ABSTRACT

Hendricks, Jeremy Perkins. Late Season Management Considerations for Cotton in North Carolina (Under the direction of Drs. Keith Edmisten and Guy Collins, co-chairs).

North Carolina's cotton production is positioned in a more northern and eastern state than many other cotton-producing states. There are many reasons as to why a grower would need to pursue late blooms to increase yield. Also, North Carolina's cotton crop is subject to encountering tropical weather in the late summer or fall that can penalize yield.

A study was conducted to evaluate the last effective bloom date across locations in North Carolina. Research was conducted to determine the latest date at which a majority of white blooms have a reasonable chance of maturing into harvestable bolls, and to determine the effect of crop termination dates on the last effective bloom date. Last effective bloom dates can safely and conservatively be extended to approximately September 1st in most years in NC, or September 5th in years with warmer fall temperatures. Contrary to popular belief, delaying defoliation until near the first frost (or when no meaningful heat unit accumulation is likely) does not improve the probability of maturation and opening of later set bolls. This data suggests that last effective bloom dates could be extended to mid-September in years with warmer fall temperatures, and especially if defoliation occurs during mid-October, allowing boll openers to work with additional, modest heat unit accumulation and time before a frost occurs. Defoliation during mid-October can result in harvestable bolls developed from as few as 200-350 heat units, whereas delaying defoliation until first frost may require noticeably more (~465+) heat units to develop bolls fully. Delaying defoliation until closer to first frost allows for additional heat unit accumulation to develop bolls, but does not allow enough time for boll openers to be effective. Therefore, results become more erratic.

A second study was conducted to quantify the effects of known tropical wind speeds on the degree of stormproofness, degree of exposure (percent open bolls), and yield loss. The degree of cultivar stormproofness impacted yield loss, as the stormproof cultivar resulted in less loss than the showy cultivar. The degree of exposure significantly impacted yield loss as losses associated with defoliation before a tropical event (90% open boll) were significantly greater than defoliation after a tropical event (20% open boll). The degree of exposure is as impactful to yield losses as the degree of stormproofness but stormproofness appeared to be more meaningful when exposure was high. As hypothesized, wind speeds of 113 km hr^{-1} resulted in the greatest loss compared to wind speeds of 64 km hr^{-1}. Wind speeds appeared to be more critical than cultivar stormproofness regarding yield loss, but losses appear to be less for stormproof cultivars. Wind speed influences yield loss, but the degree of exposure may be more important for showy cultivars compared to stormproof cultivars. The value of stormproofness is high when exposure and wind speeds are high. The level of exposure, as defined as percent open bolls, significantly influences yield loss of a showy cultivar compared to a stormproof cultivar, suggesting that defoliation should be delayed until after the tropical event, if closed bolls are present.

Late Season Management Considerations for Cotton in North Carolina

by
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DEDICATION

I would like to dedicate this thesis to my family, who has supported me and always pushed me to pursue my dreams. I would like to also dedicate this to my wife Abbi Hendricks, thank you for always pushing me and believing in me throughout this process.

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BIOGRAPHY

Jeremy Perkins Hendricks was born September 7, 2001, in Raleigh, NC. He grew up most days in the outdoors with his family. Through a farm in the family and the love of working outdoors in landscaping he decided to pursue a degree in Agriculture Business Management with a minor in Crop Science and Agricultural Entrepreneurship from North Carolina State University. Through an undergraduate research assistant position under Dr. Keith Edmisten starting in 2021 he found a passion for agriculture research and cotton agronomy. He graduated with a B.S. in 2023 and directly after in the fall he began his M.S. in Crop Science under the direction of Dr. Keith Edmisten and Dr. Guy Collins. His thesis research focused on the last effective bloom date and a hurricane trial. Jeremy enjoys spending time with his wife and dog, as well hunting and fishing with friends.

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CHAPTER I

Evaluating Last Effective Bloom Date with Various Termination Dates in NC Cotton

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Abstract

North Carolina's cotton production is positioned in a more northern and eastern state than many other cotton producing states. There are many reasons why growers need to pursue late blooms to increase yield. The last effective bloom date in North Carolina has previously been believed August 15th for the northern regions of North Carolina, which extended into August 20-25th more recently. Research was conducted across four locations in North Carolina to determine the latest date at which a majority of white blooms have a reasonable chance of maturing into harvestable bolls, and to determine the effect of crop termination dates on the last effective bloom date. Last effective bloom dates can safely and conservatively be extended to approximately September 1st in most years in NC, or September 5th in years with warmer fall temperatures. Contrary to popular belief, delaying defoliation until near first frost does NOT improve the probability of maturation and opening of later set bolls. This data suggest that last effective bloom dates could be extended to mid-September in years with warmer Fall temperatures, and especially if defoliation occurs during mid-October, allowing boll openers to work with additional, modest heat unit accumulation and time before a frost occurs. Defoliation during mid-October can result in harvestable bolls developed from as few as 200-350 heat units, whereas delaying defoliation until first frost may require noticeably more (~465+) heat units to fully develop bolls.

Introduction

Cotton (*Gossypium hirsutum)* is one of the most important fibers in the world, averaging about 25 percent of total world fiber use (Economics of Cotton, 2025c). An often-overlooked component of the crop is the vast amount of cottonseed that is produced along with the fiber. This seed is fed whole to livestock or can be crushed for meal or oil (Cotton's major uses, 2025b). Cotton lint is used for clothing/apparel, home furnishing, and industrial products (Cotton's major uses; Robertson and Roberts, 2010). The United States is the world's third-largest cotton producer and leading exporter. The US cotton industry accounts for more than $21 billion in products and services annually (Economics of Cotton, 2025c). In the US, cotton is grown in 17 southern-tiered "Cotton Belt" states – from Virginia to California (Charts and Maps 2025). In the 2024/2025 farming season, 14,414,000 480 lb bales were produced in the United States, with around 11 million acres planted (Quick Stats; Production – cotton; Cotton and Wool 2024a). North Carolina, from 2021 – 2023, on average produced around 6% of national production (Cotton and Wool 2024a). In 2024, in North Carolina, the value of production was 232,298,000 dollars, where 755,000 480 lb bales were produced with around 410,000 acres planted (2024 State Agriculture Overview). In 2023, in North Carolina, the value of production was 276,466,000 dollars, where 719,000 480 lb bales were produced and was the 5th largest commodity in North Carolina (United States Cotton Area, Yield and Production, 2025i).

Management improvements will be an ongoing challenge as cotton producers face market realities and environmental challenges (Edmisten & Collins, 2025d). Successful cotton production depends on an integrated management strategy that recognizes and adapts to the unique characteristics of the crop (Edmisten & Collins, 2025b). The key to successful cotton production in North Carolina is the adoption of a short-season management strategy. There are five specific goals important to producing a profitable crop in a short-season production system: maximize early-season growth, stimulate early flowering, prevent rank growth, protect investments from pest, and harvest quality cotton (Bednarz et al., 2005).

Planting and Establishing the Cotton Crop

The cotton planting window ranges from April 25th to June 7 – 10 for full yield potential in North Carolina (Edmisten & Collins, 2025c). Cotton seed are very sensitive to cool temperatures within the first 2-3 days after planting (Collins & Edmisten, 2015). The cotton plant requires 50 DD 60s from planting to emergence and another 50 from emergence to first true leaf (Snider et al., 2022). Cotton seeds need to be planted around ½ to ¾ inches deep and planted into warm soils with good moisture in North Carolina (Collins & Edmisten, 2015). Temperature is a key factor governing germination and emergence. Chilling temperatures are above freezing but below 50 degrees F If this is experienced, it could cause the primary root tip to die or growth abnormalities in the root (Snider et al., 2022; Robertson and Roberts, 2010). Large seeded varieties are more vigorous which can help in poor planting environments and vigorous growth is desirable to lessen the negative impacts of early season pathogens and insects and minimizes the risk of stand loss (Holladay et al., 2024; Snider et al., 2022). Tiling, improving ditches, plant on beds, and deep tillage are ways to mitigate risk from increased precipitation and drainage to help cotton which doesn't perform well in water saturated soils (Laws, 2021). The insurance cutoff date for planting in North Carolina is May 25th with 1 percent deductions in coverage per day through May 31st (Collins et al., 2017; A Risk Management Agency Fact Sheet 2018). Planting on June 1st or later is not covered by insurance. Recommendations from NC Cooperative Extension Service recommend that for crop insurance purposes, farmers should complete planting by May 25th for maximum coverage and by May 31st for reduced coverage (Edmisten & Collins, 2025c).

Establishing a stand and getting the crop off to a good start can be challenging during the early season when above-ground growth may begin slowly (Robertson and Roberts, 2010). Early planting for upland cotton is not critical unless early crop termination is planned (Kittock et al., 1981). Early cotton planting in the Texas coastal bend can potentially improve performance through drought avoidance (Davidonis et al., 2004). In 2011, in Georgia mean lint yield and economic returns from May planting dates were significantly greater than June planting dates, and in 2012, lint yield and economic returns were greater in plots established in early May compared with late planting dates (Pulakkatu-Thodi et al., 2014). In South Carolina, densities of thrips are significantly less in later-planted cotton when compared to on-time or early planted cotton (Kerns et al., 2018). Early planted cotton may escape a late insect flight because it has reached a growth stage that worm and insect pressure will no longer affect yield unless pressure is extreme (Delayed planting alters pest pressure 2020). In Texas, an early planting can improve yield by 10% over a normal planting and can shift the blooming period to June and early July, where some beneficial rains and more sunlight occur, compared to the blooming period occurring in late July and August, where it is drier and hotter (Pettigrew, 2002).

There are plenty of reasons a producer may not be able to plant cotton in a timely manner. A farmer may need to plant later in the planting window or past the planting window because of heavy rains and not being able to get into the field (Collins et al., 2017; Laws, 2021). Water saturated soils may deprive the embryo of oxygen, resulting in death (Snider et al., 2022). An unusually cool, wet spring may delay planting for many growers, which sets up a scenario for increased in-season insect pressure when the crop is highly susceptible (Delayed planting alters pest pressure 2020). The formation of compacted soil at the soil surface, known as crusting, can mechanically impede emergence (Snider et al., 2022). Using lower seeding rates to cut costs can increase the risk of needing to replant if your crop fails to emerge for any reason (Siebert et al., 2006). The average farm size in the United States and North Carolina is constantly increasing over time, meaning individual farms will have to plant more acres every year in a confined planting window (Farms and Land in Farms, 2025e). In this confined planting window, farmers must also plant other crops like peanuts, which is popular in farms with cotton and can delay the planting of cotton. With late planting, we encounter a limiting factor, which is the growing season, which means there is a reduced time to accumulate heat units that are necessary to grow a fully mature crop (Peng et al., 1989).

In North Carolina, late May and early June may be favorable conditions for cotton establishment, but it should be planted at a higher seeding rate to avoid late maturity and to avoid reliance on outer position or vegetative bolls for the final yield (Collins & Edmisten, 2015; Collins et al., 2017). Cotton that begins fruiting higher on the plant is more likely to grow rank, so retaining early squares and bolls becomes more important when cotton begins fruiting higher on the plant than normal (Edmisten & Collins, 2025d). Planting crops late and at high densities also accelerates the opening of the last flower, giving rise to a harvestable boll (Sekloka et al., 2007). Planting less than 2 seed per foot can delay maturity as cotton will develop more bolls on outer positions and on higher nodes (Robertson and Roberts, 2010).

Yield potential in a late-planted crop can depend on two things: the year (weather during summer and fall) and how timely a grower can be with management (Collins et al., 2017). An example of a year where late planting will not result in acceptable yields is when the summer is wet with cloudy days, insects are problematic and not properly controlled, if rain prevents timely applications of PGRs and insecticides, fall is cool and cloudy, and an early frost occurs (Collins et al., 2017). This environment illustrated can result in a poor retention of early set bolls due to insects, rank growth, cloudy days, and slow maturity of upper set bolls in the fall. Late irrigation, and delayed boll opening through reduced water stress, could cause a significant yield reduction with either an early or normal frost date (Kittock et al., 1983). An example of a year where late planting does result in acceptable yields is when the summer consists of sunny days, timely rains but not excessive rains that delay field work, low insect pressure, and when followed by warm sunny days in the fall with a normal to late frost (Collins et al., 2017). Another example a later planted crop could benefit your success in North Carolina is the limiting risk you have against early bolls being damaged by a hurricane or tropical storm (Collins et al., 2017; Kerns et al., 2018). Data suggest that planting after June 1st yields become erratic and more variable, while optimum yields can be achieved in planting between late April and May 25th (Collins et al., 2017). Delaying planting resulted in higher lint yield in Florence and Blackville South Carolina in 2021 (Holladay et al., 2024). While planting cotton late, you should plant as early as possible, increase seeding rates, be as early as possible (variety and PGRs) and be timely with pest control and growth regulator applications. (Collins et al., 2017).

Crop Maturity Delays

A late crop is defined by bolls produced in the upper or outer periphery of the plant canopy; late crops can be caused by late plantings or excessive early fruit shed (Edmisten & Collins, 2025c). Exposure to cool and damp conditions can also increase the chance of seedling infections by soil-borne pathogens. In one year of different experiments in the Mississippi Delta and Texas, the early planted crop was stunted by an early season cool period and in the Mississippi Delta its yields were still equivalent to the normal planting (Pettigrew, 2002;

Wanjura & Newton, 1981). Thrips are usually in the top three of North Carolina's most economically damaging insect pests of cotton (Reisig & Huseth, 2025). Thrip damage is significantly lower in later-planted cotton than in on-time or early planted cotton (Kerns et al., 2018). This study shows that the delayed planting of cotton in the planting window or before the crop insurance cutoff is an agronomically acceptable way to manage thrips but does not result in reduced yield (Kerns et al., 2018). Thrips have the potential to cause significant yield losses and maturity delays (Reisig & Huseth, 2025). Plant bugs are season-long insects that can decrease your yield tremendously, especially in early squaring, where we are focused on square retention of the bottom bolls, which can delay maturity (Delayed planting alters pest pressure 2020). In Arkansas, both thrips and tarnished plant bugs were associated with delayed crop maturity, thrips severely reduced leaf area and caused a significant decrease in nodes above white flower (NAWF) values during early flowering, which delayed NAWF= 5 by 25 days, tarnished plant bugs caused a high rate of square shedding which caused a higher NAWF in late flowering and a delay of 1 week to obtain NAWF = 5 (Bourland et al., 1992). Tarnished plant bugs feed directly on small squares which can cause them to abort, and they also feed on small bolls, which can cause spotting and some internal damage (Reisig & Huseth, 2025). The extended effective boll population is that contemporary cotton may have an upward shift of the fruiting profile on the plant because of new management technologies such as the use of transgenic varieties containing the Bt gene. Another reason for late season boll production is the regional effects of the boll weevil eradication program (Viator et al., 2008). Protection of bolls already on the plant requires a knowledge of pest ecology and a common rule of thumb about boll age and insect damage (Bernhardt et al., 1986). A boll older than 16-18 days is safe from successful attack by a small or medium-sized stink bug and could be reduced to 10 days with a reduced number of fruit and few larvae becoming established (Bernhardt et al., 1986). An insect-safe boll is a boll that has accumulated at least 350 heat units (Oosterhuis et al., 2008).

Causes of early square shed are insect damage, cloudy, cool weather, water-saturated soils, and drought (Edmisten & Collins, 2025d). Stresses during cotton square and boll formation can result in fruit abscission from several continuous nodes, resulting in a fruiting gap on a plant, which can cause a shift in timing various agronomic practices aimed at maximizing yield and quality (Faircloth et al., 2004b). In many years in the southeast, fields have distinct bottom and top crops, usually the result of mid-season drought or severe insect infestation (Wrona et al., 1996). In Arizona Patterson et al (1978) found that plant boll load exerts a large influence on fruiting behavior in cotton, the more determinate variety was more responsive to alterations of boll load by defloration. Patterson et al (1978) also found that the relatively high abscission rate of the more indeterminate variety is due to factors other than, or in addition to, competition of other bolls, because when severe defloration occurred, the indeterminate variety did not equal the determinate variety in boll retention until late August. Percent boll set and the number of flowers developing into mature bolls were high during the normal cutout period when boll load was restricted (Patterson et al., 1978). Cotton did compensate for early square removal but did not overcompensate for early reproductive loss and produce higher yields (Pettigrew & Meredith, 2009). A greater number of bolls on outer positions or monopodial branches can delay maturity and cause problems with heat unit accumulation in short growing seasons (Siebert et al., 2006; Pettigrew, 2004).

Cutout was delayed by 6 days in the irrigated plots compared to the dryland cotton (Pettigrew, 2004). A NAWF value of 5 was attained 10 and 14 days sooner in non-irrigated cotton than in irrigated cotton in 1989 and 1990, respectively (Wanjura & Newton, 1981). Dry summers, high temperatures, and water stress can accelerate yield by speeding up boll opening, but are not ideal (Collins et al., 2017; Kittock et al., 1983; Pettigrew, 2008). Temperature affects the rate of fruit development by determining metabolic rates and, in turn, the interval between flower opening and boll opening (Ehlig, 1986). Bolls from stressed cotton opened on average 17 days earlier than bolls of unstressed cotton (Kittock et al., 1983). Lint yield reduction due to moisture deficit stress is primarily due to a reduction in the number of bolls produced, although this stress can reduce the amount of lint produced per seed in some cases (Pettigrew, 2004). Excessively high temperatures during the blooming and boll fill period can result in a loss in lint yield due to reduced boll size because of fewer seeds per boll (Pettigrew, 2008). In 3 of 4 years, therefore, N fertilization delayed crop maturity relative to zero N, measured as heat units from planting to open boll at the NAWF = 5, and cover crops had a relatively small influence on crop maturity (Gwathmey et al., 2010). Increased N fertilization rates generally extended the effective flowering period but delayed maturity on the coarser-textured soils (McConnell et al., 1995). Laws (2021) reported backing off nitrogen can help with earliness. Bennet (2014) found it is a lot easier to manage a plant with good fruit retention, as it will somewhat manage itself. In this study, an untreated plant is 8 inches taller than a treated plant and the treated plant has 80% fruit retention whereas the untreated plant has 20 to 30% fruit retention. Delaying cotton planting can cause excessive vegetative growth, so in later planted cotton the use of plant growth regulators is usually expected (Kerns et al., 2018). Rapid cotton boll development and opening can be beneficial in the late season. It can result in increased lint yield, earlier harvest, higher grade, less insecticide use, and reduced storm damage (Kittock et al., 1983).

Fiber Quality

Fiber qualities are highly genetically influenced. Thus, to maximize fiber qualities, cultivar selection is of greatest importance, while management of plant densities is secondary. Plant density modifications significantly improved micronaire and fineness (Bednarz et al., 2005). Davidonis (2004) reported high temperatures before and during boll development accompanied by adequate moisture increased fiber quality, long fiber mote percentages increased under water deficit conditions, fiber length and micronaire values decreased in late planted cotton, most fiber length and micronaire values differences were between early and middle planting dates. There were no overall improvements in fiber quality traits associated with early square removal to justify some occasional loss in yield (Pettigrew et al., 1992). Most fiber properties were less sensitive than yield to defoliation timing based on heat unit accumulation (Gwathmey et al., 2004). All predictors (open boll percentage at defoliation (OBPD), nodes above cracked boll (NACB), micronaire values at defoliation) are significant in their ability to affect micronaire at harvest (Faircloth et al., 2004a). In years with high micronaire readings, cotton not containing a fruiting gap may also require defoliating before 60% OBPD to avoid discounts due to high micronaire, where, if micronaire values are low, delaying defoliation would be acceptable (Faircloth et al., 2004b). However, the penalty for low micronaire is approximately half that of high micronaire in NC. Fiber development is also impaired by chilling injury at temperatures from 32 and 50 F (Gwathmey et al., 2001).

Degree Days

Cotton is an indeterminate species, which continues to produce squares, flowers, and bolls until some environmental factor, such as low temperature causes cessation of growth and development (Smith et al., 1986). Cotton growth milestones are often given in terms of days after planting or between growth stages, but the development rate of cotton is strongly influenced by temperature (Ritchie et al., 2004). Heat units, or DD 60s are an estimation of this accumulated temperature effect during a day, based on the average of the maximum and minimum daily temperatures (Ritchie et al., 2004). In the southeast, a crop matures in an average of 150 days (ranges from 135 to 170 (Wrona et al., 1996). Raper et al (2023) reported that DD 60s to each developmental stage varied greatly from site year to site year; the range of DD60s required to reach emergence, square, flower, cutout, cracked boll, and 60% open was 13-292, 245-1209, 620-1550, 1210-2286, 1691-3027, 1978-3218, respectively. Based on these findings, the season-long base of 60°F in the DD calculation appears to be appropriate for simple predictions of emergence, square, flower, cutout, cracked, and 60% open, but the previously published DD60 guidelines to reach a given developmental stage should be updated (Raper et al., 2023). Days and DD 60 requirements from two specific growth stages square to flower, planting to first flower, flower to open boll, planting to harvest ready are 20 – 25 days and 300 – 350 HUs, 60 – 70 days and 775 – 850 HUs, 45 to 65 days and 850 – 950 HUs, 130 – 160 days and 2200 – 2600 HUs, respectively (Robertson and Roberts, 2010). A study in Georgia by Bednarz and Nichols (2005) found that across cultivars, nodes, and years, the average vertical and horizontal flowering intervals are 2.5 and 3.8, respectively, compared to the previously believed 3 and 6-day intervals, respectively. Horizontal flowering interval is a heritable trait and can be manipulated in breeding programs, so some pathways to an earlier crop maturity that are useful from this study are shortening of the horizontal flowering interval, shortening of the boll maturation period, and lengthening of sympodial branches at lower main stem nodes (Bednarz & Nichols, 2005). The bloom period for cotton is usually seven to eight weeks, but can be lengthened by poor fruit retention (Edmisten & Collins, 2025d). North Carolina cotton normally produces 12 to 15 fruiting branches, bolls produced in the first position from nodes 6 - 10 and 18 or higher have a

50-70 percent and a less than 10 percent chance of finding their way into the picker basket, respectively (Edmisten & Collins, 2025d). COTMAN says you need 850 DD60s to mature the last effective boll population, but this does not appear to be universal (Bednarz, 2006; Bourland et al., 1997). A boll needs about two weeks of decent weather after it becomes full-sized to mature, and it is previously thought that a boll requires 6 weeks or 700 DD 60s to reach maturity and become harvestable (Edmisten & Collins, 2025d). Cotton grown in Arkansas requires about 850 growing degree days from flowering to boll opening, where the last 75 to 100 are associated with drying and boll opening (Gwathmey et al., 2001). Degree days with base 17°C proved to be a more accurate lower threshold than the DD 15.5°C model in regard to boll maturation, and an upper threshold does not improve accuracy, which contradicts their hypothesis that a lower threshold is needed in the northern, rainfed region of the US cotton belt (Viator et al., 2005). DD 17 may be proved better in this study because DD 15.5 is based off a very large pool of research that studies multiple growth stages (Viator et al., 2005). Bynum and Cothren (2008) suggest that an upper limit threshold may help the accuracy in HU determining the defoliation timing across the cotton belt. Gwathmey et al (2004) found across environments, the heat units required to reach the earliest maximum yield was associated with yield level, as each increment of 100 kg lint per ha was associated with 12 more DD15, this suggest that the existing heat unit model may be improved for use in more diverse environments by incorporating a yield predictor, such as bolls per plant at NAWF = 5.

Measuring Crop Maturity and the Last Effective Bloom Date

Cotton producers seek to monitor the maturity of their crops as the season progresses, not only to determine when to terminate applications of insecticides and irrigation, but also to plan late-season defoliation and harvest operations (Gwathmey et al., 2010). This study found that there are some relationships between NDVI and crop maturity, but they do not provide a simple basis for predicting maturity and readiness for defoliation in a manner similar to COTMAN (Gwathmey et al., 2010). Understanding and knowing where and when physiological cutout or seasonal cutout happens is crucial. Base considerations to create as many fruiting positions as possible until cutout or the last effective bloom date (Laws, 2021). The fruit load is the primary cause for mid-season decreases in fruit retention and flower production, commonly called cutout (Ehlig, 1986). Finding the exact time the plant goes into cutout can make decisions easy for farmers to stop insecticide or decide when to terminate the crop. An established cutout benchmark provides a focal point for all management decisions involving factors that affect fruiting (Bourland et al., 1992). Identifying the last effective boll population is essential for making end-of-season decisions (Robertson and Roberts, 2010). Management decisions involving cultivar selection, planting rate, irrigation, and insect control may be aided by knowing the expected effects of these factors on fruiting as quantified by documented values of NAWF (Bourland et al., 1992). There are a lot of different opinions on when cutout occurs across the cotton belt. COTMAN, a computerized decision aid tool, defines physiological cutout as crop development stage characterized by an average NAWF = 5, and cutout as a general empirical term used to signify the cessation or extended lapse in terminal growth because of the development of the boll load sink and the resulting demand for available nutrient and photosynthate resources, and seasonal cutout as when the flowering date of the last effective boll population is determined by the end of season weather constraints (Oosterhuis et al. 2008). Bolls produced in the late season often will not mature before cessation of growth and development (Smith et al., 1986).

As NAWF decreased, the probability of white flowers successfully developing into a boll decreased, and bolls produced had fewer seeds and less weight (Bourland et al., 1992). As cotton plants develop and mature, first position white flowers progressively occur closer to the plant apex, with physiological cutout attained at nodes above white flower = 5 (Bourland et al., 2001; Edmisten & Collins, 2025d). A hard cutout occurs when NAWF reaches three or fewer (Edmisten & Collins, 2025d). As NAWF moves closer to the terminal of the plant as the developing bolls become the major sink for photosynthate, which in turn also results in the slowing of new node or square development (Robertson and Roberts, 2010). Flowers required per 1 lb of seed cotton was relatively constant for NAWF = 11 to NAWF = 6, then increased as NAWF decreased, from NAWF 6 to 5, from 5 to 4, and from 4 to 3 flowers required to generate 1 lb of seed cotton increase 53, 154, 77 % (Bourland et al., 1992).Thus, NAWF = 5 was chosen as a conservative indicator of the last flower that will effectively contribute to yield (Bourland et al., 1992) NAWF techniques effectively evaluated maturity differences in cotton due to N fertilization on the two silt loam soils. whereas on a clay soil, either the N fertilization treatments had little impact on the earliness of cotton, or these techniques were inadequate to evaluate the earliness of cotton on clay soils (McConnell et al., 1995). COTMAN defines NAWF = 5 as the last effective boll population (Bednarz; Bourland et al., 1997). Physiological cutout date is defined as days after planting to nodes above white flower = 5 (Bourland et al., 2001). Maturity measured by physiological cutout date does not include the influence of any late-season factors after cutout (Bourland et al., 2001). Data indicates that the physiological cutout date provides a measure of crop maturity that is not confounded by boll opening conditions nor by timing of harvests; also, because physiological cutout date is determined during the season, it provides a convenient and timely measure of crop maturity (Bourland et al., 2001). Days to NAWF = 5 should be an effective method to quantify physiological delay associated with insect damage and other factors that influence crop maturity (Bourland et al., 1992). Because earliness is determined before the last effective boll population reaches maturity, the physiological cutout date can be used effectively to plan and schedule sequential events, such as termination of insecticide applications, defoliation, and harvest (Bourland et al., 2001). Physiological cutout at NAWF = 5 may be true for the mid-south, but in the lower southeastern USA, effective flowers may proceed to NAWF = 3 (Bednarz & Nichols, 2005). Cotton could be economically produced at NAWF 2 and 3 for ultranarrow row cotton (UNRC) and conventional row cotton (CONC), respectively (Viator et al., 2008). Data demonstrates that physiological cutout occurred at NAWF less than 5 in both UNRC and CONC (Viator et al., 2008). Boll weight for NAWF 4,5,6,7, and 8 was not different, which contradicts previous research that reported a drastic decrease in boll size at NAWF less than 5 (Viator et al., 2008).

The last effective boll population can be used to schedule and determine cotton management strategies such as defoliation and harvest timing (Viator et al., 2008). The last effective boll population was considered that NAWF position where cotton could be economically produced (Viator et al., 2008). The last effective boll population is the latest developing fruit that has a high probability of being retained and developing into bolls having adequate size and fiber properties to substantially contribute to harvest (Oosterhuis et al., 2008). COTMAN found NAWF=5 is the last effective boll population to contribute to economic yield, but this does not appear to be universal because of yield potential, yield distribution, and cultivar selection (Bednarz, 2006). Nodes above white flower = 5 may not be the last effective flowering position for south central Texas; it may occur at NAWF less than 5 (Bynum & Cothren, 2008). Perhaps the most reliable method of determining boll maturity is to slice open bolls with a knife

(Robertson and Roberts, 2010). The Sharp knife method is to select the uppermost boll you think will be in the picker and cut it, if you see well-formed cotyledons, dark seed coats, it's probably mature (Bennett, 2014). Some characteristics of mature harvestable bolls are too hard to depress, too hard to slice easily with a sharp knife, have lint that strings out when bolls are sliced, have seed coats that are dark yellow to tan in color, have seed kernels completely filling the cavity with no gelatinous material present (Wrona et al; Edmisten & Collins, 2025a). Some signs of immaturity are jelly surrounding a seed, glistening water in the boll, white cotyledons, and white seed coats (Wrona et al., 1996; Edmisten & Collins, 2025a). When the seed coat becomes light brown, the boll is mature enough not to be adversely affected by harvest aid chemicals (Edmisten & Collins, 2025a).

In the Mississippi north delta, the LEBD is around August 15th, August 20 in the central delta, and August 25 in the south delta according to Robinson, 2014 and Bennett, 2014. The last effective bloom date for central Arkansas is August 12 and 15th (Robinson, 2014). In Tennessee, the LEBD is often between August 12th and 23rd (Laws, 2021). Ultimately, our last effective bloom date depends on Fall weather, primarily heat unit accumulation during September and October, as well as the date of the first frost (Collins & Edmisten, 2023b; Edmisten, 2014). Boll load also plays a role; you are more likely to set a harvestable boll with a bloom later in the bloom period if the crop does not have a lot of young developing bolls (Edmisten, 2014). A crop with fewer developing bolls has more resources to available for late bloom development (Edmisten, 2014). Historically, some have considered North Carolina's last effective bloom date to be as early as August 15th, and more recently, August 25th, on average in North Carolina (Collins & Edmisten, 2023b; Edmisten, 2014).

Defoliation Timing

Defoliants can be categorized as having either herbicidal or hormonal activity. (Edmisten & Collins, 2025a). Herbicidal-type defoliants injure the plant, causing it to produce ethylene in response to this injury (Edmisten & Collins, 2025a). The ethylene promotes abscission and leaf drop (Edmisten & Collins, 2025a). Hormonal defoliants result in increased ethylene synthesis by the plant (Edmisten & Collins, 2025a). Ethephon releases ethylene, which stimulates further ethylene synthesis in the plant, resulting in abscission zone formation in the boll walls and leaf petioles (Edmisten & Collins, 2025a). Thidiazuron (Dropp, FreeFall, Klean-Pik, and other generics) is a type of hormone called a cytokinin (Edmisten & Collins, 2025a). Because these hormonal-type defoliants bypass herbicidal injury, they are not as likely to cause leaf desiccation as herbicidal defoliants (Edmisten & Collins, 2025a). Boll-opening materials are often used in combination with defoliation materials to allow early harvest and can be important to open bolls before a frost (Edmisten & Collins, 2025a). Boll openers promote and synchronize the opening of bolls regardless of boll age or maturity (Robertson and Roberts, 2010).

Ethephon is reported to cause immature and mature bolls to open, which can allow cotton producers to harvest more cotton or allow for earlier and more timely harvest. Forcing immature bolls to open could affect fiber quality at harvest. When ethephon is applied to cotton with an undefined number of unopened bolls, then total seed cotton yield should be less than when cotton is allowed to open naturally, assuming an adequate growing season (Smith et al., 1986). This article found that ethephon will accelerate boll opening and can therefore increase the percent or crop harvested earlier, ethephon did not result in a significant yield decrease in three of four comparisons when applied to later planted cotton with 25% or fewer opened bolls, and the greater decrease in seed cotton yield occurred when ethephon was applied to earlier planted cotton and therefore more mature cotton (Smith et al., 1986). Early treatment of excess acreage can decrease yields, expose lint to weather, and increase the likelihood of significant regrowth (Robertson and Roberts, 2010; Edmisten & Collins, 2025a). While early defoliations may achieve goals aimed at reducing micronaire and harvest before late-season adverse weather conditions, premature defoliation can result in some yield reductions (Faircloth et al., 2004a; Faircloth et al., 2004b; Gwathmey et al., 2001). Under Tennessee field conditions, ethephon required more than seven days and 52-to-108-degree day base 60°F accumulation after treatment to significantly increase the boll opening of Deltapine 50 cotton variety (Gwathmey et al., 2001). If rain occurs as the ethephon-treated bolls are beginning to open, “hard-locking” of the bolls can occur and cause significant yield loss (Gwathmey et al., 2001; Robertson and Roberts, 2010).

Defoliation may be sequenced by the number of heat units needed for the development of the last effective flowers (Bourland et al., 1992). Gwathmey et al (2004) found that in Arkansas timing of defoliation at 472 DD 15 after NAWF = 5 resulted in the earliest maximum yield in 5 of 13 environments, in 4 environments where this timing was too early, yield loss averaged 18.5%, in 4 other environments where this timing was too late, time loss average was 4 days to harvest. Bynum and Cothren (2008) found that defoliation based on 472 HU accumulated beyond NAWF = 5 severely reduced yield in south central Texas. Larson et al (2002) found that in Tennessee incomplete defoliation at the early 650 DD defoliation date caused significantly lower lint yields, poorer fiber quality, and leaf grades than cotton defoliation at a later date. Improved fiber quality and enhanced yields from cotton harvest at 950 DD, which produced the largest net revenue among all defoliations, which allowed only a single harvest compared to multiple harvests in other defoliations (Larson et al., 2002). A study by Gwathmey et al. (2004) across four different cotton belt states indicated that relying on traditional indicators of crop maturity, such as percent open bolls and Nodes Above Cracked Boll (NACB), would have provided a more precise method for determining the optimal defoliation date compared to using a fixed timing of 472 Degree Days (DD) with a base temperature of 15°C (DD15) after the crop reached physiological cutout (NAWF = 5).This suggests that while heat unit accumulation (like the 472 DD15 after NAWF=5 rule) offers a general guideline for cotton defoliation, visual and morphological indicators like percent open bolls and NACB offer a more "fine-tuned" approach to achieve consistent results, likely due to variations in environmental conditions and crop development that aren't fully captured by heat unit models alone.

A study by Bednarz (2006) found that 9 of 13 site years across four different cotton belt states indicated defoliations at or near 850 DD60s resulted in statistically the highest yields. Gwathmey et al (2001) found that yield reduction of 14 percent for each 100-degree day increment of earlier termination, but the reduction was not consistent between the years. However, Larson et al (2002) found results that indicate the potential advantages of harvest after defoliation at 950 DD 60’s after cutout, but producers also need to weigh the potential risks of later harvest, especially along the northern edge of the US cotton belt.

Evaluation of NACB has been developed to help determine harvest aid application timing (Robertson and Roberts, 2010). This simply tracks the progress of the first position cracked boll relative to that of the uppermost harvestable boll (Robertson and Roberts, 2010). NACB gives more focus to the unopened portion of the crop and is less likely to result in premature defoliation (Edmisten & Collins, 2025d). Faircloth et al. (2004a) indicated that the use of NACB is a potentially accurate tool for timing cotton defoliation to improve micronaire. Edmisten and Collins (2025d) further reported that defoliation at an NACB of five could lead to an approximate 1% yield loss, while defoliation at an NACB of six might result in about a 2% yield loss, assuming normal planting densities. Faircloth et al (2004a) (2004b) found in North Carolina

NACB appears to be as correlated to micronaire values as either OBPD or micronaire values taken at defoliation. Therefore, using NACB as an alternative to measuring the OBPD would be cost-effective as the time required for taking NACB is considerably less (Faircloth et al., 2004a; Faircloth et al., 2004b). NACB appeared to be at least as effective as OBPD for timing defoliation. Cotton is generally safe to defoliate when NACB is less than or equal to 4 (Bednarz, 2006; Robertson and Roberts, 2010; Edmisten & Collins, 2025d; Edmisten & Collins, 2025a). Cotton is almost always safe to defoliate at 60% open boll, but this strategy may not work well in situations where the crop is set faster or slower than normal (Edmisten & Collins, 2025d; Edmisten & Collins, 2025a). Rehman and Farooq (2020) found that delaying defoliation at 40-60% open bolls will enhance the lint yield by 75kg ha in cotton. Rehman and Farooq (2020) found that chemical defoliation at 20-40% open boll causes yield reduction and stronger and lengthier fibers because of the abscission of younger bolls in cotton, while defoliant application at 60% open boll did not cause yield or fiber quality deterioration. Faircloth et al. (2004b) reported that there did not appear to be a significant advantage to using either NACB or OBPD for timing defoliation. Bednarz found that few site years met both criteria (NACB less than or equal to 4, or after 60% open boll) at 850 DD60s after NAWF = 5. Bynum and Cothren (2008) found that defoliation occurring at 60 percent open boll (NAWF = 5 plus 583 HU) resulted in as much as 29% more lint yield than the benchmark. To safeguard against yield loss, harvest aids should not be applied before 60% open bolls (Bednarz, 2006). Faircloth et al (2004b) reports in 1999 and 2000, there was a yield advantage to delaying defoliation past the 60 percent OBPD in treatments containing a gap. This study also demonstrates that in some years where there is not fruiting gap it might be possible to terminate cotton before the 60% open boll recommendation without sacrificing yields (Faircloth et al., 2004b). Faircloth et al (2004b) reports based on yields and micronaire, defoliation timing benchmarks can shift with fruiting pattern. Gaps in fruiting require growers to decide what part of the cotton plant to target for defoliation (Wrona et al., 1996). Yield data from 2000 and 2001 suggest cotton containing a fruiting gap may require delaying defoliation until more bolls open to achieve yields similar to cotton not containing a fruiting gap (Faircloth et al., 2004b). The importance of delaying defoliation in cotton containing a fruiting gap shows when yield produced late in the season represented a relatively high proportion of overall yields because of a hurricane that destroyed the bottom crop and boll rot (Faircloth et al., 2004b).

Inclement weather becomes more probable as harvest is delayed, possibly leading to losses of fiber quality and harvest efficiency (Larson et al., 2002). Weather factors that most influence harvest aid performance are temperature, sunlight, relative humidity, drought stress, and the occurrence of rainfall shortly after application (Gwathmey et al., 2001) Producers who wait for rank cotton to finish a top crop may very well lose much of their bottom crop to boll rot, especially if wet weather occurs (Edmisten & Collins, 2025a). In the northern region of the southeastern region of the cotton belt faces challenges with cool temperatures, and rain reducing the effectiveness of harvest aids (Gwathmey et al., 2001). Boll opening may be prevented if boll development is arrested by some factor such as excessively cool weather, boll rot, wind or rain damage, insect damage or mechanical damage (Oosterhuis et al., 2008). The greatest threat to cotton harvest is weather-related, especially a premature freeze of green bolls that interferes with boll opening (Gwathmey et al., 2001). Conversely, in some areas cold weather and frost terminate the crop and defoliate it (Wrona et al., 1996). The wait for a frost to defoliate your cotton is not desirable because of the loss of quality and yield while waiting for the frost (Edmisten & Collins, 2025a). Generally, you want to defoliate at least 2 to 3 days ahead of a frost to get those defoliants working before the plant shuts down (Hand, 2021; Edmisten & Collins, 2025a). If it is a true killing freeze, bolls that are not starting to crack will not open at all and vegetation will exhibit signs of damage compared to a frost in the high 20s or low 30s for a few hours with a breeze where you may just see some vegetation damage and some bolls turning brown on the side facing up (Raper, 2021; Edmisten & Collins, 2025a). Freeze events typically only impact cotton that is either immature or a crop that has a high percentage of open bolls but has not been defoliated (Raper, 2021). After a frost if it was not a killing freeze, harvest aids can still be effective on bolls and leaves but may take 3 – 4 weeks to open (Raper, 2021). Boll openers do not usually work if the frost is strong enough to turn the boll brown (Edmisten & Collins, 2025a). Producers should wait several days after a frost event to make defoliation decisions (Edmisten & Collins, 2025a)

Small fields in this region often make it difficult to coordinate harvest -aid application and harvest timing, and these areas have limited harvesting capacity, many fields are defoliated correctly but cannot be harvested due to equipment limitations and weather (Gwathmey et al., 2001). Defoliation should be coordinated with picker availability and applications should be timed so that the harvest can keep up with defoliation (Edmisten & Collins, 2025a). Some areas of the Southeast have problems managing application of harvest aids around the harvest schedule of other crops, especially peanuts, the profit margin for peanuts is typically higher for them compared to cotton. In this case, producers could spray early and limit yield or wait and spray after, possibly resulting in yield and quality losses due to weathering (Gwathmey et al., 2001).

In rain-fed areas of the cotton belt, growers race against the late summer and fall rain and storms, sometimes hurricanes, to get their crop harvested and to the gin to maintain their yields and quality (Wrona et al., 1996). Avoiding insufficient harvesting capacity by weather-related problems, or all of the fields being ready at once, or not get in the field at one time starts at planting time, varying planting dates, and growing varieties with different maturities spreads the risk of drought as well as defoliation and harvesting operations (Wrona et al., 1996). The potential for -induced yield and quality loss in the oldest bolls must be balanced against any additional fiber gain that can be accrued in the top (youngest) bolls (Wrona et al., 1996). By targeting a realistic, achievable harvestable boll and watching the forecast, we should be able to use the last remaining heat units in the season to achieve a successful defoliation and boll opening application (Laws, 2021). A successful defoliation strategy balances yield increases due to delayed leaf removal with risks associated with postponing defoliation (high micronaire, yield losses due to adverse weather, damaging early frosts) all of which are common in the North Carolina cotton-growing region (Faircloth et al., 2004a; Faircloth et al., 2004b).

Materials and Methods

Experiments were conducted in North Carolina initially during 2021 and 2022 to determine proof of concept, and subsequently during 2023 and 2024 as replicated multi-factor trials with further objectives to determine the most common last effective bloom dates for cotton in North Carolina and to determine the effects of termination date (defoliation timing) and how it potentially could influence the last effective bloom date. During 2021, simple experiments to investigate last effective bloom date were conducted at the Upper Coastal Plain Research Station (UCPRS) near Rocky Mount, NC (35.89°N, -77.68°W), the Peanut Belt Research Station (PBRS) near Lewiston-Woodville, NC (36.13°N, -77.17°W), and the Tidewater Research Station (TRS) near Plymouth, NC (35.87°N, -76.65°W). In 2022, an additional location was added at the Sandhills Research Station (SRS) near Jackson Springs, NC (35.18°N, -79.67°W) along with the aforementioned locations. During 2021 and 2022, cotton was planted at 111,197 to 118,611 seed

ha^{-1} on 91-cm conventionally tilled rows during June 20-25th which is later than ideal in NC, but was done to ensure continuity of blooming later in the season than normal. August 25^{th} is the currently accepted estimation for a generalized last effective bloom date in North Carolina. To represent this timeframe, 10 first-position white blooms per plot were flagged (Figure 1), beginning during the week of August 20^{th}-25^{th} in each year of the study. Weekly flagging of blooms was conducted through mid-September or until no additional white blooms were observed. These trials were defoliated at various times, ranging from early to mid-October (normal defoliation timing for North Carolina) to early November (near the time of first frost in North Carolina) using various tank mixtures, which led to differential results between locations and led to hypotheses for phase two of this experiment. During November 6^{th} – 10^{th}, flagged bolls were evaluated and placed into one of the following categories: opened, cracked, closed, or aborted. This data was used to calculate the percentage of harvestable bolls by bloom date to determine when the majority of white blooms matured into harvestable bolls (last effective bloom date) for each location.

During 2023 and 2024, this experiment was expanded into multi-factor replicated trials across all four locations (UCPRS, PBRS, SRS, and TRS). Upper Coastal Plain Research Station and Peanut Belt Research Station represented environments of the coastal plain's region where the majority of North Carolina's cotton acreage is typically grown. The Tidewater Research Station represented the Blackland's of North Carolina, which typically has a slightly later frost date due to higher coastal water temperatures as this location is closer to the ocean. Sandhills Research Station represented the southern counties as well as higher elevation environments that are typical of the Piedmont region. All trial locations used conventional tillage and bedded rows to 91-cm in UCPRS and PBRS and 96.5 cm in SRS and TRS. Despite later planting than is commonly recommended in North Carolina, intermittent drought during 2021 and 2022 led to premature cessation of first-position blooming in some cases during the proof-of-concept phase of this research. Therefore, during 2023 and 2024, cotton was planted during July 2 through July 6, which is considered to be well beyond the ideal range for optimal yields in North Carolina but was found to be necessary in order to ensure continuity of the upward progression of first-position blooming, which was essential in achieving the objectives of this research. Phytogen (PHY) 415 W3FE (Corteva AgriScience, Indianapolis, IN) was planted at 118,611 seeds ha^{-1} using commercial vacuum planters. Plots across all site years were single rows by 30.48 meters long. Plots were managed according to recommendations from the North Carolina Cooperative Extension (Edmisten et al., 2025). Weekly insecticide applications occurred during bloom to minimize losses from lygus insects which can be problematic in abnormally late planted cotton.

Experiments were conducted using a split-block design where the whole-block factor was termination date, and the sub-block factor was flagging date. Treatments were replicated four times and included two termination dates, and six flagging dates. The two termination dates were targeted for mid-October (16-October, 2023 and 15-October, 2024) and early November (1-November in both years). The mid-October termination date was targeted to represent the average point in time that additional meaningful heat unit accumulation, that is likely to contribute substantially towards boll maturity, begins to diminish or gradually declines, however this point in time is generally two weeks before the first frost is commonly observed. The objective of this termination date was to determine if terminating boll development prematurely, in advance of a frost and while a few minor heat units remain, could affect last effective bloom date, or if boll opening activity could be enhanced. The early November termination date was targeted to represents the average point in time when first frost is likely to occur in North

Carolina. This objective of this termination date was to determine if last effective bloom date could be prolonged by allowing all available heat units to contribute to boll development prior to both crop termination or a frost, however no time or heat units would be available to contribute towards enhancing boll opening. Defoliation was conducted using thidiazuron + diuron (NuFarm, Alsip, Illinois) (CutOut) at .56 kg a.i. per hectare and ethephon (NuFarm, Alsip, Illinois) (SuperBoll) at 2.94 kg a.i. per hectare to remove foliage and enhance boll opening at both termination dates during both years of this experiment, and is a commonly used tank mixture used by growers in North Carolina.

Approximately six weekly flagging dates were evaluated for each site year, beginning at first bloom, and weekly thereafter through the end of September in each year. Ten or more first-position white blooms were flagged per plot. Flagged bolls were evaluated and counted during the week of 6-November in both 2023 and 2024 (one week after the last termination date) and categorized as fully open and cracked boll, easily cracked with light pressure applied, closed boll (unable to crack with significant pressure applied), or missing/aborted boll (Figure 2). Percent guaranteed harvestable was calculated using only fully open/cracked bolls, whereas likely harvestable bolls were calculated using the sum of both fully open/cracked and easily cracked bolls. Both were used to calculate last effective bloom date. In the statistical software SAS (SAS institute, Cary, NC) using GLM and GLIMMIX data was subject to ANOVA and means were separated according to Tukey's HSD at p=0.05. Flagging dates were normalized into groupings of flagging dates that were the same treatment that occurred in a span of three days. The treatment number for the flagging date groupings (1, 2, 3, 4, 5, 6) were used for ANOVA in place of the date of flagging. Data were also subjected to linear and polynomial regression analysis. Regression analysis was developed using raw data instead of the flagging groups used in the analysis of variance. These regression models were used to estimate the last effective bloom date specific to when each bloom was tagged. Heat unit accumulation (Degree Day-15.6s) was calculated for regression to illustrate the relationship of harvestable bolls to heat units from each bloom date until each termination date for assigned plots and locations. The estimated regression trendlines and raw data were used to determine the latest date at which a bloom had a 50 percent probability of maturing into a harvestable and likely harvestable boll. The heat units needed to mature 50 percent harvestable and likely harvestable bolls was also determined.

Results and Discussion

Heat Unit Accumulation

Heat unit accumulation between August 15th and November 1st are reported in Figure 3 for 2020 to 2024 and averaged over all locations as this research was conducted to illustrate general fall conditions experienced. Of the 5-year period observed, 2020, 2022, and 2024 experienced cooler than average fall temperatures while 2021 and 2023 experienced warmer than average fall temperatures. Both cooler and warmer environments were experienced during each phase of this research. Overall, heat unit accumulation between August 15th to September 20th was nearly identical in all years except during 2024 which was noticeably less, indicative of a cooler early fall. There is slight differentiation of heat unit accumulation between September 20th through October 1st but October 1st through October 15th exhibited greater and clearer differences among the years observed. Little meaningful heat accumulation occurred beyond October 15th in any year. The year 2023 represents a warmer than normal fall although heat unit accumulation plateaued in early/mid-October as expected and the first frost date was normal (early November). The year 2024 represents a noticeably cooler than normal fall during most of September, however heat unit accumulation by early October was similar to several other years.

The year 2024 experienced a similar plateau of heat unit accumulation by mid-October as well as a very light frost on October 17 and a killing frost occurring in late November.

Proof of Concept Phase

During 2021 and 2022, which was the initial proof-of-concept phase for this research, last effective bloom dates were calculated by determining the latest date at which 50 percent or more white blooms mature into an opened harvestable boll or cracked boll when evaluated post first frost during the first week of November in each year. In 2021, data illustrated that the last effective bloom date was September 13, August 31st, and September 13th for UCPRS, PBRS, and TRS, respectively (Figure 4). In 2022, data illustrated the last effective bloom date was August 29th for all locations (UCPRS, PBRS, and SHRS) (Figure 5). Although inconsistent and inconclusive, this data suggested the last effective bloom date is likely to be in mid-September in warmer years (such as 2021) whereas the last effective bloom date is late August in cooler years (such as 2022), however the site-years during the proof of concept phase were defoliated at inconsistent times within and between years (some defoliated prior to first frost while others were defoliated after), leading the investigators to hypothesize that defoliation timing relative to first frost may have a greater influence on boll opening probability than initially thought.

Replicated Trials Including Termination Date

For both likely harvestable boll (open/cracked boll plus easily cracked with little pressure applied) and guaranteed harvestable boll (open/cracked boll), data is separated by site year because of the influence of location and to illustrate the effect of the different environments experienced from the two years. Regression graphs are separated by site-year and by defoliation timing to show their effect on the last effective bloom date. Regression is used to graph a trendline from likely harvestable bolls and guaranteed harvestable bolls by flagging date to estimate the last effective bloom date.

The mid-October defoliation timing represented the point at which meaningful heat unit accumulation generally becomes less likely in North Carolina. Mid-October is approximately two weeks prior to first frost and a few heat units typically remain likely, which would allow for some time and minor heat accumulation for boll openers to perform prior to first frost. This defoliation timing was conducted on October 16th in 2023 and October 15th in 2024. When calculating last effective bloom date for this defoliation timing, the percentage of guaranteed harvestable bolls (open/cracked boll) are reported because sufficient numbers were reached in both years. In both 2023 and 2024, when defoliated in mid-October, 50% or more white blooms matured into guaranteed harvestable bolls as late as September 16th in all locations (UCPRS, PBRS, TRS, SHRS) (Figure 6 and 7). At both PBRS and SRS the relationship being modelled in the data achieved a high r-squared in 2023 (Figure 6). At both UCPRS and the TRS there was no decline observed in guaranteed harvestable bolls across flagging dates which resulted in a poor r-squared value. However, this data still illustrates the latest date at which 50% or more white blooms matured into harvestable bolls because this flat line and data stays above 75% guaranteed harvestable bolls in 2023 (Figure 6). At UCPRS in 2024, there is a relationship between flagging date and guaranteed harvestable bolls with a high r-squared value, whereas all other locations illustrated no decline across flagging dates staying above the 50% guaranteed harvestable limit with poor r-square values across flagging dates (Figure 7).

The November 1st defoliation timing was targeted to be on or near the average first frost date in North Carolina, which would allow developing bolls to acquire all available heat units to contribute to maturation prior to termination. When calculating last effective bloom date for this defoliation timing, likely harvestable bolls (open/cracked boll plus easily cracked with little pressure applied) were used to estimate the last effective bloom date, as there were little open/cracked bolls observed in 2024. In 2023, 50% or more white blooms were likely to mature into open bolls, or bolls that would open with little pressure applied as late as September 6th, September 11th, September 16, and September 16th, for SHRS, UCPRS, TRS, and PBRS, respectively (Figure 8). In 2023, at SRS and PBRS there is a relationship being modelled with r-square values above .5 (Figure 8). At the TRS in 2023, there is a U-shaped trend across flagging dates with a low r-squared value, however, data points conclude the latest date at which 50% or more white blooms matured into likely harvestable bolls is September 16th (Figure 8). At the UCPRS in 2023, there is a small downward sloping trend with a low r-squared value, however, data shows that we can conclude the latest date at which 50% white blooms matured into likely harvestable bolls is September 11th (Figure 8). In 2024, 50% or more white blooms matured into likely harvestable bolls or bolls that cracked with little pressure applied as late as September 5th and September 15th for SHRS and UCPRS, respectively (Figure 9). Likely harvestable bolls did not reach 50% at TRS and PBRS when delaying defoliation until November 1st in 2024 (Figure 9). At SRS in 2024, the relationship being modelled has a high r-square value. At the UCPRS there is a gradual decline across flagging dates which results in a moderate r-square value. This relationship and data indicates that September 16th is the latest date at which 50% or more white blooms matured into likely harvestable bolls (Figure 9).

Likely Harvestable Bolls and Guaranteed Harvestable Bolls as a Function of Heat Unit Accumulation

Regression analysis was again used to determine the number of heat units required to mature the majority of guaranteed harvestable bolls when defoliation timing was targeted during mid-October. The heat unit accumulation used in figures 10, 11, 12, and 13 is the amount of heat units accumulated from flagging date to defoliation timing. In 2023, when defoliation was initiated in mid-October, 50% or more guaranteed harvestable bolls could be developed in as little as 200 heat units following anthesis for UCPRS, PBRS, and TRS, whereas 250 heat units were required for SHRS (Figure 10). In 2023, at PBRS and SRS there is a high r-square value for the relationship between heat unit accumulation and guaranteed harvestable bolls. In 2023, at UCPRS and TRS there was a flat line near 100% guaranteed harvestable bolls (Figure 10). In 2024, when defoliation was initiated in mid-October, guaranteed harvestable bolls could be developed in as little as 200 heat units for TRS, PBRS, SHRS and 325 heat units for UCPRS (Figure 11). In 2024, at TRS, PBRS, and SRS there was a minimal increase observed with low r-square values and an approximately flat line near 100% guaranteed harvestable bolls (Figure 11). This is inconsistent with previous literature that demonstrated that at least 700 heat units are required for bolls to reach full maturity and harvestability (Edmisten & Collins, 2025d; Robertson and Roberts, 2010; Bednarz; Bourland et al., 1997).

Regression analysis was used to determine the number of heat units required to mature 50% or more likely harvestable bolls. The second defoliation on November 1st used only likely harvestable bolls to graph the relationship with heat unit accumulation, as there were not sufficient guaranteed harvestable bolls for this termination date. In 2023, when defoliation was delayed until November 1st, 250, 250, 300, and 450 heat units were required to develop 50% or more likely harvestable bolls at PBRS, TRS, UCPRS, and SHRS, respectively (Figure 12). At SHRS in 2023, the relationship has a high r-square value (Figure 12). At PBRS in 2023, there is an increasing trend with a moderate r-square value where data shows that 250 heat units were required to develop 50% or more likely harvestable bolls (Figure 12). At UCPRS in 2023, there was a small increasing trend that resulted in a low r-square value however data shows that 300 heat units were required to develop 50% or more likely harvestable bolls. At TRS in 2023, there was a U-shaped trend where data shows 250 heat units were required to develop 50% or more likely harvestable bolls (Figure 12). In 2024, when defoliation was delayed until near the first frost, 350 and 465 heat units were required to develop 50% or more likely harvestable bolls at UCPRS and SHRS, respectively (Figure 13). In 2024, when defoliation was delayed until November 1st, likely harvestable bolls did not reach 50% at the TRS and PBRS (Figure 13). At SHRS in 2024, there relationship resulted in a high r-square value (Figure 13). At UCPRS in 2024, there was an increasing trend with a moderate r-square value and 350 heat units were required to develop 50% or more likely harvestable bolls (Figure 13).

Conclusion

Prior to this research, the commonly accepted last effective bloom date in North Carolina would generally be between August 20th-25th, and perhaps as late as September 1st in southern-most counties or in years with warmer fall temperatures. This research clearly illustrated that last effective bloom date in North Carolina can be much later than ever previously thought, however, with clarifiers of fall temperatures and defoliation timing. Despite experiencing very different fall temperatures during 2023 and 2024, results were relatively consistent across both years. Data suggested that last effective bloom dates can safely be extended beyond September 1st in most years in North Carolina regardless of defoliation timing. In years with warmer fall temperatures the last effective bloom date could safely be extended to September 5th regardless of defoliation timing. However, if properly managed and defoliation timing is carefully considered, these data also suggest that last effective bloom date could be extended much further into mid-September. This research clearly demonstrated that, contrary to popular belief, delaying defoliation until near first frost does not improve the probability of maturation and opening of later set bolls, despite allowing all available heat units to contribute to boll maturation. Likewise, targeting defoliation in mid-October or a couple weeks before the average frost date drastically improved the probability of opening later set bolls. With the initiation of defoliation several weeks before a frost, the last effective bloom date could be extended to as late as September 16th which is much later than ever previously thought. This implies that targeting defoliation for mid-October, well ahead of first frost, improves the boll opener efficacy with additional, modest heat unit accumulation and time before a frost occurs. This may be more meaningful for improving the probability of boll opening when compared to defoliating at or near first frost, where the intention is to use the last available heat units to aid in the maturation of the boll. Delaying defoliation until first frost may allow for additional heat unit accumulation to develop bolls but does not allow for enough time or heat units for boll openers to be effective, therefore, results appear to become more erratic. Defoliation during mid-October, as evidenced by this research, can result in a higher probability of harvestable bolls developed from as few as 200-325 heat units. Delaying defoliation until first frost may require noticeably more (> 465) heat units to fully develop bolls, which is inconsistent with previous research (Edmisten & Collins, 2025d; Robertson and Roberts, 2010; Bednarz; Bourland et al., 1997).

Results from this study illustrate the potential of later set bolls that may have not been considered for yield contribution in past years in North Carolina. These findings may necessitate the need for the reevaluation of planting dates in North Carolina, as well as revising research in determining which bolls are important to protect from insects during late summer or early fall.

Future research should quantify the contribution of these later set bolls to overall yield and fiber quality. Additionally, results from this study illustrated the importance of scouting, defoliation timing, and future forecasts for heat units and first frost. Future research should evaluate the use of future forecasts to conduct timely defoliations. Other studies should conduct similar research under different temperature regimes and under different concentrations of ethephon to evaluate the last effective bloom date.

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Figure 1. Flagged first position bloom at a flagging date.

Open Boll | Cracked Boll | Cracked Under Light Pressure | Closed Boll

Figure 2. Categories used for bolls present at evaluation.

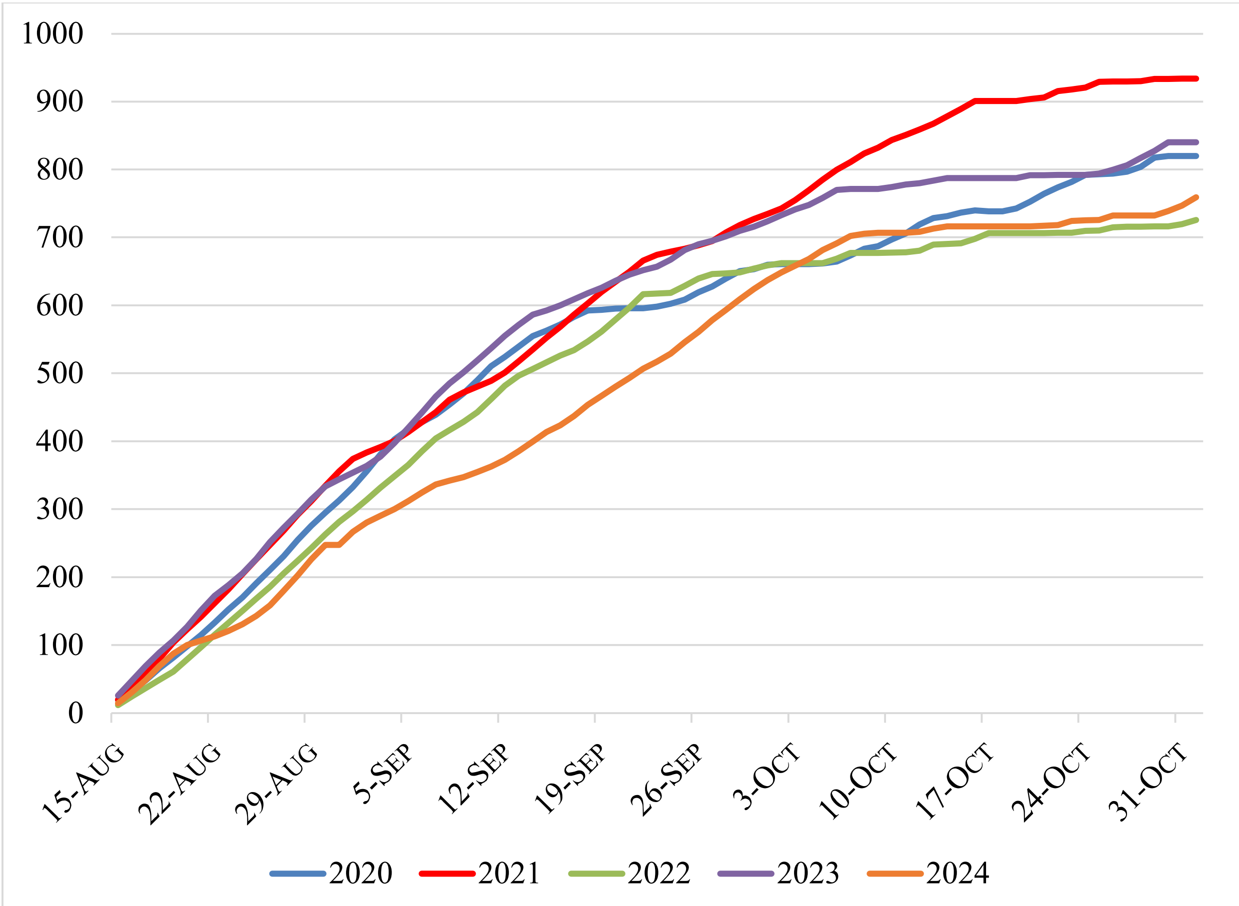

Figure 3. Heat Unit Accumulation over the last five years in NC across LEBD locations from Aug 15th to Nov 1st.

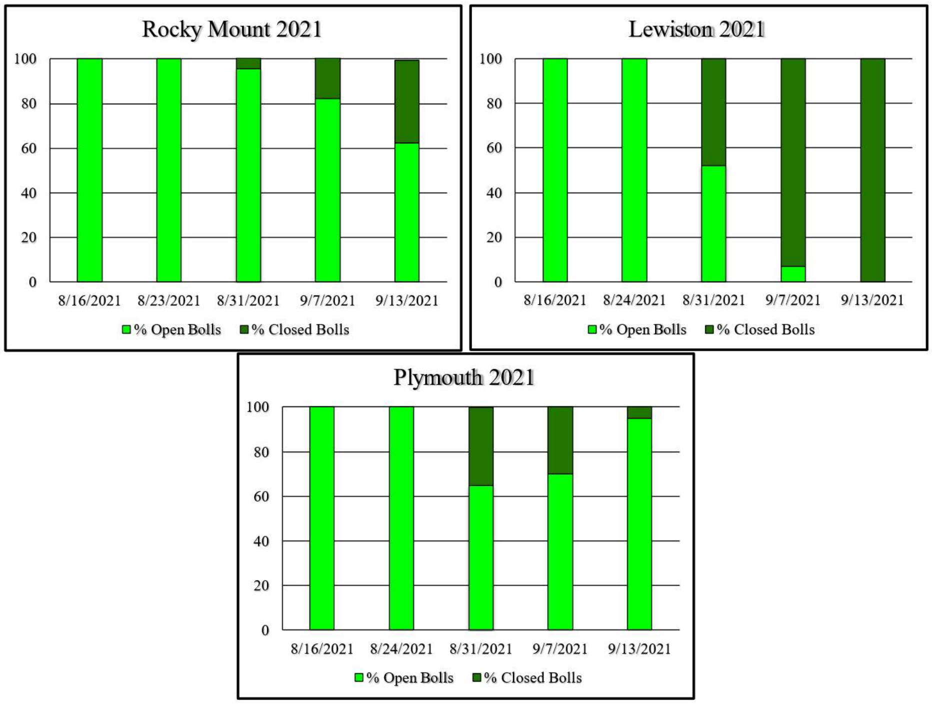

Figure 4. Anecdotal observations for the last effective bloom date in the proof-of-concept phase in 2021 for three locations across North Carolina.

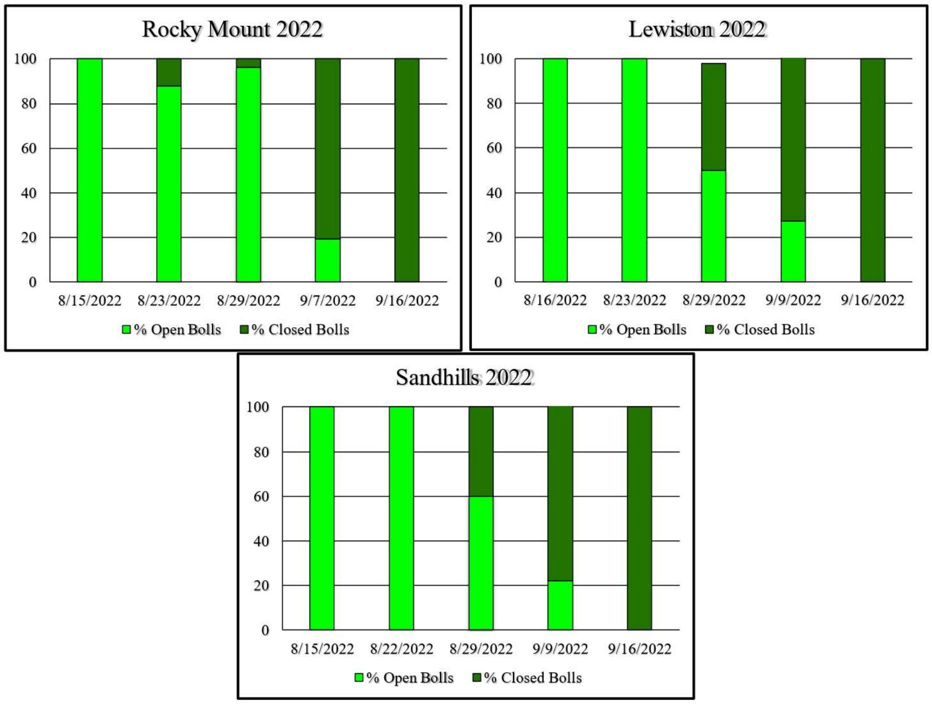

Figure 5. Anecdotal observations for the last effective bloom date in the proof-of-concept phase in 2022 for three locations across North Carolina.

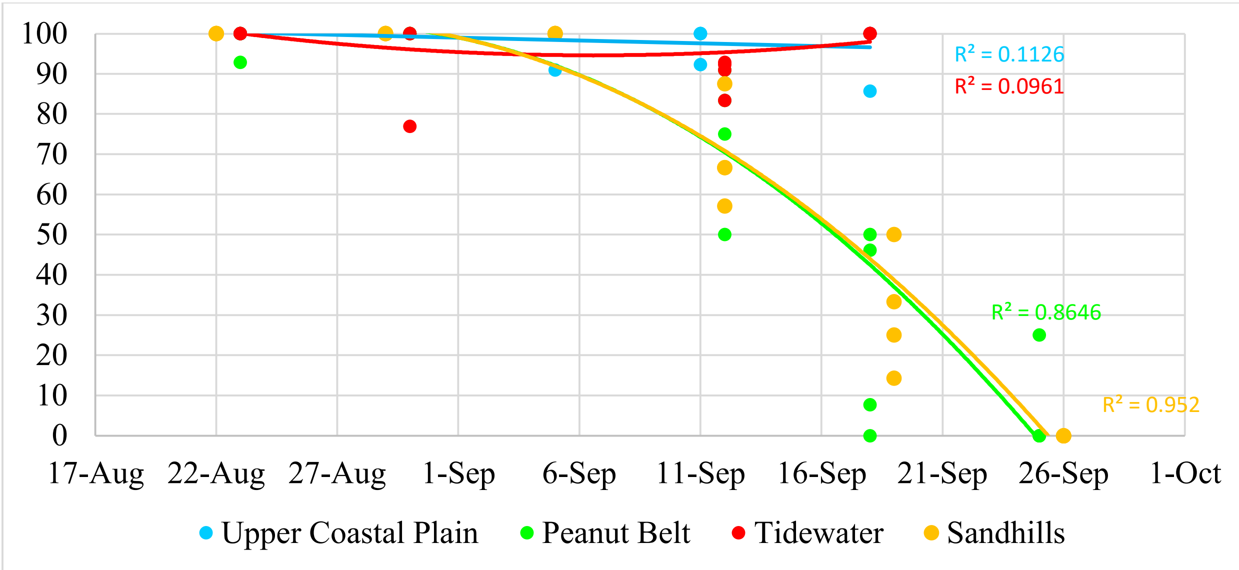

Figure 6. Percent guaranteed harvestable bolls by bloom date when defoliated in mid-October in 2023.

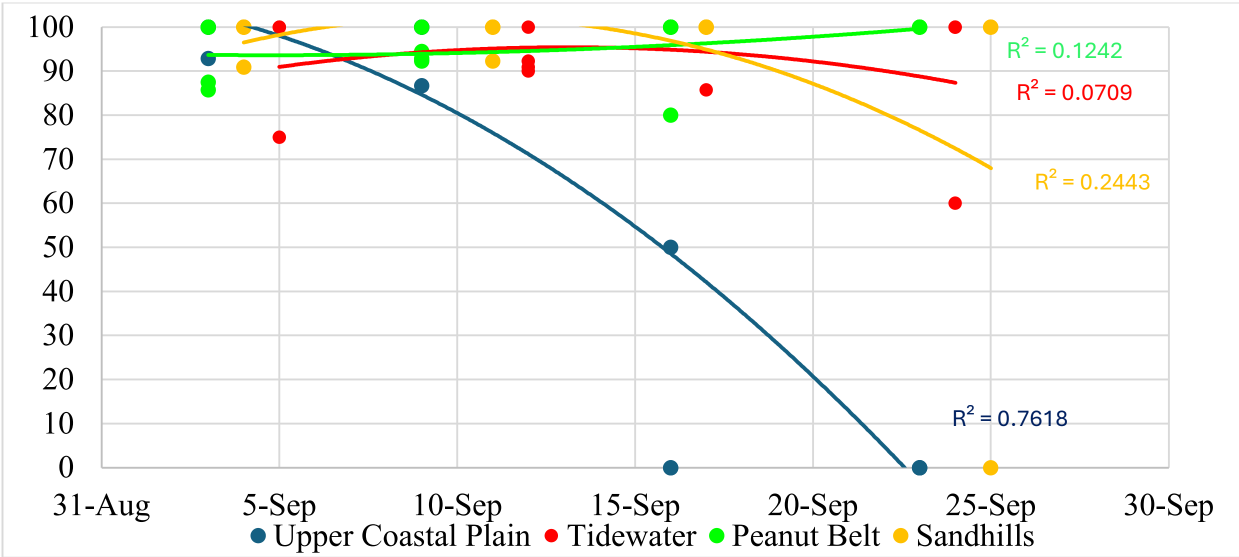

Figure 7. Percent guaranteed harvestable boll by bloom date when defoliated in mid-October in 2024.

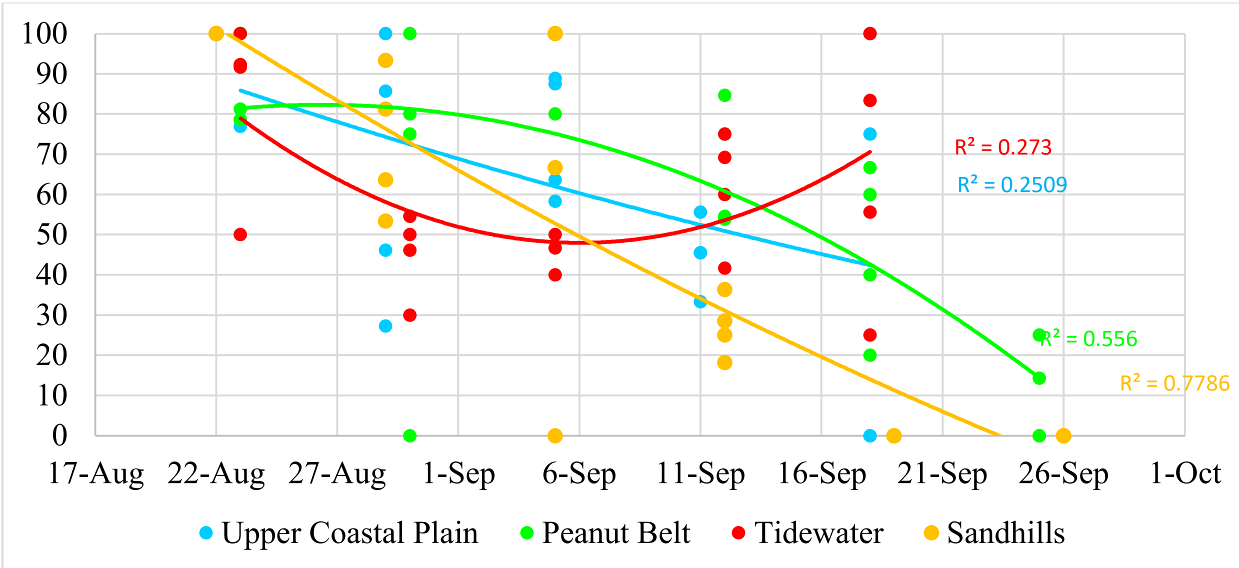

Figure 8. Percent likely harvestable bolls by bloom date when defoliated near first frost (11/1) in 2023.

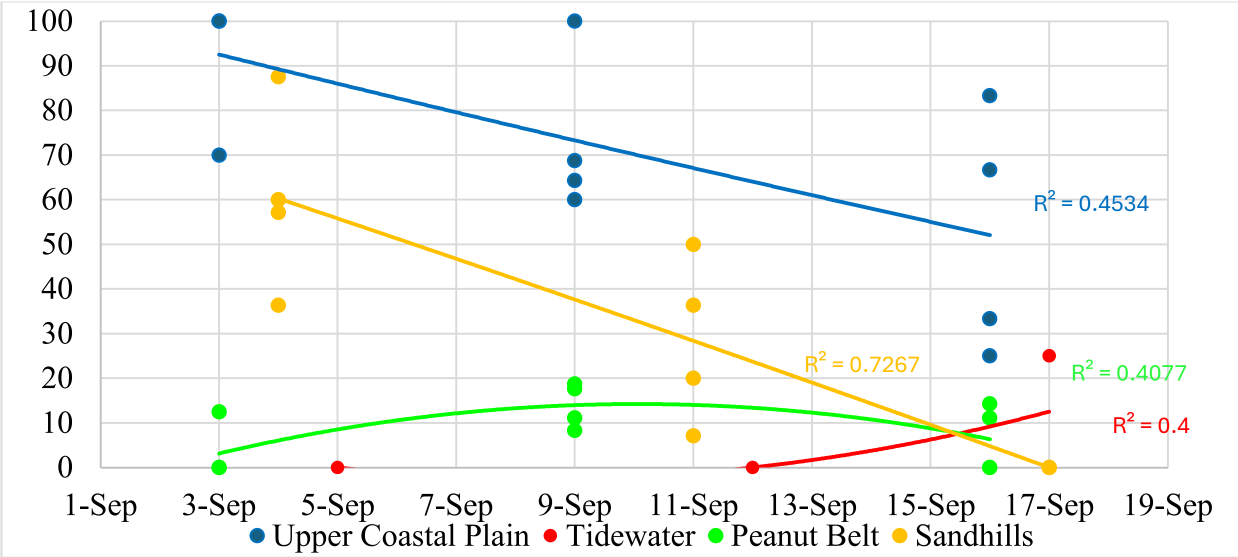

Figure 9. Percent likely harvestable boll by bloom date when defoliated on November 1st in 2024.

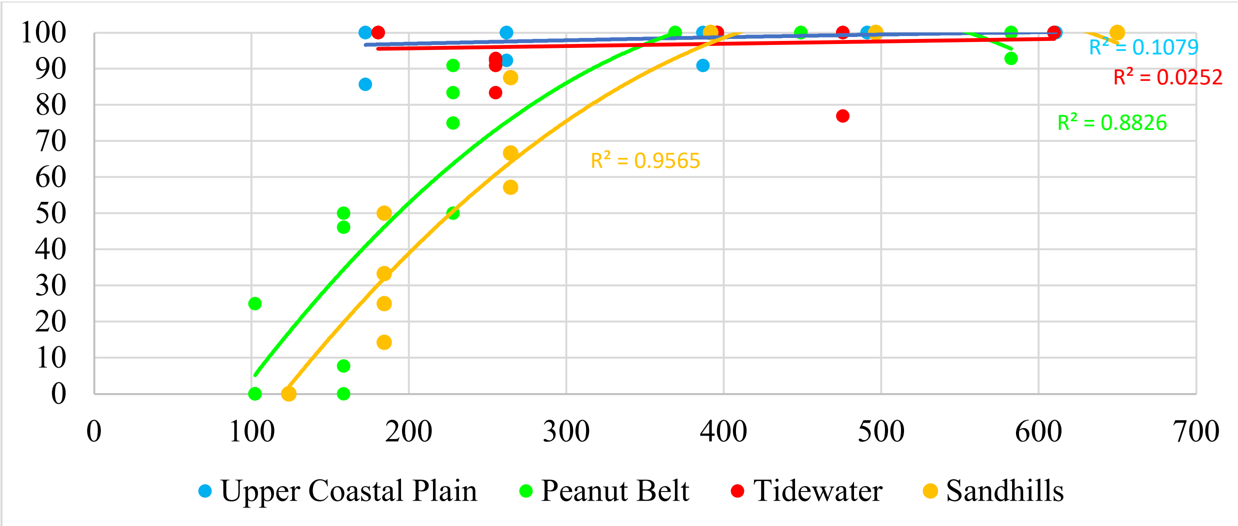

Figure 10. Relationship between heat unit accumulation and percent guaranteed harvestable bolls when defoliated mid-October in 2023.

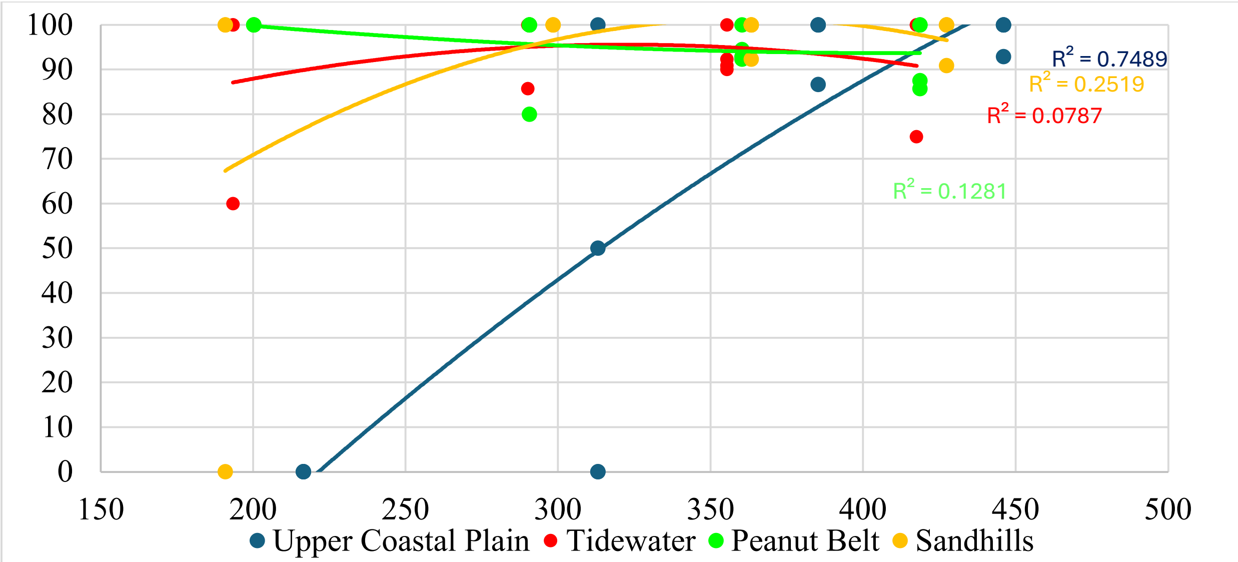

Figure 11. Relationship between heat unit accumulation and percent guaranteed harvestable bolls defoliated in mid-October in 2024.

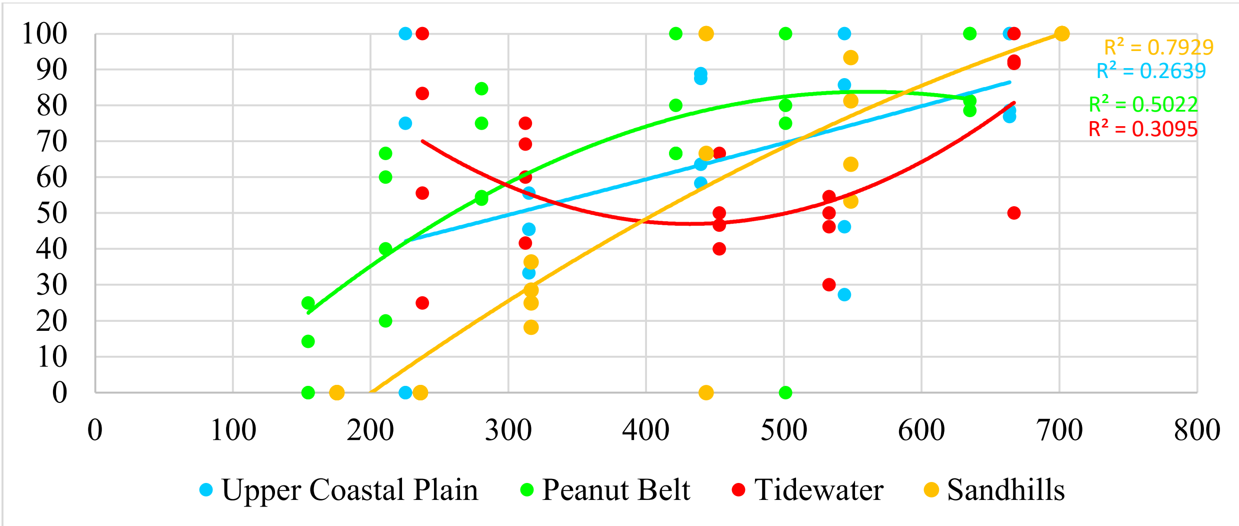

Figure 12. Relationship between heat unit accumulation and percent likely harvestable bolls when defoliated near first frost (11/1) in 2023.

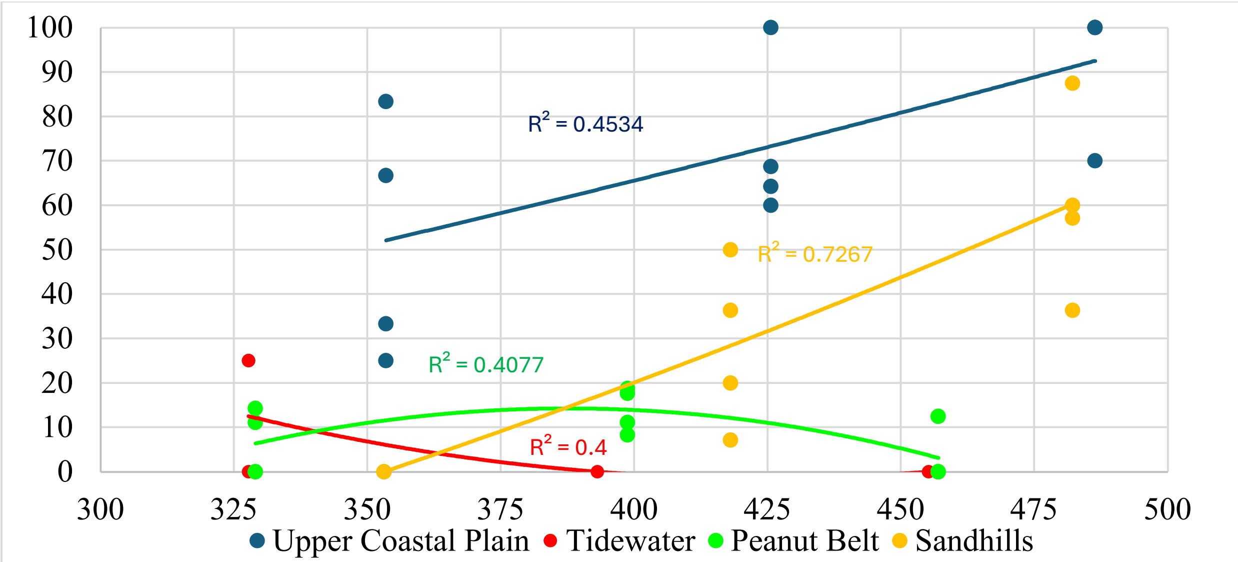

Figure 13. Relationship between heat unit accumulation and percent likely harvestable bolls when defoliated November 1st in 2024.

CHAPTER 2

Evaluating the Effects of Simulated Tropical Wind Speeds, Degree of Exposure, and Cultivar Stormproofness on Cotton Yield

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Abstract

Due to its geographical location, North Carolina is subject to encounter tropical weather during August through October annually, similarly to other southeastern coastal states. Furthermore, the majority of cotton is produced in the coastal plain's region of NC, which in general, is lower in elevation and nearer the coastline that interfaces the ocean more easterly than neighboring states. However, yield losses as related to wind speed are often unpredictable, and as such, the value of stormproof varieties in these weather events is also difficult to quantify, necessitating research into this matter.

The objectives of this research were to quantify the effects of known tropical wind speeds on both stormproof and non-stormproof varieties, to determine and quantify the effects of stormproof characteristics on yield loss of cotton subjected to tropical winds, and to quantify yield losses due to the degree of exposure of cotton to various tropical wind speeds.

The stormproof cultivar resulted in less loss compared to the showy cultivar. Losses associated with defoliation prior to a tropical event was significantly greater than defoliation after a tropical event. Results suggest that the value of stormproofness is higher when exposure and wind speeds are higher. It is reasonable to conclude that both the degree of exposure and cultivar stormproofness can contribute to potential losses when interfacing tropical winds and rain prior to harvest, therefore the interaction of these three parameters collectively influence potential losses. Exposure should be minimized by delaying defoliation until after tropical weather passes.

Introduction

Storm resistance is an agronomic characteristic associated with cotton cultivars that refers to how tightly the locks of fiber are held in open bolls (Faircloth et al., 2004). Quisenberry and Dilbeck (1981) define storm proofness (lock tenacity) of cotton as the amount of force required to extract a locule of seed cotton from the bur of a mature boll. Young (1975) defines lock tenacity as the grams of force required to remove a lock of seedcotton from the bur of a fully open boll. McCall et al (1982) defines lock tenacity is a measure of the storm resistance trait. Friesen (1968) found the following factors influence lock removal from the boll: a mucous type of substance left on the fiber acting as a gluing agent, protrusions along the boll suture, friction between the fiber and carpel wall, diseases affecting the fiber and carpel wall, fibers pinched in the base of the burr, fibers clamped in convolutions formed in the carpel wall during dehiscence.

Stormproof characteristics of a variety are usually expressed as either poor, fair, good, or excellent (Edmisten & Collins, 2025e). The term stormproof is applied to cotton cultivars, in which seedcotton remains in the boll during adverse weather that scatters the seedcotton of conventional open boll cultivars over the ground (Dilbeck & Quisenberry, 1979). The stormproof boll is an important characteristic of cotton cultivars grown in regions where severe weather prevails after bolls open (Quisenberry et al., 1980). The stormproof boll is a desirable trait for cultivars of cotton grown for once over stripper type harvest (Dilbeck & Quisenberry, 1979). Stormproof cultivars of cotton have been accepted in the high and rolling plains of Texas, New Mexico, Oklahoma as a deterrent to losses cause by unfavorable weather conditions (Dilbeck & Quisenberry, 1979). In this region (high and rolling plains of Texas, New Mexico, Oklahoma) cotton must remain in the field exposed to weather until its 90 to 95 percent of the crop is mature and is often subjected to violent weather in forms of wind, rain, and occasionally ice and snow before harvest (Dilbeck & Quisenberry, 1979; Faircloth et al., 2004). Unfortunately, people who live and work in the southeastern Unites States are familiar with the devastation and loss of life and property that can accompany a hurricane event (Collins et al., 2021). Hurricanes can cause substantial damage to cotton crops through heavy winds, heavy rainfall, and flooding (Paradigm Futures, 2024). Cotton crops are particularly vulnerable to hurricanes due to their growth cycle and physical structure (Paradigm Futures, 2024). There is limited research investigating the storm resistance trait in upland cotton in the Southeast cotton belt where spindle picking is most common.

In broad terms, the ideal cotton will remain in the boll until harvest yet yield to complete removal by machine without droppage (Friesen, 1968). Cultivars lacking such characteristics may lose yield by dropping significant amounts of seedcotton on the ground when harvest is delayed (Faircloth et al., 2004). Storm resistance may also be desirable in spindle-picked cotton when harvest is delayed (Faircloth et al., 2004). Storm resistance may be shown better in the lower third of the crop where the bolls are exposed to longer periods of weather and the upper two thirds would give a better estimate of lock tenacity (Young, 1975). Using hurricane proof varieties would be a good strategy if hurricanes were guaranteed to come through quickly and be followed by sunny weather (Collins et al., 2021). However, stormproof varieties may withstand wind and rain, but they are more susceptible to hard lock, which can be devastating when cloudy, wet weather occurs during boll opening (Collins et al., 2021) Stormproof varieties may not harvest as well with a spindle picker compared to a stripper harvester. In areas where spindle pickers are used, approximately 11 percent of the total crop is left in the field every year, with most of this cotton reaching the ground (Friesen, 1968). Increasing storm resistance of cotton bolls will in general result in less pre harvest loss and higher harvest loss (Friesen, 1968). Poor stormproof ratings tend to pick cleaner and often result in less hard locking (Edmisten & Collins, 2025e).

There is not much a cotton grower can do about a hurricane except try not to have the whole crop vulnerable to loss (Haire, 2019). Minimizing the amount of cotton open in the field at any given time is a good way to spread risk of hurricane damage (Collins et al., 2021). The amount of seed cotton that a particular cultivar exposes to the elements at a given time can be related to maturity, so differences in maturity may account for differences in observed seedcotton loss (Faircloth et al., 2004). Spreading the date of a cotton crop can be challenging since a farmer has several crops to plant (Smith, 2024). Planting varieties with a range of maturity times in addition to spreading out planting dates can, therefore, reduce losses (Collins et al., 2021; Smith, 2024; Paradigm Futures, 2024; Managing cotton through a hurricane 2024; Gwathmey et al., 2001). Planting early may lead to harvesting before the hurricane or planting later may enable the cotton to protect itself from early hurricanes (Collins et al., 2021; Haire, 2019). Poor or fair stormproof ratings should be planted in fields that can be harvested in a timely manner, and fields that are expected to be harvested in a less timely manner should be devoted to varieties with good stormproof ratings (Edmisten & Collins, 2025e). It is also important to plant your crop before the final planting date for crop insurance to ensure the crop is covered (Managing cotton through a hurricane 2024). It may be wise to plant varieties with good stormproof characteristics in fields that can be harvested in a less timely manner and plant poor stormproof characteristics in fields that can be harvested in a timely manner (Edmisten & Collins, 2025e).

Tropical events and Defoliation

One of the most damaging hurricanes in Georgia's cotton crop was hurricane Michael, which came through a very mature and ready-to-harvest crop that caused an estimated $600 million loss to Georgia cotton growers alone (Haire, 2019). Tropical storm Debby lingered and brought historic flooding to much of Georgia, Florida, and the Carolinas (Cotton Producer's Guide to Hurricane Prep and Recovery 2024). Hurricane Helene hit cotton at its most vulnerable stage. Between 400,000 to 800,000 bales may have been lost and some growers faced total loss in Georgia (Peng, 2024). Hurricane Helene delayed harvest by up to two weeks in some areas of the Southeast (Peng, 2024). Hurricane Helene sustained winds of 115 mph and heavy rainfall which led to defoliation, boll rot, lodging, destroying bolls, seed sprouting from open lint (Paradigm Futures, 2024). Some moderate rains from tropical storms and hurricanes can help finish a crop out or carry us through a good portion till harvest (Cotton Producer's Guide to Hurricane Prep and Recovery 2024).

Proper defoliation timing can be critical to yield maximization because delaying defoliation increases risks of yield loss due to damaging early frosts and late season inclement weather, both of which are possible in the North Carolina cotton-growing region (Faircloth et al., 2004b). Faircloth et al (2004b) reported that cotton containing a fruiting gap in 1999, any additional yield produced late in the season represented a relatively high proportion of overall yields and increased importance of delaying defoliation (because a hurricane destroyed the bottom crop and boll rot). The southeast frequently experiences difficulty in harvest-aid application and harvesting because of late-season tropical storms and hurricanes (Gwathmey et al., 2001). Southeastern producers may elect to manage harvest-aid programs to spread the risk of yield and quality losses related to weather factors and the associated performance deterioration of harvest-aid materials as the season progresses (Gwathmey et al., 2001).

Growers should avoid defoliation on cotton when a hurricane is approaching unless you think you can harvest before the hurricane arrives, as leaves will help protect open cotton from the winds and rain (Collins et al., 2021; Paradigm Futures, 2024; Managing cotton through a hurricane, 2024; Edmisten and Collins, 2025a; Robertson and Roberts, 2010; Gwathmey et al., 2001). Collins et al (2021) found in past hurricanes, cotton that was defoliated prior to the hurricane consistently experienced more lint loss than cotton that had not yet been defoliated especially if the plant has some closed bolls. Closed bolls are protected bolls during hurricanes (Collins et al., 2021; Edmisten & Collins, 2025a). Mature or open bolls that have experienced heavy wind and rain are prone to falling out onto the ground (Collins et al., 2021; Wrona et al., 1996). It’s possible leaves on the plant provide protection for the open bolls (Attaway, 2024). Hurricane winds have likely defoliated a few older leaves that were already aging, and some of the remaining leaves will begin to turn reddish because of the wind injury, the remaining leaves may defoliate themselves but is not an adequate defoliation so some defoliants will still be needed (Collins et al. 2021; Questions about cotton following a Hurricane, 2025g; Paradigm Futures, 2024). The loss of leaves will allow better airflow and sunlight penetration into the canopy, aiding in the rapid drying of open and closed bolls (Collins et al.,2021; Managing cotton through a hurricane 2024). Even though most of the leaves may be gone, cotton has a tremendous ability to compensate and may transport needed nutrients to immature bolls (Questions about cotton following a Hurricane, 2025g).

High winds will blow lint to the ground, and tangled plants will make harvesting difficult (Attaway, 2024). Post hurricane lodging and tangling of branches can be significantly reduced when growth regulators are used to control plant height (Collins et al., 2021; Managing cotton through a hurricane 2024). Cotton will straighten up if defoliated where the leaves have it tangled up, if the crop is rank and has a heavy top crop then it may take longer (Questions about cotton following a Hurricane, 2025g). Collins et al. found that defoliation should resume as soon as possible after a hurricane to help the cotton straighten back up and reduce boll rot. If the cotton bolls are lying on the ground, there is a pretty good possibility they will rot (Questions about cotton following a Hurricane, 2025g). Cotton that is blown over will expose some axial buds, which were previously shaded, to direct sunlight, this will promote rapid and significant regrowth of foliage, which can make harvest more difficult and affect the quality of the crop (Collins et al., 2021). The bolls that were beginning to crack when the storm hit stand a pretty good probability of hard locking (Questions about cotton following a Hurricane, 2025g). If hard lock conditions prevail during late August and September (prolonged cloudy, foggy, damp conditions) when bolls are trying to open, which is not uncommon in North Carolina, varieties that are a little looser in the burr are best suited, although they are lower in terms of storm tolerance (Smith, 2024; Edmisten & Collins, 2025e). Cotton can and usually does recover, but sunlight plays a key role at airing out and drying the plant (Peng, 2024). Floodwater can carry salt and other contaminants into cotton fields and cause waterlogging, which is detrimental to cotton (Paradigm Futures, 2024).

Harvest and Data

Cotton maturity and harvest usually happen about the same time hurricane season heats up in the region (Haire, 2019). Faircloth et al (2004) found that when combined with yield data, information regarding the storm resistance of a particular cultivar can be used in harvest scheduling. Recommendations include harvesting as much cotton as possible before the arrival of the storm (Paradigm Futures, 2024). Harvest the fields most vulnerable to flooding or restricted areas, or the fields that are most mature first (Collins et al., 2021; Managing cotton through a hurricane 2024). Don’t defoliate more than can be harvested 10 to 14 days later, and let the picker follow the sprayer at a similar pace (Collins et al., 2021). Try harvesting the windblown cotton into the leaning cotton and slow the picker down to improve picking and to reduce shattering of any open bolls in the wind damaged cotton (Collins et al., 2021). Wet ground also makes it difficult to use heavy equipment (Attaway, 2024). Harvest efficiency reduces as the level of lock tenacity increases, so if cotton harvest is timely, the stormproof trait would not be desirable (Young, 1975; Faircloth et al., 2004). Farmers in the southeastern US growing both cotton and peanuts often harvest peanuts first even though both crops are mature and ready for harvest at the same time (Collins et al., 2021; Gwathmey et al., 2001). Cotton has a resilience to remain in the field, whereas peanuts require precise harvest timing, as it is important to dig peanuts at the right time (Haire, 2019). Cotton farmers should try and set up a portion of your crop to be ready before peanut season starts (Haire, 2019). Edmisten and Collins (2025a) report it is generally best to delay defoliation until after the storm passes, if closed bolls are present.

Faircloth et al (2004) found significant differences for cultivar seedcotton loss were observes in all years and for percent loss and seedcotton yield in 1999 and 2000 in North Carolina. The data reported here should not be construed to indicate a cultivar's actual expected seedcotton loss, but rather its potential for loss relative to other cultivars (Faircloth et al., 2004). Faircloth et al (2004) found storm proofness was relatively stable across environments. Quisenberry and Dilbeck (1981) reported a relationship between lock tenacity and the percentage of storm loss (seedcotton that fell on the ground), showing that hybrids between non-stormproof cultivars may suffer relatively high storm losses. This relationship demonstrated lock tenacity was relatively well correlated with storm proofness (Quisenberry & Dilbeck, 1981). McCall et al (1982) found stormproof boll types (in contrast to open boll cotton, which are normally harvested with spindle pickers) substantially decrease preharvest seedcotton loss due to adverse weather. McCall et al (1982) also reported a separation between the two boll type categories (open boll and stormproof) consistent for irrigated and dryland conditions. Quisenberry et al (1980) found that at two locations, high lint yield was correlated with high tenacity, demonstrating the importance of the storm-resistant and stormproof boll to cotton in the southern great plains. Quisenberry et al (1980) also found that lock tenacity correlated to fiber strength, fiber length, and seed size.

Estimating yield loss

There are two types of losses after a hurricane event occurs, productivity losses and quality losses (Collins et al., 2021). Estimating yield by boll counting can be misleading because of variation in boll size, lint percent, future weather conditions, harvest losses, and ginning losses which can all effect how boll counts relate to final yield (Estimating Yield by Boll Counting; Collins & Edmisten, 2019; Appendix: Harvest loss calculations 2020). Hard-locked bolls or signs of boll rot should not be counted in the estimate (Goodman & Monks, 2003). The best way to estimate productivity losses is to count the number of locks of seed cotton blown onto the ground and determine how many bolls per foot of row are lost (Collins et al., 2021). Collins et al (2021) and Collins and Edmisten (2019) found that it takes 12 bolls per foot of row on 36-inch rows to make a bale, and roughly 4 locks per boll, therefore, one lock per foot of row would loosely equate to 10 to 11 pounds of lint per acre. To estimate yield, divide the number of bolls counted per 10-foot section and divide by 120 (equals approximately 1 bale per acre) (Appendix: Harvest loss calculations 2020). Goodman and Monks (2003) reports a general rule of thumb is that 100 bolls per 10 feet equals one bale per acre. A more precise way to estimate yield is to use row spacing, average weight per boll in 10 feet, bolls per 10 feet, and gin turnout to estimate yield or bolls needed to make a bale (Goodman & Monks, 2003; Estimating Yield By Boll

Counting). There is no real way to predict quality losses, but it is safe to assume that some quality loss may have occurred if bolls were open prior to the hurricane (Collins et al., 2021). Quality losses will be more severe if the remaining lint is muddy or experienced flooding (Collins et al.,2021).

Materials and Methods

Field experiments were conducted during 2023 and 2024 to investigate the effects of simulated hurricane conditions (wind and rain) on both stormproof and non-stormproof cultivars in order to quantify potential losses due to tropical weather. Cotton was planted on a soil of a Goldsboro fine sandy loam, at the Upper Coastal Plain Research Station (UCPRS) near Rocky Mount, NC on April 12, 2023, and on April 29, 2024, on conventionally tilled 91-cm bedded rows using a John Deere vacuum planter at 114,904 seeds/ha at 1.27 cm deep. Fertilizer and crop protection inputs followed recommendations from the North Carolina Cooperative Extension (Edmisten et al., 2025).

Treatments consisted of two cultivars, two degrees of exposure at the time that wind treatments were applied, and three simulated tropical wind speeds. The two cotton cultivars were Phytogen 400 W3FE (Corteva AgriScience, Indianapolis, IN) which is touted to be a highly stormproof cultivar and hold its lint tighter in the burr relative to other cultivars, and Deltapine 2127 B3XF (Bayer CropScience, Saint Louis, Missouri) which is known to be an open-type, “showy” cotton with loose lint in the burr and is noticeably less stormproof than other modern cultivars commonly planted in NC. The stormproof characteristic is considered to be more resilient to weathering and hold the lint tighter (high lock tenacity) but may have a higher tendency for hardlocking under prolonged wet conditions. The showy characteristic is lint that is considered to be more loose in the burr (low lock tenacity) and is less resilient to weathering but also less likely to hardlock.

The first exposure timing was at 15-20 percent open bolls to simulate and quantify the effects of a tropical weather event that occurs prior to defoliation. In this scenario, few bolls are open, and therefore, minimal lint is exposed while leaves remain on the plant. The second exposure timing occurred after defoliation, at 90-100 percent open bolls to simulate and quantify the effects of a tropical weather event that occurs shortly before harvest. In this scenario, with no leaves remaining, there is maximum lint exposure. During both years of this experiment, 0.56 kg a.i. per hectare thidiazuron+diuron (Cutout; NuFarm, Alsip, Illinois) and 2.94 kg a.i. per hectare ethephon (SuperBoll; NuFarm, Alsip, Illinois) was applied for defoliation and boll opening, and is a customary tank mixture used by growers in this region. The three treatments for simulated tropical wind speeds were 1.) 0 km hr^{-1} (as a nontreated control), 2.) 64 km hr^{-1} (to simulate commonly experienced Tropical Storm winds or peripheral Hurricane force winds; this is considered the minimal wind speed at which cotton losses might occur), and 3.) 113 km hr^{-1} (to simulate commonly experienced Hurricane force winds when a direct hit occurs). Wind treatments were applied using two using standard RedMax Model EBZ7500 (10.16 cm air tube, capable of delivering 21.75 m3/min) commercial leaf blowers (RedMax, Lawrenceville, Georgia) (Figure 2). The blowers were first calibrated using a handheld Kestrel 3000 (Nielsen-Kellerman, Boothwyn, Pennsylvania) wind meter at a defined distance from the plots (58.42 cm and 91.44 cm for the 64 km hr^{-1} and 113 km hr^{-1} wind treatments respectively) and the throttles were set using the throttle position brakes so that wind speeds were held constant during the application process. Both wind treatments were conducted using oscillating motion to each assigned 3.05-meter plot for five minutes simultaneously on each side of the plot. In order to properly simulate the effects of Tropical weather and wind on exposed cotton, prior to the implementation of the wind treatment, and during the wind treatment, all plants within each plot were thoroughly saturated with water using a 7.75 horsepower Craftsman Professional Series ReadyStart pressure washer that delivered 8.33 lpm at 158.58 bar (Craftsman, Towson, Maryland) (Figure 1).

Treatments were arranged in a split-split block design with each block divided by the degree of exposure at the time of treatment (percent open bolls when simulated wind treatments were induced), then subdivided by cultivar (Stormproof and non-stormproof, with one row of each planted adjacent to each other). The three wind speed treatments were assigned randomly to a plot within each sub-split block. Plots consisted of 2 rows, each planted to one of the aforementioned varieties, and were 3.05-meters in length.

Prior to the implementation of wind treatment at either timing of exposure, data were collected consisting of the number of missing locks per 3.05-meter, the number of open bolls per 3.05-meter, and the percentage of open bolls. Data collected post wind treatment consisted of the number of missing locks per 3.05-meter. Due to the nature of this research, losses could not be measured using regular harvest practices, therefore losses were estimated. Lint Percentage Adjusted method was used to estimate yield losses by collecting a 55-boll sample of each cultivar in 2024 to calculate gin turnout. This lint percentage was then used to calculate yield loss for each cultivar independently based on the number of locks lost per meter of row as follows: assuming an average of 4 locks per boll the average lint weight per lock was calculated based on lint percentage. Average lint weight per lock was multiplied by 14520 (feet of row in 1 acre on 91-cm rows). The yield loss of one missing lock per foot of row was then converted to metric meter of row and yield in kg ha $^{-1}$. One lock missing per meter of row for the cultivar

PHY 400 equated to a 5.95 kg ha $^{-1}$ lint yield loss. One lock missing per meter of row for the variety Deltapine 2127 equated to a 7.35 kg ha $^{-1}$ lint yield loss. In Figure 3, the photo illustrates a stormproof boll after tropical storm treatments applied and Figures 4, 5, and 6, the photos illustrate examples of loss from the tropical storm simulation. Data was subjected to analysis of variance, and means were separated using the Tukey's HSD test within SAS statistical software (SAS institute., Cary, NC) using glm and glimmix at a p= 0.05. The non-treated control of 0 km hr^{-1} was excluded from data in analysis because we automatically assigned yield loss to be 0 kg ha^{-1} with this wind speed. In this experiment year, exposure, cultivar, wind speed, and their interactions between these effects were treated as fixed effects, while replication was treated as a random effect.

Results and Discussion

There was an effect of year on lint percentage adjusted loss, therefore data will be presented by year. In all tables lint percentage adjusted loss was greater in 2024 compared to 2023, which is likely due to different environmental conditions. In 2023, there was an interaction effect for lint percentage adjusted loss between the cultivar and degree of exposure as well as between the degree of exposure and wind speed. In 2024, there was an interaction effect of all pairwise comparisons on lint percentage adjusted loss.

Lint Percentage Adjusted Method

The Lint Percentage Adjusted Method was used as a more precise measurement of losses, in order to account for actual lint losses as cultivars differ in seed size and gin turnout. This was calculated using gin turnout from nontreated plots for the two cultivars planted by collecting a 55-boll sample of each cultivar in 2024 and subsequently ginning each sample through a table-top gin to calculate lint percentage for each cultivar independently.

The interaction effect of cultivar by the degree of exposure was significant in both 2023 and 2024 (Table 1). In table 1, data is pooled over wind speed. As illustrated in Table 1, when the cultivar Deltapine 2127 was subjected to exposure of 90% open bolls, lint percentage adjusted loss was significantly greater than that of Phytogen 400 at the same degree of exposure, and both cultivars at exposure of 20% open bolls in 2023 and 2024. In 2024, both cultivars resulted in significantly greater lint percentage adjusted loss at 90% exposure compared to exposure of 20% open bolls (Table 1). These data suggest that cultivar stormproofness may have a greater influence on lint percentage adjusted loss when exposure is high, but not when exposure is low.

The interaction of cultivar by wind speed was significant in 2024 for lint percentage adjusted loss but not in 2023 (Table 2). In table 2, data is pooled over the degree of exposure. Lint percentage adjusted loss of Deltapine 2127 was significantly greater than that of Phytogen 400 at wind speeds of 113 km hr^{-1}, however there were no differences in losses between these two cultivars at wind speeds of 64 km hr^{-1} (Table 2). Yield losses of both cultivars at wind speeds of 64 km hr^{-1} were significantly less than those at wind speeds of 113 km hr^{-1} (Table 2), which further suggests that cultivar stormproofness may be more important in higher wind speeds but not when subjected to milder ones.

The interaction of the degree of exposure (percent open bolls) and wind speeds was significant in both 2023 and 2024 for lint percentage adjusted loss. In table 3, data is pooled over cultivars. In both years, the combination of exposure at 90% open bolls and wind speeds of 113 km hr^{-1} resulted in the greatest lint percentage adjusted loss (Table 3). In 2023, the combination of exposure at 20% open bolls and wind speeds of 113 km hr^{-1} resulted in significantly more lint percentage adjusted loss than the exposure of 20% open bolls at the lower wind speed of 64 km

hr^{-1} but was similar to the combination of exposure of 90% open bolls and wind speed of 64 km hr^{-1} (Table 3). In 2023, both levels of exposure at wind speed of 64 km hr-1 was statistically the same (Table 3). In 2024, the combination of exposure of 20% open bolls and wind speed of 113 km hr^{-1} was statistically similar to both combinations of exposure to the wind speed 64 km hr^{-1} (Table 3). These data suggest that the degree of exposure may have a greater influence on lint percentage adjusted losses at higher wind speeds, but not necessarily when subjected to milder wind speeds.

Conclusion

This research demonstrated that cultivar stormproofness can impact potential yield losses in certain situations when tropical weather is encountered pre-harvest. The stormproof cultivar used in this study resulted in a significantly lower lint percentage adjusted loss compared to the non-stormproof variety in many scenarios. However, this was more evident when the degree of exposure was higher (90% open bolls) and especially when subjected to higher wind speeds. Data also clearly illustrate the importance of the degree of exposure in the cotton crop relative to when a tropical event occurs. It appears that the degree of exposure is as impactful to yield losses resulting from tropical weather as cultivar stormproofness. As hypothesized, wind speeds of 113 km hr^{-1} resulted in the greatest loss compared to wind speeds of 64 km hr^{-1} although the lower wind speeds could also influence yields in some situations. Wind speed appeared to be more important than cultivar stormproofness in regard to impact on lint percentage adjust loss. It is reasonable to conclude that both the degree of exposure and cultivar stormproofness can contribute to potential losses when interfacing tropical winds and rain prior to harvest, therefore the interaction of these three parameters collectively influence potential losses. Cultivar decisions are made based on many factors unrelated to stormproofness and made many months in advance of when tropical weather is likely to occur during the pre-harvest season. Given the uncertainty of if and when tropical weather will be encountered relative to cotton maturity, it is unreasonable for growers to make cultivar decisions based solely on stormproofness. However, it may be reasonable for growers to consider spreading risks by planting multiple cultivars with consideration given to stormproofness, and spreading risks by planting over several planting dates to minimize crop exposure in an effort to mature (or open bolls) over a longer period of time during the Fall. Likewise, this research has demonstrated that if tropical weather is approaching, exposure should also be minimized by delaying defoliation, or avoid accelerating boll opening, until after the tropical weather passes.

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Table 1. Lint percentage adjusted loss as impacted by cultivar and degree of exposure (kg ha^{-1})[a]

Cultivar	Exposure[b]	2023	2024
DP 2127 B3XF	90% OB	168.96 A	345.67 A
PHY 400 W3FE	90% OB	91.81 B	197.00 B
DP 2127 B3XF	20% OB	65.97 B	70.27 C
PHY 400 W3FE	20% OB	69.52 B	31.63 C
LSD[b] ($p \leq 0.05$):		63.78, 51.71[c]	82.92, 82.78[c]

[a]Data Pooled over wind speeds. Means within a column that share the same letter are not significantly different according to Tukey-Kramer test at p=0.05.

[b]Abbreviations: OB, open boll; LSD, least significant difference.

[c]This least significant difference value is used when comparing means where both means have the same cultivar as a factor.

Table 2. Lint percentage adjusted loss as impacted by cultivar and wind speed (kg ha^{-1})[a]

Cultivar	km hr^{-1} Wind Speed	2024
DP 2127 B3XF	113	353.08 A
PHY 400 W3FE	113	214.14 B
DP 2127 B3XF	64	62.87 C
PHY 400 W3FE	64	14.49 C
LSD[b] ($p \leq 0.05$):		73.04, 68.64[c]

[a]Data Pooled over degree of exposure. Means within a column that share the same letter are not significantly different according to Tukey-Kramer test at p=0.05.
[b]Abbreviations: LSD, least significant difference.
[c]This least significant difference value is used when comparing means where both means have the same cultivar as a factor.

Table 3. Lint percentage adjusted loss as impacted by degree of exposure and wind speed (kg ha^{-1})[a]

Exposure[b]	Km hr^{-1} Wind Speed	2023	2024
90% OB	113	193.96 A	489.36 A
20% OB	113	103.29 B	77.86 B
90% OB	64	66.82 BC	53.31 B
20% OB	64	32.20 C	24.04 B
LSD[b] ($p \leq 0.05$):		48.05	72.90, 68.64[c]

[a]Data Pooled over wind speeds. Means within a column that share the same letter are not significantly different according to Tukey-Kramer test at p=0.05.
[b]Abbreviations: OB, open boll; LSD, least significant difference.
[c]This least significant difference value is used when comparing means where both means have the same degree of exposure as a factor.

Figure 1. Pressure washer used for water supply.

Figure 2. Commercial blowers used for wind treatment.

Figure 3. Stormproof boll after wind treatment.

Figure 4. Boll that has locks missing and boll that is missing all locks.

Figure 5. Cotton lint blown out and caught on plant (example of loss).

Figure 6. Cotton lint blown out and strung out from locks (example of loss).