COTTON HARVEST AID EFFICACY AND COTTON FIBER QUALITY AS INFLUENCED BY APPLICATION TIMING

By

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Abstract: Harvest aid chemicals are used to terminate cotton growth and promote boll opening, with optimal application timing recommended at four nodes between the uppermost first position cracked boll and the uppermost first position harvestable boll (4 NACB). However, recommendations rely on data from the southeast and mid-south regions of the Cotton Belt, which may not reflect conditions in much of the southwestern region. Producers in Oklahoma may delay harvest-aid applications until the crop is nearly mature potentially sacrificing fiber quality to weathering, or be in a situation where triggering applications early could allow for optimal harvest aid activity prior to a freeze event. The objectives of this study were to quantify, (1) the relationship between cotton maturity, as determined by the NACB method and the percent of open bolls, (2) the efficacy of boll opening from harvest aid applications made at various maturity levels, as well the amount and response of undersized bolls present at each application timing, and (3) impact of harvest aid application timing on cotton fiber quality. A standard harvest aid mix of tribufos and ethephon was applied at four-to-five-day intervals for three site-years from 2019 to 2020. A non-treated control was included at both locations and site-years. Across all site-years there was a strong relationship between NACB and percentage of open bolls (R^2 = 0.85), agreeing with previous findings that 4 NACB generally occurs when approximately 60% of bolls are open. By seven days after application, approximately 80% of harvestable-sized bolls were open regardless of application timing, with no impact on fiber quality. Early application may prevent yield and fiber quality losses if inclement weather is encountered prior to the crop reaching maturity.

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CHAPTER I

LITERATURE REVIEW

Upland cotton (*Gossypium hirsutum* L.) production within the state of Oklahoma has expanded tremendously since 2015. In 2016, Oklahoma producers planted 123,500 hectares of cotton while in 2019 Oklahoma it reached over 291,000 planted hectares and ranked as one of the top five cotton producing states (USDA-NASS, 2020). There are five growing regions for cotton in the state of Oklahoma, with the southwest and west central being the main regions, followed by the panhandle, central, and north central regions (USDA-NASS, 2018). The southwest and west central areas are home to the largest production in Oklahoma due to the desirable temperatures for optimal cotton growth and a longer growing season compared to the other regions (Oklahoma Climatological Survey, 2018). The challenge for cotton producers is to achieve a mature crop in a short season environment, which is why production in the northern region requires earlier maturing varieties, as heat unit accumulation is limited, particularly towards the end of the growing season (Schulze et al. 1996). Other regions in the U.S. Cotton Belt such as the southeast and mid-south accumulate more seasonal heat units than many of the cotton producing regions of Oklahoma. This short season environment often places producers at risk for drastic reductions in yields and fiber quality if their crop has not reached maturity at the end of the growing season (Schulze et al. 1996).

Managing a cotton crop for early maturity consists of limiting vegetative growth through variety selection, nitrogen fertility, and use of plant growth regulators (Gwathmey and Craig, 2003). Early maturing cotton will allow for the application of harvest aids to occur in more favorable conditions. Chemical defoliation is a cultural practice which accelerates abscission of cotton foliage with the use of harvest aids. Harvest aids are products used for terminating cotton growth, defoliation, opening of bolls, or desiccating the cotton plant (Kelley, 2002). Timely harvest aid applications can shift vegetative growth to reproductive growth and promote earliness in a variety (Gwathmey and Craig, 2003). Appropriate timing of harvest aid applications is critical to achieve optimal defoliation while avoiding early applications that may result in the opening of immature bolls and long term exposure to severe weather which may decrease cotton lint quality (Barker et al., 1979).

Gwathmey and Craig, (2003) reported that determining the correct timing of applications can be difficult for producers, as achieving boll opening prior to a frost in short season environments is challenging. As cotton production expands into non-traditional areas of Oklahoma and other states in the Great Plains region, determining the response of the crop to various harvest aid application timings will be critical to guide producers in this short season environment towards optimizing both fiber quality and efficacy of harvest aid applications.

Cotton Overview

Cotton is perhaps the most complex plant when compared to other major agronomic crops. While the growth of a cotton plant is fairly predictable under favorable environmental conditions, it’s indeterminate growth habit and sensitivity to adverse environments is unique. By studying cotton consistently, we may use this knowledge to manage the crop to improve yields, earliness, quality, and other characteristics (Kerby et al., 1987).

The above ground growth of a cotton plants is a balance between vegetative and reproductive growth phases, with the goal of developing the optimal number of potential fruiting sites governed by plant characteristics and management practices including fertility, disease, weed, and insect management (Brecke et al. 2001). The accumulation of heat units or DD16’s (°C), are used to determine the thresholds needed for cotton development. DD16’s values are calculated by subtracting 16 from the average of the maximum and minimum daily temperatures. The premise of this formula is that cotton growth is null at temperatures lower than 16°C. The resulting number that is calculated is then referred to as the amount of DD16’s acquired for that specific day (Ritchie et. al 2008).

Different amounts or ranges of heat unit accumulation are required for cotton to reach various developmental growth stages in a timely manner. Calculation of the accumulated heat units and knowledge of the heat unit requirement for any particular growth stage can be used to explain and predict the occurrence of events or duration of stages in crop development (Kerby et al., 1987; Landivar and Benedict, 1996; Oosterhuis, 1990). Acquiring adequate heat units is essential while the plant is accumulating vegetative biomass, as this stage establishes the majority of potential fruiting sites that will produce harvestable bolls (Main, 2010).

After planting, emergence will typically occur within 4-14 days (Bednarz and Nichols, 2005). Once emergence occurs, the developmental stage of squaring is then reached with flower buds, referred to as squares, representing the fruiting structures prior to bloom. The growth period from square to bloom takes about 21 days, while the blooming or flowering period lasts approximately six weeks (Ritchie et al., 2008). The end of the flowering stage, referred to as cutout, signals that the plants energy is being put towards boll development and ceasing flowering development (USDA, 2000).

A common issue seen within the life cycle of a cotton plant is fruit shedding. There are several factors that may cause fruit shedding such as: water stress, insect damage, high temperatures, and nutrient deficiency (Chaudlgry and Guitchounts, 2003). Although all fruiting positions are susceptible to fruit shed, the first position bolls are typically retained when compared to further position bolls on the fruiting branches (Chaudlgry and Guitchounts, 2003). However, while fruit shedding is undesirable, cotton quickly attempts to compensate for the loss with new fruit production (Chaudlgry and Guitchounts, 2003).

A successful cotton crop is dependent on proper variety selection. Since variety selection is probably one of the most important decisions affecting a cotton crop's success, it is essential to select the correct cotton variety that fits in a specific geography to ensure optimal performance (Silvertooth, 2001). When considering variety selection, maturity is a key factor to consider, and there are three different primary maturity classes used to categorize cotton varieties. The classes consist of short season determinate plants; long or full season varieties which are more indeterminate in nature; and varieties classed as mid-maturing or those that fit in between early and late (Silvertooth, 2001). Breeders have used technology to develop cultivars intended for specific regions. Breeders have also developed cultivars referred to as “determinate”, meaning that these early maturing cultivars begin by fruiting at nodes lower on the plant, shed fewer squares, and require fewer days for fruiting position development (Brecke et al., 2001). It is important to note the significance of these early maturing cultivars because while an indeterminate variety will likely be more tolerant of environmental stresses, when the growing season is shortened because of poor weather conditions, an indeterminate variety will be less responsive to harvest aids, because the plant has not reached natural senescence (Brecke et al., 2001). Selecting varieties with characteristics that match both the production environment and proper management techniques is crucial, particularly in short season growing regions (Silvertooth, 2001). Schulze et al. (1996) noted that because of the short growing season in areas such as Oklahoma when compared to other regions of the Cotton Belt, the enhancement of maturity through variety selection and management practices are crucial to develop premium fiber quality. Variety characteristics and their compatibility and response to a management program is very important to consider so that the cotton plant can respond to the harvest aid chemicals properly (Schulze et al., 1996). Beyond the necessity brought on by a short season environment and the benefit in the crop’s response to late season management, enhancing maturity is also essential to shift the window of susceptibility of insect pests and pathogens (Schulze et al., 1996)

Fiber Development and Quality

Boll development is a process that is determined by temperatures throughout the growing season. Bolls set later in the season typically encounter cooler temperatures, and thus require a longer period to mature (Cathey et al., 1982). Adequate accumulation of heat units is not only required to mature the fiber contained in the bolls, but is also essential for defoliation success (Cathey et al., 1982). In a two-year study of defoliation timing, Stringer et al. (1989) found that yields along with micronaire values were affected greatly if adequate heat units are not acquired. Micronaire is a representation of the measurement of the degree of cotton fiber fineness by determining air permeability while indicating both the fineness (linear density) and maturity (degree of cell-wall development) (Kiron, 2010). The significance of assessing micronaire is one of the most important fiber characteristics for international cotton classers and spinners that help establish the fiber maturity measurement when in the classing office (Kiron, 2010).

A micronaire reading is defined as a measurement of the degree of cotton fiber fineness with the use of an airflow instrument known as the Micronaire (Saville, 1999). In general, the micronaire readings above 4.9 pertain to the coarser cottons, while readings below 3.5 pertain to the finer cottons. The micronaire readings of 3.5 to 4.9 are generally pooled into an "average or near average" category in micronaire (Raskopf, 1966). Another important aspect of boll maturity is the development of strong fibers. Fiber strength is defined as the force required to break a fiber that varies depending on the length of the fiber, while also considering the level of fiber fineness measured as a perimeter, diameter, or cross section (Hsieh et al., 1995). While fiber strength is largely determined by variety, it may be affected by plant nutrient deficiencies and weather. The distinctive breaking strength of individual cotton fibers is considered to be the most important factor in determining the strength of the yarn that is spun from those fibers (Munro, 1987; Patil and Singh, 1995; Moore, 1996). Cotton with high fiber strength is highly desired because it is less likely to be diminished during the manufacturing process (USDA, 2012).

All management decisions and harvest aids may affect one or more of the fiber characteristics of cotton. For example, fiber characteristics such as length are primarily determined by variety, while environmental influences such as temperature, water, and potassium availability have a significant impact determining the genetic potential for overall fiber length (Guthrie et. al., 1993). Fiber length has been shown to be highly correlated with genetics, meaning that the ultimate goal for cotton breeders is to improve fiber quality characteristics, without reducing fiber yields (Naoumkina et al., 2019). The development of elongated fibers is also very important for the textile industry, since longer fibers can be more efficiently spun into yarn. Fiber quality measurements may be determined with the use of an Advanced Fiber Information System (AFIS) instrument (Naoumkina et al., 2019). Another important characteristic of fiber quality is color grade. Color grade may be affected adversely if bolls are exposed to inclimate weather conditions (Ray and Minton, 1973). These conditions along with a number of factors such as rainfall, insects, fungi, contact with vegetation, and freezing weather events can affect color grade. Color grade is determined by the angle of reflectance and how dull or bright a sample is. The standards for depicting color grade are met by determining the degree of reflectance and the yellowness of fibers which are measured using a HVI (high volume instrument) (USDA, 2012).

The final factors influencing cotton net returns are leaf grade and trash. These cotton parameters are defined as the measure of the amount of non-lint materials in cotton, such as leaf and bark from the cotton plant. Leaf grade is affected by cultivar, harvest methods, and weather conditions at the time of harvest (Anonymous, 1993). The proper application and timing of harvest aids is an important factor in minimizing leaf content of seed cotton and ginned lint. The amount of leaf material remaining in the lint after ginning depends on the amount present in the seed cotton prior to ginning and on the type and amount of cleaning and drying equipment used during ginning (Cotton Foundation, 2001).

Harvest Aid Overview

Chemical harvest aids are used to terminate cotton growth by removing leaves, opening bolls, or desiccating the cotton plant to prepare it for harvest (Brecke et al., 1991). Because the timing of harvest aid applications in cotton is critical, insufficient yield and fiber quality may be resulted if mistimed (Faircloth et al., 2004a). Larson et al. (2002) reported that while reaching full boll maturity early is a challenge, an earlier harvest is highly desired by producers to prevent the risk of their crop being exposed to inclement weather conditions. The challenge of reaching maturity within this timeframe is difficult, particularly in the shorter season within the northern region of the Southwest. Although it is difficult to consistently reach complete maturity, or open every boll while warm weather persists, the physiological activity in cotton is much higher during warm conditions compared to cool temperatures (Silvertooth and Howell, 1988). Snipes and Baskin (1994) stated that, while an early harvest may be desired by producers, delayed harvest aid applications may potentially increase yields by allowing immature bolls to further develop. However, delaying harvest aid applications increases the risk of yield loss to early frosts and inclement weather, and both of which are possible in Oklahoma as cotton season draws to a close.

There are various categories of harvest aid products, including boll openers, defoliants, and desiccants that are currently utilized by producers. Boll openers are primarily products that contain ethephon which accelerates boll opening through stimulation of ethylene production when applied at the proper rate to mature unopened bolls (Stewart et al., 2000). However, while boll openers affect natural plant processes associated with boll opening, they do not accelerate boll or fiber maturation (Stewart et al., 2000). Ethephon, an ethylene harbinger, is a commonly used harvest aid and its effect on opening bolls following application has been reported in a number of field studies (e.g., Cathey et al., 1982). These boll opening compounds perform by accelerating the opening of green bolls (Cathey et al., 1982). The process of boll dehiscence requires dehydration of the entire boll, and is influenced by the plant growth hormone ethylene and temperatures at, and following application (Morgan et al., 1971).

Defoliation may be achieved in one of two ways, the application of a chemical injuring the leaf resulting in increased levels of the hormone ethylene that promotes abscission, or application of hormonal products or plant growth regulators that stimulate ethylene production (Hake et al., 1990). Tribufos and thidiazuron are two examples of chemical defoliants that slightly injure the leaf to result in increased ethylene production (Stewart et al., 2000). Thidiazuron, a hormonal defoliant, also enhances production of ethylene and inhibits regrowth (Cotheran et al., 2001). While leaf abscission in cotton is usually a result of natural senescence due to maturity, the application of chemicals for defoliation merely involves the use of compounds to elicit a response from the plant that ultimately induces the plant to abscise its leaves (Addicott, 1982; Cathey, 1986; Sexton et al., 1985). This abscission process takes place near the base of the leaf petioles and is distinguished by a structural line of weakness (Addicott, 1982; Cathey, 1986; Sexton et al., 1985). This abscission process is controlled by an interaction of hormones that cause cells within the abscission zone to degrade the cell wall, permitting the leaf to fall from the plant (Addicott, 1982; Cathey, 1986; Sexton et al., 1985). While leaf abscission may occur naturally, management for earliness with the use of defoliant chemicals may be used to alter the hormonal balance and accelerate abscission and may be influenced by hormone levels and environmental factors (Cathey, 1986.)

Desiccants such as paraquat are commonly used in preparation for a stripper harvest. Stripper harvested cotton requires defoliation of the leaves with some desiccation of the plant. An evaluation of harvest-aid materials by Supak et al. (1994) illustrated the effectiveness as defoliants and desiccants in the stripper cotton growing areas. Desiccants disrupt cell membranes through the production of super oxide resulting in rapid moisture loss (Stewart et al., 2000). However, if harvest is delayed after complete desiccation, stalk deterioration may occur resulting in excessive trash in mechanically harvested cotton (Brecke et al., 2001).

The two harvest aids' functions that have the largest influence on fiber quality are defoliation and boll opening. Harvest aids may be used to open bolls uniformly at a specifically desired time in efforts to avoid excessive weathering. Exposure to harsh weather conditions can diminish the cotton lint yield and quality, resulting in economic losses. Harvest aids not only mitigate losses in fiber quality by opening bolls at the most crucial and efficient times, but also play a key role in defoliation and boll opening in short season environments that must contend with frost prior to harvest (Cathey, 1986; Oosterhuis et al., 1991).

While the majority of bolls will open naturally over time, harvest aids are a key component in acquiring the best fiber quality possible (Hake et al., 1989). Thus, proper utilization of harvest-aid materials is crucial in order to preserve fiber quality by facilitating a timely harvest, while also reducing plant trash that is collected during mechanical harvesting (Hake et al., 1989). Enabling an earlier harvest also helps minimize trash content and staining of the lint (Brecke et al., 2001.) Raper and Gwathmey (2016) reported that managing for earliness improves the efficacy of defoliants and boll openers prior to harvest due to favorable temperatures present at application. Management practices such as establishment of healthy and uniform stands, adequate moisture, proper fertilization, and proper insect, disease, and weed control all contribute to the success of cotton defoliation and boll development (Brecke et al., 2001). However, while there are several factors that contribute to the success of harvest aid applications, there are two primary aspects including environmental and crop conditions at and following application (Cathey, 1986; Oosterhuis et al., 1991).

Weather Impacts

Oklahoma experiences extreme weather patterns during the growing season and similar to many production environments, water availability remains the most limiting factor for production (Guthrie et al., 1995). However, often early frosts or periods of cool weather limit temperatures compared to other production regions in the U.S. Cotton Belt such as the southeast and mid-south, which accumulate more seasonal heat units than many of the cotton producing regions of Oklahoma. With much of the west central and northern portions of the state falling into a short season production environment consisting of a seasonal heat unit accumulation ranging from 2057-3565 heat units; therefore, managing for earliness is a priority. The challenge of reaching boll maturity within such a short period of time means that enhancing maturity through variety selection and management practices is crucial for improved development, yield, and fiber quality (Schulze et al., 1996).

Weather conditions before and after applications is important as harvest aids are more efficient when temperature, sunlight exposure, and relative humidity are high (Lane et al., 1954). The condition of the plant and prevailing weather also impact the success of spray coverage and the absorption and translocation of harvest aid chemicals (Cathey and Hacsklaylo, 1971). These factors further stress the importance of application timings as long-term exposure to severe weather may decrease cotton lint quality (Barker et al., 1979). The condition of the plant such as maturity and crop health, along with weather conditions at the time of application and immediately following have a huge effect on the success of cotton boll opening (Stewart et al., 2000). Harsh weather conditions or unfavorable crop conditions such as early cutout, excessive fruit shed, and the toughening of leaves may all contribute to poor harvest aid performance, although, these conditions often can be overcome by proper selection of harvest aid materials used together (Snipes and Cathey, 1992).

Heat unit accumulation heavily influences cotton growth and development. A study by Lane et al. (1954) reported that a night temperature above 16 °C is crucial, as plant response to defoliants doubles for each 10-degree Celsius increase between 15 °C and 35 °C. Although producers cannot control the weather environment, the condition of the cotton crop throughout the growing season has a significant impact on the efficacy of harvest-aid chemicals. The epitome of crop condition for optimal harvest-aid performance includes an early maturing crop, a heavy boll load, adequate moisture throughout the growing season, proper nutrients, and a naturally senescing crop (Brecke et al., 2001). However, all these conditions are rarely met, so proper management practices should be implemented to prepare the crop for optimal harvest-aid performance such as plant stand, fertility and water management, and insect control (Brecke et al., 2001). In contrast, the growing season is much shorter in northern areas where low temperatures are experienced which can lead to slow boll maturation and poor harvest aid efficacy (Brecke et al., 2001).

Scheduling Harvest Aid Applications

The proper timing of harvest aid applications aims to strike a balance of reducing the degradation of earlier developed open bolls and the maturation of later developing bolls (Kelley, 2002). Harvesting cotton as early as possible is ideal in an effort to capitalize on favorable weather conditions and higher lint quality while minimizing the exposure of open bolls to detrimental conditions as fall progresses. While accomplishing an early harvest is favorable to avoid weathering losses, decreases in lint quality and yield from premature applications and immature bolls must also be avoided to optimize the value of the crop (Brecke et al., 2001).

Boll maturity is often gauged by boll size, as a "harvestable sized boll" is defined as a closed boll that is >2 cm in diameter and turgid (Gwathmey et al., 2011). However, while some of the late developed bolls may not reach maturity before harvest aid applications are implemented, and many may still reach maturity and open if the bolls are physiologically mature and weather conditions are favorable following application (Faircloth et al., 2004a, 2004b).

Cotton boll maturity consists of two phases: physiological maturity and fiber maturity (Bruns, 2009). Physiological maturity is reached once the seeds and fiber inside the boll both have matured. Fiber maturity, which is essential for an efficient harvest, is marked by the completion of the secondary wall composed of cellulose deposits (Haigler, 2010; Stiff and Haigler, 2012). Once a boll consisting of seed fiber has matured, the level of development needed to prepare the crop for harvest with the use of harvest aids has been met. At this point, harvest aids applications will not adversely affect quality, and the age and condition of the crop is complementary in response to harvest aid chemicals (Brecke et al., 2001). A study by Cothren et al. (2001) reported that following application, naturally senescing cotton is more responsive to harvest-aid chemicals than less mature cotton, especially if the crop consists of a heavy boll load. Once harvest aid applications are made, if adequate management and weather conditions permit, bolls that are physiologically mature are expected to open containing mature fiber (Cothren et al., 2001).

Factors such as weather, heat unit accumulation, and cotton cultivar pose a challenge for producers when making the decision on when to apply harvest-aids (Brecke et al., 2005). Currently, there are a number of traditional methods used to determine boll maturity, all further verifying each other. The most common techniques implemented are percent open boll (POB), the cut boll technique, and nodes above cracked boll (NACB) (Brecke et al., 2005). Percent open bolls is determined by assessing the number of open bolls and then dividing by the total number of unopened, harvestable sized bolls. The cut-boll technique is used to determine boll maturity by cutting into the actual boll itself to examine the cross section. Once a boll is split in half across the seeds, seeds of a mature boll will have a dark seed coat and a pale green embryo inside (Brecke et al., 2001). The NACB method involves counting the number of nodes from the uppermost first-position cracked boll to the uppermost harvestable first-position boll (Kerby et al., 1992). These methods are used to assess boll maturity in preparation for a timely and efficient harvest. Precise assessment of crop maturity is crucial in order to maintain yields and fiber quality in preparation for harvest (Bednarz et al., 2002; Bange et al., 2010). The timing of applications may have a significant effect on lint and seed yield as reductions may be resulted if applications are made too early. Snipes and Baskin (1994) reported that when chemical defoliants were applied prior to 60% open bolls, significant decreases in lint yield and undesirable changes in fiber quality were observed. Plants are also considered sufficiently mature for harvest-aid application with minimal loss of yield and micronaire when NACB values are ≤4 (Kerby et al., 1992; Bange et al., 2010; Edmisten, 2013a; Roberts et al., 1996). Bednarz et al. (2002) and Bange et al. (2010) independently demonstrated that 4 NACB corresponded to 60% open bolls. Proper assessment of cotton maturity is essential for maximizing yield, crop quality and economic return. Both Snipes and Baskin (1994) and Bange et al., (2010) conveyed that an immature crop resulted in lower yields consisting of a large portion of immature fiber. Harvesting a crop much later than its maturity date also resulted in loss of yield, crop quality and fiber characteristics all impacting economic return (Williford, 1992; Bednarz et al., 2002; Constable and Bange, 2007).

The majority of studies representing harvest-aid timing strategies have been conducted in areas such as the Southeast and Midsouth regions, which vary considerably regarding environment when compared to the Southwest. The Southeast and Midsouth cotton production regions receive roughly 127 cm of precipitation per year, when compared to 38 to 50 cm of precipitation per year in the Southwest (MSU, 2020; Mcpherson et al., 2007). Seasonal heat unit accumulation also varies among regions. Heat unit accumulation in the southeast is roughly 3186 per year (UGA, 2020) and 2930 per year in the midsouth (MSstate, 2020) while only about 2522 per year in the Southwest region (Mcpherson et al., 2007).

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CHAPTER II

COTTON HARVEST AID EFFICACY AND COTTON FIBER QUALITY AS INFLUENCED BY APPLICATION TIMING

Introduction

Upland cotton (*Gossypium hirsutum* L.) production within the state of Oklahoma has grown tremendously since 2015, with cotton production expanding in parts of Oklahoma with a shorter growing season than that of traditional cotton areas. In 2016, Oklahoma producers planted 123,500 hectares of cotton, while in 2019 Oklahoma reached over 291,000 planted hectares and ranked as one of the top five cotton producing states in the United States (USDA-NASS, 2020). Historically, cotton has been grown in Oklahoma's Southwest and West Central agricultural districts, but with the advent of shorter season cotton varieties, production has expanded to include Central, North Central, and Panhandle regions (USDA-NASS, 2018). While the Southwest and West Central areas lead cotton production in Oklahoma due to the desirable temperatures for optimal cotton growth and a longer growing season compared to other regions, production is more challenging for producers in the northern parts of Oklahoma with shorter growing season. This short season environment often places producers at risk for yield losses and poor fiber quality if their crop has not reached maturity by the end of the growing season (Raper and Gwathmey, 2015).

Achieving early maturity is key for cotton production in Oklahoma as this allows for the application of harvest aid chemicals under more favorable weather conditions that are crucial for harvest aid efficacy. Harvest aids are chemical products used to terminate cotton growth, by defoliating or desiccating cotton plants and opening cotton bolls (Kelley, 2002). Appropriate timing of harvest aid applications is critical to achieve optimal defoliation and boll opening which allows for a timely harvest. Applications that are too early can result in the opening of immature bolls and decreases in lint quality caused by longer exposure to severe weather, while applications that are too late may result in incomplete defoliation and boll opening (Barker et al., 1979). Several management factors will impact the maturity of the crop, including variety selection, appropriate nitrogen fertility, and use of plant growth regulators to limit vegetative growth (Gwathmey and Craig, 2003).

The condition and maturity of the plant, along with weather conditions at the time of application and immediately following will determine the success of cotton boll opening (Stewart et al., 2000). Weather conditions before and after application are key as the activity of harvest aids is optimal when temperature, sunlight exposure, and relative humidity are high (Brecke et al., 2001). The condition of the plant and prevailing weather also impact the success of spray coverage and the absorption and translocation of harvest aid chemicals (Cathey and Hacsklaylo, 1971). Inclement weather or unfavorable crop conditions such as early cutout, excessive fruit shed, and the toughening of leaves may all contribute to poor harvest aid performance, although, these conditions often can be overcome by proper mix of harvest aid materials (Snipes and Cathey, 1992). Optimizing the timing of harvest aid application can be difficult for producers, as achieving boll opening prior to a frost in short season environments is challenging (Gwathmey and Craig, 2003). Much of Oklahoma is more prone to early frosts or periods of cool weather when compared to the southeast and mid-south production regions in the U.S. Cotton Belt. This presents the challenge of reaching boll maturity within such a shorter growing season, meaning that enhancing maturity through variety selection and management practices is crucial for optimal yield, and fiber quality (Schulze et al. 1996).

Timing of harvest aid application is typically based on the maturity of the crop, which is determined either by using the percentage of open bolls or using the nodes above cracked boll NACB method (Brecke et al., 1996). NACB is determined by locating the uppermost first-position cracked boll and counting the number of main-stem nodes to the uppermost harvestable boll (Guthire et al., 1993). Thresholds of 60 to 70% open bolls (percent of open bolls, POB) or 4 NACB are often the recommended threshold for harvest aid application timing, although a combination of the two methods is typically recommended (Bednarz et al., 2002; Brecke et al., 1996; Byrd et al., 2021; Faircloth et al., 2004). Plants are considered sufficiently mature for harvest-aid application with minimal loss of yield and fiber quality when NACB values are four or fewer (Bednarz et al., 2002, Kerby et al., 1992, Bange et al., 2010, Edmisten, 2014a, Roberts et al., 1996).

Variation has been noted for the most appropriate method to determine the proper timing of harvest aid application. The use of the NACB method is preferred over the POB method to optimize fiber quality in North Carolina (Faircloth et al., 2004). In contrast, the POB method is in favor for maximizing lint yield in Louisiana (Siebert and Stewart, 2006). Bednarz et al. (2002) revealed that four NACB and 60 POB occur at the same time in Georgia, while Bynum and Cothren (2008) revealed that in Texas regardless of nodal position, 60 POB was not synchronized with four NACB, which could partially explain the inconsistencies seen across the Cotton Belt. While slicing bolls to determine maturity is commonly recommended to be performed in conjunction with the quantification of NACB, a common concern when assessing maturity among many producers is opening immature bolls that will negatively impact lint quality.

As cotton production expands into non-traditional areas of Oklahoma and other states in the Great Plains region, understanding the effect of harvest aid application timings is critical for cotton producers in short season environments. Although the timing of harvest aid application has received considerable attention in much of the Cotton Belt (Brecke et al., 1996; Bednarz et. al, 2002; Faircloth et al., 2004; Siebert and Stewart, 2006), information on timing in short season environments like central and northern Oklahoma is lacking. Additionally, the earlier maturing varieties that now dominate much of the market in the northern areas of the southwest Cotton Belt differ in fruit distribution than the later maturing varieties that were utilized in those previous studies. Therefore, our objectives were to quantify the relationship between cotton maturity as determined by the NACB method and the percent of open bolls, the success of boll opening and proportion of undersized bolls present at applications made at various maturity levels, and the impact of harvest aid application timing on cotton yield and fiber quality. This information could be compared to previous studies to determine if optimal harvest aid application timing in the northern areas of the Southwest is similar to those determined for other areas of the Cotton Belt. This information can also be used to evaluate the yield and quality impact of early application in scenarios in which inclement weather is forecasted prior to the crop reaching optimal maturity.

Materials and Methods

Two sites were evaluated in the state of Oklahoma to determine optimal harvest aid application timing essential for an efficient harvest. This study was conducted during 2019 and 2020 growing seasons. Locations included a non-irrigated Teller loam at the Cimarron Valley Research Station in Perkins, OK (35.989032, -97.044654) in 2019, and an irrigated Binger fine sandy loam at the Caddo Research Station in Fort Cobb, OK (35.160530, -98.452855) in 2019 and 2020. Due to limited fruit production in the non-irrigated system, only the Ft. Cobb site was utilized in 2020 to achieve a greater range of application timings. These two locations represent the north central (Perkins) and west central (Fort Cobb), areas of Oklahoma that have recently experienced large increases in production. The early-mid maturating variety Phytogen 300 W3FE (Corteva Agriscience, Indianapolis, IN) was planted at a seeding rate of 111,000 seeds ha^{-1} at Fort Cobb on 03 June 2019, and 21 May 2020, while the mid-maturing variety Deltapine 1820 B3XF (Bayer Crop Science, Research Triangle Park, NC) was planted at a seeding rate of 81,680 seeds ha^{-1} on 30 May 2019 in Perkins. Varieties were selected based primarily on herbicide trait compatibility with surrounding production systems, and moisture variances (irrigated at Fort Cobb and non-irrigated at Perkins). In 2019, 67 kg/ha of N was applied at the Perkins site, and 179 kg/ha of N, 45 kg/ha of P, and 30 kg/ha of K was applied prior to planting at Fort Cobb in 2019 and 2020. All management inputs excluding harvest aids followed OSU extension recommendations for these production regions.

Cotton plots were comprised of four rows spaced 91 cm apart in Fort Cobb and 76 cm apart in Perkins, with plots being nine meters in length at both locations. The fixed effect of application timing was randomized within each of the four replications for a factorial arrangement of treatments. The center two rows served as treatment rows that received harvest aid applications and were utilized for boll opening measurements and harvest, with the outer two rows of each plot serving as borders.

Harvest aid treatments consisted of application timings using the NACB method to assess maturity. Applications were initiated once a majority of plants reached seven NACB and then proceeded at four to five day intervals. The timings targeted various NACB levels and were intended to include applications when plants reached ranges of seven-six, six-five, five-four, four-three, three-two, two-one, and one-zero NACB. A non-treated control (NTC) was also included which did not receive a harvest aid application. Actual NACB values and percent of open bolls on each application date for each site-year were recorded (Table 1). Later application timings in 2019 were omitted due to a killing freeze (-2.5°C at Fort Cobb, and -1°C, at Perkins) on 12 October. The killing freeze occurred after the four-three NACB application in Fort Cobb and the three-two NACB application at Perkins, thus timings after this point were not evaluated. At each timing, a harvest aid mix was applied consisting of 0.47 L ha^{-1} tribufos (Folex 6 EC, Amvac Chemical, Newport Beach, CA) and 0.95 L ha^{-1} ethephon (Boll'd 6 SL, Winfield Solutions, St. Paul, MN). This is a commonly applied harvest aid mixture for cotton in Oklahoma (Byrd et al., 2021). The application equipment consisted of a CO_2 pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} through a 4-nozzle boom equipped with TeeJet® XR11002 flat fan tips. Daily maximum and minimum air temperatures after application were recorded using the Oklahoma Mesonet (Mcpherson et al., 2007) for determination of heat unit accumulation between application date and harvest.

Determining Boll Maturity Prior to Harvest Aid Application

On the day of application, the diameter at the widest point of all closed bolls on seven plants per plot was determined using digital calipers. Bolls were placed into two categories based on their diameter, harvestable and undersized. Boll maturity is often gauged by boll size, as a "harvestable sized boll" is defined as a closed boll that is >2 cm in diameter and turgid (Gwathmey et al., 2011). The harvestable and undersized categories in the current study were based on diameters of U.S. currency due to the common comparison of a quarter-sized boll (24 mm) being considered harvestable, and anything smaller being undersized, or too undeveloped to open after a harvest aid application (Prostko et al., 1998). Thus, the diameters of a nickel, penny, and dime, were used as a measurement tool to classify undersized bolls within the field, with the smallest category being any boll smaller than a dime. Bolls were also marked with various colors of flagging tape based on their size category on the day of harvest aid application. However, there were no differences observed in boll opening response across the various size categories of undersized bolls, thus the data presented for the current study will only refer to the bolls as either harvestable or undersized. The NACB and total number of open and closed harvestable bolls were quantified on the day of application so that open boll percentage could be determined. Boll opening success for harvestable and undersized bolls was recorded every four-to-five days after application (DAA) until either no additional boll opening activity was observed, 100% of the bolls were open, a killing freeze occurred, or the plots reached a minimum of 20 DAA and were harvest ready. During the 2020 Fort Cobb site-year, paraquat was applied 14-15 days following the previous harvest aid application when POB $\geq$ 98% to further desiccate the plant tissue in preparation for stripper harvest. The application equipment consisted of a CO2 pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} consisting of 1.5 L ha^{-1} paraquat dichloride 3 lb. ai/gal (Parazone 3SL, AMVAC Chemical, Newport Beach, CA) through a 4-nozzle boom equipped with TeeJet® XR11002 flat fan tips.

At all site-years, the seven plants tagged the day of application were cut and removed from the field at approximately 20 DAA to ensure all boll opening had ceased. Lint from open, harvestable bolls on these plants was then removed by hand so that the size characteristics of bolls that contributed to the seed cotton could be recorded. Seed cotton from all hand-harvested samples was weighed prior to ginning on an 8-saw laboratory gin at Oklahoma State University in Stillwater, OK for determination of gin turnout. After ginning, approximately 200 g of lint from each plot was sent to the Texas Tech University Fiber and Biopolymer Research Institute in Lubbock, TX. to determine if yield was impacted from these treatments by assessing whole plot weight, as well as to obtain fiber quality data more representative of commercial production, the entire center two rows were also harvested in 2020. After the seven tagged plants were removed, the remaining crop was harvested with a John Deere 482 (John Deere, Moline, Illinois) cotton stripper equipped with a bagging attachment for plot harvesting. This stripper did not include a burr extractor so harvested cotton included burrs as well as increased levels of sticks and other plant material. Cotton harvested from the whole plots was weighed after harvest and then approximately four kg samples from each plot were sent to the University of Tennessee MicroGin in Jackson, TN. This gin is more representative of the processes the cotton will go through in a commercial gin, and while the lack of a bur extractor limits the ability to properly analyze quality parameters such as color and leaf grade, this will provide a larger and more representative sample to evaluate properties such as yield, turnout, micronaire, fiber strength, fiber length, and uniformity.

The relationship between NACB and open boll percentage was determined through regression analysis in SAS 9.4 (SAS Institute, Cary, NC). Statistical analysis for boll opening was performed using analysis of variance (ANOVA) for the randomized complete block design using Proc Mixed in SAS 9.4 (SAS Institute, Cary, NC) with means separated by Fisher's Protected LSD. Because of differences in application timings that were evaluated across site-years, boll opening for each site-year was analyzed separately.

RESULTS AND DISCUSSION

Node above cracked boll (*NACB) and Percent of Open Bolls (POB)*

Because harvest aid application timing has traditionally been established by observing the POB, an essential first step of the current study was to quantify the relationship between POB and NACB. When pooled across all site-years, a strong correlation ($R^2 = 0.85$) existed between NACB and POB (Fig. 1). Previous studies have documented that traditional harvest aid application window is optimal at 60 – 75% open boll, which correlates to approximately 4 NACB. At 3.5 – 4.5 NACB in the current study, the majority POB values ranged from 61-73%, similar to previous studies implemented across the Cotton Belt (Bednarz et. al, 2002; Faircloth et al., 2004; Siebert and Stewart, 2006), although there were instances where percent open was lower than the trend for NACB values. Specifically, at four and one NACB the percentage of open bolls at Perkins 2019 was 37% and 75% respectively, falling below the trend. The most obvious explanation for this deviation is that this data is from the lone non-irrigated site-year included in the study. However, the relationship between NACB and POB is fairly strong despite differences in irrigation availability, variety, and production year across all site-years. Our results corroborate previous work that has equated 4 NACB with 60% open bolls (Brecke et al., 1996; Bednarz et. al, 2002; Faircloth et al., 2004; Siebert and Stewart, 2006).

Application Timing and Boll Opening

Boll opening success was quantified across five application timings in 2019 at Perkins and Fort Cobb, and eight application timings at Fort Cobb in 2020, in addition to the NTC included at each site-year. The results below refer only to harvestable-sized bolls, or those $\geq$ 24 mm in diameter. Boll opening activity for undersized bolls will be presented in a later section.

Perkins, 2019

At the Perkins dryland site-year of the study, five applications were made beginning at 5.4 NACB, at which point the crop had reached 29% open bolls (Table 2). Applications continued until the crop reached 1 NACB at which point 77% of harvestable sized bolls were open. Due to a terminal freeze event that occurred three days after the 1 NACB application, the only boll opening evaluation on this treatment and the NTC occurred when plants were removed and hand harvested, at 21DAA. For the first four treatment timings, boll opening activity was recorded 4 – 5 DAA, and with the first two timings also evaluated at 8 – 10 DAA. At 5 DAA, there was no difference between treatments, and by harvest time all treatments had reached at least 84% open with all but one treatment containing 90% open bolls.

Fort Cobb, 2019

Five application timings were made at Fort Cobb in 2019, beginning at 7 NACB, and boll opening data was collected at 5 DAA on the four earliest applications. Unlike the Perkins location, there were still differences present in open boll percentage across the application timings at 5 DAA, although there had been enough activity even at the earliest timing to bring all treatments to over 75% open at this point (Table 3). There was again no difference in open boll percentage at harvest with all treatments containing at least 94% open harvestable bolls.

Fort Cobb, 2020

Treatments at the Fort Cobb 2020 site consisted of eight application timings starting at 7.6 NACB. In contrast to the sites in 2019, there was little boll opening activity among applications made at or before 4.5 NACB at the first observation (3-4 DAA). While statistical differences were present at 7 DAA, all treatments were over 75% open bolls, and by 11 DAA no differences were observed with all treatments at least 93% open, while POB at harvest was ≥ 99% (Table 4).

One trend that was present across both Fort Cobb site-years was the difference in boll opening success recorded at the evaluations made shortly following application. For earlier applications made on less mature (lower percent open, higher NACB) plants, there was often a significant amount of boll opening fairly rapidly, 5 and 7 DAA in 2019 and 2020, respectively. Boll opening efficacy was likely due to warm temperatures during the early application timings. Boll opening success is typically higher during the warmer months due to the stimulation of ethylene (Gwathmey *et al*., 2001; Silvertooth and Howell 1988; Dodds et al., 2010).

Impact of Harvest Aid Application Timing on Undersized Bolls

The proportion of undersized bolls on the day of application pooled across all treatment timings varied greatly between locations. The 2019 Perkins, OK site, 55.6% of closed bolls were in the undersized category on day of application (Table 2). At Fort Cobb 2019, there were 2.4% undersized bolls present on the day of application (Table 3), and at Fort Cobb 2020, 0.85% of closed bolls were undersized at application (Table 4). The large number of undersized bolls at the dryland location of Perkins, OK, 2019 was likely due to the differences in cultivar and irrigation practices implemented at Fort Cobb, 2019, and 2020. Even at Perkins where there was a higher proportion of undersized bolls when harvest aids were applied, the harvestable boll load consisted of less than 5% undersized bolls regardless of application timing. The small amount of undersized bolls is likely due to the fact that the bolls were most likely either aborted by the plants prior to harvest, or they only cracked and never fully opened for all the lint to be removed by hand or harvest equipment.

Micronaire from Hand Picked Samples

Due to the challenges of season length, micronaire is often a focus for producers and researchers in short season environments, as low micronaire is a common fiber quality issue. At Perkins 2019, the earliest application timing (5.4 NACB) resulted in micronaire values lower than all other timings except the application made at 3.7 NACB (Table 5). There was no effect of application timing on micronaire at Fort Cobb in 2019 or 2020. More importantly, micronaire values in the present study ranged from 4.0-4.9, within the range of premium or base quality values (USDA AMS, 1995). The little to no effect on micronaire is likely due to the small amount of undersized bolls that opened contributing minimal lint, with the bulk of lint contribution from mature, harvestable bolls. Similar to the findings of Snipes and Baskin (1994), there was a general pattern of increased micronaire with increasing open boll percent data for both cultivars among both site years.

Similar to previous studies (Snipes and Baskin, 1994; Faircloth et al., 2004; Siebert and Stewart, 2006; Bednarz et al., 2002; Kerby et al., 2002), there was a positive relationship observed in the present study between POB and delaying defoliation (Table 1; Fig. 1). The measurements taken at both Fort Cobb site-years illustrate the relationship between POB and NACB (Table 1; Fig. 1), similar to other studies implemented across the Cotton Belt (Faircloth et al., 2004; Siebert and Stewart, 2006; Bednarz et al., 2002). Kerby et al. (1992) also indicated that the optimum timing for harvest aid application was four NACB or 60 POB, although defoliation prior to 60% open is possible without sacrificing lint yield or micronaire values (Table 5 and 6), similar to findings of Snipes and Cathey (1994), Bednarz et al. (2002), and Faircloth et al. (2004).

Lint Yield and Fiber Quality from Whole Plot Harvest

Lint yield from whole plot harvests was quantified at Fort Cobb in 2020 (Table 6). Lint yield averaged 1,762 kg ha^{-1} across all treatments and there was no effect of harvest aid application timing. Similarly, there was no effect of application timing on turnout, length, micronaire or strength and none of the quality parameters were at levels that might result in value discounts. There were significant differences present for fiber uniformity with the very earliest and latest application timings resulting in the highest uniformity values. However, all fiber uniformity values were above 82% and thus not likely to result in a decline in fiber values similar to other quality parameters measured. A probable reason for the lack of treatment influence on fiber quality parameters could be the high percentage of mature or harvestable sized bolls present on the day of application.

Other Application Timing Considerations

While boll opening activity and fiber maturity tend to be the primary concerns for cotton producers when considering harvest aid application timing in Oklahoma and other areas of the Great Plains, there are other factors that should be considered. Namely, the increased amount of immature foliage present on the plants at earlier application timings. Visual observations of foliage levels in the current study illustrated the benefit of allowing natural senescence of the crop to remove leaves. Further, while the warmer conditions present at early application timings benefitted boll opening efficacy, these conditions are also more favorable for regrowth to occur should moisture or excess nitrogen be present (Silvertooth et al., 2001). These warmer conditions and increased green vegetation also result in increased risk of burning or desiccating foliage with defoliant applications, resulting in “stuck leaves” that are difficult to remove prior to harvest. This was observed in early applications, particularly in 2020 when favorable conditions all year resulted in large plants with high amounts of green foliage being subjected to harvest aid applications during warm early September temperatures. A UAV was employed in 2020 to analyze the amount of green foliage present across the application timings at various intervals, although due to software issues this data was not able to be utilized. Due to limitations in harvest equipment (lack of burr extractor on plot stripper), the present study is likely not reflective of fiber quality properties a producer may experience in this same scenario, particularly regarding leaf and color grade. In a stripper harvested scenario, it may be that with a proper burr extractor the increased foliage observed at early application timings could be removed, although adequate desiccation would be necessary to prevent moisture from further degrading the lint quality.

This research relates back to our objective utilizing the NACB method to assess maturity that is well known in many major cotton producing regions including Georgia (Bednarz et al., 2002), Louisiana (Siebert and Stewart, 2006), North Carolina (Faircloth et al., 2004), and Central Texas (Bynum and Cothren, 2008). The present study illustrates that the strong correlation between POB and NACB documented in previous studies still exists even in short season environments utilizing earlier maturing varieties. Also similar to previous studies, boll-opening success was observed even at earlier than recommended application timings and by 11 DAA optimal boll opening was achieved across all site-years. Although, due to the increased amount of foliage present at these earlier application timings, a subsequent defoliant or desiccant application would likely be necessary prior to harvest or detriments to fiber color and grades are likely. While some undersized bolls cracked very few were actually harvestable which explains some of the lack of fiber quality effect observed. The results of this study suggest that if adequate time exists (7 – 11 days) prior to forecasted inclement weather, application of harvest aids made prior to cotton reaching the traditional application windows will be successful for boll opening and not detrimentally impact fiber quality. However, these earlier applications will also increase the risk of discounts due to leaf and color grade, while waiting for traditional application windows allows for natural senescence and boll opening to reduce this risk. Additional research utilizing harvesting equipment more representative of a commercial setting would be necessary to capture the impact of harvest aid timing on defoliation and corresponding fiber quality properties.

Figure 1. Regression of measured node above cracked boll (NACB) at the time of harvest aid application and percent of open bolls at application, variation in 37% open bolls aligning with 4 (NACB), Fort Cobb and Perkins 2019-2020.

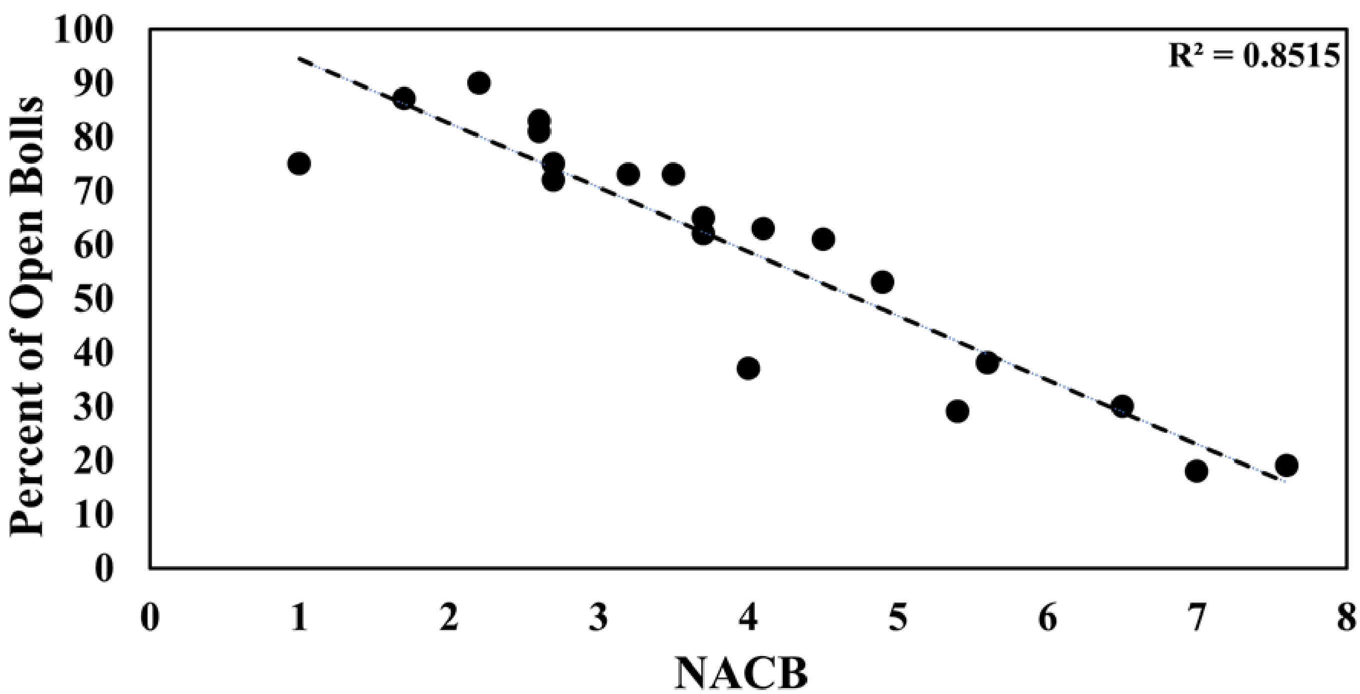

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Table 1. Treatment details from each site-year, including application date, nodes between uppermost first position cracked boll and uppermost first position harvestable boll at application (NACB), percentage of open bolls (POB) at application, and heat units accumulated between application and harvest.

Application Date	NACB	POB	Heat Units Accumulated
Perkins, 2019			
9/20/2019	**5.4**	**29**	**163**
9/25/2019	**4.0**	**37**	**119**
9/30/2019	**3.7**	**62**	**66**
10/4/2019	**3.2**	**73**	**29**
10/9/2019	**1.0**	**77**	**15**
NTC[z]	**2.7**	**76**	**N/A**
Fort Cobb, 2019			
9/25/2019	**7.0**	**18**	**125**
9/30/2019	**4.9**	**53**	**73**
10/4/2019	**4.1**	**63**	**37**
10/9/2019	**2.5**	**72**	**19**
10/11/2019	**1.7**	**87**	**13**
NTC[z]	**1.0**	**87**	**N/A**
Fort Cobb, 2020			
9/11/2020	**7.6**	**19**	**160**
9/15/2020	**6.5**	**30**	**143**
9/18/2020	**5.6**	**38**	**107**
9/22/2020	**4.5**	**61**	**94**
9/25/2020	**3.7**	**65**	**103**
9/29/2020	**3.5**	**73**	**75**
10/2/2020	**2.6**	**81**	**63**
10/6/2020	**2.2**	**90**	**86**
NTC[z]	**2.6**	**83**	**N/A**

[z] Non-treated control that didn't receive any harvest aid applications. Measurements on these plots were taken on the same intervals as the final harvest aid timing.

Table 2. Boll opening efficacy resulting from five harvest aid application timings at Perkins, 2019. Ratings recorded at 4 – 5 days after application (DAA) intervals and reported at point until either 100% of bolls were open or no differences between treatments were observed.

NACB at App.	0 DAA		4-5 DAA	8-10 DAA	Harvest	Undersized Bolls at App.	Harvestable Undersized Bolls at Harvest[x]
	---			%	---		
5.4	29	c	81	92	94	19	3.4
4.0	37	c	92	96	97	21	2.9
3.7	62	b	84	N/A[y]	84	26	0.3
3.2	73	ab	90	N/A[y]	93	18	1.5
1.0	77	a	N/A[y]	N/A[y]	91	16	0.9
NTC[z]	76	ab	N/A[y]	N/A[y]	93	12	1.7
p-value	.0001		.2414	.2012	.0623	.1929	.2321

[z]Non-treated control that didn't receive any harvest aid applications. Measurements on these plots were taken on the same intervals as the final harvest aid timing.
[y]No boll opening data taken due to killing freeze prior to reaching 5 DAA.
[x]This only includes bolls that were open and harvestable. Bolls that were only cracked or that lint couldn't be removed were omitted.

Table 3. Boll opening efficacy resulting from five harvest aid application timings at Fort Cobb, 2019. Ratings recorded at 4 – 5 days after application (DAA) intervals and reported at point until either 100% of bolls were open or no differences between treatments were observed.

NACB at App.	0 DAA		4-5 DAA		8-10 DAA	Harvest		Undersized Bolls at App.	Harvestable Undersized Bolls at Harvest[x]
	--%--								
7.0	19	d	75	b	100	100	a	2.2	0.6
4.9	53	c	79	b	98	100	a	2.5	0.9
4.1	63	bc	92	a	N/Ay	99	a	7.9	1.0
2.5	72	b	92	a	N/A[y]	94	b	1.2	0.3
1.7	87	a	N/A[y]	N/A[y]	N/A[y]	98	a	0	0
NTC[z]	87	a	N/A[y]	N/A[y]	N/A[y]	99	a	0	0
p-value	.0001		.0019		.1275	.0036		.0529	.3065

[z]Non-treated control that didn't receive any harvest aid applications. Measurements on these plots were taken on the same intervals as the final harvest aid timing.
[y]No boll opening data taken due to killing freeze prior to reaching 5 DAA.
[x]This only includes bolls that were open and harvestable. Bolls that were only cracked or that lint couldn't be removed were omitted.

Table 4. Boll opening efficacy resulting from eight harvest aid application timings at Fort Cobb, 2020. Ratings recorded at 4 – 5 days after application (DAA) intervals and reported at point until either 100% of bolls were open or no differences between treatments were observed.

NACB at App.	0 DAA		4 DAA		7 DAA		11 DAA		14 DAA	Harvest	Undersized Bolls at App.	Harvestable Undersized Bolls at Harvest[x]
	-------------------		-------------------		-------------------		-------------------	%	-------------------	-------------------	-------------------	-------------------
7.6	19	f	30	d	90	ab	95	ab	96	100	0	0
6.5	32	e	45	c	88	b	93	b	99	100	0.6	0.6
5.6	38	e	45	c	77	c	98	ab	99	100	0	0
4.5	61	d	67	b	98	a	100	a	100	100	0	0
3.7	65	cd	84	a	98	a	98	ab	98	100	0	0
3.5	73	bc	86	a	97	a	100	a	100	100	0	0
2.6	81	ab	90	a	98	a	100	a	100	100	0	0
2.2	88	a	95	a	95	ab	99	ab	100	100	0	0
NTC[z]	86	a	92	a	92	ab	96	ab	98	100	0	0
p-value	.0001		.0001		.0004		.0135		.6638	.7295	.4613	.4616

[z]Non-treated control that didn't receive any harvest aid applications. Measurements on these plots were taken on the same intervals as the final harvest aid timing.
[x]This only includes bolls that were open and harvestable. Bolls that were only cracked or that lint couldn't be removed were omitted.

Table 5. Cotton micronaire taken from hand-picked plant samples.

Perkins 2019		Fort Cobb 2019		Fort Cobb 2020	
NACB	Micronaire	NACB	Micronaire	NACB	Micronaire
5.4	4.0 b	7.0	4.2	7.6	4.4
4.0	4.4 a	4.9	4.3	6.5	4.2
3.7	4.3 ab	4.1	4.8	5.6	4.5
3.2	4.6 a	2.5	4.5	4.5	4.6
1.0	4.6 a	1.7	4.9	3.7	4.5
(NTC)[z]	4.6 a	(NTC)[z]	4.3	3.5	4.7
				2.6	4.0
				2.2	4.9
				(NTC)[z]	4.7
p-value	.0455		.1062		.0517

[z]Non-treated control that didn't receive any harvest aid applications. Measurements on these plots were taken on the same intervals as the final harvest aid timing.

Table 6. Fort Cobb 2020 fiber quality parameters from whole plot harvest at the end of season.

NACB[z]	Lint Yield	Turnout	Length	Micronaire	Strength	Uniformity	
	kg ha^{-1}	%	cm		g tex^{-1}	%	
7.6	1,747	28.3	3.01	3.8	32.85	82.95	ac
6.5	1,662	29.0	2.95	3.7	32.65	82.65	bc
5.6	1,750	28.4	2.99	3.7	33.20	82.75	bc
4.5	1,819	29.8	2.93	3.9	32.60	82.25	c
3.7	1,815	28.4	2.99	4.1	31.70	82.65	bc
3.5	1,704	29.0	2.97	4.3	32.50	82.70	bc
2.6	1,901	30.1	2.99	4.1	32.82	83.20	ab
2.2	1,751	29.2	3.02	4.2	33.75	83.60	a
NTC[y]	1,706	28.2	2.95	4.2	32.28	83.15	ab
p-value	.8264	.0814	.0577	.0935	.3330	.0473	

[z]Nodes between the uppermost first position cracked boll and the uppermost first position harvestable boll on the day of application.

[y]Non-treated control that didn't receive any harvest aid applications. Measurements on these plots were taken on the same intervals as the final harvest aid timing.

APPENDICES

1.1 Field experiment at the Perkins, 2019 Research Station five days following harvest aid application.

1.2 Bolls flagged and placed into colored categories based on diameter. Color of tape corresponding to boll diameter.

1.3 Cracked undersized boll following harvest aid application.

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