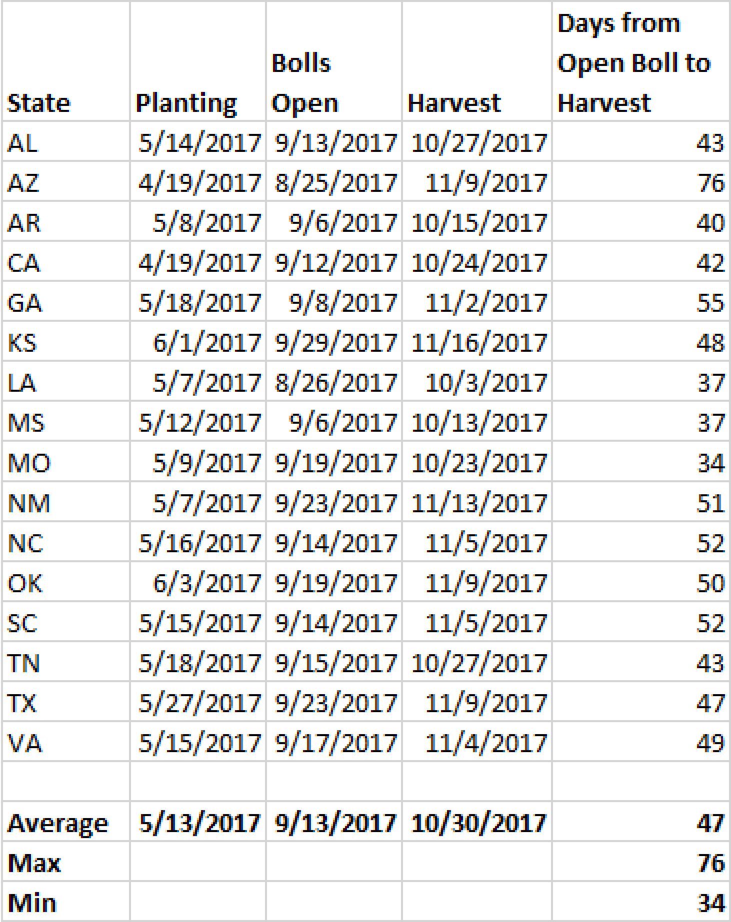


Figure 3.1. Total United States cotton lint discounts and premiums from USDA base values for upland cotton. The base parameters for upland cotton are 41 for color, leaf 4, micronaire of 3.5-4.9, 80-82.9 for uniformity, 26-28.9 g tex^{-1} for strength, and 2.65 cm for length. (Adapted from USDA-ERS, 2019).

In modern machine-picked upland cotton production systems, harvest aids are routinely applied when 60-80% of cotton bolls are open, followed by a target harvest one to two weeks after the first harvest aid application (Gwathmey, 1986). The physiological development of the cotton plant leads to the earlier maturation of the lower position bolls and the cotton fiber being exposed to weathering for 30-60 days while the upper position bolls continue to mature (Table 3.1). The longer the duration of exposure to weather, the greater the risk for fiber degradation and seed cotton loss due to intense storms with high rainfall and high wind, or extended periods of wet weather.

Table 3.1. Dates shown by state when 50% of the acres were planted, had open bolls, and were harvested using average data from 2017 from United States Department of Agriculture (USDA) Crop Progress Reports (Adapted from USDA_FSA, 2019).



State	**Planting**	**Bolls Open**	**Harvest**	**Days from Open Boll to Harvest**
AL	5/14/2017	9/13/2017	10/27/2017	43
AZ	4/19/2017	8/25/2017	11/9/2017	76
AR	5/8/2017	9/6/2017	10/15/2017	40
CA	4/19/2017	9/12/2017	10/24/2017	42
GA	5/18/2017	9/8/2017	11/2/2017	55
KS	6/1/2017	9/29/2017	11/16/2017	48
LA	5/7/2017	8/26/2017	10/3/2017	37
MS	5/12/2017	9/6/2017	10/13/2017	37
MO	5/9/2017	9/19/2017	10/23/2017	34
NM	5/7/2017	9/23/2017	11/13/2017	51
NC	5/16/2017	9/14/2017	11/5/2017	52
OK	6/3/2017	9/19/2017	11/9/2017	50
SC	5/15/2017	9/14/2017	11/5/2017	52
TN	5/18/2017	9/15/2017	10/27/2017	43
TX	5/27/2017	9/23/2017	11/9/2017	47
VA	5/15/2017	9/17/2017	11/4/2017	49
Average	**5/13/2017**	**9/13/2017**	**10/30/2017**	**47**
Max				**76**
Min				**34**

When the time from boll opening to harvest is reduced, cotton fiber quality is preserved from weather degradation (Hake et al., 1992), potentially increasing producer profitability. Multiple pass harvesting events increase fiber uniformity of cotton fiber as abiotic and biotic factors affecting seed and fiber development are more similar within a field for bolls developing at similar times (Bradow, 2000). Also, cotton lint quality varies as bolls develop higher on the plant regardless of environmental factors. Higher fruiting positions typically exhibit less favorable fiber characteristics, such as lower length uniformity, strength, maturity, and length, as well as higher short fiber content (Kothari, 2015). A consequence of varying length up the plant is that a single-pass harvest combines all boll positions; this process reduces uniformity.

Considering the large U.S. acreage and potential loss of lint quality in earlier opening bolls, this could be an immense loss of value to the American cotton producers. Multiple harvest events during the season, by hand or robotic harvesters, preserve the fiber quality by lessening the time of weather exposure. Additionally, multiple harvests reduce the risks from detrimental weather events, such as high wind, rain, and/or hail, removing seed cotton from the plant, leading to reduced yields.

A British company, Small Robot Company, has recently produced autonomous robots to monitor soil and plant conditions, sow seeds, conduct plant population counts, and provide weed control (2019). An Australian company SwarmBot, will release an autonomous unit in 2020 capable of identifying weeds from crops then removing weeds, as well as monitoring crop conditions (Blain, 2019). In 2018, Cotton Incorporated began an initiative to determine the potential for developing a small robotic cotton harvester and the value robotic harvesting can bring to the grower and the entire industry. With the creation of autonomous robotic harvesting systems, producers would be able to gather seed cotton over multiple harvesting events, starting when the first cotton bolls reach full maturity. These multiple harvesting events would potentially preserve fiber and seed yield and quality by removing seed cotton before detrimental weather events occur, increasing fiber uniformity due to similar boll maturation conditions, eliminate harvest aid application, decreasing the large expenditure for a single harvesting machine, allowing upper position cotton bolls to completely mature in many regions, reducing soil compaction from the use of lighter machinery, and reducing the risk of delayed harvest due to mechanical failure by having numerous harvesters. Furthermore, hurricanes, hail, high winds, and flooding are a significant risk for substantial yield and quality losses after first open boll in much of the US Cotton Belt.

The long-term goal of this project is to provide proof of concept for the utilization of autonomous harvest robots to add profitability to a cotton producer's operation through preserved fiber quality, increased harvested cotton yield, and reduced end-of-season risks. The objectives of this study are: 1) to compare fiber quality and lint yield from multiple hand-harvesting events, simulating a robotic harvester, to the traditional methods of single-pass machine harvesting for high and low yield environments and 2) collect fruiting position information for yield and fiber quality in one high and one low yielding environment.

Materials and Methods

The study was conducted in seven site-years with two cotton varieties, an early maturity, lightly hairy DeltaPine 1612B2XF (DP1612) and smooth leaf mid-full maturity 1646B2XF (DP1646) (Bayer AG, 2019), except for 2018 Tifton, GA location that utilized Stoneville 4946GLB2, a semi-smooth leaf, early-mid maturity, in a cultivar by harvest method factorial design. All locations had a target planting population of 111,150 seeds ha^{-1}. The agronomic information for each site is listed in Tables 3.2 and 3.3.

Table 3.2. Locations, soil type, harvest dates, agronomy practices.

Site	Soil Type	Planting Date	CMHP[1] Harvest Dates	Machine Harvest Date	Yield Goal (kg ha-1)	Irrigation
2018						
College Station, TX	Ships Clay	4/29	8/16; 8/20; 8/23; 8/27; 8/30; 9/4; 9/7; 9/17; 9/24	10/3	1681	furrow
Tifton, GA	Tifton Loamy Sand	6/11	9/20; 9/24; 9/27; 10/1; 10/4; 10/8; 10/15; 10/18; 10/22; 10/24	10/24	1681	overhead
Vernon, TX	Abilene Clay Loam	5/30	8/30; 9/4; 9/11; 9/13; 9/25; 10/2; 10/4	10/29	560	dryland
2019						
College Station, TX	Belk clay	4/25	8/19; 8/22; 8/27; 8/30; 9/2; 9/6; 9/9; 9/16	9/27	1681	furrow
Jackson, TN	Loring Silt Loam	5/8	9/3; 9/6; 9/11; 9/13; 9/17; 9/20; 9/23; 9/27; 10/1; 10/4; 10/8	10/11	1345	overhead
Tifton, GA	Tifton Loamy Sand	4/22	8/15; 8/15; 8/22; 8/26; 8/29; 9/3; 9/6; 9/12; 9/16	9/9	1681	overhead
Vernon, TX	Rowena clay loam	6/14	9/17; 9/19; 10/1; 10/3; 10/10; 10/17; 11/15	11/18	560	dryland

[1] Combined Multiple Hand Pickings

Table 3.3. Each site-year's plot configuration.

Site	Row Spacing (m)	Replications	Plot length (m)	Machine Harvester Type
2018				
College Station, TX	1.00	5	13.72	Picker
Tifton, GA	0.91	6	15.24	Picker
Vernon, TX	1.00	6	15.24	Stripper
2019				
College Station, TX	1.00	5	12.19	Picker
Jackson, TN	0.97	6	9.144	Picker
Tifton, GA	0.91	6	15.24	Picker
Vernon, TX	1.00	5	15.24	Stripper

Eight-row plots were planted when a minimum of 35 DD15.5's was forecasted for the following five days. Each location followed their state's fertility recommendations based on soil sampling for the desired yield goal (Stichler and McFarland, 2001; Main, 2012; Whitaker, et al., 2018). Integrated Pest Management (IPM) strategies outlined from each state's respective guidelines were utilized (Vyavhare et al., 2018). Weather data (rainfall, day lengths, daily temperatures, solar radiation) were collected from a weather station at each research center.

In each plot, rows 1, 5 and 8 were buffer rows (Figure 3.2). Rows 2 and 3 were mechanically harvested following harvest aid application of diuron, thidiazuron, and ethephon at 70% open bolls to all rows except the combined multiple hand picking (CMHP) row. Two separate subsamples, approximately 1 and 3 kg, were collected from the harvester. Machine-harvested samples were stored in a climate-controlled environment at 21ºC and 50% humidity for a minimum of 48 hours in paper sacks prior to being ginned and recording lint turnout. Seed cotton subsamples from machine and hand harvest events were weighed at the time of harvest, oven-dried, and reweighed to obtain an adjusted cotton fiber moisture for machine and hand harvest weights and then calculating final seed cotton yield. The 3 kg seed cotton sub-samples from the machine harvested plots were pre-cleaned at the USDA-ARS Cotton Production and Processing Research Unit in Lubbock, TX before ginning (referred to as the cleaned harvest method); the 1 kg subsamples were ginned without pre-cleaning (machine harvest method).

In the pre-cleaning machine, an extractor-feeder, seed cotton is fed onto a dispersing cylinder at a controlled rate through a set of star rollers that turn at 3.67 rpm. The dispersing cylinder runs at 1269 rpm and breaks up any clumps of cotton as it is fed in through the star rollers. The cotton is next engaged by the inclined (45 degrees) cylinder cleaning portion of the machine where the cotton is scrubbed between the cylinder pins and the grid-rod sections. The grid-rods below the pinned cylinders are 0.95 cm in diameter with 0.95 cm open space between each rod and are oriented parallel to the axis of the pinned cylinders. Each of the four pinned cylinders contain 8 rows of evenly spaced pins that are 5.08 cm long and about 3.81 cm apart. The cylinders were operated at 745 rpm with 1.27 cm clearance between the tip of the pins and grid-rods. Once the cotton exits the cylinder cleaning section, it is fed onto the primary cleaning saw of the extractor section. The extractor cylinders are 37.47 cm in diameter and contain channel saws which engage the cotton and remove large foreign material though centripetal force as the cotton and foreign matter are agitated against grid bars located around the periphery of the saws. The extractor saws were run at 607 rpm. Foreign material separated by the cylinder cleaning and extractor sections of the machine was collected in a bin at the base of the machine during the processing of these samples but is normally removed by a pneumatic conveying line. The cleaned cotton is removed from the extractor saws by a doffer with steel flights.

The center 2 m of the defoliated row 4 (Figure 3.2) was completely hand harvested within 24 hours before machine harvest to measure harvest efficiency and the effect of the machine harvester on fiber quality. Row 6 (Figure 3.2) was used to quantify physiological development of the cotton plants. Measurements included seedling emergence in 3.05 meters of row; ten consecutive plants were used to measure first square, first flower, nodes above white flower, 80% open bolls and node of first fruiting branch; weekly measurements after first flower date of first cracked boll and number of open bolls. Row 7 (Figure 3.2) was utilized for multiple hand harvests of seed cotton. Row 7 was plastic covered prior to harvest aid application to all other rows to eliminate potential drift.

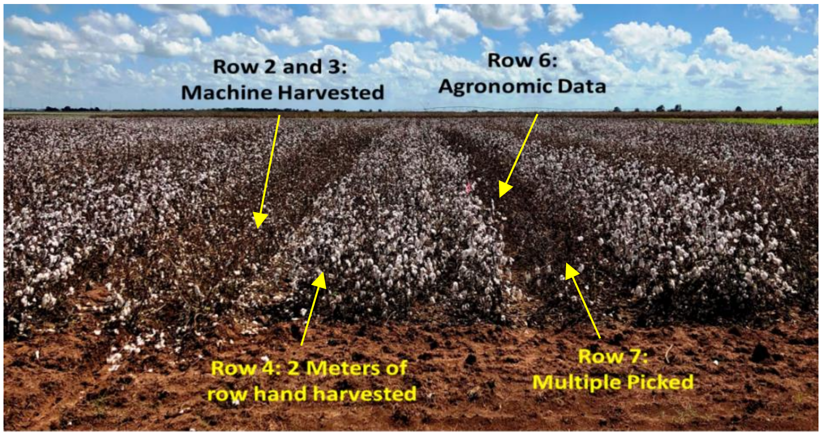


Figure 3.2. Comparison of multiple and single pass harvest methods effect on cotton yield and fiber quality plot layout design in College Station, TX for 2018 and 2019.

Harvest of the multiple hand-picked rows was conducted twice weekly, beginning at first mature open boll and continuing until no more open bolls were present on the plant. Bolls were hand harvested when the cotton was easily removed from the locules. Picked seed cotton samples were stored in a dark room at 21^{o}C and less than 50% humidity to preserve fiber quality. Cotton boll samples were also sorted by fruiting position: 1st, 2nd, 3rd and vegetative, during the hand-picking process at the College Station and Vernon, TX locations. Each week, harvested nodes were documented for each individual plot.

All samples were ginned on the same 20-saw laboratory gin (Dennis Manufacturing, Athens, TX) in College Station, TX by the same operator after the conclusion of season. For, the machine-picked, pre-cleaned machine-picked, and end of season hand-harvested (row 4) seed cotton, sample sizes of 120 g were ginned. For the seed cotton hand-harvested throughout the season (row 7), 120 g of each sample, or the entire mass of smaller samples, were ginned. The HVI testing of fiber quality properties was conducted at Cotton Incorporated’s Fiber Testing Laboratory in Cary, NC.

Data obtained from HVI included reflectance (Rd), yellowness (+b), leaf grade, staple length, strength, uniformity, and micronaire. Cotton loan values were calculated from these data using the Cotton Loan Calculator (Cotton Incorporated, 2019). The 2019 Jackson, TN site-year had unusually poor color grades from the first four CMHP events due to improper storage. To address this issue, the average reflectance (Rd) and yellowness (+b) grades from each replication’s hand-pickings five through ten, and then the lint cotton color grade chart was utilized to estimate a color grade for the first four CMHP timings. These color values were needed to calculate loan values used to calculate gross revenue.

An analysis of variance (ANOVA), (Table A1) with a significance level of 0.05, was performed on fiber yield and quality data using a mixed model (Proc Mixed, SAS v9.4) with the site-year combination as a random variable and harvest method, cultivar, and their interaction as independent variables. Like machine harvest, picker or stripper, site-years were combined due to similar trends. Cultivars were analyzed separately due to different fiber quality values. Fisher’s Protected Least

Significant Difference (LSD) test was used to identify significant differences between all four harvest methods in fiber quality data, yields, and economic values. All cotton sample treatments were compared with calculated mean quality and value data for CMHP on a weighted basis.

Results and Discussion

Stripper-Harvested Location

When combining both years for the Vernon, TX location (Table 3.4), the average yields were lower than picker-harvested locations, with mean yields of 341 and 367 kg ha^{-1} for DP 1612 and 1646, respectively. Yields are typically low in the Rolling Plains of Texas, and these yields were 57% of the long-term average for stripper harvested cotton in the region due to the drought events during the study years. The machine harvest yielded significantly more compared to the other harvest methods, but the higher weights were the result of increased leaf, bur, and stem being mixed with the lint. After the machine harvested samples were cleaned, no differences in lint yield were observed between the pre-cleaned machine harvest method, the 2M (end of the season two meters of row) or the CMHP.

The revenue was higher for the DP1646 than DP1612 due to the improved fiber quality characteristics of this cultivar as reported by Smith et al., (2020). The revenue for DP1612's CMHP method was significantly higher than both machine-harvested methods, but comparable to the 2M method. For DP1646, the cleaned method yields were similar to the other harvest methods, although revenue from the 2M was significantly higher than both CMHP and the machine harvest methods. For both varieties, both hand-harvesting methods (2M and CMHP) had a higher loan value than the machine and cleaned harvest methods. For DP1612 the loan value of hand-harvested methods was more than double the machine-harvested methods, while DP1646's loan value was 95% higher for the hand-harvested cotton than the machine-harvested cotton. The differences in loan value between the hand and machine harvest methods were attributed to discounts from color and leaf grades, higher micronaire, and lower uniformity and strength. Previous research has shown machine harvesting increases foreign matter and can decrease color grade (Smith, et. al, 1946). For the stripper-harvested location, significance differences are noted among cultivars for yield and revenue but not loan values.

Table 3.4. Combined 2018 and 2019 Vernon, TX stripper harvested Data.

	Yield (kg ha^{-1})		**Revenue (\$ ha^{-1})**		**Loan Value (\$ kg^{-1})**	
	DP1612	DP1646	DP1612	DP1646	DP1612	DP1646
2M	307 B	368 B	298 A	404 A	0.99 A	1.11 A
Cleaned	329 B	352 BC	134 B	308 AB	0.41 B	0.58 B
CMHP	297 B	278 C	324 A	235 B	1.10 A	1.11 A
Machine	431 A	471 A	176 B	211 B	0.35 B	0.43 B
LSD	71	85	81	114	0.18	0.20

Each cultivar's fiber quality for each harvest method are shown in Table 3.5. For DP1612, the machine and cleaned harvest method had micronaire above 5.0, in the discount range, while the two hand-picking methods were significantly lower and below the discount range. The two machine harvested treatments had extremely high leaf grades, which has been shown to artificially inflate micronaire and decrease reflectance values (Ahmed, 2016). DP1612 lengths (UHML) were above 25.4 mm UHML for all the harvest methods, except 2M was significantly lower at 24.9 mm. The uniformity for CMHP was superior to the other harvest methods resulting from similar fruiting positions being harvested at each picking date versus intra-plant averaging for the other harvest methods. These results are consistent with research by Kothari (2015), which demonstrated cotton plants exhibit varying fiber qualities by sympodial branch. Additionally, the fiber strength was significantly higher for CMHP than the three other harvest methods and can be explained by less environmental exposure to sunlight, rainfall, and high humidity. The higher uniformity of the multiple harvest may also play a role in the higher strength measurements. Similar findings have been reported by Bednarz in 2002 at Tifton, GA by picker harvesting at various first boll opening timings. Reflectance was significantly better for the CMHP compared to all other harvest methods and can also be attributed to less exposure to weathering. The impact of weathering on reflectance is especially notable between 2M and CMHP, where both were hand harvested and promptly stored in dark and low humidity conditions. For yellowness, the two hand harvest methods, 2M and CMHP, were not different but were significantly different than the machine harvested cotton, cleaned or not. Leaf grades for CMHP averaged 1.5 with 2M and machine averaged 2.9 and 7.9, respectively. The higher leaf grades for 2M are most likely due to the defoliation application and greater amount of leaf drop at the time of the harvest event. These results were consistent with Porter (2013) who reported leaf grade and leaf grade discounts much lower for hand-harvested cotton than mechanically harvested cotton. Although in this study, the machine harvest leaf grades are not representative of commercial practices' expected leaf grades, due to the limited gin cleaning.

For DP1646, CMHP produced the lowest micronaire (4.6) but was not different from the 2M harvest method (Table 3.5), while the machine and cleaned-harvested cotton had a micronaire of 5.22 and 5.03, respectively. Much like DP1612, DP1646, CMHP had the longest fiber, significantly better than 2M. CMHP had the best uniformity and was significantly better than the machine harvested treatment. Much like with the DP1612 cultivar, CMHP had the greatest strengths for DP1646 by 2 g tex^{-1}. The highest values for reflectance were with the CMHP method, being significantly better than all other treatments. Even with the cleaned method, the cotton still had extremely high leaf grades, which resulted in high discounts and was reflected in the loan value reported in Table 3.4. Leaf grades of both hand-harvesting methods were below 3, but the CMHP leaf grade was less than 1.5, significantly lower than 2M.

Table 3.5. Micronaire, Upper Half Mean Lengths (UHML), Uniformity Index (UI), Strength, Reflectance (Rd), Yellowness (b+), of DeltaPine 1612 and 1646 cotton samples from 2018 and 2019 Vernon, TX stripper harvested locations.

	DP1612						
	Micronaire	UHML (mm)	UI	Strength (g tx^{-1})	Reflectance	Yellowness	Leaf
2M	4.63 B	24.89 B	79.6 B	27.63 B	70.38 B	9.61 A	3.0 B
Cleaned	5.03 A	25.65 A	79.27 B	28.0 B	63.61 C	8.73 B	8.0 A
CMHP	4.67 B	26.16 A	80.59 A	30.78 A	75.26 A	10.07 A	1.58 C
Machine	5.22 A	25.65 A	79.11 B	26.99 B	59.13 D	8.22 B	8.0 A
LSD	0.26	0.51	0.66	1.22	1.80	0.52	0.61
	DP1646						
2M	4.71 C	26.67 B	79.74 AB	27.73 B	73.89 B	8.43 B	2.75 C
Cleaned	4.96 B	27.18 AB	79.01 B	27.21 B	69.37 C	8.26 B	7.08 B
CMHP	4.6 C	27.69 A	80.32 A	29.54 A	78.73 A	9.28 A	1.46 D
Machine	5.28 A	27.18 AB	79.26 B	27.14 B	65.95 D	7.73 C	7.82 A
LSD	0.25	0.76	0.86	1.33	2.23	0.42	0.64

Picker-Harvested Locations

Yields for each of the locations were representative for the region, except for Tifton, GA in 2018, when a hurricane substantially decreased harvestable yields. For the picker-harvested DP1612, CMHP had the highest yield, over 190 kg ha^{-1} more than 2M or the machine- harvested treatments (Table 3.6). Prompt removal of seed cotton from the field would be expected to result in higher yields of seed cotton, even under non-inclement weather events. The end of the season hand harvesting or pre-cleaning was not able to obtain the same yields as compared to the timely harvesting of the CMHP. Moreover, cleaning cotton removes foreign matter, but also removes lint, decreasing marketable lint weight. The revenue from CMHP was significantly greater than all other harvest methods, with CMHP's gross revenue being \$512 and 513 ha^{-1} higher than the 2M and cleaned, respectively. This was mostly due to CMHP's impressive loan value, but also higher yield, which far exceeded any other harvest method for DP1612. The 2M had the closest loan value to CMHP but was still \$0.12 kg^{-1} lower. Although both 2M and

CMHP were handpicked, minimizing leaf and trash, 2M was exposed to prolonged weather events that deteriorated color values.

There were no significant differences in yield among harvest methods for DP1646, although numerically CMHP had the highest yield,1870 kg ha^{-1}. Much like DP1612, CMHP's revenue was far superior to all other harvest methods. The cleaned method was the closet to DP1646's CMHP revenue but was still \$146 ha^{-1} less. Again, as with DP1612, the revenue was much greater than other harvest methods due to the superior loan value obtained by CMHP. CMHP's loan value for DP1646 (\$1.22 kg^{-1}) was significantly greater than all other treatments, 0.09 and 0.12 \$ kg^{-1} more than the next closest treatments of 2M and cleaned, respectively.

The only site-year to use Stoneville 4946 was the 2018 Tifton, GA location, and it was the only cultivar used at that site-year. The CMHP out yielded the other harvest methods in 2018 due to Hurricane Michael causing seed cotton yield loss. This was the only site-year where the earlier harvest events of the CMHP treatment resulted in a superior yield due to a hurricane but should be considered an advantage for coastal locations with high potential for tropical weather. Although loan values were not statistically different for CMHP, 2M and cleaned at the 2018 Tifton, GA site-year, the added yield created \$324 ha^{-1} greater revenue for the CMHP method.

Table 3.6. 2018 and 2019 Picker Harvested Combined data by Cultivar from Tifton, GA, Jackson, TN and College Station, TX.

	Yield (kg ha^{-1})			**Revenue (\$ ha^{-1})**			**Loan Value (\$ kg^{-1})**		
	DP1612	DP1646	ST4946[1]	DP1612	DP1646	ST4946	DP1612	DP1646	ST4946
2M	1629 B	1757 A	899 B	1687 B	1938 B	1101 B	1.09 B	1.13 B	1.22 A
Cleaned	1580 B	1778 A	888 B	1688 B	2030 B	1032 B	1.06 B	1.1 B	1.17 A
CMHP	1819 A	1870 A	1153 A	2199 A	2276 A	1425 A	1.21 A	1.22 A	1.24 A
Machine	1560 B	1793 A	903 B	1376 C	1532 C	771 C	0.79 C	0.86 C	0.9 B
LSD	177	205	124	240	219	158	0.11	0.07	0.14

[1] Stoneville 4946 was used exclusively at the Tifton, GA 2018 site and no other cultivar

To better understand the greater loan values of the CMHP treatment, fiber characteristics of each cultivar and harvest method are shown in Table 3.7. The two hand-harvested methods both had significantly lower micronaire values than the two machine-harvested methods with DP1612. The lengths of DP1612 were similar for all harvest methods with only machine being significantly lower than CMHP. Much like the stripper portion of this study, the DP1612 strength for CMHP was the highest. The reflectance of DP1612 exhibited the greatest amount of variance among harvest methods, with CMHP being higher than all other treatments. CMHP yellowness score was higher than all other treatments possibly due to prolonged storage compared to the other harvest methods. Although higher, the CMHP color remained in the white grades. Leaf grades for CMHP were far lower than any other treatment, even the other hand harvest method of 2M (2.21 difference). The machine and cleaned treatments possibly had lower color grades but may have been higher due to large amounts of leaf content.

Interestingly, with the picker harvested locations, there were no differences between the micronaire values for DP 1646, although CMHP did have the lowest numerical value (4.37). DP1646 did not exhibit any difference in lengths or uniformity among harvest methods but again CMHP had the best numerical value for both, 1.23 and 83.24 respectfully. The strength of DP1646 was greater for CMHP (30.71) than cleaned (29.84) and 2M (29.70), but similar to machine. Reflectance and leaf once again exhibited the greatest benefit for the CMHP loan value over the other three harvest methods, and these fiber quality characteristics contributed the most to the higher loan values reported in Table 10.

ST4946 was only grown in one location and for only the first year of this study, unlike DP1612 and DP 1646, which had six site-years included in the analysis. However, similar trends were observed for ST 4946 and the other varieties. Micronaire values were similar across all harvest methods, except for CMHP, which had the lowest value, 4.06. For length and uniformity of ST4946, the cleaned method demonstrated the lowest values and was different from the other three harvest methods. No differences were observed in fiber strength, but CMHP did have the highest numerical value. Unlike with DP1612 and DP1646, reflectance, yellowness, and leaf values with CMHP of ST4946 were not different than with

2M, which is surprising considering the amount of precipitation received by the 2M lint due to Hurricane Michael. However, both hand-harvest methods were superior to the two machine-harvest methods.

Table 3.7. Micronaire, Upper Half Mean Lengths (UHML), Uniformity Index (UI), Strength, Reflectance (Rd), Yellowness (b+), of Stoneville 4946, DeltaPine 1612 and 1646 cotton samples from 2018 and 2019 Tifton, GA, Jackson, TN and College Station, TX picker harvested locations.

	DP1612						
	Micronaire	UHML (mm)	UI	Strength (g tx^{-1})	Reflectance	Yellowness	Leaf
2M	4.41 B	29.46 AB	83.02 A	30.78 B	71.53 B	8.06 B	4.27 B
Cleaned	4.54 A	29.72 AB	82.96 A	31.60 AB	68.98 C	8.16 B	5.73 A
CMHP	4.37 B	29.97 A	83.44 A	32.22 A	76.56 A	9.47 A	2.06 C
Machine	4.55 A	29.21 B	82.80 A	30.54 B	66.50 D	8.14 B	6.41 A
LSD	0.10	0.51	0.78	1.10	2.37	0.38	1.06
	DP1646						
2M	4.37 A	30.73 A	83.09 A	29.70 B	72.90 B	7.43 B	4.27 C
Cleaned	4.40 A	30.73 A	82.43 A	29.84 B	71.56 B	7.68 B	5.18 B
CMHP	4.28 A	31.24 A	83.24 A	30.71 A	79.00 A	9.00 A	2.12 D
Machine	4.35 A	30.48 A	82.82 A	30.05 AB	68.39 C	7.40 B	6.32 A
LSD	0.16	0.76	0.84	0.75	2.60	0.42	0.91
	ST4946						
2M	4.26 AB	28.70 A	83.96 A	30.87 A	77.48 A	9.41 A	1.75 C
Cleaned	4.25 AB	27.94 B	83.12 B	31.00 A	74.25 B	8.70 B	4.00 B
CMHP	4.06 B	29.21 A	84.1 A	31.79 A	78.36 A	9.61 A	1.33 C
Machine	4.28 A	28.96 A	84.53 A	31.30 A	71.48 C	8.62 B	6.50 A
LSD	0.22	0.51	0.64	1.17	1.31	0.34	1.28

While examining the lint quality factors, the fiber values that contributed the most to loan value differences (Figure 3.3 and 3.4), were color and leaf grades. Leaf grades were artificially inflated due to minimal ginning practices conducted on the machine harvested samples and even the cleaned samples were less intensively cleaned than commercial gins (Mangialardi, 2003). The lower level of cleaning likely reduced loan values for the two machine-harvested methods, but ginning practices were kept constant across all harvesting methods. Color grades are more likely a fair representation of a commercial scenario. Prolonged weathering of seed cotton in the field reduces color grades, namely reflectance (Barker et al., 1979; Bednarz, et. al, 2002), as shown by the comparison of CMHP and 2M treatments.

Aggregated totals of machine, cleaned, and 2M samples brought net discounts of -0.395, -0.229, and -0.048 \$ kg^{-1} from base loan value, respectively, while CMHP brought a net premium over the base of 0.056 \$ kg^{-1} for grades and length (Figure 3.3). The 2M, machine and cleaned had discounts for high or low micronaire values, while CMHP had micronaire values consistently in the base or premium range. Lastly, the CMHP treatment produced the greatest premium for strength, averaging 23.59 points (Figure 3.4).

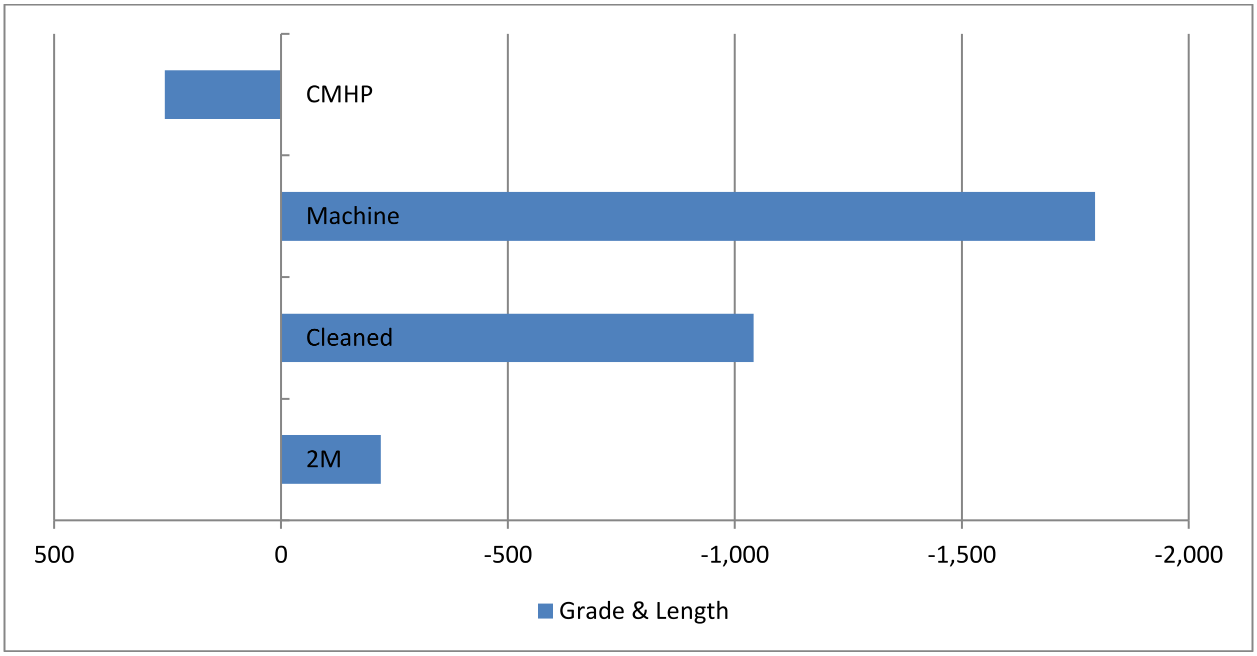


Figure 3.3. Aggregate cotton loan value premium or discount (net points kg^{-1}) for grade and length from the combined cultivars and site-years by harvest method.

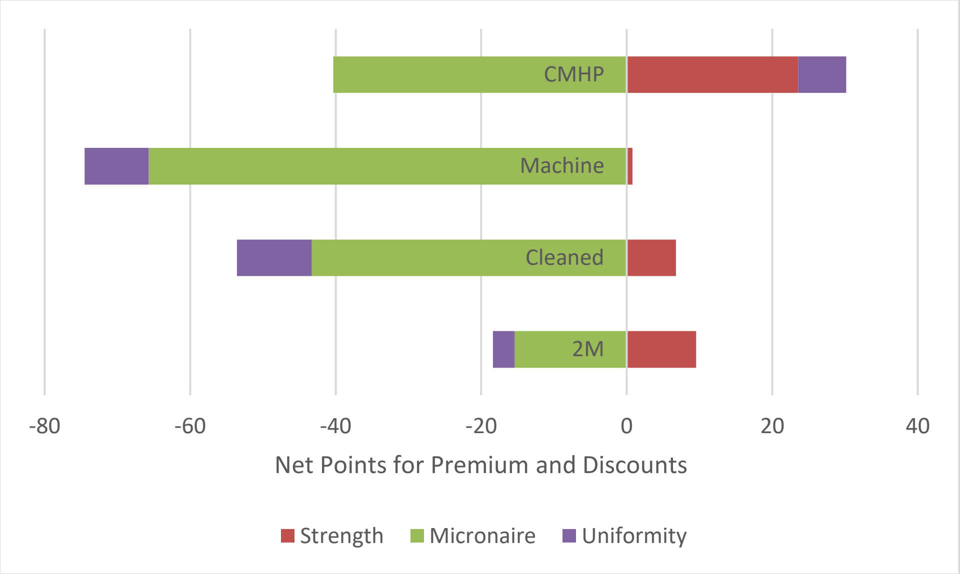


Figure 3.4. Aggregate cotton loan value premium or discount (net points kg^{-1}) for strength, micronaire, and uniformity from the combined cultivars and site-years by harvest method.

The multivariate correlation demonstrated a strong positive correlation among trash count and percent trash area (0.94) (Table 3.8). Loan values were greatly improved as reflectance increased (0.81) and sharply deceased as trash count (-0.85) and percent trash area (-0.83) both increased.

Table 3.8. Multivariate Correlation of Reflectance (Rd), Yellowness (b+), Trash Count, Percent Trash Area (Area %), and Loan Value of cotton samples from all seven site years.

	Rd	+b	Trash Count	Area %	Loan Value
Rd	1.00	0.38	-0.86	-0.81	0.81
+b	-	1.00	-0.43	-0.45	0.19
Trash count	-	-	1.00	0.94	-0.85
Area %	-	-	-	1.00	-0.83
Loan Value	-	-	-	-	1.00

Much of the loan value loss was due to reflectance decrease in both the picker and stripper locations as shown previously in Table 3.7 and 3.8. To better understand causality, rainfall during harvest and reflectance from each CMHP and 2M events were compared. The Vernon, TX data, shows the impact of rainfall events on the reflectance of seed cotton remaining the field (Figure 3.5). As an example, in 2019 between the second and third handpicking, reflectance values dropped from 78.54 to 76.65 once a rain event occurred. Conversely, there was not always a perfect relationship as shown in the figure. Interestingly, from the sixth to seventh picking, although there are multiple rainfall events, reflectance increased. A constant shown for both years at Vernon is that the reflectance values for the end of the season handpicking (2M) is lower than any of the individual CMHP events.

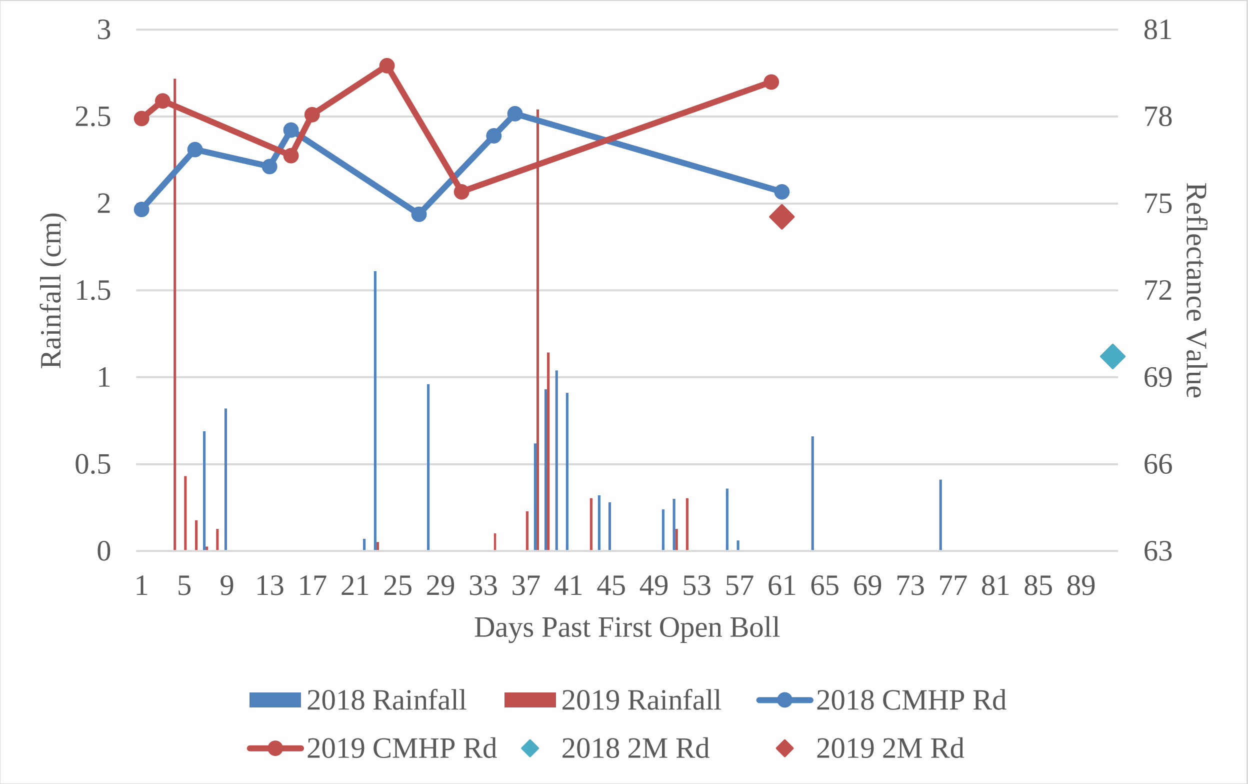


Figure 3.5. 2018 and 2019 Vernon, TX rainfall amounts and reflectance values from CMHP and 2M.

Similar trends were observed at College Station (Figure 3.6). The figure shows slight reflectance decreases between CMHP events from rainfall events, such as between the seventh and eight hand pickings in 2019. But again, as in Vernon, there were rain events between timings that do not demonstrate this reflectance drop. When large rain events and a greater amount of time between harvests occur, greater effects are seen, such as between 2018 hand pickings seven (79.09) and eight (74.2). The overall consistent effect is much lower 2M reflectance values compared to the CMHP reflectance values. This result was most likely caused by prolonged exposure to weather.

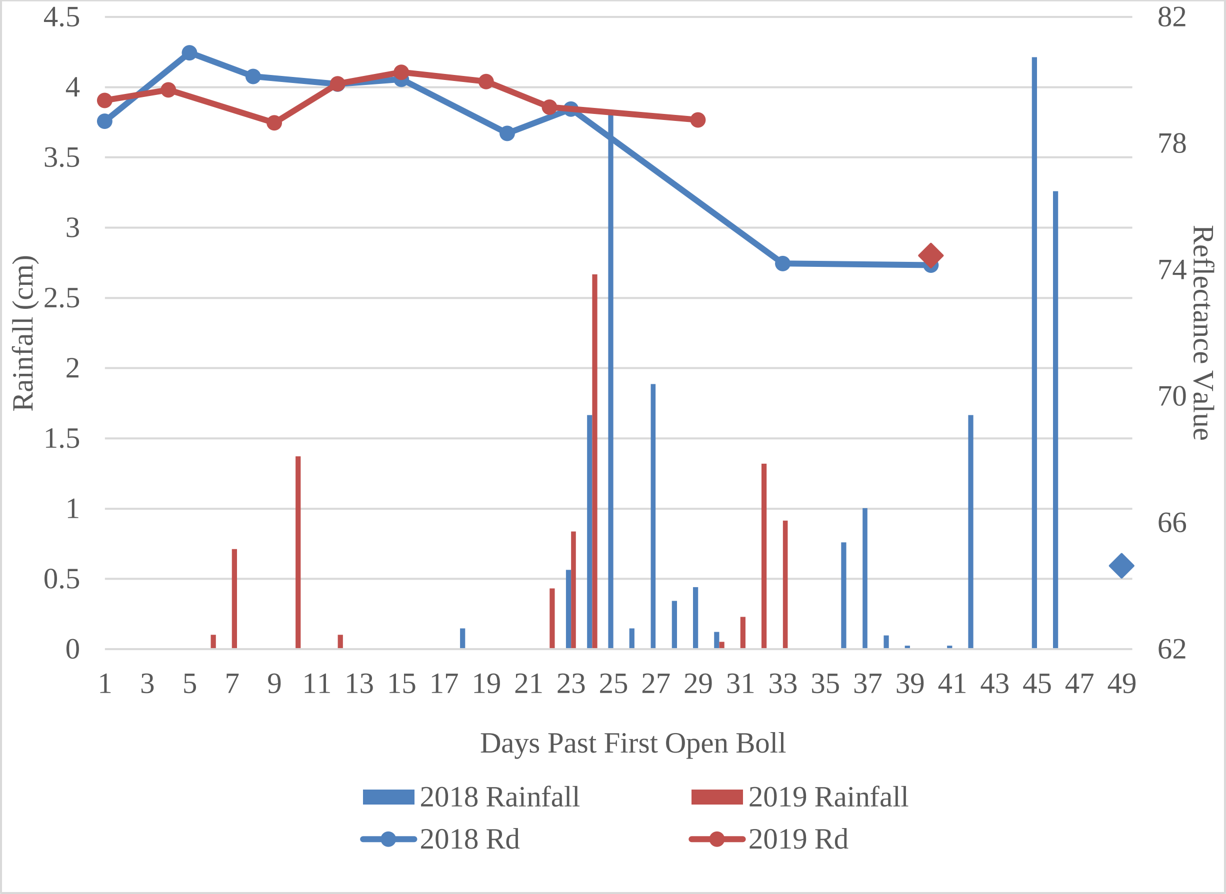


Figure 3.6. 2018 and 2019 College Station, TX rainfall amounts and reflectance values from CMHP and 2M.

The Georgia 2018 and 2019 results offered little consistency compared to the Vernon and College Station, TX sites. Unlike the two previously mentioned sites, often reflectance values decreased with little or no rain, or increased after heavy rainfall events. 2018 at the Georgia site did once again offer mostly higher CMHP reflectance values compared to the end of the season 2M single hand-picking event. Conversely, in 2019 at the Georgia site, the majority of hand-picking events did not have higher reflectance than the 2M treatment.

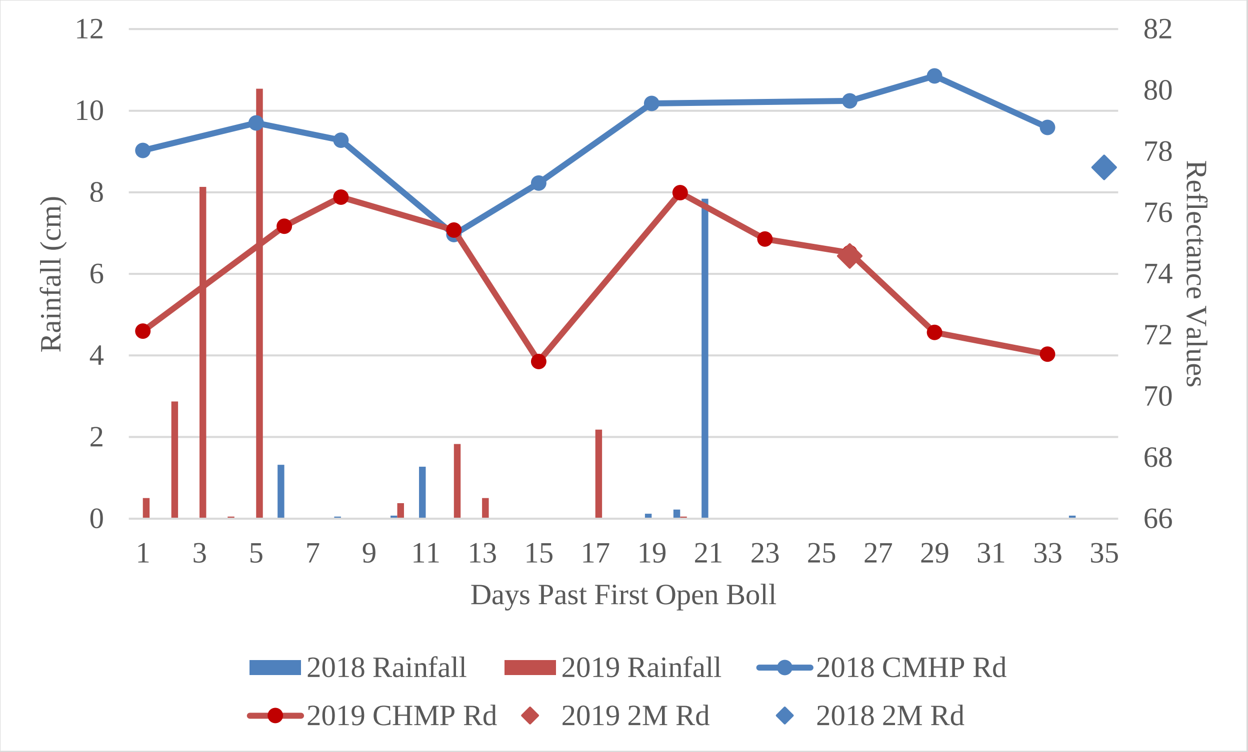


Figure 3.7. 2018 and 2019 Tifton, GA rainfall amounts and reflectance values from CMHP and 2M timings as days past first open boll.

Conclusion

Multiple hand harvests preserved the cotton lint quality by reducing the exposure of lint to weather degrading factors and significantly increased cotton loan value over all end-of-season harvesting methods. The machine-harvested treatments had inflated leaf grades that could be decreased with additional cleaning equipment in commercial gins, but intensive cleaning comes at an economic cost to the gin and decreases marketable weight and fiber quality. When only comparing CMHP to 2M, loan values were higher for DP1612 and 1646. Although yield from the Vernon, TX site-years did not show improvements, the picker locations did show increased yield for all cultivars. The higher loan values and yield resulted in the CMHP harvest method having the greatest gross revenues among harvest methods across a diversity of environments, except for DP1646 at Vernon, TX. The CMHP harvest method improved loan values primarily from greater reflectance due to earlier removal from environmental conditions such as dust, sunlight and mostly rainfall. Furthermore, CMHP lowered trash content and percent trash area even compared to the end of the season once over hand harvest.

Three cultivars with broadly different maturities and fiber quality characteristics were included in this research. Over the seven site-years, for both picker and stripper harvested varieties, very similar trends were observed for yield, fiber quality, and revenue. This result indicated that the multiple harvest method provides comparable value for short and mid-late season cotton varieties. Also, in a high-quality cultivar like DP 1646, multiple harvests preserved the full potential value of the lint. Timely harvesting of the seed cotton is reported throughout the literature to preserve seed and fiber yield and fiber quality (Faircloth, et a.l, 2004; Tian, et al., 2017; Williford, 1992). For lint yields, this research indicated there is more benefit to timely harvest for cotton grown in high-yielding and picker-harvested environments than non-irrigated, low-yielding, and stripper-harvested cotton. However, extreme weather events can occur in any cotton production environment after cotton bolls are mature and timely removal of cotton from frequent multiple harvests will ensure a higher percent of the yield potential. For example, in GA in 2018, multiple harvesting preserved 22% of the potential yield before Hurricane Michael hit.

The CMHP had the lowest yields for both DP1612 and 1646, which created the lowest revenue for DP1646 at the stripper harvested location. DP1612 was able to overcome the lowest yields amongst treatments to produce the highest revenues among treatments at the stripper-harvested location. The CMHP loan values were statistically similar to the end of the season 2M harvest treatment. Both handpicking methods were superior to the machine and cleaned methods for both cultivars. Bowman et al. (2011) reported a 37.2 kg yield increase with stripper harvested cotton in High Plains of Texas compared to picker harvested cotton due to the aggressive nature of stripper harvesters. However, picker harvesting preserved the fiber quality better, resulting in $0.011 more value per kg of lint. Development of a robotic harvester has the potential to further preserve the fiber quality and provide additional return on investment for growers.

At the picker sites, CMHP created the highest revenue and loan values for all three cultivars and comparable or higher lint yields. Notably, CMHP would likely also cost less to gin due to decreased foreign matter. The end-of-season harvest methods were generally similar for all the fiber quality characteristics. This indicates that much of the fiber quality loss is attributable to the weathering of the cotton in the field. Future research on cottonseed quality should also be taken into consideration.

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CHAPTER IV

EFFICACY OF RECOVERY SPRAYS TO COTTON INJURED BY SYNTHETIC AUXINS

Auxin-resistant traits in cotton are widely used across the Cotton Belt for control of glyphosate-resistant and other troublesome weeds. With these new traits, off-site movement and spray tank contamination of auxins has become a major concern for all agriculturalists, especially in south and east Texas where both XtendFlex® and Enlist® cotton cultivars have significant market share, 67 and 21% respectively (USDA, 2018). The objective of this project was to identify the efficacy of recovery sprays from induced injury of dicamba and 2,4-D. Rates of 56.1 g and 4.1 g of a.i. ha^{-1} of dicamba and 2,4-D, respectively, were applied on their respective field portions to FiberMax® 1953 GLTP at the first bloom stage. Early visual ratings of the dicamba trial indicated a high rate of overall foliage injury and stunting. The 2,4-D injury symptomology included taller plants with longer internodes. Plants injured by both auxin herbicides displayed high levels of first position fruit loss, retaining 58% and 73% for 2-4-D and dicamba in 2017, respectively compared to the UTC. In the 2018-2019 study, the 2,4-D and dicamba injured plots retained only 47 and 51% first positions, respectively compared to the UTC.

In 2017, three dicamba recovery products showed some encouraging results, including mepiquat chloride, N-Demand + Advantigro, and Radiate, with significantly higher yields than other recovery treatments. This trend was not present for 2018 or 2019, as none of the recovery treatments produced yields comparable to the untreated check. For all three years of the 2,4-D trial, all the recovery treatments were comparable in yield and none of treatments improved yields, although in 2017, the auxin-only treatment resulted in similar lint yields as the untreated check.

Introduction

Palmer amaranth (*Amaranthus palmeri*) and tall waterhemp (*A. tuberculatus*) are two weeds that are notorious for developing resistance to multiple herbicides (Riar, et al., 2013). Control of these *Amaranthus* species should be performed before the weeds reach 10 cm in height (Norsworthy et al., 2012). The only consistent control mechanism beyond this height is mechanical removal. Effective weed management options are decreasing with the discovery of Protoporphyrinogen oxidase (PPO) inhibitor resistance (Salas et al., 2016), preceded by the discovery of glyphosate resistance in 2006 and Acetolactate synthase (ALS) inhibitor resistance in 1992 (Gaeddert et al. 1997; Culpepper et al., 2006). Resistance of *A. tuberculatus* (tall waterhemp) to synthetic auxins has already been identified in Illinois and Nebraska (Heap, 2019) More recently, waterhemp has been reported to be resistant to mitosis inhibitors (Group 15 herbicides), namely S-metolachlor, in Illinois (Smith, 2019). As additional weeds develop resistance to more herbicide sites of action, researchers, producers, consultants, and agriculture chemical manufacturers are increasingly concerned with the diminishing efficacy of synthetic auxins. Norsworthy et al. (2012) outlined 12 herbicide best management practices for the preservation of herbicide modes of action, including methods to reduce field seedbanks, correct herbicide application, and other methods of field weed control.

Despite the broad-spectrum weed control of synthetic auxins, such as dicamba and 2-4-D, off-site movement is a major concern. Herbicides move off-site by three primary mechanisms: volatility, physical drift, and temperature inversions. Volatility occurs when an herbicide lands on the intended target as a spray solution but changes to a gaseous state then moves off-site. Physical spray-particle drift occurs when the carrier droplet sizes are typically less than 200 microns, and pushed by wind to an undesired location (Al-Khatib, 2019). Application of herbicides at lower wind speeds reduces the occurrence of physical drift (Carlsen et al., 2006). Furthermore, lower application pressures, slower applicator speeds, and appropriate nozzle selection reduce the quantity of fine droplets, while still maintaining the same carrier volume. Due to their lighter physical weight, small droplets take longer to fall to the target, and are more easily moved by lower wind speeds. Increased herbicide carrier volumes have shown a reduction in off-site drift injury (Ellis, Griffin, and Jones, 2016; Banks and Schroeder, 2002). Lower boom heights also assist in minimizing off-site movement due to decreasing the travel distance prior to reaching the target site; therefore, less drift occurs. The third primary mechanism of off-target movement is temperature inversions. Temperature inversions develop in the troposphere when warmer air is layered between cooler air layers. These layers create boundaries that restrict upward movement and disbursement of smaller carrier droplets that can then be blown horizontally onto undesired target areas at greater concentrations. Wind speeds above 4.8 kph (3 MPH) allow air layers, through convection, to properly mix, reducing the concentration of the herbicide.

Compounding the off-site movement concern is the sensitivity of cotton to 2,4-D and dicamba compared to other herbicides. With the 2,4-D amine and dicamba dimethylamine salt formulations, rates as low as 0.06 and 0.28 g ai ha^{-1}, respectively, cause visual herbicide injury to cotton foliage (Everitt and Keeling, 2009). Cotton injury at higher rates of 2,4-D and earlier in the cotton plant’s life cycle increases yield loss (Miller et al., 1963). Byrd et al. (2016) posed two interesting question regarding dynamics of 2,4-D injury on cotton plants that have yet to be researched: does increased water stress magnify injury and does a cotton cultivar’s maturity affect lint yield, where later-maturing varieties have more opportunity to compensate following early-season injury? An Egan et. al (2014) meta-analysis found a dicamba tank contamination application of 56 g ha^{-1} and particle drift equating to 5.6 g ha^{-1} will cause yield reductions of 64.2% and 54.5%, respectively, when the cotton is at the flowering stage. However, capturing exact acreage affected by auxin drift is extremely challenging. Incidents of drift, either residential or agricultural, often go unreported through the regulatory channels. A meta-analysis from Egan et al. (2014) surmised visual herbicide injury from dicamba (r^2=0.001) does not correlate to actual yield, regardless of growth stage on cotton plants. On the contrary, visual injury from 2,4-D has a stronger correlation to yield loss for cotton plants (r^2=0.32). The correlation of yield to either auxin visual injury was less for cotton than soybean. Marple et. al (2007) demonstrated that 2,4-D caused the greatest visual injury and yield loss of cotton of the seven synthetic auxin herbicides tested.

Steps have been taken to minimize off-site movement of herbicides. Products containing dicamba diglycolamine or dimethylamine salts, designed for lower volatility and in-season use, were labeled as restricted-use pesticides in 2018. An applicator must complete restricted-use pesticide and synthetic auxin training; keep records on wind speeds, application timing, and tank cleanout events; and document crops surrounding the application site. Dicamba-containing products, such as Engenia® (BASF, 2019), FeXapan® (Corteva, 2019) and, Xtendimax® (Bayer, 2019), may only be applied twice over-the-top, between one hour after sunrise and two hours before sunset, up to sixty days after planting cotton. The application of synthetic auxins must have a minimum spray volume of at least 142 liters per hectare (15 GPA), use a sprayer speed above 24 kilometers per hour (15 MPH), be made between wind speeds of 4.8 and 16 kilometers per hour (3 and 10 MPH), and be applied with approved nozzles and tank-mix partners (Bayer Ag, 2019).

These strict label requirements make timely application of synthetic auxins to small weeds difficult. Hartzler (2017) demonstrated that only half of the days in the last week of May in Iowa meet the label requirements of synthetic auxins due to rainfall or wind speed. Two weeks later, in mid-June, wind and field conditions improved, but average daily temperatures were elevated. Higher temperatures or lower relative humidity increase the chances for volatility (Behrens and Lueschen, 1979) which is seen throughout much of the cotton belt. Further complicating the application timing are unexpected temperature inversions (Grant and Mangan, 2019), which occur throughtout agriculture landscapes worldwide.

From realizing the challenges farmers face attempting to apply auxin chemistries within weather-generated time restraints, cotton’s sensitivity to auxins, and the proven fact offsite movement will occur, this study was created. Furthermore, farmers have and will likely continue to attempt to use products to remediate auxin injury to their cotton. The objective of this study is to evaluate the potential of commercially available treatments to improve cotton's recovery and increase lint yield following injury from dicamba or 2,4-D.

Materials and Methods

The study was conducted at the Texas A&M AgriLife Research Center at Snook, TX (GPS coordinates for 2017: 30º32'52" N -96º25'57" 2018: 30°32'57"N -96°26'11"W, and for 2019: 30º32'52" N, -96º25'56" W). In 2018, the study was planted on May 3rd into a Ships Clay (very-fine, mixed, active, thermic Chromic Hapluderts) soil. In 2017 and 2019, the study was planted on April 25th and April 30th, respectively, both into Belk clay (fine, mixed, active, thermic Entic Hapluderts). A transgenic cotton cultivar, tolerant of glyphosate and glufosinate, but not tolerant of synthetic auxins, FiberMax® 1953GLTP (BASF Ag, 2019) used for the study. FiberMax® 1953GLTP seed had a reported germination rate of 80%, size was 9,858 seeds kg^{-1}, and was treated with COPeO Prime™ Aeris Trilex Advanced® which contains metalaxyl, triadimenol, thiodicarb, fluopyram, imidacloprid, trifloxystrobin, myclobutanil, ipconazole and penflufen. Plots were managed for 1700 kg ha^{-1} lint yield with furrow irrigation using the recommended Texas AgriLife fertility levels of 168, 34, 34, 4.5, and 6.7 kg ha^{-1} of nitrogen, phosphorus, potassium, zinc and sulfur, respectively, and by the Integrated Pest Management (IPM) strategies outlined in the "Managing Cotton Insects in Texas" publication (Vyavhare et al., 2018). All plots received a two-shot harvest aid application at 75% open bolls. The first harvest aid application consisted of thidiazuron at 83.3, tribufos at 312.5 and ethephon at 1,197.6 g of ai ha^{-1}. The second harvest aid application consisted of thidiazuron at 83.3 and tribufos at 312.5 g of ai ha^{-1}.

The two separate trials, one using dicamba and the other using 2,4-D, were designed as randomized complete block designs (RCBD) with four replications. Each of the 40 individual plots in each study consisted of four 12.2-m long rows with 1-m spacing. Each trial included an untreated check (UTC) receiving no synthetic auxin, synthetic auxin spray only (2,4-D or dicamba), and eight recovery treatments (Tables 4.1 and 4.2). Once 50% of cotton plants in the field reached first bloom, a N,N-Bis-(3-

aminopropyl) methylamine formulation of dicamba and a quaternary ammonium salt formulation of 2,4-D, were applied to specified plots at 56.1 (1/10th of recommended rate) and 4.1 (1/200th of recommended rate) g of a.i. ha^{-1}, respectively. Carrier volume was 140 L ha^{-1}. These dicamba and 2,4-D rates correspond to off-site and tank contamination scenarios, respectively, in accordance with Byrd et al. (2016) and Everitt and Keeling (2009) and intended to create 50% yield loss. Seven days after the 2,4-D or dicamba were applied to create the injury in cotton, the collective treatments, referred to as "recovery" treatments throughout the remainder of the dissertation, were applied. Eight recovery treatments were evaluated in 2017, and seven recovery treatments were evaluated for both 2018 and 2019. The recovery treatments were applied to the center two rows of each plot with a pressurized backpack hand boom applicator at 140 L ha^{-1}. The recovery products were categorized in two distinct groups: hormonals and nutritionals. These products were carefully selected from discussion with industry representatives, farmers, plant physiologists, and literature searches. The rationale of these product selections was to aid synthetic auxin decomposition and suppression or aid the plant in more rapidly commencing normal growth after injury. For the 2018 and 2019 studies, a higher fertility treatment was included as a side-dress application of N, P, K, S, and micronutrients, 0.4, 1.5, 10, and 1.8%, respectively above the UTC levels.

Table 4.1. Trade name of products (active ingredients), their rates, and representative treatment numbering administered for the Synthetic Auxin Injury Study for 2017 study.

Treatment	Products (a.i.)[1]	Manufacturer	g of a.i. L^{-1}	Rate (L Ha^{-1})
1	Untreated Check (UTC)			
2	Engenia®, Enlist® (dicamba and 2,4-D) only	BASF®, Corteva®	600, 455	0.090, 0.006
3	Mepiquat (Mepiquat Chloride)	Loveland Products®, Inc.	42	1.1315
4	Pentia® (Mepiquat Pentaborate)	BASF®	98	1.754
5	Palisade®(Trinexapac-ethyl)	Syngenta® Chemical Co.	120	1.681
6	Megafol® (3-0-8)	Valagro®		1.754
7	Radiate® (IBA and Kinetin)	Loveland Products®, Inc.	21.5, 3.8	0.356
8	CoRoN® (25-0-0)	Helena Chemical Co.®		9.354
9	Finish-Line® (8-4-6-.1B-.2Cu-1Mn-1Zn)	Nachurs®		2.339
10	NDemand88® (10-8-8-2S-.25B-.06Cu-.25Mn-.25Zn)	Wilbur-Ellis®		4.677
	+ Advantigro® (Kinetin, IBA, GA)			0.2923

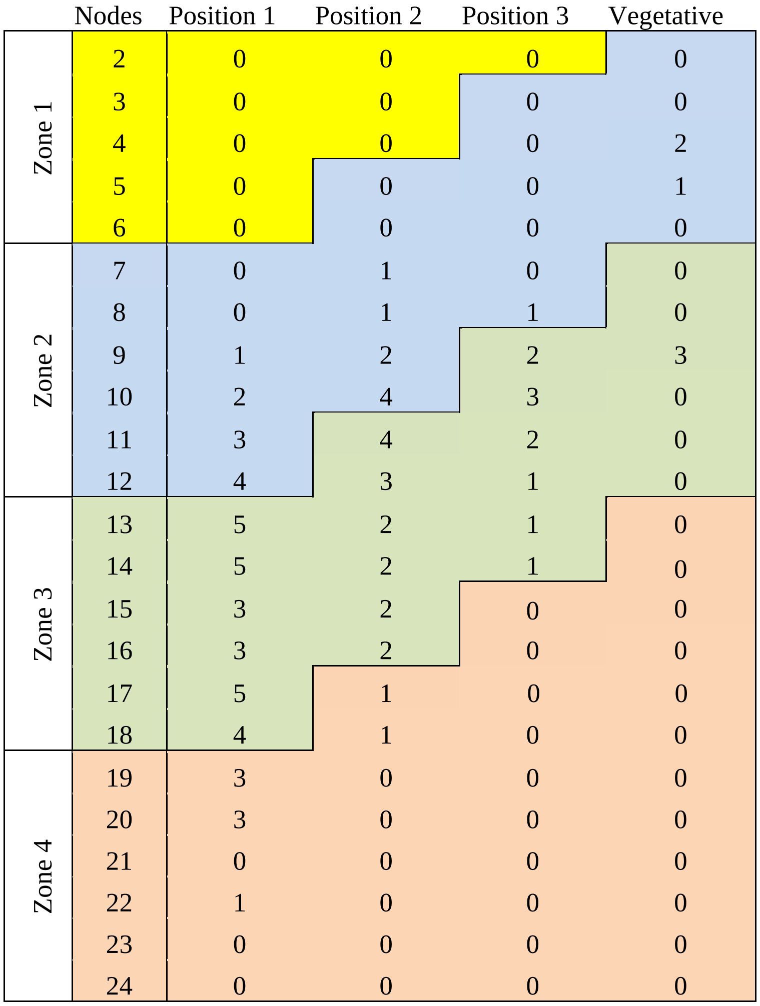
[1]Active Ingredients

Table 4.2. Trade name of products (active ingredients), their rates, and representative treatment numbering administered for the Synthetic Auxin Injury Study for 2018 and 2019 synthetic auxin injury study.

Treatment	Products (a.i.)[1]	Manufacturer	g of a.i. L^{-1}	Rate (L ha^{-1})
1	Untreated Check (UTC)			
2	Engenia®, Enlist® (dicamba and 2,4-D) only	BASF®, Corteva®	600, 455	0.090, 0.009
3	Mepiquat (Mepiquat Chloride)	Loveland Products®, Inc.	42	1.1315
4	D-Aspartic Acid	GNC®		11.5 g/ 1.94 of H_20
5	L and D-Aspartic Acid	GNC®		11.5 g/ 1.94 of H20 each
6	N-Pact® (25-0-0)	Loveland Products®, Inc.		9.354
7	Radiate® (IBA and Kinetin)	Loveland Products®, Inc.	21.5, 3.8	0.585
8	ProGibb® 4% + NutriSync® Ca	Valent® + Loveland Products®, Inc.		0.438 + 4.677
9	Treatment 6 + Treatment 8			
10	Liquid Side-dress K-fuel® (0-0-24) + NDemand88 (10-8-8 + micro's)	Nauchur's®+ Wilbur-Ellis®		9.354 + 4.677

[1]Active Ingredients

Visual ratings for crop injury and recovery were made 14 days and 75 days (7 days prior to harvest aid application) after the recovery spray application. Percent visual injury ratings were on a scale of 0-100%, for epinasty, leaf elongation, chlorosis and necrosis of leaf tissue, and reduction or addition of plant heights, compared to the UTC. Following harvest aid application, five consecutive plants were removed from the center of each plot for plant mapping. For each cotton plant, retained or aborted fruit structure, internode length, height, and total nodes were recorded. Aggregate total boll zone mapping was also compiled to analyze effects of the treatments on fruiting position architecture. Cotton plants were split into 4 zones (Figure 4.1) and staggered by node and fruiting position to represent similar overlapping fruiting periods created from the each of the plot's five samples and averaged. Total boll numbers were taken from these zones. Zone total boll counts from each of the plot's five plants sampled were analyzed by zone and treatment. The aggregated four zones were analyzed for resolution of fruiting pattern due to a cotton plant's expected and probable fruiting pattern (Miley and Oosterhuis, 1990). Vegetative bolls were included in the zone total due to increased upper node vegetative bolls produced from auxin injury.



	Nodes	Position 1	Position 2	Position 3	Vegetative
Zone 1	2	0	0	0	0
	3	0	0	0	0
	4	0	0	0	2
	5	0	0	0	1
	6	0	0	0	0
Zone 2	7	0	1	0	0
	8	0	1	1	0
	9	1	2	2	3
	10	2	4	3	0
	11	3	4	2	0
	12	4	3	1	0
Zone 3	13	5	2	1	0
	14	5	2	1	0
	15	3	2	0	0
	16	3	2	0	0
	17	5	1	0	0
	18	4	1	0	0
Zone 4	19	3	0	0	0
	20	3	0	0	0
	21	0	0	0	0
	22	1	0	0	0
	23	0	0	0	0
	24	0	0	0	0

Figure 4.1. Nodes by Fruiting Positions Divided into Four Zones from 2019 Auxin Recovery Planting Mapping Data from College Station, TX.

The center two rows of each plot were harvested with a 2-row John Deere® 9920 spindle picker (John Deere, 2019). Plot weights were recorded from each plot with the onboard harvester scale. A 120 g sample was ginned on a 20-saw tabletop gin, with no lint cleaning, to establish lint turnout and lint weight per hectare and evaluate fiber quality. Fiber samples were packaged and HVI analysis was conducted by the Fiber and Biopolymer Research Institute (FBRI) in Lubbock, TX within 45 days of harvest.

Mixed linear models (PROC MIXED, SAS v9.4) were used to perform an analysis of variance. Replications and years were applied as random effects and treatments as fixed effects. The 2017 data (Table 14) were analyzed separately due to the modification of the treatment list for 2018 and 2019. Fisher's protected least significant difference (LSD) was used to compare treatment means.

2018 Greenhouse Project

A greenhouse study was established in the spring of 2018 at the Borlaug Center for Southern Crop Improvement, College Station, TX. The purpose of the greenhouse study was to reevaluate products used in the 2017 field protocol as well as potentially identify new, more beneficial treatments for the 2018 field study. The greenhouse mean temperature was 25.1°C (range 16.8°C - 28.2°C) and relative humidity was 59.5%. Light was provided for 10 hours per day either by natural sunlight or artificial light. Plants were watered every 3 days. The water pH was 5.6 and the water filtering system removes 98% of the nitrates, microorganisms, and other chemicals. Forty-eight pots (12 recovery treatments, 2 soil media, and 2 auxins) were planted with three seeds of FiberMax® 1953GLTP (same as field trials) and then later thinned at cotyledon stage to a single seedling per pot. After a literature review and discussions with a plant physiologist, a total of twelve recovery products were selected and evaluated in this study for each synthetic auxin (Table 4.3). Two fertility levels were also tested, with fertilizer incorporated (Miracle Gro, 2019) in one pot for each treatment, representing a high fertility regime, and the other using a sterile media (Pro-Mix, 2019) with a low amount of fertilizer (15 g 20N-20P-20K) at the initiation of the 3rd node, representing a lower fertility regime. Both soil media will receive 15 g 20-20-20 at the 8th node and 4 weeks prior to the herbicide injury being induced by either 2,4-D or dicamba. Pots were arranged in a completely randomized design.

Table 4.3. Products, rates applied, and representative treatment numbering administered for the greenhouse synthetic auxin injury study in College Station, TX in 2018.

Treatment Number	Products	Rate (ha^{-1})	Manufacturer
1	1-MCP	45.5 kg	AgroFresh
2	2,4,6-trichlorobenzoic acid	0.5 kg	Sigma Life Sciences
3	Hand topping	N/A*	N/A*
4	Silver Solution 12ppm	5 L	Sigma Life Sciences
5	L-glutamic acid	11.25 kg	GNC
6	L-Aspartic acid	5 kg	Source Naturals
7	D-Aspartic acid	5 kg	AI Sports Nutrition
8	L- and D-Aspartic Acid	5 and5 kg	GNC
9	Aspartame	1 kg	Spring Valley
10	Untreated Control (UTC)		
11	Auxin Only (dicamba, 2,4-D)	56.1, 4.1 g	BASF, Corteva
12	Melatonin	1.25 kg	Spring Valley

*Plants will be cut between the second and third node below the apical meristem of the main stem.

Dicamba or 2,4-D was independently applied at 140 L ha^{-1} carrier volume using 8002XR tips, which were cleaned and flushed with a water: acetone solution between treatments, on all treatments except treatment 10 (UTC). Greenhouse plants were bought to an outdoor location to be sprayed by the initial auxin treatments. The two plants receiving each individual recovery product were spaced one meter apart to ensure similar spray coverage. The auxin herbicides were applied when 50% of cotton plants reached first bloom. Eight days later, the recovery treatments were applied to the auxin-injured cotton plants at an outside location and spaced one meter apart.

Measurements of height; total nodes; height to node; total numbers of bolls, flowers, squares, malformed squares and flowers, and other relevant observations were made 14 and 30 days after recovery spray application. The two treatments with the most fruiting positions, indicating some recovery from the auxin injury, were selected to be included in the field experiment for 2018 and 2019.

RESULTS AND DISCUSSION

2,4-D Injury

In 2017, the visual injury rating from the 2,4-D alone at 14 DAA was 36%, while the recovery treatments ranged from 35 to 45% (Table 17). By the end of the season, about 60 days after the induced 2,4-D injury, the cotton visual ratings improved for all treatments, ranging 25 to 38%. This reduction in visual symptoms indicates the plasticity of the cotton plant, and its ability to recover from systemic herbicide injury. At the end of the season (EoS), nearly all the leaf deformation and leaf strapping symptoms were concentrated on the main stem with the newest growth, while lower reproductive and vegetative branches showed few symptoms. By the EoS the mean visual ratings for 2,4-D alone was 30% and the mean across the recovery treatments was comparable at 31%. However, some statistical differences between recovery treatments were observed. The UTC remained the only treatment that statistically differed from all other treatments. Among the recovery treatments at EoS, Palisade recovered the least (38%) 14 DAA and had significantly more injury than the recovery sprays of CoRoN, Radiate, Megafol, and Mepiquat Chloride. Megafol had the least visual injury (25%) and was significantly lower than the recovery sprays of Palisade, Mepiquat Chloride and N-Demand + Advantigro. However, none expedited or mitigated the auxin injury when comparing to the auxin-only treatment.

The 2017 2,4-D yield results generally coincided with the EoS visual ratings for crop injury, where difference between only the 2,4-D only and Palisade recovery treatment having the lowest yields by 248 kg ha^{-1} or a 27% yield loss% (Table 4.4). The 2,4-D injured treatments averaged 310 kg ha^{-1} less than the UTC which was a 30% yield reduction. None of the recovery treatments statistically improved yield compared to the 2,4-D only treatment which yielded 116 kg ha^{-1} (13%) higher than the average of the recovery treatments. With less range in 2,4-D injury among the treatments included in this trial, higher visual injury to lint yield loss was observed as compared to Everitt and Keeling (2009), who demonstrated a -0.51 and -0.45 correlation between cotton lint yield and visual 2,4-D injury visual ratings at the 14

DAA and EoS timings respectively.

Table 4.4. The 2017 cotton response to applications of 2,4-D injury and recovery sprays evaluated by 14 days after application and end of the season visual ratings and lint yield

		Cotton Response					
		Visual Injury Ratings % (SD)					
	Products	14 DAA[1]		End[2]		Lint Yield (kg ha^{-1})	
	Untreated	0 B	(0.0)[3]	0 E	(0.0)	1147 A	(177.5)
	2,4-D Only	36 A	(11.1)	30 A-D	(9.3)	915 AB	(145.6)
2,4-D @ 0.009 L ha^{-1} fb;	CoRoN[4]	45 A	(11.5)	29 BCD	(6.0)	901 BC	(203.2)
	Pentia	38 A	(17.6)	26 CD	(9.5)	859 BC	(83.9)
	Radiate	43 A	(8.7)	26 CD	(9.0)	839 BC	(161.5)
	Megafol	35 A	(14.7)	25 D	(2.2)	813 BC	(202.7)
	Finish-Line	40 A	(10.8)	33 A-D	(7.5)	792 BC	(201.0)
	Mepiquat Chloride	38 A	(9.6)	36 AB	(4.3)	789 BC	(130.5)
	N-Demand 88 + Advantigro	45 A	(8.2)	35 ABC	(4.8)	730 BC	(82.0)
	Palisade	41 A	(11.8)	38 A	(5.4)	667 C	(75.3)
	Avg. of recovery treatments	41		31		799	
	CV%	10.9		11.6		4.6	
	LSD (0.05)[5]	17.3		9.4		242.0	

[1] Days after recovery application

[2] End of the season ratings were made one week prior to harvest aid application

[3] Numbers in parenthesis are standard deviations

[4] Recovery products are listed in order of high to low yield

[5] LSD numbers were computed using Fisher's Protected LSD at alpha=0.05

The preliminary screening of products from the 2018 greenhouse study showed silver nitrate solution having the greatest amount of cotton bolls and new squares; however, this product was eliminated due to excessive product cost for field application (data not shown). The next highest total of fruiting sites came from the treatment of L- and D-Aspartic Acid with thirteen fruiting positions. The high fertility soil produced more bolls (0.43) and new squares (2.07) per plant than the low fertility media. Due to these impressive numbers, a treatment of adding nutrients, P and K as a liquid side-dress, was included in the 2018 and 2019 field studies.

The average 2018 and 2019 2,4-D visual injury ratings at 14 DAA were considerably less than the 2,4-D ratings in 2017 (Tables 4.5 and 4.6). The delayed onset of 2,4-D injury is suspected to be the result of drier soil conditions and high temperatures leading up to and following the 2,4-D application in both 2018 and 2019 compared to 2017. This delayed observation of symptomology has been reported by Devkota, (2019) and Wiese and Rea (1962), where hot, dry conditions slow effects of systemic herbicides. Like 2017, the 2018-2019 injury ratings at 14 DAA were significantly higher for all the injured treatments than the UTC by 6-13%. Of the recovery treatments, the ProGibb + foliar calcium had the highest numerical injury (13%) but was statistically not different from all the other treatments, except for Mepiquat chloride, D-Aspartic Acid, and the P and K liquid side-dress treatment. The P and K side-dress had the least visual injury and was significantly different than the ProGibb + foliar calcium + N-Pact and the ProGibb + foliar calcium.

EoS visual injury increased by 3-4-fold from the 14 DAA rating and ranged from 28-41%. All differences observed at 14 DAA had dissipated by the EoS ratings, where all had comparable injury to the 2,4-D alone.

In 2018-2019, the yields from the 2,4-D alone (679 kg ha^{-1}) and mean recovery treatments (684 kg ha^{-1}) were comparable and were 61% lower than the UTC (Table 4.5). Similar to the visual injury ratings, no statistical differences in cotton yield were observed between the 10 recovery treatments. The highest numerical yielding treatment was the phosphorus and potassium liquid side-dress, while the lowest yielding was N-Pact, at 787 and 608 kg ha^{-1} respectively. Four recovery treatments yielded numerically higher than the 2,4-D only treatment, which was 679 kg ha^{-1}. In cotton, auxin injury at drift comparison rates can cause up to 40% yield reduction if damaged by 2,4-D at first bloom (Byrd et al. 2016). These previous findings were in accordance with our 2018-2019 trials (61.7% loss) and the 2017 study (20% loss), as the site-year effect on yield losses due to 2,4-D varied greatly.

Table 4.5. The 2018-2019 cotton response to applications of 2,4-D injury and recovery sprays evaluated by 14 days after application and end of the season visual ratings and lint yield.

		Cotton Response					
		Visual Injury Ratings % (SD)					
	Products	14 DAA[1]		End[2]		Lint Yield (kg ha^{-1})	
	Untreated	0 D	0.0	0 B	(.)	1773 A	(217.9)
	2,4-D	9 ABC	(5.2)	38 A	(15.9)	679 B	(368.0)
2,4-D @ 0.009 L ha^{-1} fb;	P and K Liquid Side-dress	6 C	(4.7)	28 A	(18.0)	787 B	(466.7)
	L and D-Aspartic Acid	9 ABC	(3.8)	40 A	(16.7)	723 B	(393.6)
	D-Aspartic Acid	7 BC	(5.0)	32 A	(15.4)	706 B	(406.5)
	ProGibb + Foliar Ca + N-Pact	11 AB	(6.5)	41 A	(17.3)	689 B	(358.0)
	ProGibb + Foliar Ca	13 A	(6.9)	35 A	(15.9)	667 B	(344.5)
	Mepiquat Chloride	7 BC	(4.4)	39 A	(18.4)	664 B	(399.5)
	Radiate	10 ABC	(5.7)	33 A	(17.6)	628 B	(342.4)
	N-Pact	10 ABC	(4.9)	40 A	(16.3)	608 B	(310.9)
	Avg. of recovery treatments	9		36		684	
	CV%	13.0		11.2		13.2	
	LSD (0.05)	5.0		16.0		365.2	

[1] Days after recovery application

[2] End of the season ratings were made one week prior to harvest aid application

[3] Numbers in parenthesis are standard deviations

[4] LSD numbers were computed using Fisher's Protected (α=0.05)

The 2,4-D injured plants had a higher percentage of vegetative bolls in 2017 compared to the UTC (Figure 4.2). Despite a 55 to 67% reduction in lint yields compared to UTC, some treatments had higher total boll counts. However, the UTC first position boll counts were higher, 7.1 compared to a 4.2 average across all other treatments. Fruiting positions from auxin-injured plants were consistently delayed to upper fruiting branches, resulting in smaller bolls and immature bolls. While these bolls were more numerous, the lighter weight accounted for less yield, compared to the UTC. In 2017, a difference in 3rd position bolls between CoRoN (1.55) and Pentia (0.45) and N-Demand + Advantigo (0.35) was observed. Finish-Line and Radiate showed significantly higher vegetative bolls than the 2,4-D alone (Figure 4.2). The 2018 and 2019 UTC retained a greater number of first and second position bolls than the 2,4-D injured cotton (Figure 4.3). This was due to sympodial branches' apical meristem loss from the synthetic auxin application injury. The loss of apical dominance of the sympodial branches and main stem was diverted to the monopodial branches causing more upper node vegetative bolls.

There were no significant differences for the combined 2018-2019 years for total bolls (Figure 4.3) The only statistical difference in 2018 (data not shown) was the 2,4-D only treatment, which had the most total bolls, 16.3, of all the treatments. Furthermore, the UTC had 15.2 total bolls, but these were a high percentage of 3rd position bolls relative to other treatments.

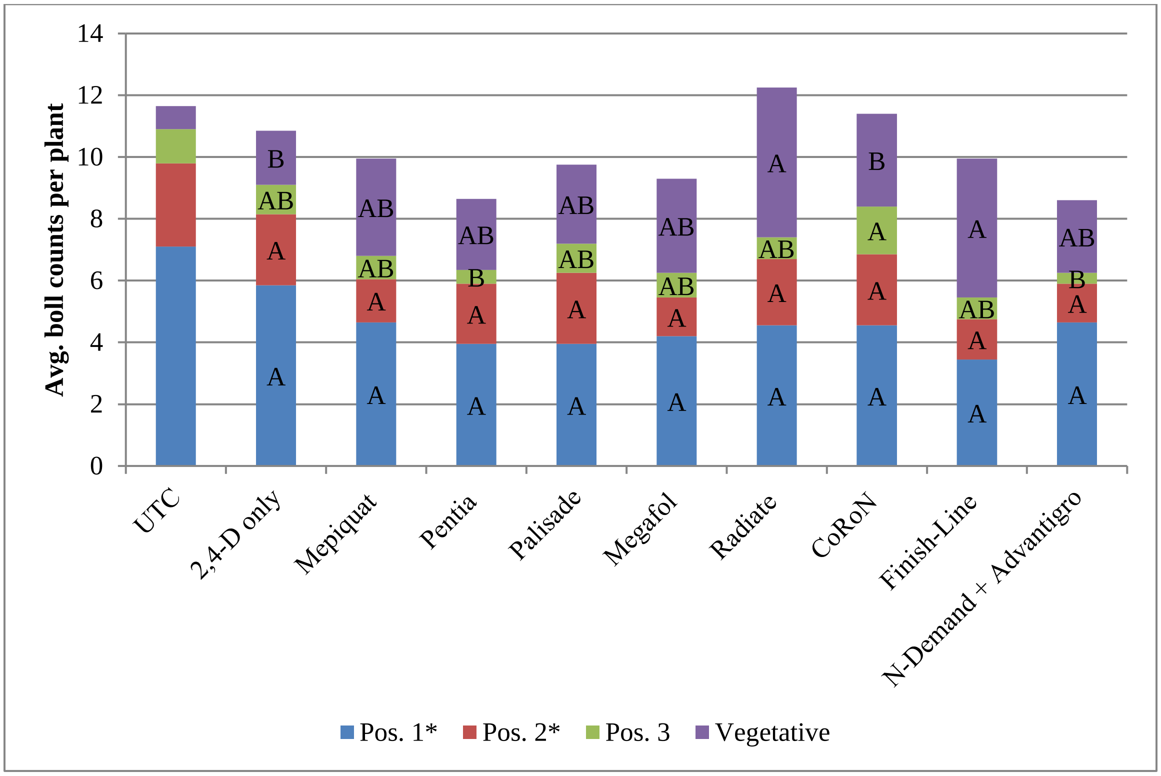


Figure 4.2. The 2017 average boll counts by cumulative fruiting position from 2,4-D injury recovery treatments conducted in College Station, TX. Treatments are ordered based on high (left) to low (right) lint yield. Only plots receiving 2,4-D injury are represented by means comparison lettering. *Positions 1, 2 and total bolls have no significant differences among the auxin only and recovery products.

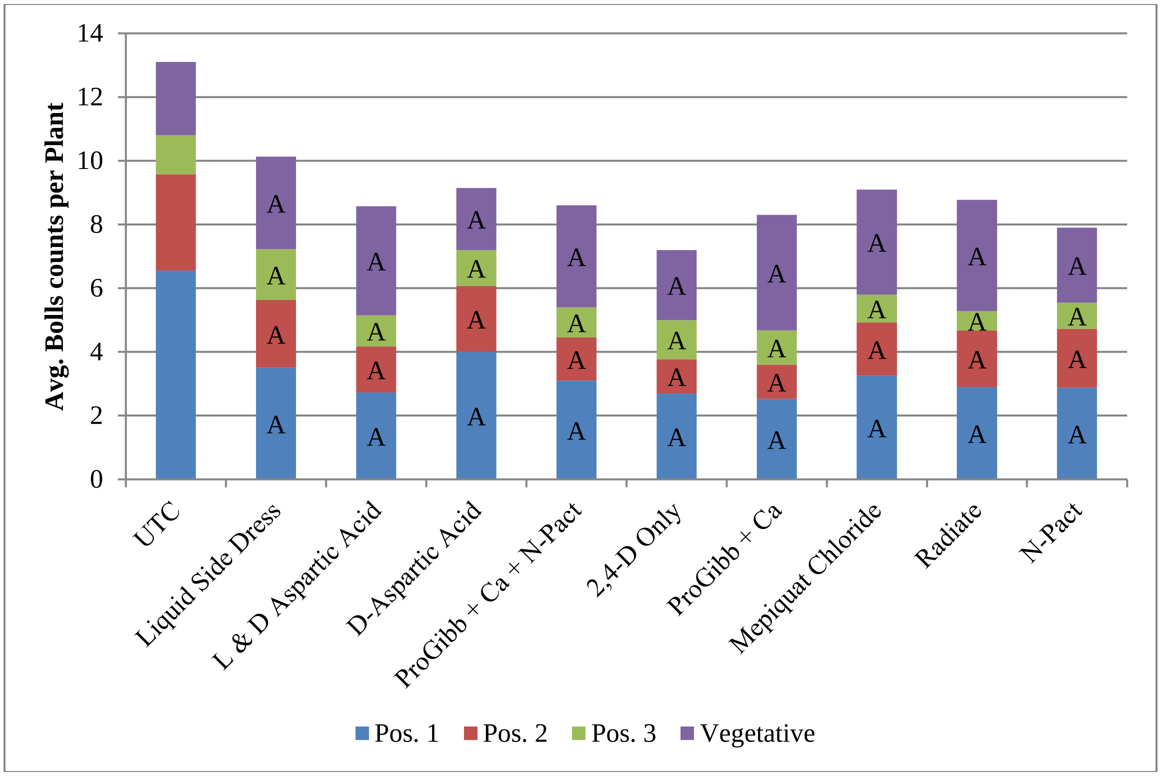


Figure 4.3. 2018 and 2019 2,4-D study combined average number of bolls per plant by cumulative fruiting position from each auxin injury recovery study and treatment conducted in College Station, TX. Treatments are ordered based on high (left) to low (right) lint yield.

In 2019, the ProGibb + Foliar Ca and N treatment, foliar nitrogen (N-Pact) and the D-Aspartic Acid treatment 2,4-D recovery treatments were able to retain first position bolls at a rate of 40 to 50% on first fruiting branch nodes but then boll retention numbers severely dropped after these nodes (Figure A1).

In 2017, plant mapping data showed Radiate (4.7) and Finish-Line (4.2) resulted in the greatest number of Zone 1 bolls. In zone 2, the UTC (6.1) had significantly higher bolls counts than mepiquat chloride (4.85) and Finish-Line (3.5). In Zone 3, the UTC (4.2) had more significant boll counts for all recovery products except for Pentia and Radiate. The 2,4-D only (1.7) application resulted in the greatest amount of bolls in Zone 4 and was only significantly higher than UTC (0.4), Pentia (0.2), and N-Demand + Advantigo (0.4). The plant mapping in 2018 only noted a significant difference in Zone 4 from the UTC (2.1) and the 2,4-D only (4.1) application.

From the 2019 zoned plant mapping data, significant differences were only found between the UTC and other treatments. For zone one, UTC (0.3) was different from the 2,4-D only (0.0) treatment, N-Pact (0.0), and liquid side-dress (0.25). In zone two, the UTC (4.8) was the highest and was different from all applied products except the ProGibb + Foliar Ca + N-Pact (3.45) treatment. Zone three had the greatest separation among the treatment levels as the UTC had 26.25 average bolls and was different from all others. 2,4-D only was the next closest treatment with 6.25 average total bolls. Again, in zone four, the UTC (0.7) had the highest number of bolls but was not different from mepiquat chloride (0.2) or the two aspartic-acid treatments with 0.2 boll.

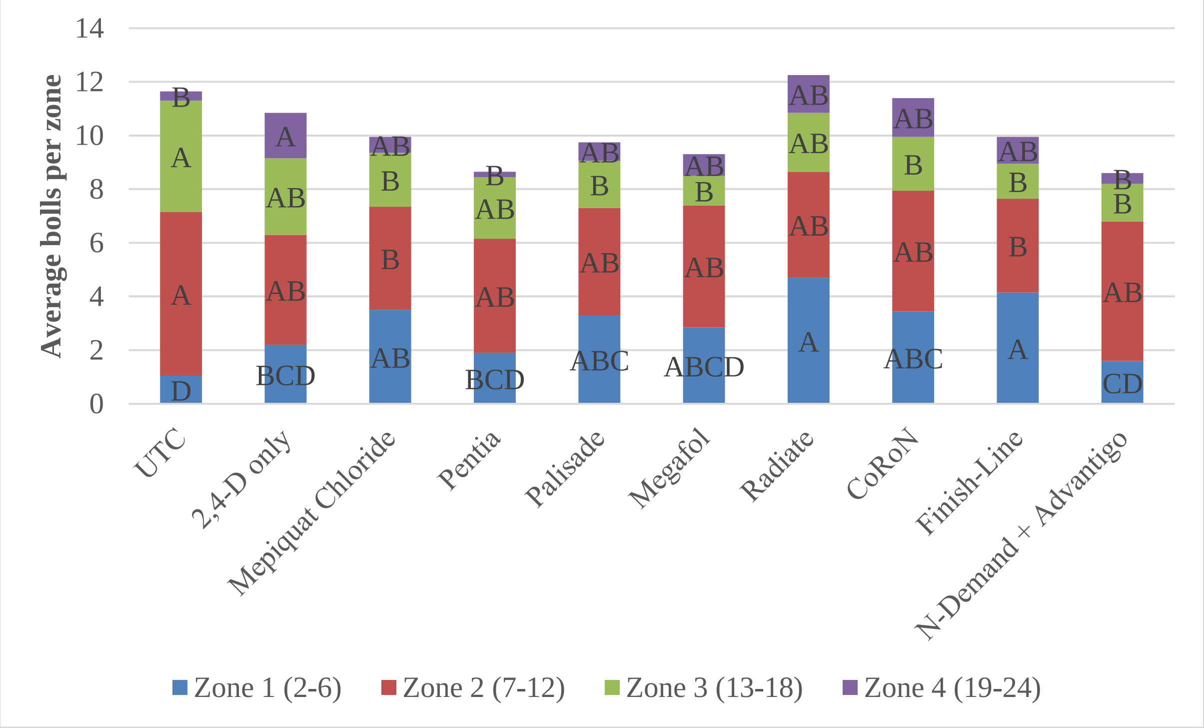


Figure 4.4. 2,4-D recovery compare means between zones and treatments for 2017.

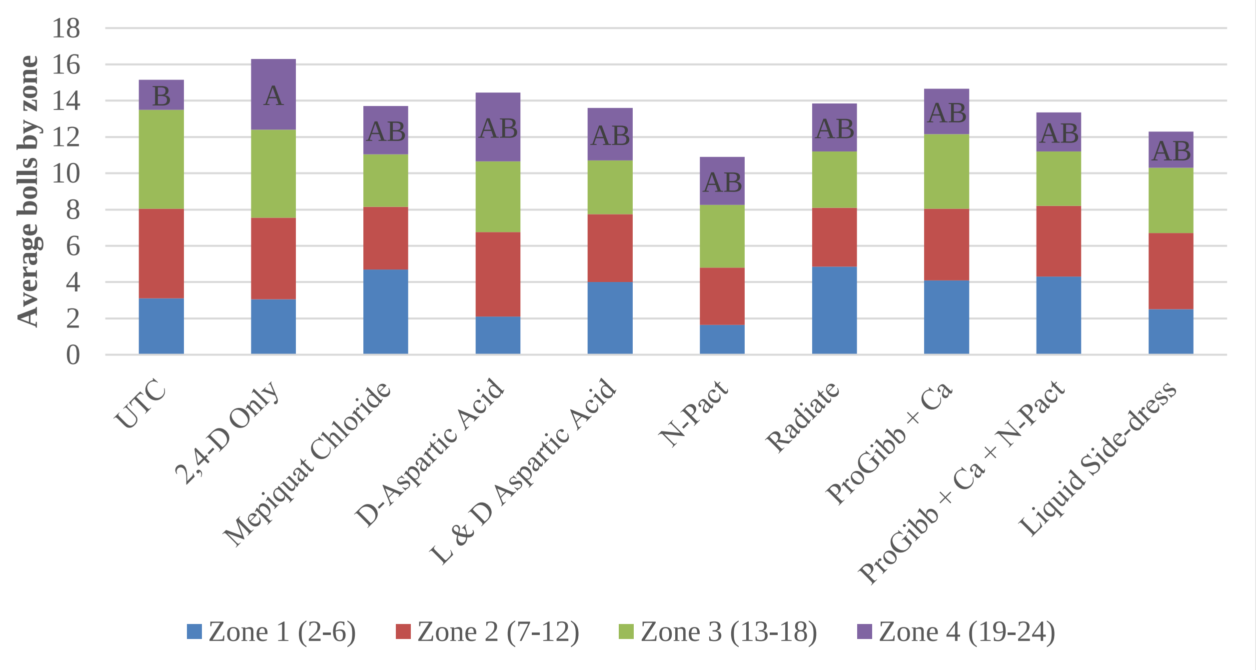
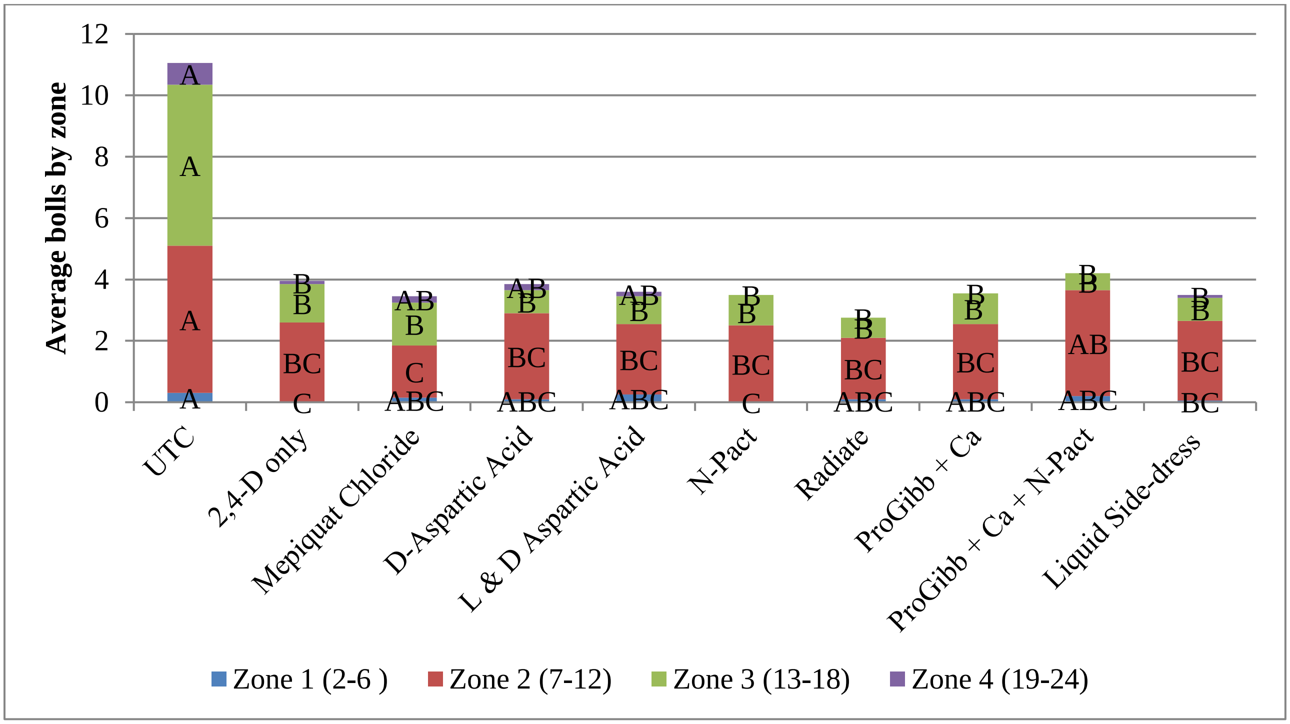


Figure 4.5. 2,4-D recovery means comparison between zones and treatments for 2018. Only zones significantly difference show lettering.



[1]Numbers in parenthesis represent node numbers

Figure 4.6. 2,4-D recovery means comparison between zones and treatments for 2019.

Table 4.6. ANOVA of 2019 total boll counts by plant mapping four zones for 2,4-D injury and recovery treatments in College Station, TX

	p-value
Zone	<.0001
Treatment	<.0001
Zone*Treatment	0.0002

[1] ANOVA were ran without the inclusion of untreated boll count numbers
[2] Replication was a random factor

Fiber quality analysis from the 2,4-D recovery study resulted in few treatment differences (Table 4.7). In 2017, treatment differences were observed for fiber length (p = 0.04), where N-Demand + Advantigro (29.53 mm) and Palisade (29.34 mm) were longer than the UTC (25.40 mm) and the 2,4-D only treatment (25.38 mm). While in 2018-2019, reflectance (p = 0.01) and yellowness (p = 0.02) were reduced by recovery treatment. For reflectance, mepiquat chloride (60.6), Radiate (60.5), and ProGibb + Foliar Ca (60.2) treatments were lower than the UTC. The yellowness grades only showed an increase between the UTC (6.4) and L- and D- aspartic acid (7.1).

Table 4.7. Impact of 2,4-D Recovery Treatments on Cotton Lint Quality Characteristics from College Station, TX in 2017-2019.

Year / Fiber Grades[3,4]	2017	2018 & 2019
Micronaire[4]	-----NS----	
Length	0.04	---NS---
Uniformity	-----NS----	
Strength	-----NS----	
Elongation	-----NS----	
Rd	--NS-	0.01
+ b	--NS--	0.02
[5]Loan Value	----NS----	

[1] 2017 was analyzed separately from 2018 and 2019 due to different treatments
[2] 2018 and 2019 were analyzed combine due to no interactions among years.
[3] Fiber grades were derived from HVI
[4] Non-auxin applied plots were included in the ANOVA analysis
[5] Loan values were computed using Cotton Incorporated 2019 Loan Calculator

Dicamba Injury

Dicamba foliar injury (Table 4.8 and 4.9), such as yellowing, leaf margin necrosis, was observed much sooner than the 2,4-D in adjacent plots, often displaying effects the very next day after the initial dicamba injury spray.   The cause was likely the higher rate applied to resemble tank mix contamination instead of the 2,4-Drates simulating drift. The 2017 visual injury ratings were highest for the mepiquat chloride treatment (46%), which was statistically different from all other treatments, except for Pentia (40%) and CoRoN (34%) (Table 4.8). Resembling the 2,4-D portion of the study, the UTC had no visual injury. The EoS visual injury diminished from the 14 DAA ratings by an average of 20%. Only the EoS visual injury rating of the Pentia treatment was significantly different from any other treatments, including the UTC and the dicamba-only treatment.

In 2017 the average lint yield losses from dicamba treatment was 20% with the UTC yielding 1251 kg ha^{-1}. Three recovery treatments produced statistically comparable lint yields to the UTC but still averaged 15% lower (Table 4.8). There were no significant differences in lint yield between the dicamba-only treatment and any of the recovery treatments. Mepiquat chloride had the highest yield of the recovery treatments, while CoRoN had the lowest yield, 1115 versus 923 kg ha^{-1}, respectively

Table 4.8. The 2017 visual ratings and lint yield response to applications of dicamba and recovery sprays at 14 DAA and end of the season in College Station, TX.

		Cotton Response					
		Visual Injury Ratings % (SD)					
	Products	14 DAA[1]		End[2]		Lint Yield (kg ha^{-1})	
	Untreated	0 E[3]	(0.0)[3]	0 B	(0.0)	1251 A	(134.9)
	Dicamba	25 BCD	(5.8)	6 B	(2.1)	995 B	(71.5)
Dicamba @ 0.094 L ha^{-1} fb;	Mepiquat Chloride	46 A	(14.4)	9 AB	(3.8)	1115 AB	(131.6)
	N-Demand 88 + Advantigro	15 DE	(10.0)	6 B	(2.6)	1049 AB	(146.8)
	Radiate	18 CDE	(12.6)	8 AB	(1.3)	1041 AB	(121.9)
	Palisade	19 CDE	(2.5)	6 B	(2.8)	1022 B	(189.9)
	Pentia	40 AB	(10.8)	12 A	(4.0)	1015 B	(166.5)
	Megafol	28 BCD	(12.6)	10 AB	(5.3)	983 B	(176.5)
	Finish-Line	28 BCD	(9.6)	11 AB	(6.7)	958 B	(195.8)
	CoRoN	34 ABC	(17.5)	10 AB	(6.6)	923 B	(182.5)
	Avg. of recovery treatments	29		9		1030	
	CV%	15.7		13.4		2.7	
	LSD[4] (0.05)	14.8		5.9		211.3	

For the 2018 and 2019 study (Table 4.9), all treatments receiving dicamba had a significantly higher visual injury rating at 14 DAA, mean 31%, than the UTC. Visual injury was comparable for all the recovery treatments (29-34%) and dicamba only (33%). By the EoS, the mean visual injury had increased by 8% with no differences being observed between any of the treatments. With less range in dicamba injury among the treatments included in this trial, a greater amount of visual injury to lint yield correlation was observed, -0.55 and -0.76, compared to the findings of Everitt and Keeling (2009) of a -0.51 and -0.50 correlation between cotton lint yield and visual dicamba injury visual ratings at the 14 DAA and EoS timings respectively.

Table 4.9. The 2018 and 2019 visual ratings and lint yield response to applications of dicamba and recovery sprays at 14 DAA and end of the season in College Station, TX.

		Cotton Response					
		Visual Injury Ratings % (SD)					
	Products	14 DAA[1]		End[2]		Lint Yield (kg ha^{-1})	
	Untreated	0 B	(0.0)[3]	0 B	(0.0)	1623 A	(266.7)
	Dicamba	33 A	(6.9)	38 A	(8.9)	761 B	(202.1)
Dicamba @ 0.094 L ha^{-1} fb;	D-Aspartic Acid	32 A	(7.5)	38 A	(6.9)	803 B	(156.7)
	ProGibb + Foliar Ca + N-Pact	31 A	(6.6)	36 A	(7.8)	790 B	(130.5)
	ProGibb + Foliar Ca	31 A	(5.7)	39 A	(7.1)	784 B	(99.8)
	L and D-Aspartic Acid	29 A	(7.9)	39 A	(9.1)	783 B	(118.1)
	P and K Liquid Side-dress	29 A	(8.3)	41 A	(8.4)	780 B	(87.1)
	N-Pact	34 A	(6.5)	41 A	(9.2)	740 B	(122.3)
	Radiate	32 A	(8.2)	36 A	(8.4)	733 B	(222.3)
	Mepiquat Chloride	33 A	(5.3)	41 A	(11.3)	719 B	(242.5)
	Avg. of recovery treatments	31		39		767	
	CV%	10.7		10.7		9.6	
	LSD[4] (0.05)	6.7		8.2		175.1	

In 2018-19, the increased level of injury did equate to more yield losses compared to the UTC. The lint yields were reduced by dicamba by 53%, compared to 20% in 2017. This may be due to 2018 and 2019 having a shorter growing season than 2017. This shorter window did not allow delayed upper bolls to become harvestable. Among the recovery treatments, no differences were observed, and they were no different than the dicamba-only treatment. The recovery treatment having the highest numerical lint yields, D-aspartic acid, averaged 83 kg ha^{-1} higher than the mepiquat chloride, which had the lowest lint yield of 719 kg ha^{-1}. Recovery treatments averaged 767 kg ha^{-1}, 856 kg ha^{-1} less than the UTC. Five recovery treatments had numerically higher yields than the dicamba-only treatment.

Similar to prior research reported by Everitt and Keeling (2009) and Miller et al. (1963), in 2017, dicamba-injured plants (Figure 4.7) compensated by producing more vegetative position bolls. Some differences were observed for the first position boll count between Radiate, 1.9, and the dicamba only, mepiquat chloride, Pentia, Palisade, and Megafol, which had 4.3, 3.8, 4.1, 3.85, and 3.85, respectively. Fewer differences were observed with the second position bolls with significant differences between

Radiate, 0.85, and mepiquat chloride, 1.9, Megafol, 2.0, Finish-Line, 1.85, and N-Demand + Advantigo, 1.85 bolls per plant. Radiate compensated with the most vegetative bolls, 7.8, but was only significantly different from the CoRoN treatment.

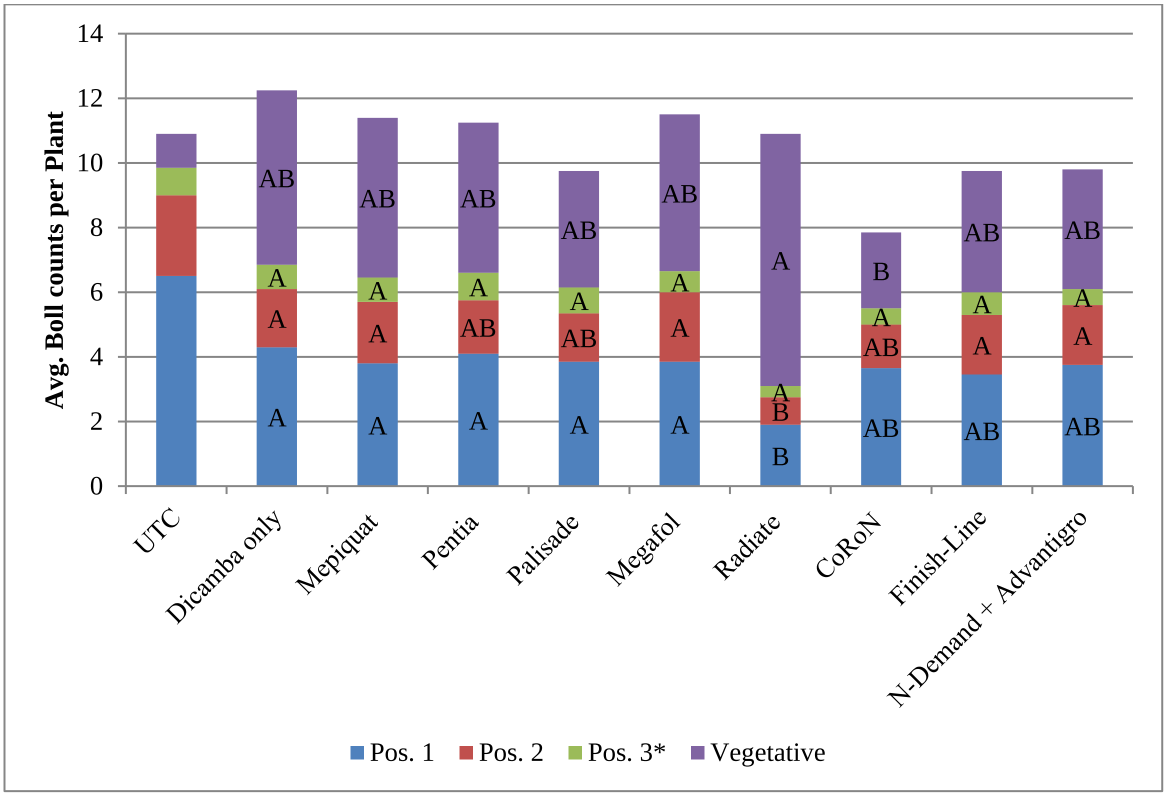


Figure 4.7. The 2017 average boll counts by cumulative fruiting position from dicamba injury recovery treatments conducted in College Station, TX. Treatments are ordered based on high (left) to low (right) lint yield. Only plots receiving dicamba injury are represented by means comparison lettering. *Position 3 and total bolls have no significance between recovery products and auxin only.

For 2018 and 2019, observed total boll counts for plots receiving dicamba exhibited what would be expected, less total fruiting positions than the UTC. The large number of vegetative bolls on plots receiving dicamba was similar between years. In the combined 2018-2019 seasons, (Figure 4.8) no significant differences in boll count by fruiting position or total boll counts were found between treatments receiving dicamba.

Considering 2018 alone (data not shown), surprisingly, the dicamba-only treatment had the highest number of first position bolls, 6.15, although this was only significantly different from the D-Aspartic Acid and ProGibb + foliar calcium treatments, with 3.25 and 2.85 first position bolls, respectively. There were no differences between second position and vegetative boll numbers. The dicamba-only treatment had just as many second and third positions as the UTC, and the UTC had more vegetative bolls than the dicamba-only treatment. Importantly, in 2018, the entire trial had high levels of thrips damage. Similar to Mauney's findings (1986), high thrips pressure resulted in a loss of apical meristem dominance early in the season, leading to multiple sympodial branches and increased monopodial branches with a higher percentage of vegetative bolls. Vegetative boll numbers were significantly different between dicamba-only (4.5), and N-Pact (4.2) than the ProGibb + foliar calcium (8.25) treatment.

In 2019 (data not shown), the cotton treated with N-Pact had significantly more first position bolls than the dicamba-only treatment, 2.7 and 0.9 first position bolls per plant, respectively. There were no differences among 2nd position bolls in 2019. For 3rd position bolls, side-dressed phosphorus and potassium, averaged 0.95 bolls per plant which was significantly higher than the ProGibb + Foliar calcium and nitrogen (N-Pact) treatment. The dicamba-only treatment had significantly more vegetative bolls than the Mepiquat chloride and N-Pact treatments.

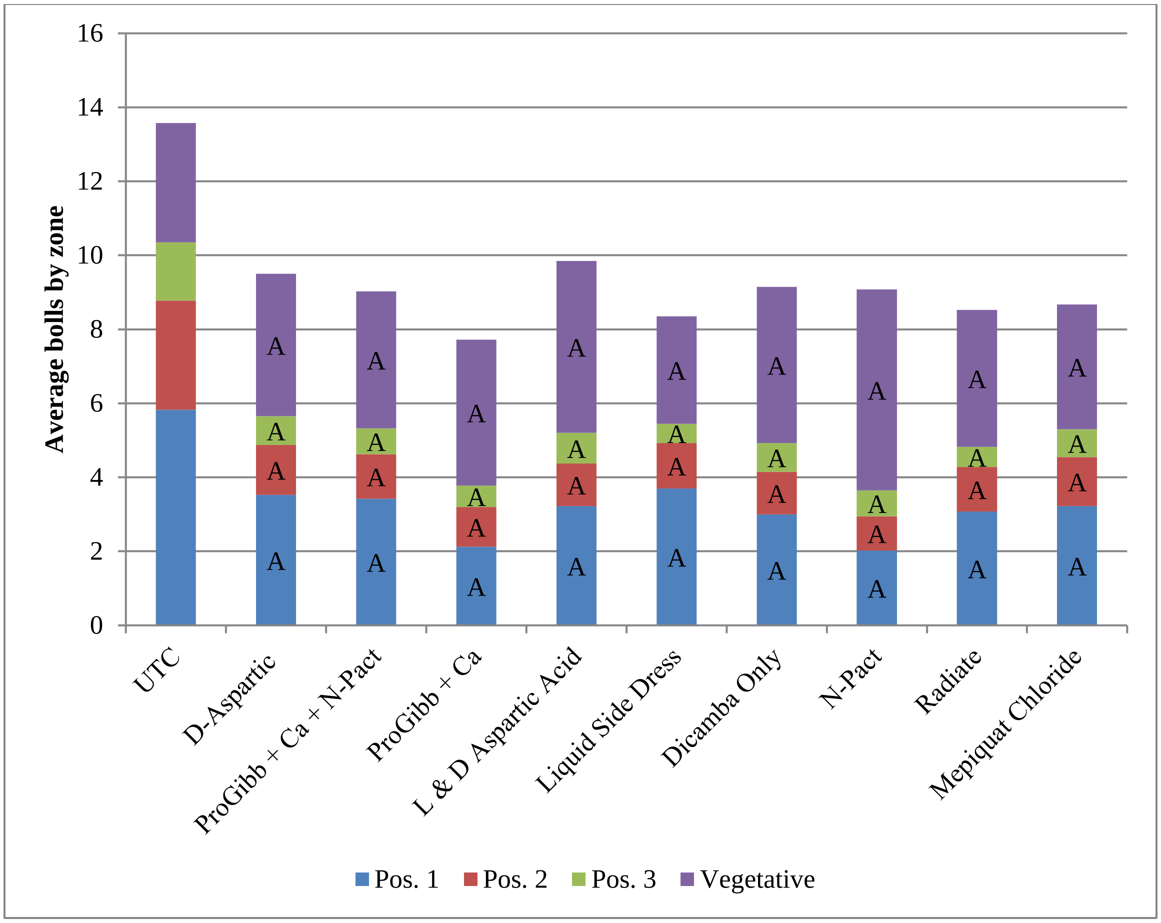


Figure 4.8. The 2018 and 2019 average boll counts by cumulative fruiting position from dicamba injury recovery treatments conducted in College Station, TX. Treatments are ordered based on high (left) to low (right) lint yield. Only plots receiving dicamba injury are represented by compare means lettering. *Positions 1, 2, 3 and total bolls have no significant interactions.

In 2019, at first bloom the dicamba application occurred June 28th and visual injury was observed the following day. Cotton plants were at approximately 50% bloom, with an average of 15.6 nodes, and the average of first fruiting branch site was 7.11. The UTC retained the highest number of first and second position bolls with no vegetative bolls beyond node 9 (Figure A1). This uninjured plant fits the physiological development exhibited by the typical fruiting pattern of a cotton plant (Heitholt, 1993). All treatments receiving the dicamba injury spray had vegetative bolls beyond the first fruiting branch (node 7). The translocation of the synthetic dicamba into the sympodial branch's apical meristems caused necrosis and loss of apical dominance, while monopodial branches were not injured and assumed dominance. Only the phosphorus and potassium liquid side dress and the foliar nitrogen (N-Pact) treatments demonstrated a return of first position fruiting sites. Mepiquat chloride and Radiate® plant mapping revealed early first position bolls were retained but upper positioned bolls were not maintained.

From the zone plant mapping data in 2017 (Figure 4.9), the UTC (1.2) and CoRoN (1.2) treatments produced significantly lower cotton boll counts than the mepiquat chloride (3.9) treatment in Zone 1. For Zone 2, the non-auxin treated UTC (6.4) had more bolls than all dicamba applied plots. In Zone 3, Megafol (5.0) produced the highest number of bolls, significantly more than the CoRoN (2.7) recovery application. Finally, in Zone 4, the dicamba only (0.7) treatment created the most bolls while only being significantly higher in boll counts than the Radiate (0.1) treatment.

Comparing boll counts from the 2018 zone mapping (Figure 4.10) Zone 2 and 4 demonstrated significant differences among the treatments. In Zone 2, the UTC (5.9) produced the highest number of bolls while the treatment of ProGibb + Ca + N-Pact (2.5) caused mapped cotton plants to have the lowest count. Conversely, ProGibb + Ca + N-Pact (3.55) created the highest number of bolls in Zone 4, while the UTC cotton plants had the fewest bolls.

No significant differences were observed in 2019 boll counts (Figure 4.11) in zone 1 between treatments with boll counts ranging from zero to 2.5 for the L- and D-aspartic acid treatment. In zone 2, the UTC (5.55) was statistically different than all other treatments. Furthermore, UTC (6.65) also significantly exceeded other treatments in zone three. Finally, in zone four, the UTC had the highest number (1.05) but was only significantly different from mepiquat (0.75) and ProGibb + Foliar Ca and N (1.0) treatments.

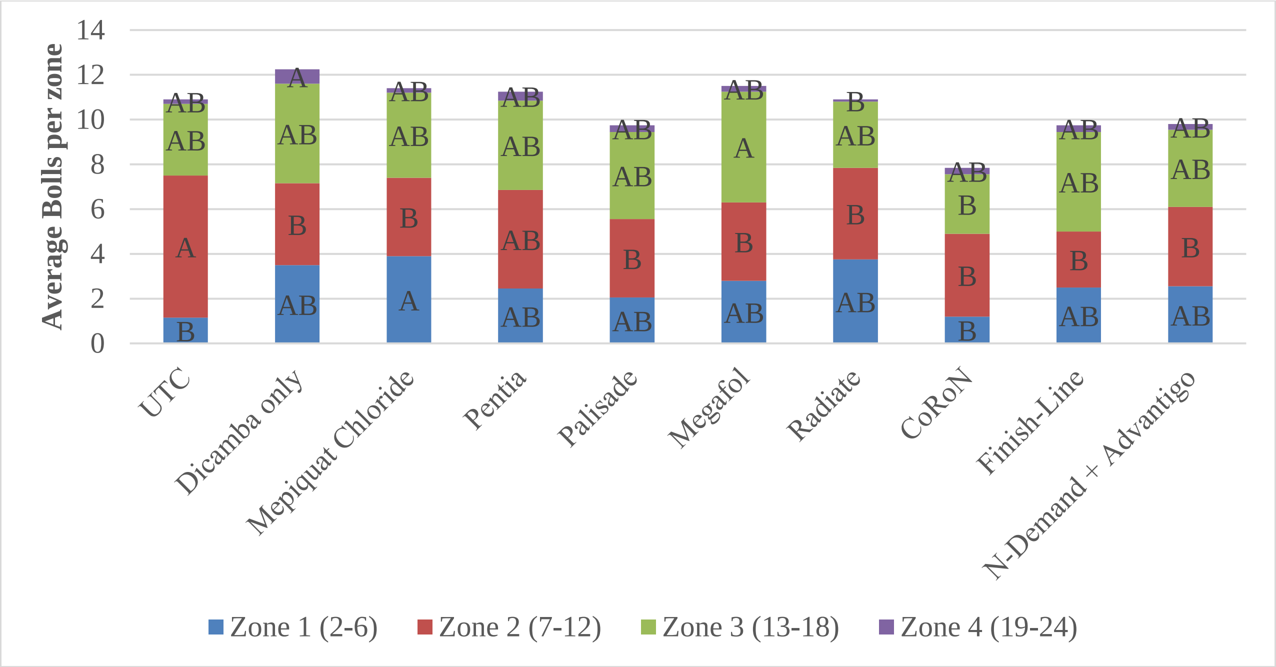


Figure 4.9. Dicamba recovery compare means between four crop zones and treatments for 2017.

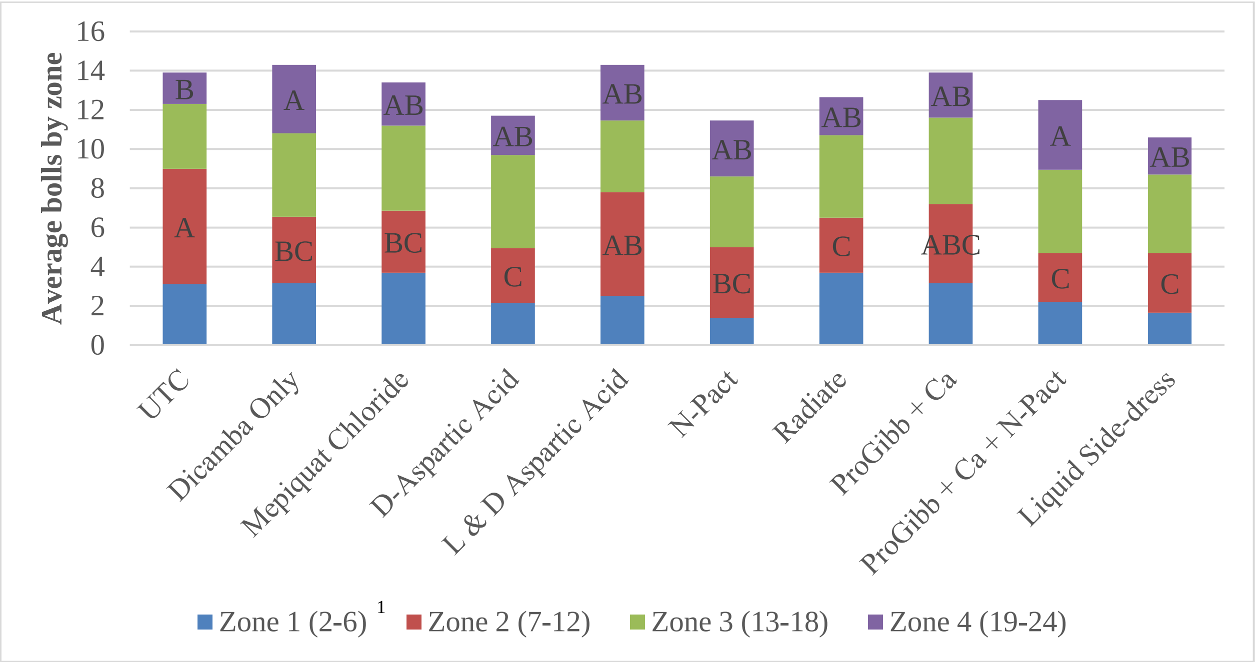
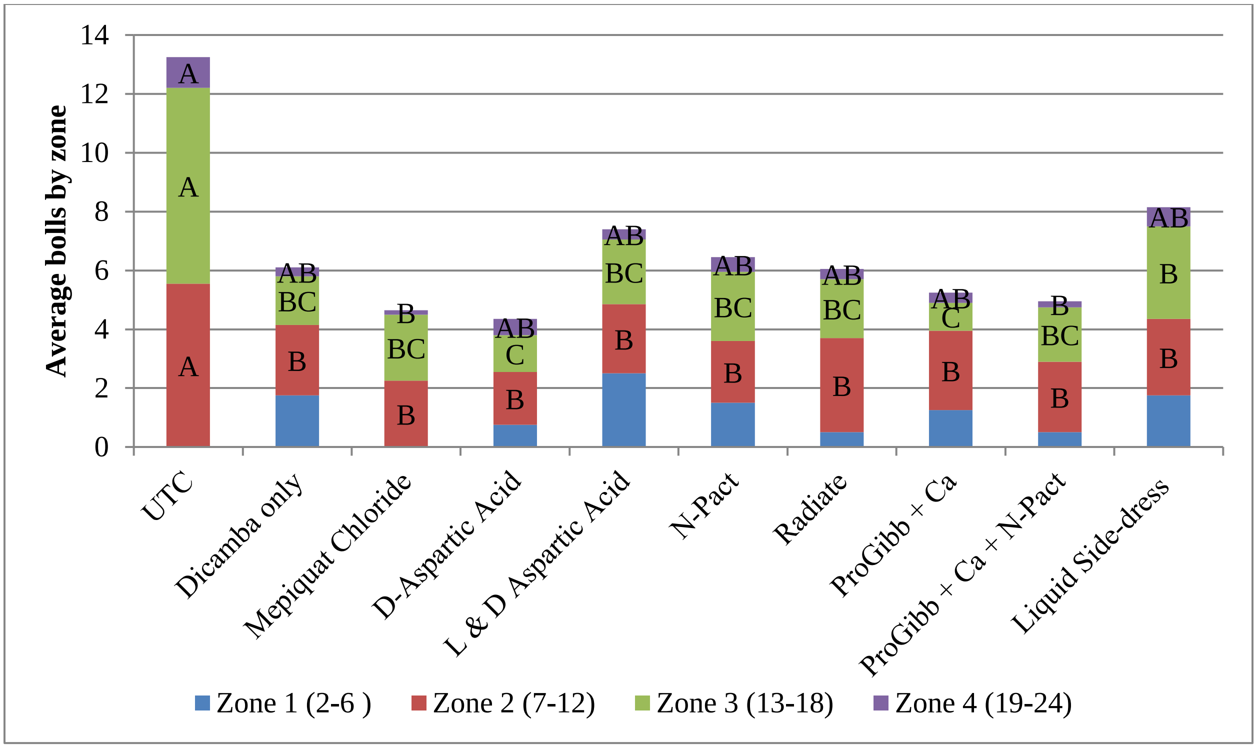


Figure 4.10. Dicamba recovery compare means between four crop zones and treatments for 2018. Only zones with lettering demonstrated significant differences.



[1]Numbers in parenthesis represent node numbers

Figure 4.11. Dicamba recovery compare means between four crop zones and treatments for 2019.

Table 4.10. ANOVA of 2019 total boll counts by plant mapping four zones for dicamba injury and recovery treatments in College Station, TX

	Dicamba
Zone	<.0001
Treatment	<.0001
Zone*Treatment	<.0001

[1]ANOVA did not include UTC for boll count numbers

[2]Replication was a random factor

No significant differences among the treatments were observed for lint quality characteristics in 2017 (Table 4.11). In 2018-2019, length was significantly different between treatments (Table 4.11). The UTC average length, 1.21 inches, was higher than all injured cotton. The reduced length could have been due to auxin effects on the fiber development but may have resulted from the change in boll distribution and lower position fruit abortion. The UTC had the lowest yellowness score of 6.43. This result was significantly different than all other treatments except for the ProGibb + Foliar Ca and N. Again, this is most likely the result of the UTC retaining a higher percentage of lower position bolls and those bolls being weathered longer. Smith and Wiese (1972) documented that 2,4-D injury at all cotton growth stages reduced micronaire and that dicamba injury only affected micronaire at the pre-bloom stage. Length was not affected by growth stage nor auxin type. Manuchehri et al. (2020) documented that 1/12th 2,4-D rates decreased micronaire, length, uniformity and strengths. Rates used below the 1/12th treatments did not result in documented fiber quality loses. Furthermore, Marple et al. (2007) found that 2,4-D only affected fiber elongation, regardless of rates or growth stages.

Table 4.11. Impact of Dicamba Recovery Treatments on Cotton Lint Quality Characteristics from College Station, TX in 2017 and 2018-2019.

Year Fiber Grades[3,4]	2017[1]	2018 and 2019[2]
Micronaire[4]	-----NS----	
Length	--NS--	0.01
Uniformity	-----NS----	
Strength	-----NS----	
Elongation	-----NS----	
Rd	-----NS----	
+ b	--NS--	0.01
Loan Value[5]	----NS----	

[1] 2017 was analyzed separately from 2018 and 2019 due to different treatments
[2] 2018 and 2019 were analyzed combine due to no interactions among years
[3] Fiber grades were derived from HVI
[4] Non-auxin applied plots were included in the ANOVA analysis
[5] Loan values were computed using Cotton Incorporated 2019 Loan Calculator

Conclusions

Only in the 2017 dicamba study were any recovery treatments able to regain lint yields comparable to the non-auxin injured (UTC) plots. Many possible factors likely caused this anomaly. First, in 2017 the yield potential was not as great as in 2018 and 2019, as demonstrated by final yields. This was most likely due to field site selection. The 2017 field site historically has shown high numbers of nematodes. Conversely, in 2017, plants exhibited fewer green bolls on the upper fruiting sites compared to 2018-2019, meaning they were given adequate time to mature as compared to other years. As stated in numerous publications, auxin injury delays maturity (Byrd et. al 2016; Everitt and Keeling, 2009; Marple et. al 2008).

An interesting aspect of the study was the compensation by vegetative bolls on the dicamba treatment in 2017 and 2018. This was most likely due to the study being irrigated, allowing the vegetative branches to continue to grow after the fruiting branch's sustained injury. Presumably, this would not occur under water stress. Despite both dicamba and 2,4-D being synthetic auxin herbicides, different yield responses were observed between the recovery treatments every year, exacerbating the difficulty of utilizing recovery sprays on auxin injured cotton plants. The assumption from this is that the cotton plant physiologically processes each synthetic auxin molecule differently and no commercially available product will disrupt this mechanism or sufficiently promote compensation.

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CHAPTER V

CONCLUSIONS

Cotton producers face an ever-changing agricultural industry and must constantly adapt to ensure short and long-term profitability. Improved efficiencies from reduced input costs and/or increased revenue are paramount to longevity and sustainability. This dissertation reports on several different key areas of agronomic research that will provide cotton producers with key information for issues they are facing. These topics include the impact of ultra-coarse droplet size nozzles on defoliation and boll opening efficacy; the viability of robotic harvesting for future cotton harvesting; and product evaluation for remediating auxin-injured cotton.

Harvest aid products require adequate spray coverage in order to be efficacious, resulting in increased mechanical harvest efficiency and preservation of fiber quality. This research found adequate defoliation can be obtained with coarse and ultra-coarse spray nozzles, but carrier volume must be at 187 L ha^{-1} to overcome the large droplet sizes of these tips. Water volumes below 47 L ha^{-1} should be avoided. Desiccation ratings were erratic, and conclusions were not drawn from this study. This study demonstrated that higher water volumes were more vital to successful defoliation and boll opening than nozzle types.

Development and adoption of new technology has been and will continue to be a key factor in U.S. leading the world in cotton production efficiency. With advances in technology, specifically autonomous vehicles and machine learning, eventually robots will become mainstays in row crop production fields, as they are in the controlled environments of other industries. However, to determine the feasibility of using robotic harvesting for cotton, the effects on lint yields and fiber quality need to be quantified. Multiple harvests, such as would be done by a robotic harvester, provided consistently higher loan values compared to both traditional stripper- and picker-harvest methods. Varietal maturity did not have an impact on the revenue of multiple-pass harvesting compared to the end-of-season harvest methods. Although seed cotton weight was lower for the multiple-pass harvest than the stripper harvester, the combined multiple harvest provided the highest loan values. Finally, the multiple harvesting method returned \$383.33 and 740.33 ha^{-1} more than the cleaned and picker harvest methods, respectively.

The likelihood of auxin-injured cotton from spray tank contamination or off-target movement has increased due to the release and widespread adoption of the XtendFlex and Enlist cotton varieties. When this auxin injury occurs, growers want to know if products are available to remediate the injured cotton. Results from this research identified the impact of 2,4-D and dicamba on cotton fruiting pattern and boll set. Once cotton plants are auxin-injured, treatments used within this study did not allow normal fruiting patterns to resume comparable to uninjured plants. The research did not identify any products that affected the likelihood of yield losses from auxin injury. Therefore, any money spent by growers on these products to remediate auxin injury would be wasted.

APPENDIX

ANOVA		DEF	DES	OB	TRG	BRG
Source	DF	Prob > F				
Nozzle type	545	0.0134	0.1784	0.0274	0.0999	0.9026
Carrier volume	545	<.0001	0.0043	<.0001	0.0841	0.4789
Nozzle type*carrier volume	545	0.7516	0.2172	0.6296	0.8148	0.4569

Table A1. ANOVA of nozzle type and carrier volume interactions to DEF, DES, OB, TRG and BRG Percentage Visual Rating Responses.

-	Lint Yield	Revenue	Loan Value	Mic	UHML	UI	Strengthen	Rd	+b	Leaf
	Stripper harvested									
Cultivar	0.1185	0.0289	0.0598	0.8932	<.0001	0.6907	0.0501	<.0001	<.0001	0.0195
Harvest methods	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Cultivar × Harvest Method	0.3806	0.3477	0.7124	0.6535	0.7985	0.7890	0.1835	0.0108	0.0754	0.1863
	Picker harvested									
Cultivar	0.0300	0.0071	0.1405	0.0061	<.0001	0.4713	0.0012	0.0084	0.0003	0.5275
Harvest methods	0.0027	<.0001	<.0001	<.0001	0.0002	0.0243	0.0013	<.0001	<.0001	<.0001
Cultivar × Harvest Method	0.6230	0.8188	0.7362	0.2519	0.1538	0.147	0.2722	0.2422	0.027	0.0576

Table A2. ANOVA table for stripper and harvest location for yield, revenue, loan value and fiber quality factors.

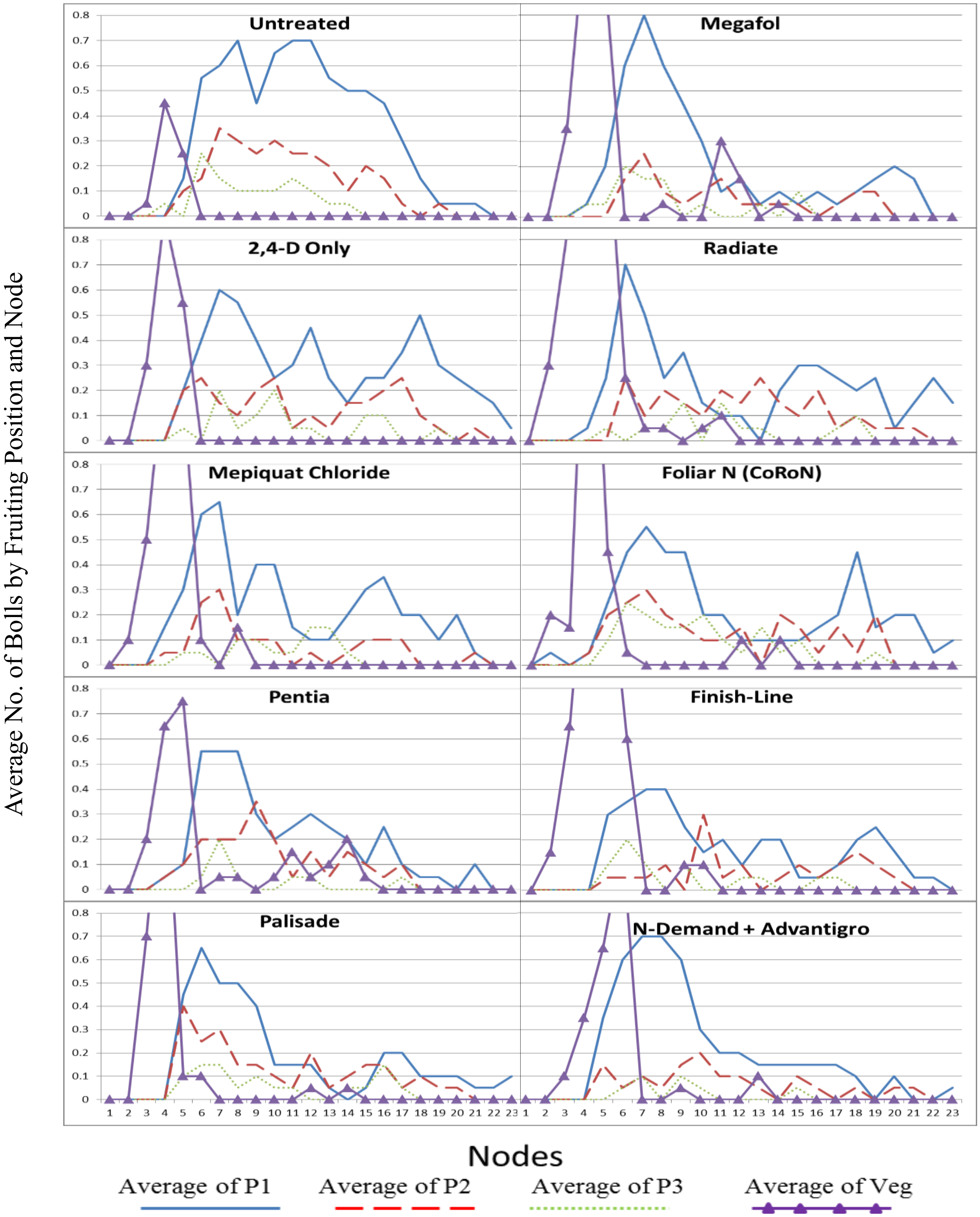

Figure A1. Average number of bolls per plant shown by fruiting position and node from College Station, TX in 2017 from the 2,4-D portion.

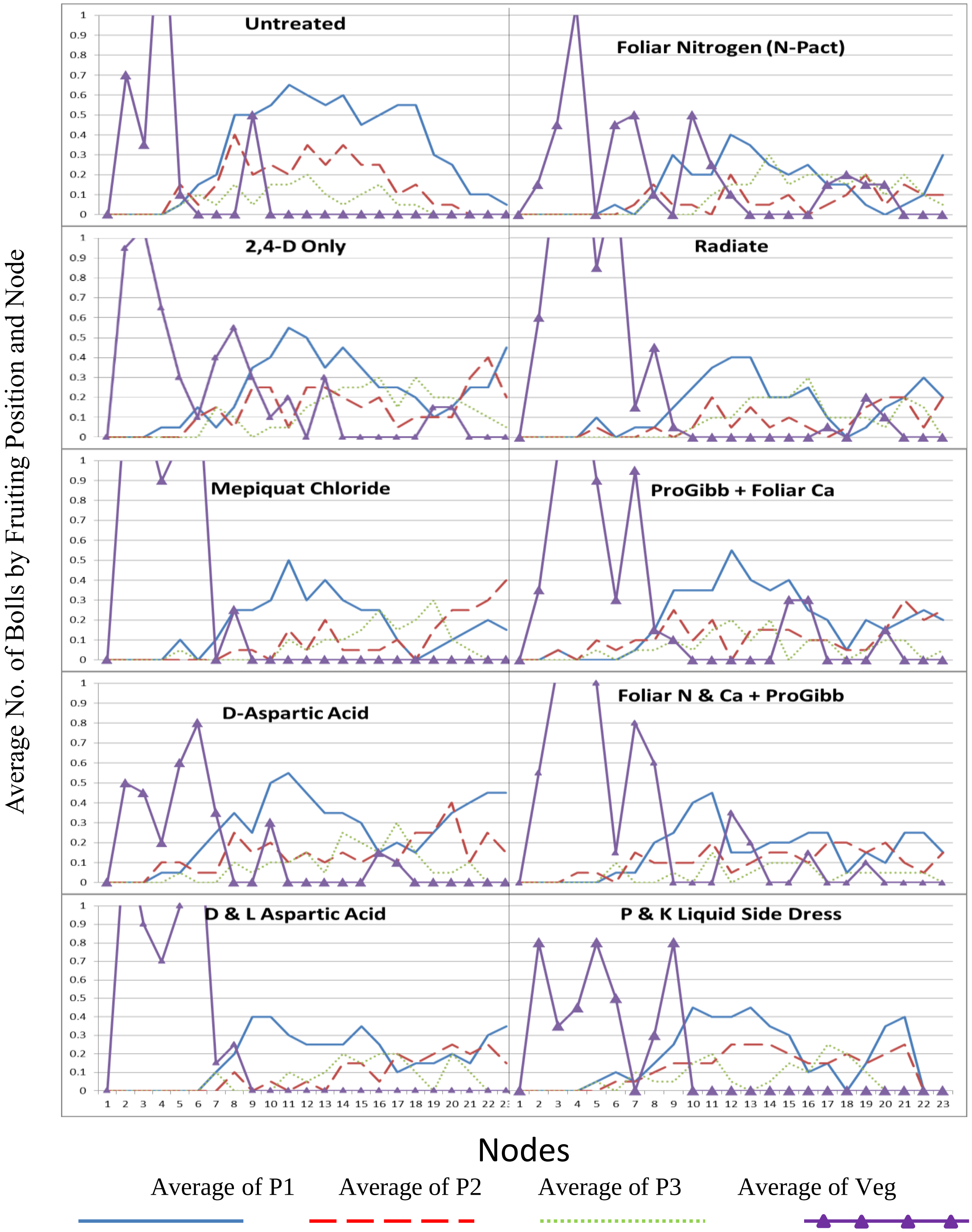

Figure A2. Average number of bolls per plant shown by fruiting position and node from College Station, TX in 2018 from the 2,4-D portion.

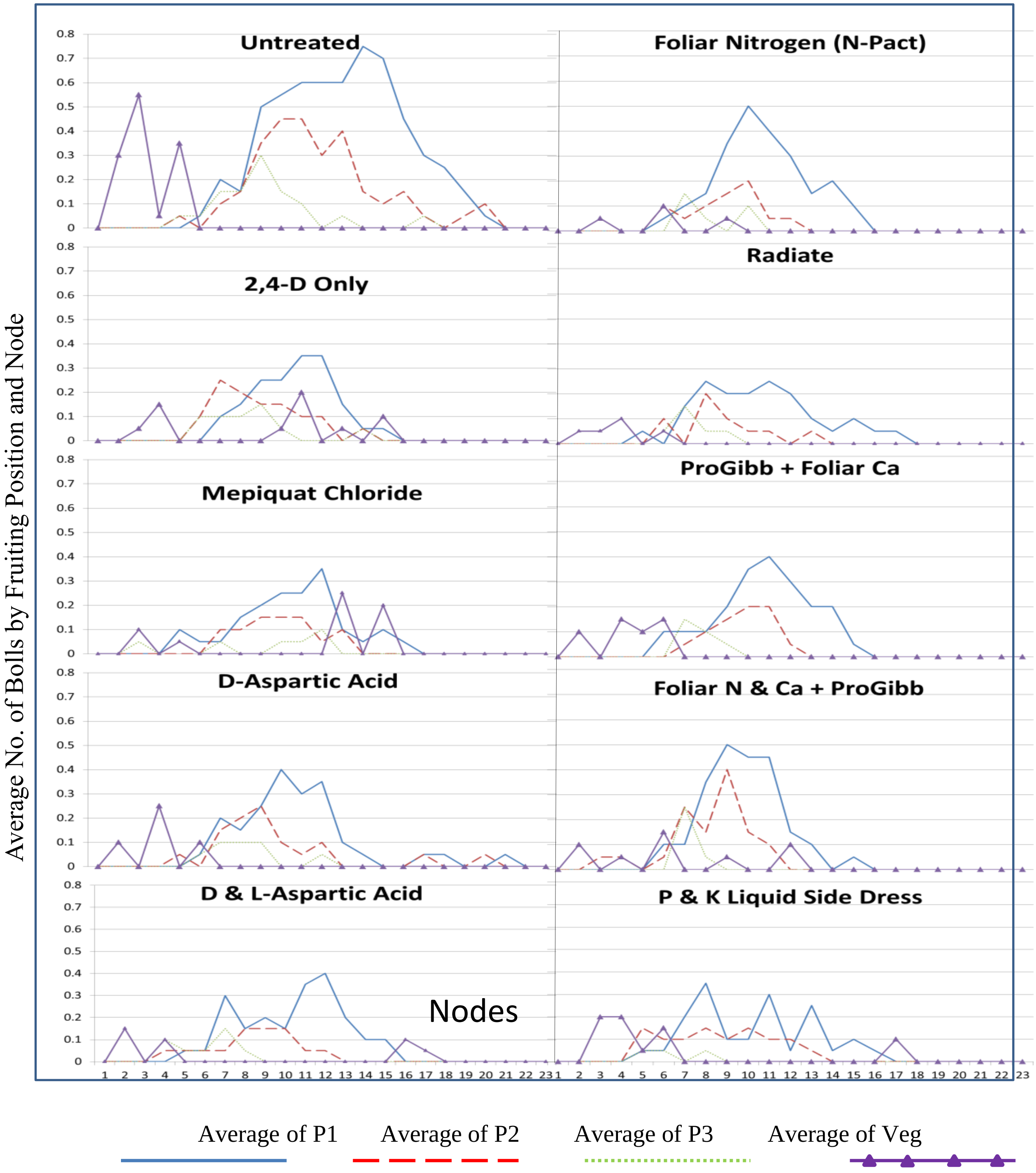

Figure A3. Average number of bolls shown by fruiting position and node from College Station, TX in 2019 from the 2,4-D portion

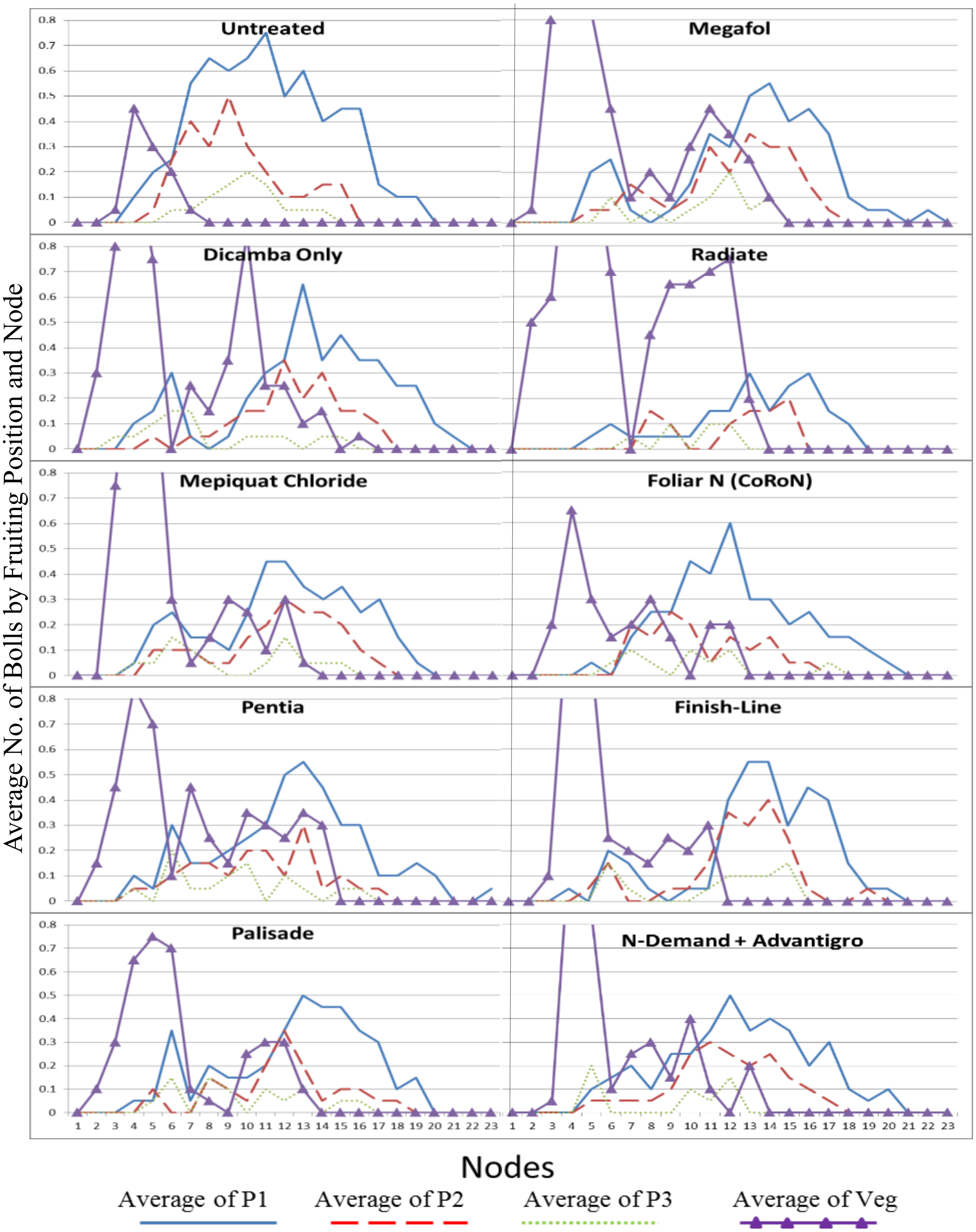

Figure A4. 2017 dicamba study plant mapping figures, average number of bolls per plant by fruiting position and node from College Station, TX

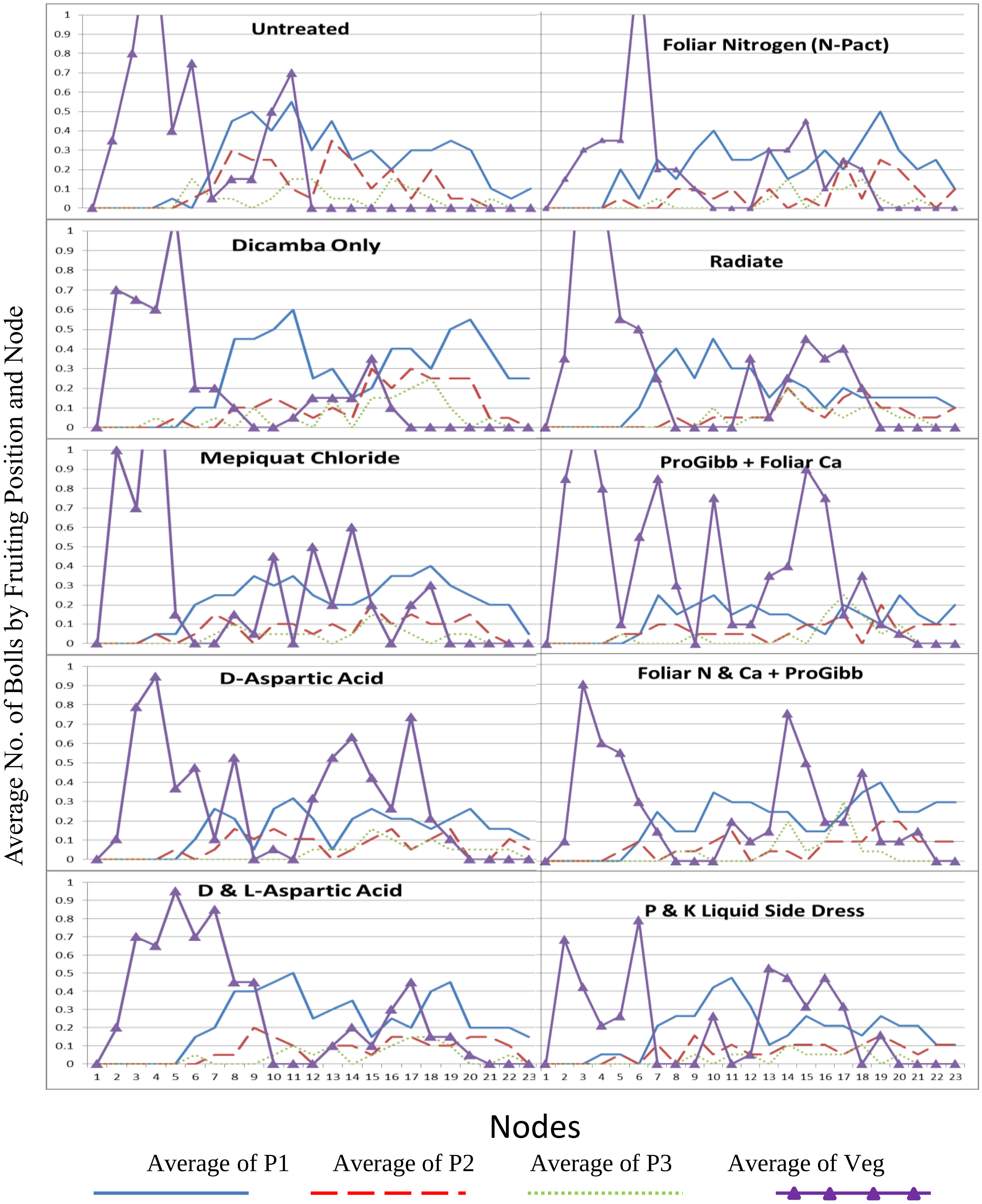

Figure A5. 2018 dicamba study plant mapping figures, average number of bolls per plant by fruiting position and node from College Station, TX

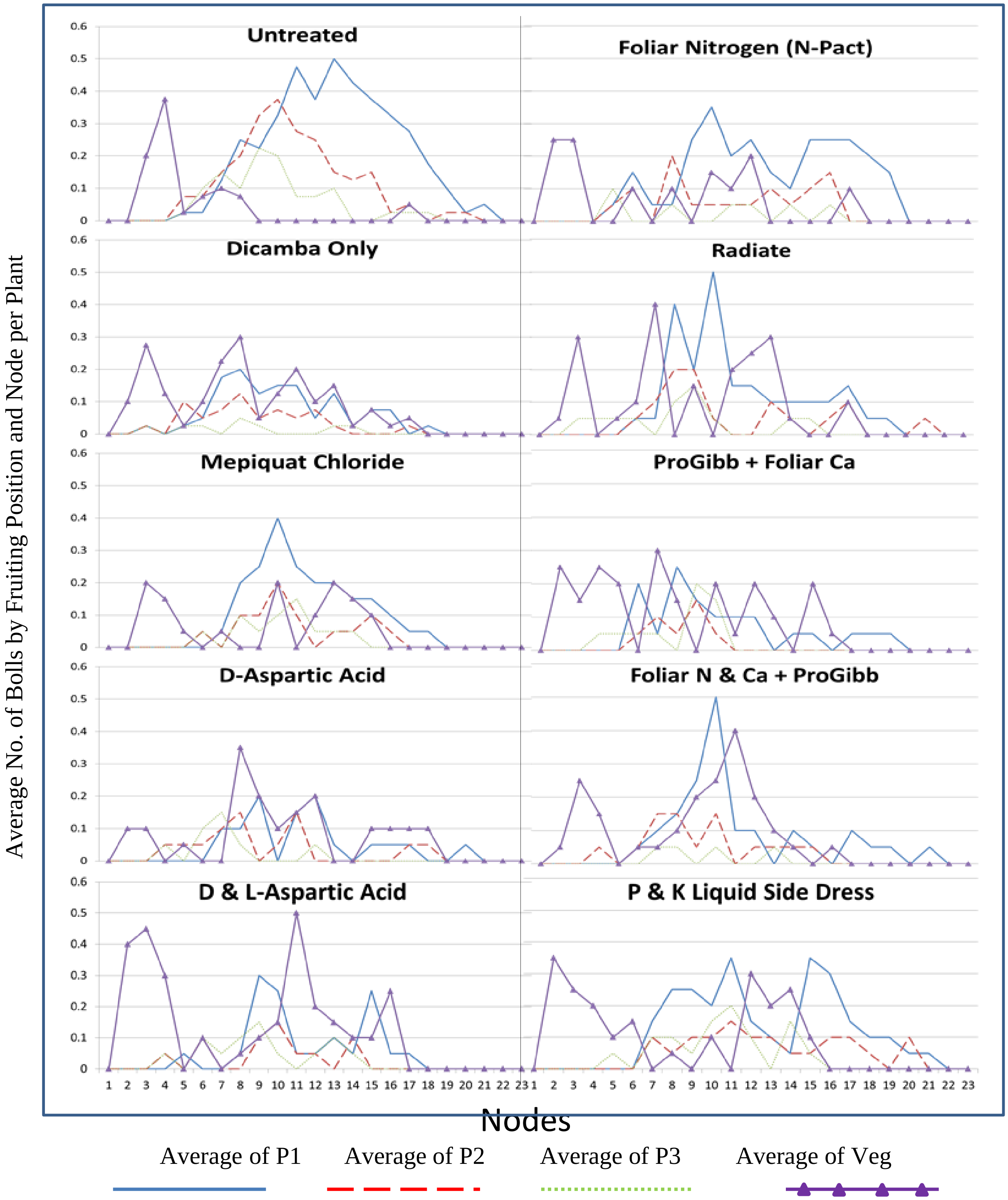

Figure A6. 2019 dicamba study plant mapping figures, average number of bolls per plant by fruiting position and node from College Station, TX.