Tillage System Effects On Upland Cotton Yield and Development In Virginia

Robert Joseph Longest

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William H. Frame, Committee Chair
A. Abaye
S. Hodges

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Abstract

Identifying the proper tillage system which provides the best agronomic benefits for cotton production in the coastal plain soils of Virginia was the basis for this research. Strip-tillage was evaluated from 2015-2016 on-farm to determine the effects of annual and biennial treatments on plant growth and lint yield, as well as measuring the impacts on soil compaction. Also, small plot tillage experiments were conducted from 2013-2016 assessing no-till, conventional tillage, minimum tillage, and strip-tillage as well as the subsequent effects of these systems on four cotton varieties. Biennial strip-tillage produced similar lint yields to annual strip-tillage at 3 of 4 locations, with only one location showing a significant difference in lint yield of 135 kg ha^{-1}. Persistence of subsoil tillage within the row from the previous year was observed at some locations and plant heights were not different at all locations, although annual strip-tillage provided deeper potential rooting depths both early season and at harvest. In short term tillage systems, minimal penalties in plant growth and lint yield were observed in no-till verses the other systems, primarily associated with greater soil compaction, shorter plant heights, and lower yields. An overall 8% reduction in yield was found with no-till systems, with no significant differences in yield among tillage systems observed in any year. Varietal effects on plant growth and yield were observed annually, with FM 1944 GLB2 being the shortest plants, and DP 1321 B2RF having the tallest plants. No tillage by variety interaction was observed, supporting the idea that varieties respond similarly across tillage systems.

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General Audience Abstract

Cotton production in the Coastal Plain region of Virginia utilizes several tillage methods for agronomic benefits to promote plant growth and lint yield. Tillage studies were conducted in Suffolk, Virginia and the Tidewater region from 2013-2016. Tillage methods of conventional tillage, strip-tillage, minimum tillage, and no-tillage and the impacts these systems had on plant growth and development of several varieties, as well as how they altered soil properties including compaction were assessed. Precision strip-tillage was investigated to determine if a zone of sub-soil tillage may remain beneficial for two growing seasons (biennial). Overall, annual and biennial strip-tillage seems to produce similar lint yields, with only one of four locations having a statistical difference in lint yield with annual strip-tillage resulting in 135 kg ha^{-1} more lint than biennial strip-tillage. No-tillage resulted in roughly an 8% decrease in relative yield compared to the other three tillage practices, as well as greater soil compaction readings. However, differences in plant growth and development as well as lint yields seemed to be more related to varietal impacts.

Dedication

I would like to dedicate this work to all of my wonderful family members who have supported me through my educational career. My parents, James and Sharon Longest have supported me every step of the way and have always loved and encouraged me to pursue my dreams and follow my passion for agricultural studies. My brother, Matthew Longest has always been there as a strong supportive figure and was always willing to help in any way possible. I would also like to dedicate this thesis to my girlfriend, Ashleigh Johnson, for her constant love and support through the entire process. To my grandparents: Charlie and Alda Spicer, and John and Margaret Longest, who have encouraged me through my life and were always there for me.

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1 General Introduction

Upland cotton (*Gossypium hirustum* L.*)* is a perennial species managed as an annual crop, which exhibits an indeterminate growth habit and taproot morphology (Oosterhuis and Jernstedt, 1999). The predominant species of cotton grown in the United States, including Virginia, is upland cotton. Upland cotton is separated from other species of cotton including Pima (*Gossypium barbadense*) by lint quality factors such as fiber length (commonly referred to as staple) (Cotton Incorporated, 2015; USDA-ERS, 2015). Upland cotton production in Virginia is an integral component of row crop agricultural systems in the southeastern (Tidewater) region of the state. Both cotton lint and cottonseed are included in the top 20 farm commodities for the state with cash receipts of lint and seed estimated at $72,000,000 and $11,000,000 respectively (National Agricultural Statistics Service, 2014). From 2012-2016, the five year average for harvested hectares in Virginia was roughly 32,698 hectares with a five year average lint yield of 1,071 kg ha^{-1} compared to the national average of 919 kg ha^{-1} (National Agricultural Statistics Service, 2017).

Climate and soil conditions dictate the geographic growing region for cotton, as the crop is tropical in nature and requires temperatures above 16°C (60°F) for accumulation of Growing Degree Days (GDD_{60}) to grow and produce lint (Ritchie et al., 2007). Coastal plain cotton production in Virginia and the southeastern U.S. (Fig. 1) occurs mostly on Ultisols, which are acidic, characterized by weathered clay minerals, layers of subsurface clay accumulation, and generally are older and relatively productive agricultural soils (USDA-NASS, 2017; Brady and Weil, 2008). Many of the soils in which cotton is produced in Virginia are sandier soils. Studies conducted on soils of the coastal plain have documented zones of subsoil compaction commonly referred to as pans, numerous soil types with varying physical and chemical properties within a given field, and different depths to root restrictive layers (Khalilian et al., 2002; Abbaspour-Gilandeh et al., 2006; Duffera et al., 2007). The variability of these factors coupled with variable weather and rainfall patterns make production decisions on tillage frequency, type, and depth difficult for producers wanting to optimize plant growth and yield, while minimizing costs.

There are many reasons as to why tillage is utilized in cotton production as cotton seedlings are easily affected by soil conditions. Crop establishment and growth depends highly on root interactions within the soil. Development of a healthy and extensive root system early in the growing season is important to allow for maximum water and nutrient uptake. Any factor which inhibits early season development may result in decreased plant growth, and ultimately lower lint yields (Ritchie et al., 2007). Taylor and Klepper (1974) explained that cotton roots continue to grow until the time of flowering and boll set; and observed that once root growth ceases due to inadequate soil moisture above-ground portions of the plant slow in growth and development. Slowed root growth near flowering in adequate moisture conditions can be explained by resource allocation shifts of carbohydrates towards fruit set (Taylor and Klepper, 1974; Smith and Cothren, 1999).

As cotton production has become more mechanized, utilization of heavy machinery to perform field operations has increased the occurrence of root limiting soil compaction. Soil compaction may also occur due to natural soil properties such as the leaching of clays with subsurface accumulation as mentioned by Brady and Weil (2008). Soil compaction as a result of mechanized agriculture and continuous tillage to the same depth are summarized by Amanullah et al. (2010). Getmos and Lellis (1997) observed decreased root dry biomass and delayed emergence in cotton as a result of increased soil compaction. Lowery et al. (1970) observed differences in cotton plant heights and seed cotton yield when a root restrictive soil pan occurred at various depths (10 cm, 20 cm, and 30 cm), and concluded that the strength of the pan coupled with the depth of the pan had an impact on yield. Ben-Porath and Baker (1990) observed a positive effect from restrictions on taproot growth in drip-irrigated cotton growth and noted earlier flowering and maturity as well as higher yields in a shortened growing season. The proposed explanation for the results was a shift in assimilate partitioning from the root and vegetative growth, to reproductive growth due to the presence of a root impeding layer (Ben-Porath and Baker, 1990). In dryland production situations where water availability may be limited, the effect of soil compaction on root and plant growth is usually negative, and exacerbated during periods of drought. Klepper et al. (1973) observed that in adequate soil moisture conditions in all soil depths, cotton roots were distributed throughout the rooting zone, with more root growth in shallower soil depths. As drought conditions set in, and soil moisture became limited at shallower depths, rooting depth increased with higher root densities being located lower in the soil profile. Accurately identifying and locating regions of subsoil compaction by depth is important and gives a better understanding of how tillage can be used to amend compaction, and allows for optimal root penetration through the soil during stressful growing conditions (Abbaspour-Gilandeh et al., 2006; Raper et al., 2007).

Soil properties including compaction can be altered by tillage, with several tillage practices commonly being used in Virginia cotton production systems. Reiter et al. (2009) mentions that conservation tillage is increasing, while conventional tillage is decreasing in the state. Historically, conventional tillage was the principle means for land preparation before planting cotton. This involves using a chisel plow, moldboard plow, or disk to deep till the soil, followed by a land conditioner or harrow to smooth out the seedbed and provide uniformity. These tillage methods are the most aggressive and disruptive to the soil. Newer technologies such as strip-tillage and reduced tillage have evolved which are less destructive, while still providing subsoil tillage. No tillage, commonly referred to as “no-till” is also practiced, which does not involve any subsurface tillage, leaving a very high percentage of ground cover with little soil disturbance. According to a national survey conducted in 2008, of all cotton acres surveyed, 17.5% utilized no-till, 13.1% reduced tillage, and 65.5% conventional tillage, with the remaining percentages as other variations of the tillage practices mentioned (Conservation Technology Information Center, 2008).

Choice of tillage method depends on region of production, soil type, and resource availability, and may be influenced by production goals and costs. An important question is: does the yield change resulting from a change in tillage practice offset the cost of implementing the tillage practice? Some costs associated with tillage include fuel, labor, equipment, and maintenance, and have been explained in numerous studies showing conventional tillage systems having higher costs than conservation and no-till systems (Buman et al., 2005; Smith and Shurley, 2008). Key factors in determining which tillage method is appropriate for field conditions are yield results and soil characteristics. Tillage is not always necessary for cotton production, and is only recommended to be utilized in situations when there is an expected yield response from tillage due to an existing field condition which may limit plant growth and development (Reiter and Frame, 2016).

Current production systems that utilize tillage are focused on annual implementation, and research has been conducted on soils of the coastal plain with results showing that annual in-row subsoiling / strip-tillage had a positive impact on crop yields (Raper and Reeves, 2007; Schomberg et al., 2006). A recent interest has been looking at the utilization of precision agriculture in the implementation of tillage and planting in cotton production. By utilizing the accuracy of Global Positioning Systems (GPS) and auto-steer, cotton growers would have the potential to implement sub-surface tillage, and utilize those zones of tillage for multiple growing seasons by programming the tractor to plant directly above the existing tillage pass. Early work by Busscher et al. (1986) concluded limited potential for this practice, but more recent work by Raper et al. (2005) has shown success. If feasible and successful for Virginia growers, they would have the potential to cut production costs, and improve the sustainability of cotton production systems. There is a large amount of uncertainty in which tillage system is best, and no consistent conclusions can be drawn from existing studies on the impact tillage has in the short term on cotton growth and yield, especially in Virginia. Different tillage systems as well as their persistence and impact on cotton growth and yield in the short term were the basis for these studies.

1.1 Overall Objectives

The objectives of this research were to 1) determine the effect of annual and biennial strip-tillage in upland cotton on soil compaction, plant growth, and lint yield and quality and 2) determine the effect of different tillage systems and variety on cotton development (i.e. plant height, number of nodes), soil compaction, and lint yield and quality.

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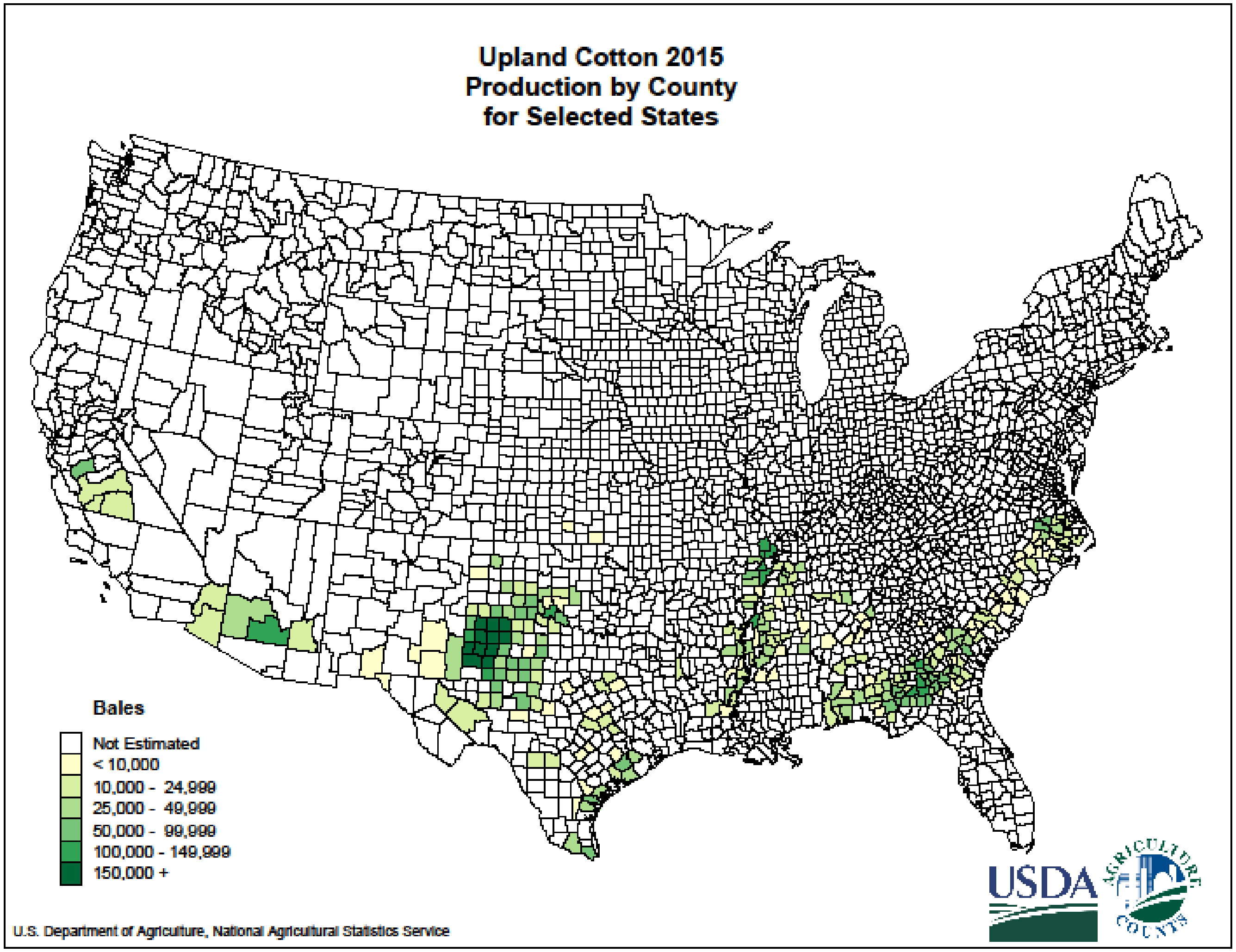

Fig. 1.1: National map of Upland Cotton Production (bales) per county in 2015.

2 Cotton Growth and Yield Under Annual vs. Biennial Strip-Tillage Systems

2.1 Abstract

Less frequent tillage such as biennial strip-tillage could potentially lower input costs and save time, while still providing agronomic benefits for plant growth. The objectives of this study were: 1) to evaluate the effects of annual and biennial strip-tillage on early season plant growth, lint yield, and quality of cotton grown in coastal plain soils of Virginia and 2) measure the impact of these tillage systems on soil compaction during the growing season. No differences in stand establishment were observed between annual and biennial strip-tillage at any location. Minimal differences in plant growth were observed, however annual strip-tillage produced taller plants at 3 out of 4 locations periodically. Soil compaction measured 10-15 cm from the row during early season growth and at harvest showed greater soil compaction in the biennial system for all locations except Barlow B. For early season and harvest measurements, the annual system had significantly less soil compaction for the depths of 7.5 – 15 cm at both Barlow C and Lowe locations. Depth to root restrictive layer at 0, 15, 30, and, 46 cm from the row showed greater potential rooting depths in the annual system during early season growth. Soil compaction increased at harvest for some locations, and decreased at others. Only the Lowe location had significant differences in lint yield with a difference of 135 kg ha^{-1}, but annual strip-tillage produced 66 kg ha^{-1} more lint over all locations compared to biennial strip-tillage. Persistence of the previous year's strip-tillage was observed, thus biennial strip-tillage may be a viable practice with minimal penalties in crop growth and lint yield for Virginia producers.

2.2 Introduction

Tillage is an important component of agroecosystems, and its methods and frequency vary depending on the specific cropping system. Tillage occurs for several reasons such as: to prepare the seedbed, decrease surface compaction, manage crop residue, and control weed species (Guthrie et al., 1993). Annual tillage for seedbed preparation before planting has been practiced by Virginia cotton farmers for many years. This typically occurs as conventional tillage or conservation tillage (i.e. strip-tillage). Reiter (2009) reported that tillage systems in Virginia agriculture have moved from conventional methods, to conservation and no tillage production systems over time, and summarizes that Virginia cotton acreages under conservation tillage (>30% surface residue), reduced tillage (15-30% surface residue), and conventional tillage (<15% surface residue) in 2007 were 63%, 11.5%, and 25.6%, respectively, with a total cotton acreage in 2007 of 24,624 hectares (Reiter, 2009).

Years of tillage to the same depth coupled with the physical and chemical properties of certain soil types can create a zone of subsoil compaction which restricts root growth, and is commonly referred to as a pan (Unger and Kaspar, 1994). Soil compaction is defined as "a process of densification in which porosity and permeability are reduced, strength is increased and many changes are induced in the soil fabric and in various behavior characteristics" (Soane and Van Ouwerkerk, 1994). It can be caused and influenced by many factors, and generally has negative effects on plant growth and yield. Differences in soil texture (% sand, % silt, and % clay) affects how a soil behaves such as the likelihood of compaction occurring, and to what extent. Raper et al. (2000a) inferred that cotton response from subsurface tillage is dependent on soil type, and was based on reviewed work of Touchton et al. (1986).

A common tillage practice for cotton production in Virginia is subsurface tillage via strip-tillage. This process is also referred to as vertical tillage, and occurs in conjunction with or prior to planting. Following strip-tillage, the crop is planted within the tilled strip (Conservation Technology Information Center, 2015). This process allows for directed subsurface tillage directly below the rows to depths of 30-40 cm using a tractor pulled implement. The implement consists of a coulter to break the soil and cut through crop residue, followed by a shank which rips through the soil profile to loosen the soil, and lastly a rolling basket that levels the disturbed soil creating a uniform seedbed (Figure 2.1a and 2.1b). The main reason for sub-soil tillage is to reduce soil compaction and allow for deeper rooting zones (McConnell et al, 1989; Raper et al. 2000b; Amanullah et al., 2010). Subsoil tillage has been shown to have an impact on plant growth and root development in crops such as corn and cotton, and in some cases increase yields of crops growing in compaction-prone soils (McConnell et al., 1989; Vepraskas et al., 1995). Raper et al. (1998) observed an increase in cotton yields as a result of fall tillage to depths of root restriction, coupled with a winter cover crop. Annual implementation of subsoil tillage is common, and Khalilian et al. (2004) found positive effects on yield and growth responses of cotton in annual strip-tillage and deep tillage compared to no-till.

Technological innovations in Global Positioning Systems (GPS) guidance systems have allowed producers to achieve sub-inch accuracy for tillage, planting, chemical applications, and harvesting. The GPS system in an agricultural application would be comprised of several components: 1) satellites which are orbiting the Earth, 2) several worldwide monitoring stations 3) the actual GPS receiver mounted on the farm implement, and 4) a base station at a known location which is used to correct any errors in location proclaimed by the GPS (Grisso et al., 2009). Information on field history and past management practices are recorded and filed on memory, and can be replicated using the same track. This technology potentially enables farmers to utilize a tillage pass for more than one growing season, and plant a new crop within several centimeters of the past seasons existing row. Raper et al (2005) evaluated this technology by using Real Time Kinematic (RTK) Global Positioning System to guide the placement of strip-tillage treatments. Real Time Kinematic technology is discussed in detail by Freeland et al., (2014) and explains that the accuracy between adjacent passes in a field setting guided by auto steering and RTK technology as recommended by Deere and Co. is ±2.54 cm. This accuracy is achieved by using a fixed reference station or tower, which sends signals to the GPS unit in the tractor guiding it on-the-go with relatively high accuracy. There are limitations however in the range of operation from the base station, which typically results in decreased positional accuracy in the auto-steer guided tractor as operations exceed the signal range (Freeland et al., 2014).

If producers are equipped with this technology, it can be used for all field operations including planting, tillage, spraying, and harvesting. Further investigation by Raper et al. (2008) showed that the further away from the sub-soiled zone cotton is planted, positive effects on plant growth and yield decreased. The best possible placement theoretically would be directly within or above the strip-tilled zone, but results showed that a positive effect on yield was observed in distances up to 49.5 cm, with the best results being observed in distances of 5.1 cm or less (Raper et al., 2008). With the accuracy obtained by using auto-steer and GPS technology to guide a tractor equipped with a strip-tillage rig or planter, the potential feasibility of using a zone of subsoil tillage for multiple years in cotton production seems viable. Using this technology to implement strip-tillage, and utilize existing zones of subsurface tillage for multiple years in cotton production was the basis for this study.

The question of how long can the zone of subsoil tillage remain effective is not very well understood, and may be complicated by varying soil types. Raper et al. (2005) assessed the longevity of strip-tilled soil zones by looking at strip-tillage frequency (annual, biennial, triennial) in cotton and determined that soil compaction through reconsolidation of soil particles into the tilled streak began immediately after tillage, and persisted up until roughly three years after treatment, resulting in similar soil compaction levels as no-till treatments. The study also found minimal lint yield differences between tillage occurrence treatments, and concluded that annual strip-tillage produced similar yields as biennial and triennial strip-tillage. Busscher and Bauer (2003) also concluded that annual subsoil tillage may be effective for longer than one year in some soils in the coastal plain, due to the absence of statistical differences found in lint yields between subsoil tillage frequencies. However other studies have shown that this may not be viable (Busscher et al., 1986). Findings from studies such as these were the basis for the proposed strip-tillage work in upland cotton production in Virginia.

2.3 Objectives

The objectives of this study were to: 1) evaluate the response in early season plant growth and lint yield of cotton when produced using annual and biennial strip-tillage and 2) measure the impact of annual and biennial strip-tillage on soil compaction during the growing season.

2.4 Materials and Methods

2.4.1 Experimental Design

The study was conducted in cooperation with two Virginia cotton producers, on-farm at field locations which were managed by the producers. These producers were selected based on their implementation of high accuracy GPS guidance systems in farm operations. The study was implemented as a strip-trial design, having three different testing sites in 2015, and one in 2016

(Table 2.1). Locations are referred to as Barlow A, Barlow B, Barlow C, and Lowe. Plots were planted on 0.91 m row spacing, and were twelve rows wide with varying plot lengths. Each treatment was replicated three times at each location. Cotton variety planted in each location was selected by the grower, and was the same across treatments within location.

Two strip-tillage management systems were compared during the study. The two treatments were: 1) annual strip-tillage and 2) biennial strip-tillage. All plots were strip-tilled the previous year before the study, and only the annual strip-tillage occurred during the study year. The Lowe location was previously planted in peanuts in 2014 with a winter rye cover crop. Barlow A, Barlow B, and Barlow C were planted in cotton the preceding year. Strip-tillage for the 2015 and 2016 growing seasons occurred approximately one week prior to planting. Producers utilized previous season's GPS data and manipulated it to move the planting pass 2.5 - 5 cm to the side of the last season's existing row for planting ease and residue management.

2.4.2 Plant Population and Early Season Plant Heights

Stand counts were taken two weeks after planting from two 3.05 m sections of row. Five plant population measurements were taken per strip plot. These measurements were then used to determine an estimated plant population within each strip and treatment. Early season plant growth and development was assessed using plant heights. Plant heights were measured from the ground to the growing point beginning at the forth week after planting (WAP) and were measured weekly until the eighth WAP. A total of twenty plant height measurements were taken in each treatment strip.

2.4.3 Soil Measurements

Soil compaction was measured early season using a *Field Scout SC 900* soil compaction meter (Spectrum Technologies, Inc., Plainfield, IL). Measurements of soil compaction were measured every 2.54 cm in kilopascals (kPa). Measurements were taken approximately 10 - 15 cm from the row to a depth of 30 cm with a total of five measurements taken in each replicated strip. These electronic penetrometer measurements were taken early season after planting, and at harvest. Depth to root restrictive layer was measured at matchhead square (MHS) growth stage and again at harvest using an analog *DICKEY- john* dial soil penetrometer (DICKEY-john Corporation, Auburn, IL.). Using the smaller cone tip (1.27 cm), the probe was pushed into the ground at a steady rate until the dial reached the red zone, approximately indicating 2,068 kPa, the threshold at which plant root growth is poor, thus this measurement was referred to as the root restrictive layer (DICKEY-john Corporation, 1987). These measurements were taken at 0, 15, 30, and 46 cm perpendicular to the row center. Measurements with the dial penetrometer were taken at five random sampling points within each strip.

2.4.4 Lint Yield and Quality

Each strip was harvested using a commercial six row cotton picker to obtain the seed cotton from each strip. Seed cotton yield was determined for each strip using a modified boll buggy with load cells, or weighing round modules at the gin. A subsample of seed cotton was weighed and ginned using a 10 saw micro-gin, and then reweighed to determine the lint turnout. Lint turnout was used to calculate lint yield. A 227 g lint sample was sent to the United States Department of Agriculture (USDA) cotton classing office located in Florence, South Carolina to undergo High Volume Instrument Analysis (HVI) to determine micronaire, length, strength, and uniformity.

2.4.5 Statistical Analysis

All in-season data was collected from the middle eight rows of each strip in order to minimize any border effects between treatments. Proc GLIMMIX in SAS 9.3 (SAS Institute,

2012) was used for ANOVA on the collected data of stand establishment, plant height, soil compaction, yield, and lint quality factors to determine any treatment differences. The Tukey-Kramer's HSD method was used for the mean separation with $\alpha = 0.1$ level of significance.

2.5 Results and Discussion

2.5.1 Stand Establishment and Early Season Growth

There was no significant effect on plant population after emergence based on strip-tillage occurrence at any of the four locations (Table 2.2). Three out of four locations showed a significant response in plant height at some point during the five week sampling period, with the annual treatment producing taller plants in all of the significant sampling intervals except for the fourth WAP at Barlow C (Table 2.2). This periodic response may be related to a deeper rooting zone established by the annual tillage that allowed for better utilization of moisture and nutrients over plants in the biennial treatment as a result of decreased compaction. Lowry et al. (1970) studied different depths of root restricting layers (soil pans) in cotton and began noticing differences in plant heights five weeks after planting, with taller plants being a result of deeper depths to a root restrictive layer.

2.5.2 Early Season Soil Compaction Measurements

Field Scout SC 900 penetrometer data during the early season showed that there is a general trend of increasing soil compaction with depth for both annual and biennial treatments. Figure 2.2 and Table 2.3 illustrates the increasing soil compaction with depth at each location for both annual (red) and biennial (blue) treatments. At the Barlow B, Barlow C, and Lowe locations, the 2,068 kPa threshold was reached within 30 cm, for both treatments during early season growth. Busscher et al. (1986) also observed that a year old subsoil trench had soil compaction levels ranging between 1,500 and 2,500 kPa which was considered root limiting when sampled to a depth of 0.55 m. At each of these three locations, the depth at which root growth would be limited differed, but ranged between 20 and 30 cm (Figure 2.2). The Barlow A location was the only location early season in which neither the annual nor the biennial treatment had a measured root restrictive layer within the sampling profile. Looking at the incremental soil depths of 2.5 cm, a clear conclusion can be drawn that for all locations except Barlow B, the annual treatment resulted in significantly less soil compaction than the biennial treatment for the depths of 7.5 cm – 15 cm (Table 2.3), as well as other increments in each location.

Soil compaction was less in the row (0 cm), and increased with distance toward the row middle (46 cm) when measured with a dial penetrometer (Fig. 2.3). At all locations, the depth to a root restricting layer (2,068 kPa) was numerically deeper in the annual treatment than in the biennial treatment for the in-row measurement (Fig. 2.3). This difference was significant for Barlow A ($P = 0.056$), Barlow C ($P = 0.089$), and Lowe ($P = 0.030$). This trend did not hold for all locations at the distances of 15 cm, 30 cm, and 46 cm from the row middle. This is most likely due to the strip-tillage effect for each row, and was supported by Raper et al. (2008) which found that the greatest effect on plant growth occurs within 5 cm of the stripped row. While the biennial treatment had a shallower depth to a root restrictive layer, persistence of the zone of subsoil tillage from the previous year was evident. In-row soil compaction was less than that measured at other distances from the row during early season growth at all locations (Fig. 2.3). Busscher et al. (1995) observed subsoil persistence two years after implementation in a coastal plain soil, with positive effects on yield in a corn crop compared to no-till treatments. This suggests that while the residual effects of biennial strip-tillage may not be as pronounced as those observed in annual strip-tillage, there was some residual benefit of in-row strip-tillage in the biennial treatment.

2.5.3 Harvest Soil Compaction Measurements

Late season dial penetrometer data had similar treatment trends as the early season measurements at Barlow A and Barlow B, although in-row differences changed (Fig. 2.4) Soil compaction levels increased and depth to a root restrictive layer was shallower in-row (0 cm) for both treatments with Barlow B having a significant treatment difference (P = 0.008) (Fig. 2.4). At locations Barlow C and Lowe, soil compaction decreased from early season to harvest (in-row) for both the annual and biennial treatments resulting in a deeper depth to a root restricting layer. This may have been a result of changes in soil moisture or other soil properties, although every effort was made to take measurements when soil moisture was not too wet or dry. Busscher and Bauer (2003) explained the effects that varying soil moistures may have on cone index measurements which measure soil strength and penetration resistance, and concluded increasing soil water resulted in lowering cone index readings. In-row treatment differences were P = 0.085 and P = 0.012 for Lowe and Barlow C respectively, with the annual treatment having less soil compaction and a deeper depth to the root restrictive layer in both locations (Fig. 2.4).

Soil compaction as measured 10-15 cm from the row generally increased from the early season sampling to the harvest sampling. At all locations, the depth at which the root restricting threshold was reached became shallower for both the annual and biennial treatments. This is supported by the dial penetrometer data that shows that compaction increased at this distance for the locations of Barlow A and Barlow B. This may be explained by Raper et al. (2005) in which soil reconsolidation began as soon as subsoiling had been implemented. Incremental soil compaction measurements show that both the Barlow C and Lowe locations have the same trend as observed early season. Annual strip-tillage had significantly less soil compaction for the incremental depths of 7.5 – 15 cm at Barlow C and Lowe (Table 2.4).

2.5.4 Lint Yields and Quality Factors

Across all locations annual and biennial strip-tillage had average lint yields of 1,252 kg ha^{-1}, and 1,186 kg ha^{-1} respectively, with a difference of 66 kg ha^{-1}. There was a trend of average lint yields being higher for annual strip-tillage than biennial strip-tillage at all locations, but was only significantly higher at the Lowe location (P = 0.0188) with a difference of 135 kg ha^{-1} (Fig. 2.5). This was similar to previous studies which concluded that no significant yield penalty was associated with strip-tilling biennially, or potentially longer, in cotton production systems (Busscher and Bauer, 2003; Raper et al. 2005). In 2015, Barlow B had the lowest yields with annual and biennial strip-tillage averaging 857 kg ha^{-1} and 791 kg ha^{-1} respectively. Significant differences in lint turnout were only observed at the Lowe location (P = 0.068) with the annual and biennial treatments resulting in averages of 448 and 433 g lint / kg seed cotton respectively (Table 2.5). The Lowe location was the only location with a yield and turnout response and could be attributed to the complex of soil types present at the site, or the preceding peanut crop followed by a rye cover crop. The peanut crop may have resulted in some residual nitrogen, and also may have decreased some surface soil compaction due to the digging of the peanut crop. Furthermore, several studies have shown a positive effect on lint yield as a result of a rye cover crop and conservation tillage (Bauer and Busscher, 1996; Raper et al., 2000b). Lint quality factors of micronaire, length, strength, and uniformity are summarized in Table 2.5. Significant differences occurred for several of these measurements, however the only consistent results across locations or treatments was annual strip-tillage producing higher uniformity in 2 out of 4 locations (Table 2.5).

2.6 Conclusions

Annual strip-tillage produced a significant response in cotton lint yields over biennial strip-tillage at the Lowe location by 135 kg ha^{-1}. This was supported by plant height data for this location which found significantly taller plant heights for annual strip-tillage in the final three of five sampling intervals. The other three locations did not show a significant response in cotton lint yields between treatments, nor did the plant height data have any consistent significant differences. These results are similar to those presented in Raper et al. (2005) in which no differences in cotton lint yields were found in the treatments of annual, biennial, and triennial in-row subsoiling. However, across both years and all locations, annual strip-tillage produced an average of 66 kg ha^{-1} more lint than biennial strip-tillage. Soil compaction data at MHS and at harvest showed that compaction was lowest in the row (0 cm), and increased with distance from the row. Raper et al. (2008) found that soil bulk density increased with depth and distance from the row in which subsoiling had occurred. Annual strip-tillage resulted in significantly greater depths to a root restrictive layer in the MHS measurements at all locations except Barlow B, with rooting depths reaching nearly 35 cm in-row at some locations. Annual strip-tillage generally had less soil compaction than the biennial strip-tillage with significant differences at varying depths for three out of four locations. Soil compaction increased with depth from early season to harvest at each location.

The use of high accuracy GPS for tillage and planting in this study allowed for precise planting within 5 cm of the tillage pass. The zone of subsoil tillage implemented by precision strip-tillage may be viable and utilized by Virginia cotton farmers in soils of the coastal plain for more than one growing season without significant declines in cotton lint yields or quality based on current findings. Yields varied between locations, however lint yields were similar for both treatments at three out of four locations. Further research would be needed to determine if the zone of tillage would persist and still remain effective for more than two growing seasons, as well as to determine the role different soil types could contribute to the results. Potential influence from preceding crops and the incorporation of cover crops should also be investigated further.

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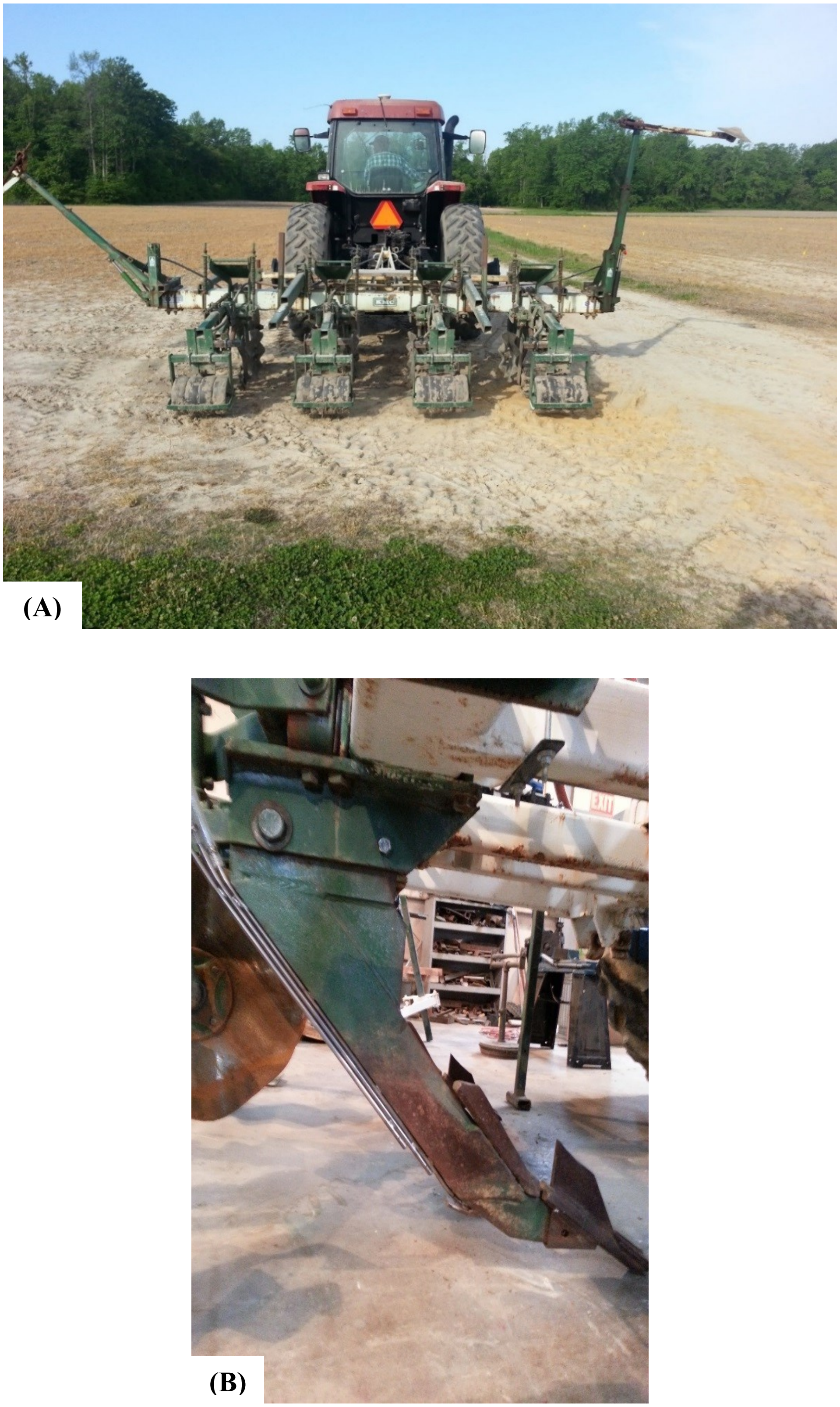

Fig 2.1a and 2.1b: Example of a strip-till implement and shank used for in-row subsoiling.

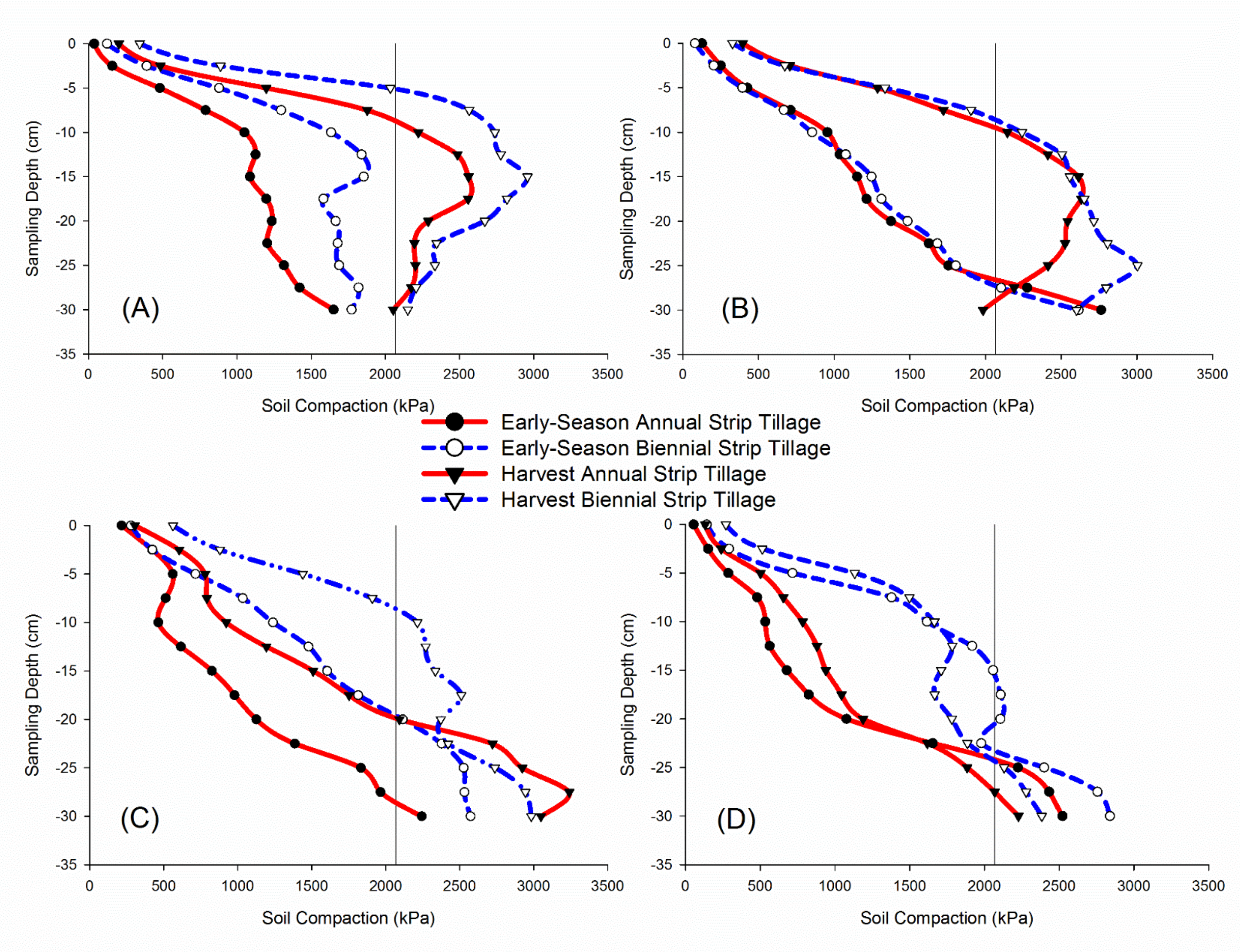

Figure 2.2:Soil compaction (kPa) as measured by depth (cm) for annual (red) and biennial (blue) treatments at locations Barlow A (A), Barlow B (B), Barlow C (C), and Lowe (D). Vertical reference lines represent 2,068 kPa, the point at which soil compaction is root limiting.

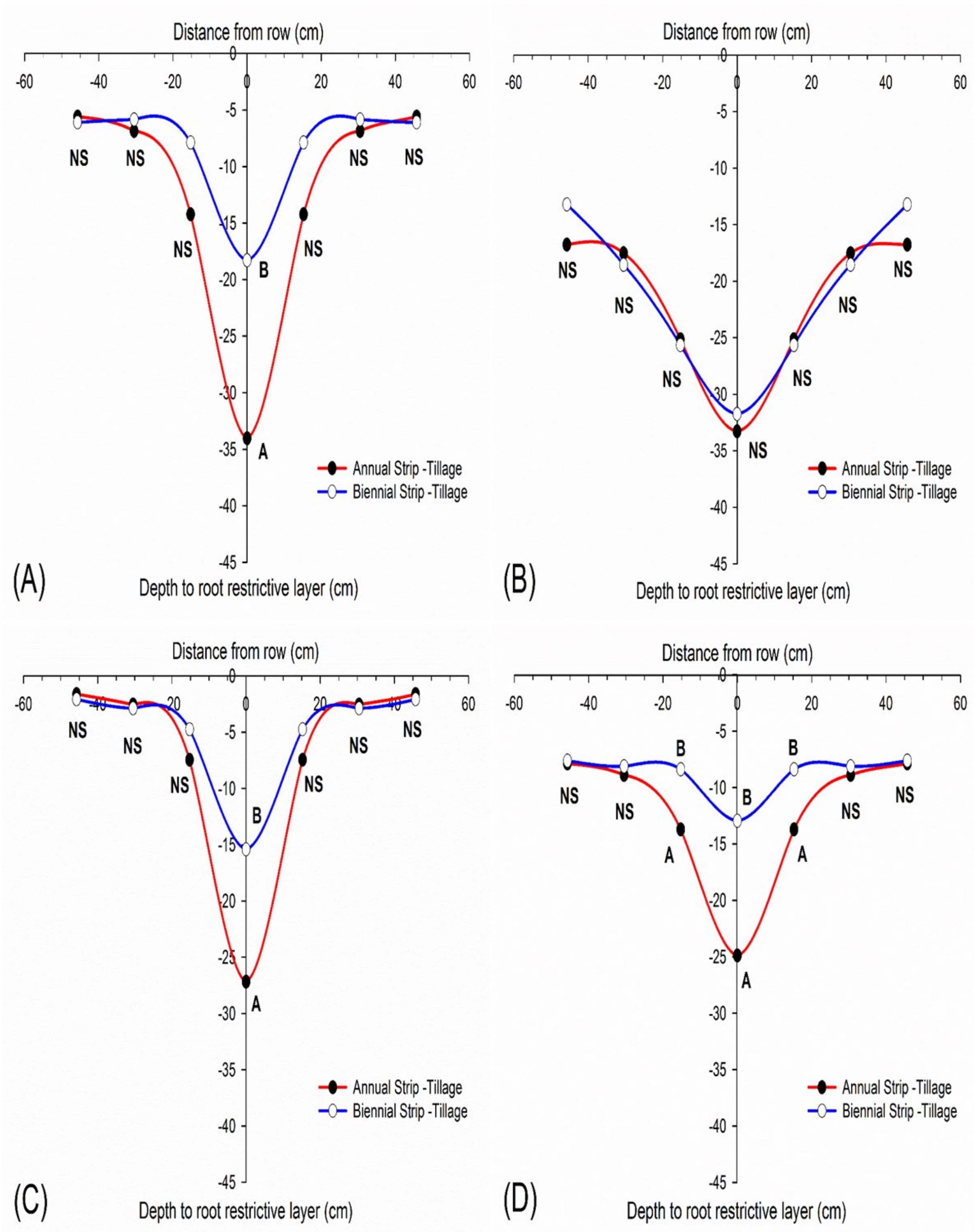

Figure 2.3: Early season (MHS) soil compaction as measured at each location for annual (red) and biennial (blue) treatments for Barlow A (A), Barlow B (B), Barlow C (C), and Lowe (D). *Different letters within distance from row are significantly different at α = 0.1.

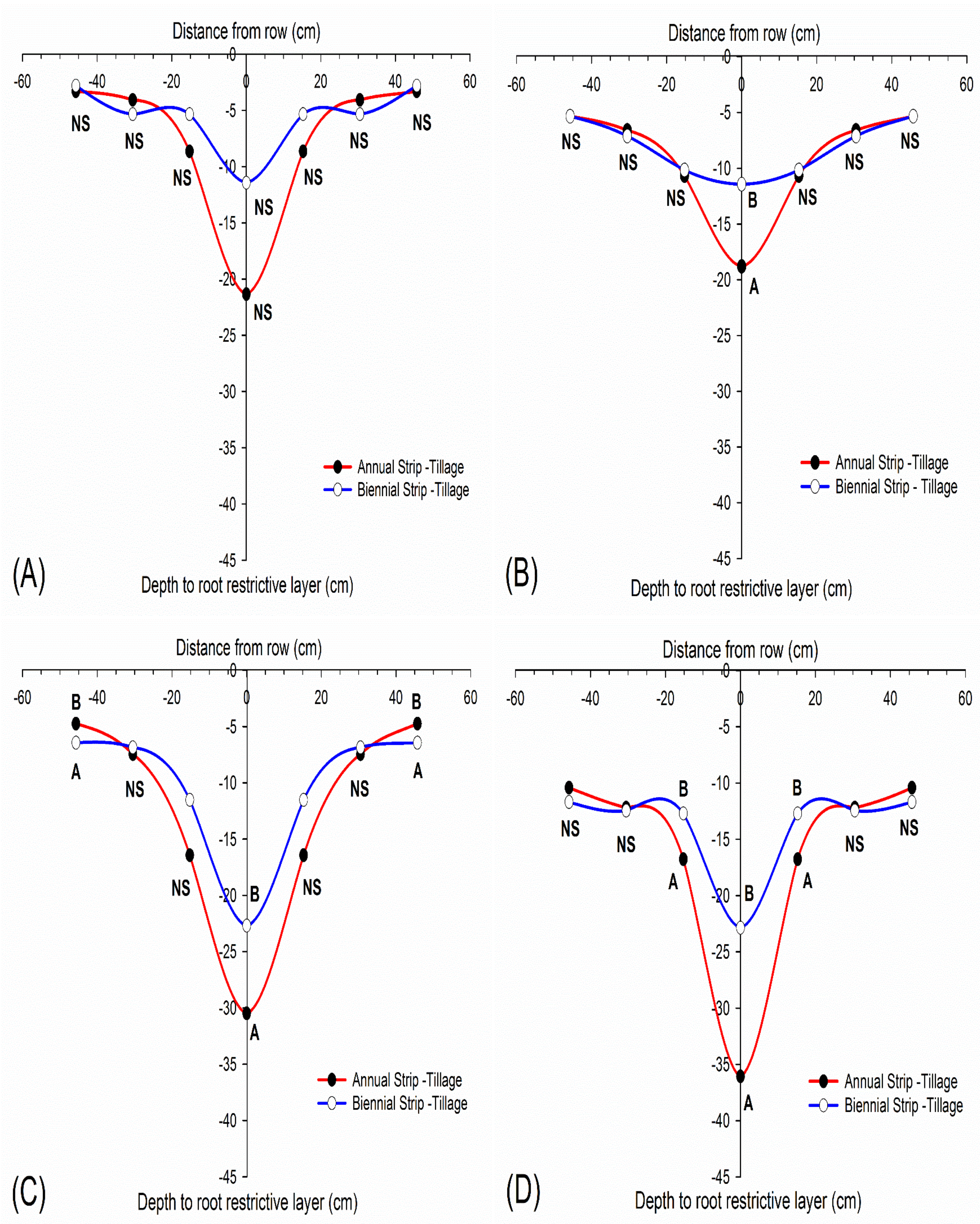

Figure 2.4: Harvest soil compaction as measured at each location for annual (red) and biennial (blue) treatments for Barlow A (A), Barlow B (B), Barlow C (C), and Lowe (D). *Different letters within distance from row are significantly different at α = 0.1.

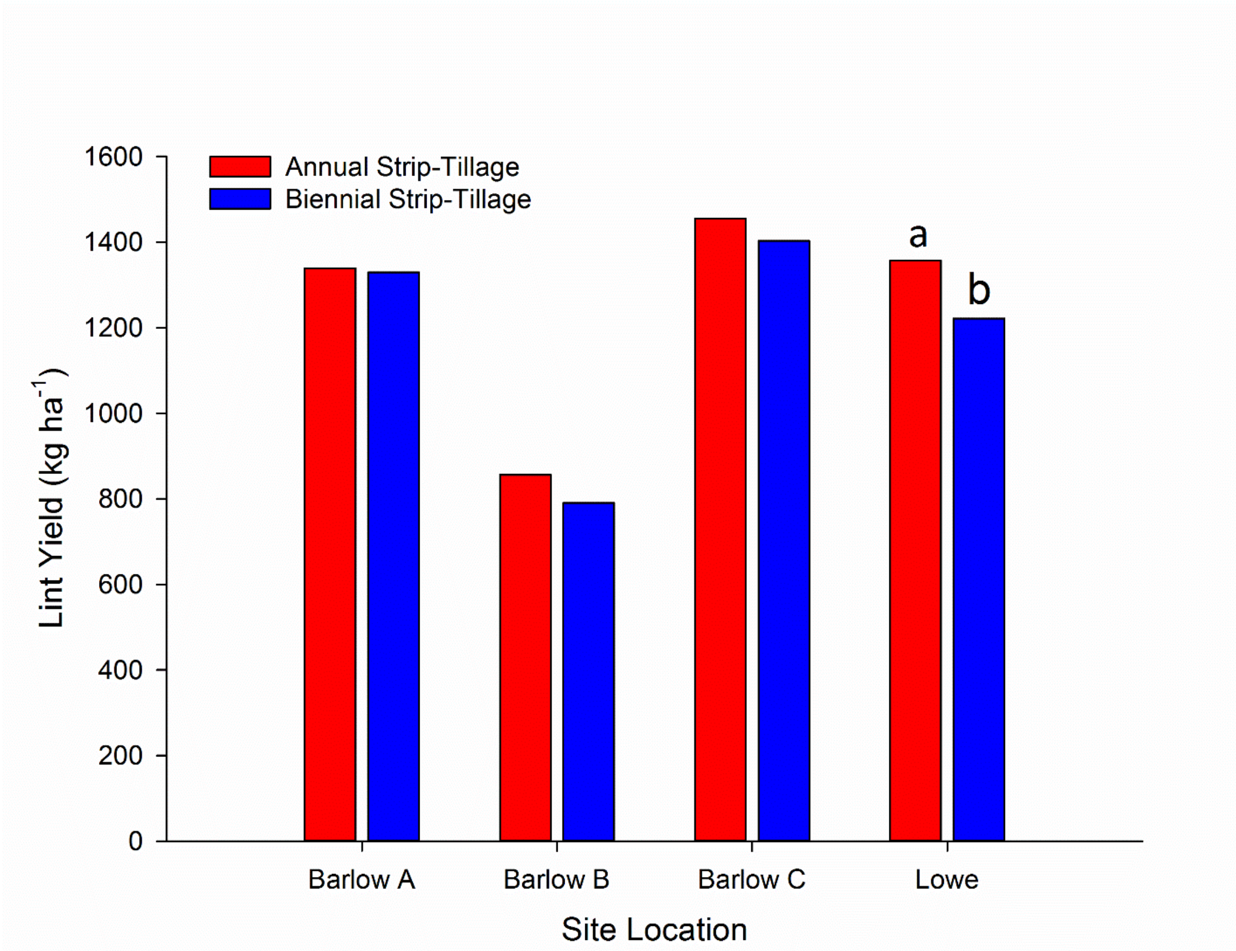

Figure 2.5: Lint yield for annual (red) and biennial (blue) strip-tillage at each location. *Values with different letters within locations are significantly different at α = 0.1.

Table 2.1: Location information for 2015 and 2016 study locations.

Location	Year	County	Soil Type	Latitude	Longitude
Barlow A	2015	Isle of Wight, VA.	Peawick silt loam	36.890831	-76.572446
Barlow B	2015	Isle of Wight, VA.	Slagle fine sandy loam	36.890968	-76.576694
Barlow C	2016	Suffolk, VA.	Tetotum fine sandy loam Wahee silt loam	36.887413	-76.565228
Lowe	2015	Southampton, VA.	Slagle, Rumford, Kenansville, Uchee Complex	36.799792	-77.087829

Table 2.2: Plant population and height data for the 4th through 8th WAP at each location.

Location	Plant Population	Plant Heights (cm)				
	(plants/ 3 m row)	4th†	5th	6th	7th	8th
Barlow A						
Annual	21.5	13 a†	19	31	42	64
Biennial	21.5	12 b	17	30	41	63
Barlow B						
Annual	21.8	12	18	30	40	61
Biennial	20.1	13	19	31	41	63
Barlow C						
Annual	24.0	9 b	13	17	30 a	47 a
Biennial	22.7	10 a	13	16	24 b	39 b
Lowe						
Annual	21.8	17	23	37 a	57 a	73 a
Biennial	22.3	16	22	33 b	53 b	69 b

† Weeks after planting

† Values within location and week with different letters are significantly different at $\alpha = 0.1$

Table 2.3: Early season soil compaction (kPa) as measured at each location in 2.5 cm intervals to a depth of 30 cm for annual and biennial treatments.

Location	Tillage	Sampling Depth (cm)												
		0	**2.5**	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**22.5**	**25**	**27.5**	**30**
Barlow A	Annual	37	159 b	480 b	789 b	1050 b	1125 b	1088 b	1198	1235	1205	1317	1422	1652
Barlow A	Biennial	124	391 a	880 a	1298 a	1635 a	1841 a	1855 a	1584	1665	1680	1689	1820	1773
ANOVA Pr > F		**NS**	**0.0833***	**0.0556**	**0.0368**	**0.0051**	**0.0209**	**0.0410**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
Barlow B	Annual	126	250	426	711	955	1036	1151	1214	1376	1626	1755	2276	2765
Barlow B	Biennial	79	204	393	667	854	1076	1247	1312	1486	1682	1804	2103	2616
ANOVA Pr > F		**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
Barlow C	Annual	215	421	561	512 b	463 b	615 b	826 b	978 b	1125 b	1385 b	1832	1965	2243
Barlow C	Biennial	278	423	714	1034 a	1237 a	1478 a	1605 a	1813 a	2115 a	2377 a	2526	2531	2573
ANOVA Pr > F		**NS**	**NS**	**NS**	**0.0049**	**0.0071**	**0.0048**	**0.0354**	**0.0282**	**0.0060**	**0.0121**	**NS**	**NS**	**NS**
Lowe	Annual	54	151	286 b	479 b	533 b	563 b	677 b	825 b	1077 b	1655 b	2225	2434	2523
Lowe	Biennial	142	291	716 a	1379 a	1616 a	1918 a	2058 a	2109 a	2107 a	1979 a	2400	2756	2841
ANOVA Pr > F		**NS**	**NS**	**0.0122**	**0.0051**	**0.0037**	**0.0015**	**0.0005**	**0.0039**	**0.0146**	**0.0607**	**NS**	**NS**	**NS**

* Values represent significant differences between tillage treatments at $\alpha = 0.1$ level. NS represents no significant treatment difference.

Table 2.4: Harvest soil compaction (kPa) as measured in each location in 2.5 cm intervals to a depth of 30 cm for annual and biennial treatments.

Location	Tillage	Sampling Depth (cm)												
		0	**2.5**	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**22.5**	**25**	**27.5**	**30**
Barlow A	Annual	203	484 b	1198 b	1879	2222	2487	2562	2559	2290	2197	2204	2176	2054
Barlow A	Biennial	344	889 a	2035 a	2566	2739	2779	2959	2821	2671	2346	2335	2208	2152
ANOVA Pr > F		**NS**	**0.0800***	**0.0900**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
Barlow B	Annual	395	707	1287	1721	2145	2412	2615	2634	2543	2526	2414	2190	1984
Barlow B	Biennial	327	674	1336	1904	2241	2505	2557	2653	2716	2807	3004	2798	2601
ANOVA Pr > F		**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
Barlow C	Annual	304	604	779	791 b	922 b	1193 b	1509 b	1752 b	2091	2721 a	2922 a	3240	3048
Barlow C	Biennial	561	880	1439	1909 a	2213 a	2269 a	2335 a	2510 a	2372	2421 b	2737 b	2943	2983
ANOVA Pr > F		**NS**	**NS**	**NS**	**0.0509**	**0.0429**	**0.0475**	**0.0626**	**0.0823**	**NS**	**0.0401**	**0.0934**	**NS**	**NS**
Lowe	Annual	131 b	239	502 b	654 b	784 b	879 b	939 b	1044	1188	1618	1884	2069	2228
Lowe	Biennial	270 a	514	1132 a	1498 a	1665 a	1784 a	1711 a	1667	1783	1886	2132	2279	2384
ANOVA Pr > F		**0.0651**	**NS**	**0.0449**	**0.0270**	**0.0326**	**0.0274**	**0.0690**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

* Values represent significant differences between tillage treatments at $\alpha = 0.1$ level. NS represents no significant treatment difference.

Table 2.5: Lint turnout and quality factors.

Location	Treatment	Lint	Length	Strength	Uniformity	Micronaire
		(g/kg)	(cm)	(G/Tex)	(%)	
Barlow A						
	Annual	417	2.92	31.1	83.7 a†	4.6
	Biennial	418	2.90	31.5	82.5 b	4.6
Barlow B						
	Annual	428	2.82	31.1	83.2	4.6
	Biennial	430	2.79	30.6	83.2	4.4
Barlow C						
	Annual	429	3.05	30.6	83.5 a	4.2
	Biennial	433	3.00	30.6	81.7 b	4.1
Lowe						
	Annual	448 a	2.87	30.2 b	83.2	4.6
	Biennial	433 b	2.87	30.4 a	83.3	4.5

† Values within location and factor with different letters are significantly different at $\alpha = 0.1$.

3 Development and Yield of Cotton Grown Under Tillage Systems in Virginia

3.1 Abstract

Current understanding of the effects of different tillage systems on cotton growth and development is limited for Virginia producers. Tillage studies were conducted in Suffolk, Virginia from 2013-2016 comparing the effects of conventional, minimal, no-tillage, and a strip-tillage control, on early season growth, soil compaction, and lint yield of four contemporary varieties using a split-plot design. Soil compaction was greatest in the no-till system with yearly depths to a root restrictive layer ranging from 8 – 26 cm. No-till had shorter plant heights compared to other tillage methods in two out of four years. Deltapine 1321 B2RF was consistently taller in all years, with significant varietal differences being present in all sampling intervals each year except 2013, while FM 1944 GLB2 tended to produce shorter plants than other varieties. In-season plant development seemed to be impacted more by varietal differences than tillage. Lint yield differed among varieties in 2013, 2014, and 2016. Deltapine 1321 B2RF produced the highest lint yields of 1,746 kg. ha^{-1}, 1,467 kg. ha^{-1}, and 693 kg. ha^{-1} in 2013, 2014, and 2015, respectively. Relative yields for no-till were 0.78, resulting in an 8% reduction in yield compared to the other tillage systems. Differences in lint quality factors were strongly influenced by variety, however tillage was only observed to affect micronaire with differences in 2013 (P = 0.0064). These findings suggest that in the short term there does not seem to be a significant growth or yield penalty associated with no-till cotton production as compared to other tillage systems.

3.2 Introduction

An important component of upland cotton (*Gossypium hirustum* L.*)* production is the tillage system. As defined by Merriam-Webster, tillage is referred to as "the activity or process of preparing land for growing crops" (Merriam-Webster, Incorporated, 2015). Virginia cotton production historically utilized several tillage systems including strip-tillage, minimum tillage, no-tillage (referred to as no-till), and conventional tillage. Tillage practices differ in many aspects including soil disturbance level, residue management, energy requirement, and depth of tillage (Reiter and Frame, 2016). Many important physiological and morphological aspects of cotton such as emergence and plant growth may be influenced by how the seedbed is prepared through tillage prior to planting. Tillage systems influence soil conditions such as compaction and water holding capacity (Guthrie et al., 1993a). Determining the longevity and sustainability of tillage practices which promote optimal growth and yield is important for Virginia cotton producers.

One common thread among tillage experiments is that field conditions (soil type, slope, climate, etc.) greatly influence which practice provides the best results. Buman et al. (2005) investigated four common tillage practices for cotton production including no-till, strip-tillage, reduced tillage, and conventional tillage, across a wide range of soil types and environments. It was concluded that after comparing these tillage treatments from 12 trials (not every treatment was at every location), there was not a significant difference in lint yields between tillage treatments, but no-till always resulted in a positive profit compared with other tillage treatments.

While conventional tillage is still utilized in some cotton production systems, there are a wide range of undesirable effects which are associated with it. Rhoton et al. (2002) observed higher runoff rates and soil loss in conventionally tilled corn and cotton plots compared to no-till under a simulated rainfall system, and found increasing soil organic matter levels in the no-till treatment over time. Bordovsky et al. (1994) reported lower soil moisture and water relations with conventional tillage in cotton and proposed a positive correlation ($R^2 = 0.75$) between percent soil water increase and percent lint yield increase. Also, conventional tillage is generally associated with large operating costs over time (Buman et al., 2005). Keisling et al. (1992) reported higher lint yields for two years of study in conventionally tilled cotton verses no-till. Bauer and Busscher (1996) observed higher lint yields of 299 kg ha^{-1} and 290 kg ha^{-1} with conventional tillage and cover crops of clover and vetch respectively, as opposed to the same systems under conservation tillage.

Conservation tillage leaves at least a third of surface crop residue after tillage and planting have occurred (CTIC, 2015). Virginia cotton producers have transitioned to conservation tillage systems through the years with only 25.6% of Virginia cotton acreage utilizing conventional tillage (Reiter, 2009). The remaining acreage (74.4%) is under some form of conservation or minimum tillage. Conservation / minimum tillage systems include no-till and strip-tillage. No-till systems use heavier planters that cut through crop residues to minimize surface disturbance while optimizing seed-soil contact. This process requires no tillage pass prior to planting and is implemented using some form of a no-till planter. Daniel et al. (1999) explained how this process works by describing a planter with “fluted coulters to cut through surface residue followed by double disk openers to make a furrow for the seed, and press wheels to firmly cover the seed.” This tillage practice has gained acceptance in recent years and according to national tillage surveys, approximately 17.5 - 20.7% of national cotton production utilized no-till during the years of 2007-2008 (Conservation Technology Information Center, 2008; Horowitz et al., 2010). Increases in production utilizing no-till may potentially be explained by several reasons including *Roundup Ready®* technology (Buman et al., 2005), decreased input costs to maintain profit margins as a result of lower lint prices (Pettigrew and Jones, 2001), and conservation attempts to reduce erosion and increase soil retention (Raper et al., 2000). Effects of no-till on cotton yield and development are mixed. No-till cotton was observed to have lower yields as well as fewer flowers and bolls as compared to conventional tillage in a two year study by Pettigrew and Jones (2001). Some studies however have seen positive effects on yield and plant development as a result of no-till verses other tillage methods in cotton (Bordovsky et al., 1994; Kennedy and Hutchinson, 2001; Boquet et al., 2004). Soil compaction in high traffic areas in no-till production had been documented, which restricts root growth (Guthrie et al., 1993a). This may limit adoption of no-till for soils which form hard pans, in favor of other forms of conservation tillage systems.

Strip-tillage and subsoiling are alternative tillage systems for cotton production which have the benefits of conservation tillage (outside the strip), as well as the ability to decrease compaction and improve crop yield and development in fields prone to soil compaction (Khalilian et al., 2004; Raper et al., 2007). Strip-tillage for growers in the coastal plains regions of the U.S. typically occurs in the spring prior to or within the same pass as planting. This tillage method involves a ripper shank which runs through the soil at depths of up to 36 cm, and loosens the soil profile below the row where the crop will be planted (Conservation Technology Information Center, 2015). Subsoiling or strip-tillage as opposed to other tillage methods including no-till has been shown by numerous studies in soils of the coastal plain to increase plant growth while decreasing compaction (Busscher and Bauer, 2003; Khalilian et al., 2004; Schomberg et al., 2006; Raper et al., 2007). Strip-tillage and other conservation tillage methods are favored for many reasons as it leaves a high amount of surface residue with little surface disturbance, while still providing adequate rooting depths for crop roots to utilize in periods of water stress (Reicosky et al., 1977).

While implementing the correct tillage practice for field conditions is important in order to optimize yield, another consideration is the relationship and interactions between cotton variety and tillage practice and its effects on plant growth and lint yield. Choosing a high yielding variety is important, and knowing which varieties perform well in each tillage system would be valuable to producers. By determining the right combination of tillage practice to allow for optimal plant growth and yield, coupled with high yielding varieties, Virginia farmers will be able to tailor their production practices and choices to achieve a profitable and sustainable cotton production system.

3.3 Objectives

The objectives of this study were to: 1) determine the effect of different tillage systems on early season cotton development (i.e. plant height and number of nodes) and soil compaction during the growing season for four commonly grown varieties, and 2) evaluate the interaction of cotton varieties and tillage systems on lint yield and quality of cotton produced in the upper southeast Coastal Plain.

3.4 Materials and Methods

3.4.1 Site Selection and Experimental Design

The study was conducted at the Tidewater Agricultural Research and Extension Center (TAREC) located in Suffolk, Virginia from 2013-2016. Three different field locations were used, but the experimental design remained the same and treatments did not change. Table 3.1 summarizes experimental site information for each location including planting date and soil types. The study was randomized complete block design with a split-plot treatment design with tillage type as the whole plot factor, and cotton variety as the sub-plot factor. There were a total of sixteen treatments with four replications. Tillage treatments included no-till, conventional tillage (chisel plow followed by a land conditioner), strip-tillage, and minimal tillage (same method as strip-tillage, but removing coulters and only utilizing the ripper shanks). The cotton varieties were chosen from data obtained through Official Variety Trials (OVT's) conducted in Virginia, as well as surveys that determined the most popular and widely grown varieties in Virginia. The varieties and their maturities that were tested were Phytogen (PHY) 499 WRF (mid), Deltapine (DP) 1321 B2RF (early-mid), Deltapine (DP) 1028 B2RF (mid), and Fibermax (FM) 1944 GLB2 (early-mid). In 2016, DP 1028 B2RF was replaced with Deltapine (DP) 1538 B2XF (mid) due to inadequate seed availability. Cotton was planted on 0.91 m row spacing and plots were 12.2 m long. Each whole plot design was twelve rows wide, with the middle eight rows containing the varieties, and the outer two rows on each side serving as tillage buffer, planted in PHY 499 WRF. Tillage treatments were implemented, and planting followed as soon as possible. All other agronomic management for the study followed Virginia Cooperative Extension recommendations for cotton (Cotton Production Guide, 2016).

3.4.2 Soil Measurements

Soil compaction was measured at the matchhead square growth stage using a *Dickey-john* dial soil penetrometer (DICKEY-john Corporation, Auburn, IL.). The depth to root restrictive layer was measured three times within each tillage treatment. The compaction reading which was used to determine the depth to root restrictive layer utilized a cone tip with a diameter of 1.27 cm. Depth to root restrictive layer was measured when inserted until the penetrometer read in the red zone, approximately 2,068 kPa (DICKEY-john Corporation, 1987). Measurements were taken 10 – 15 cm from the row.

3.4.3 Early Season and In-Season Growth and Development Measurements

Initial plant population was measured approximately three weeks after planting from two 3.05 m sections of row in each plot. To assess plant growth and development, plant heights and total node counts per plant were measured throughout the growing season. Plant heights were measured weekly beginning at the appearance of the second true leaf. Measurements were taken on five random plants within each tillage x variety treatment plot, and were measured from the ground to the growing point of the cotton plant during the 4^{th} through 8^{th} week after planting (WAP). Beginning at the matchhead square growth stage, total nodes per plant were counted starting at the first node above the cotyledonary node, and counting to the growing point for two weekly sampling intervals. Five random plants within each tillage x variety treatment plot were selected for node counts.

3.4.4 Lint Yield and Quality

Prior to harvest, a harvest aid was applied for defoliation based on recommendations from the Virginia Cotton Production Guide (2016), and was applied when 50% of bolls were open. At maturity, all plots were harvested using a commercial two-row Case IH cotton harvester modified with a load cell system for weighing individual plots. Seed cotton was weighed for each plot and used to determine the per plot yield based on treatment. A 227 gram subsample of seed cotton from each plot was set aside, weighed and ginned using a 10 saw micro-gin to determine lint turnout. The lint samples were sent to the United States Department of Agriculture (USDA) cotton classing office located in Florence, South Carolina to undergo High Volume Instrument Analysis (HVI) to determine several lint quality factors which included fiber length, strength, uniformity, and micronaire.

3.4.5 *Statistical Analysis*

An analysis of variance (ANOVA) was conducted using Proc GLIMMIX in SAS 9.3 (SAS Institute, 2012) in order to compare treatment differences in plant heights, total nodes, soil compaction, lint yield, lint turnout, and fiber quality. The Tukey-Kramer's HSD method was used for mean separation using $\alpha = 0.05$ level of significance. A relative yield analysis was performed across years to determine the effect of tillage and variety. This was calculated by dividing individual plot lint yields by the highest average tillage x variety treatment yield within year using $\alpha = 0.05$ level of significance.

3.5 Results and Discussion

3.5.1 *Stand Establishment and Early Season Plant Heights*

There were no significant differences in stand establishment between the four tillage treatments observed in any of the study years (Table 3.2). Keisling et al. (1992) evaluated conventional tillage and Schomberg et al. (2006) evaluated strip-tillage and also found no difference in stand establishment between no-till and the other tillage methods. Similarly, Bauer and Busscher (1996) observed comparable plant populations between conventional and conservation tillage systems. However, Kennedy and Hutchinson (2001) observed statistical differences two out of three years with conventional tillage resulting in greater plant populations than no-till as measured 20 days after planting. The tillage treatments in that study began five years prior to the study initiation, and were implemented annually. Varietal effects on stand establishment were observed only in 2013 ($P = 0.0004$) with DP 1321 B2RF and PHY 499 WRF producing higher stand count values (Table 3.2).

Early season plant height data for tillage systems from the 4th through 8th WAP for each year are summarized in Table 3.3. In both 2015 and 2016, tillage treatment did not produce significant differences in plant heights during any sampling interval. Similar results were found by Schomberg et al. (2006) in a four year study which showed no differences in early season plant heights for cotton grown in no-till and strip-till treatments. However in both 2013 and 2014, significant differences occurred beginning at the 5th WAP until the 8th WAP. During these two years no-till resulted in shorter plant heights than other tillage methods. This may be explained by differences in soil compaction levels. Similarly, statistically shorter plant heights for cotton in no-till than conventional tillage were observed by Pettigrew and Jones (2001) both years of a two year study when measured early season at 47 and 48 days after planting. This would be roughly 6-7 weeks after planting, and results from this study were similar with no-till producing significantly shorter plants than conventional tillage for the 6th and 7th WAP in both 2013 and 2014.

Variety was observed to have a significant impact on plant heights in all years, but especially during 2014 and 2015 (Table 3.4). There was an apparent trend for FM 1944 GLB2 to have shorter plant heights than the other three varieties. Deltapine 1321 B2RF had consistently taller plants than other varieties, and this was observed in each study year being significantly taller than FM 1944 GLB2 in at least one sampling week in every year. There were no observed variety x tillage interaction for plant heights, supporting the idea that varieties respond similarly across tillage systems

3.5.2 Total Nodes

Differences in total nodes within tillage treatment were only observed in 2014, and occurred at both sampling intervals with no-till producing fewer nodes than minimum tillage (Table 3.5). This was consistent with no-till producing shorter plant heights compared to other tillage treatments. However, Guthrie et al. (1993b) attributed new node development to temperature requirements, not production practices. Varietal differences in node development appeared in all years, with DP 1028 B2RF having fewer nodes from 2013-2015 than all other varieties (Table 3.5).

3.5.3 *In Season Soil Compaction*

Significant differences between tillage treatments were observed annually (Fig. 3.1) with no-till having the greatest in-season soil compaction in all four study years. Conventional, minimum, and strip-tillage resulted in similar soil compaction levels in every year except 2013. Shallower depths to a root restricting layer were observed in no-till, followed by conventional tillage, and deeper depths in the minimal and strip-tillage treatments. The greatest difference in depth to a root restrictive layer between tillage treatments was observed in 2013 with minimum tillage being greatest at 38 cm, and no-till being shallowest at 8 cm. Across all years, the average depth to a root restrictive layer for no-till, conventional, minimum, and strip-tillage was 14 cm, 20 cm, 29 cm, and 26 cm respectively, with subsoil tillage methods of minimum and strip-tillage having less soil compaction and deeper potential rooting depths. Many previous studies in cotton show that deep tillage such as subsoiling has a positive effect of reducing soil compaction and strength with depth (Raper et al., 1998; Akinci et al., 2004; Busscher et al., 2006). Busscher et al. (2006) found in non-irrigated cotton on a coastal plain soil, short term no-till plots had greater soil strength than those that were under chisel plowing or subsoiling or a combination of the two after measuring soil strength using a cone index method.

3.5.4 *Lint Yields and Quality Factors*

No-till produced numerically lower lint yields than other tillage treatments in three of the four years, however no significant differences in lint yield between tillage treatments were observed in any year (Fig. 3.2). Across all years, average lint yields for no-till, conventional tillage, strip-till, and minimum tillage were 1,080 kg ha^{-1}, 1,175 kg ha^{-1}, 1,155 kg ha^{-1}, and 1,168 kg ha^{-1} respectively. These results are consistent with finding from Daniel et al. (1999) and Buman et al. (2005) in which no significant differences in lint yield were observed between no-till, and other conventional and conservation tillage practices in cotton. A four year relative yield analysis was performed and showed that while there was not a statistically significant difference ($P = 0.104$), the no-till system yielded less than the other tillage systems with a relative yield of 0.78, while minimum, conventional, and strip-tillage all had relative yields of 0.86. Average lint yields were lowest in 2015, and greatest in 2013 (Fig. 3.2). These results may be explained by the later planting dates in 2014 and 2015 (Table 3.1), as well as differences in rainfall and growing degree day accumulations (Table 3.6). Lint turnout (g lint / kg seed cotton) was also observed to not differ based on tillage treatment throughout the study except for 2013 in which no-till and conventional tillage resulted in slightly higher lint turnout (Table 3.7). Tillage did not appear to have any consistent effects on micronaire, length, strength, and uniformity. The only significant difference was micronaire in 2013 ($P = 0.006$) (Table 3.8). Results from previous work supports these findings that tillage appears to play a minor role in lint quality factors (Bauer and Busscher, 1996; Daniel et al., 1999; Boquet et al., 2004).

Differences in varietal responses of yield and lint quality were much more evident than differences based on tillage treatment. Significant lint yield differences between varieties were observed each year excluding 2015. Deltapine 1028 B2RF had significantly lower lint yields than the other varieties in 2013 and 2014 with 1,418 kg ha^{-1} and 1,065 kg ha^{-1} respectively (Fig. 3.3). Decreasing yields each year until 2016 was observed with varietal treatments as they were with tillage. Lint turnout was significantly different between varieties for every year of the study, with FM 1944 GLB2 being among the lowest in all years ranging from 380 g kg^{-1} to 420 g kg^{-1}

(Table 3.7). Varietal differences in micronaire, length, and strength were observed annually, with uniformity showing a response only in 2015 (P = 0.0005) (Table 3.9). Differences in uniformity were only observed in 2015, while differences in micronaire, length, and strength were observed 2013-2016. Fibermax 1944 GLB2 and PHY 499 WRF resulted in greater lint strength than the other varieties in all years. There appeared to be no consistent results from year to year as to one variety having all lint quality factors better than other varieties.

3.6 Conclusions

The use of different annual tillage systems for cotton production in Virginia had mixed results on plant growth, soil compaction, lint yield, and fiber qualities of the tested varieties. All tillage methods appeared to produce similar stand establishments, but as plants began to grow, differences in plant heights and total nodes between tillage treatments were evident in select years. No-till appeared to promote slower plant growth producing shorter plant heights than the other tillage treatments from the 5^{th} through 8^{th} WAP both in 2013 and 2014, and fewer nodes in 2014. This difference in plant growth and development may be explained by the shallowest depth to a root restrictive layer being measured in the no-till treatment every year, with significantly greater soil compaction than strip-till and minimum tillage every year. Lint yields were not significantly different between tillage methods in any year, although no-till resulted in an 8% reduction in lint yield compared to the other three tillage methods. Tillage did not have a consistent impact on lint quality factors or lint turnout, suggesting that these variables are controlled more by genetics. Varietal differences in plant growth and development, lint yield, and lint quality were more evident throughout the study than those associated with tillage. No variety consistently had better stand establishment, but consistent differences in plant heights were observed yearly, with FM 1944 GLB2 being shorter, and DP 1028 B2RF having significantly fewer nodes. Further work is needed to determine if these results would stay constant in a longer term tillage system where the same tillage practice was implemented for multiple seasons in the same field.

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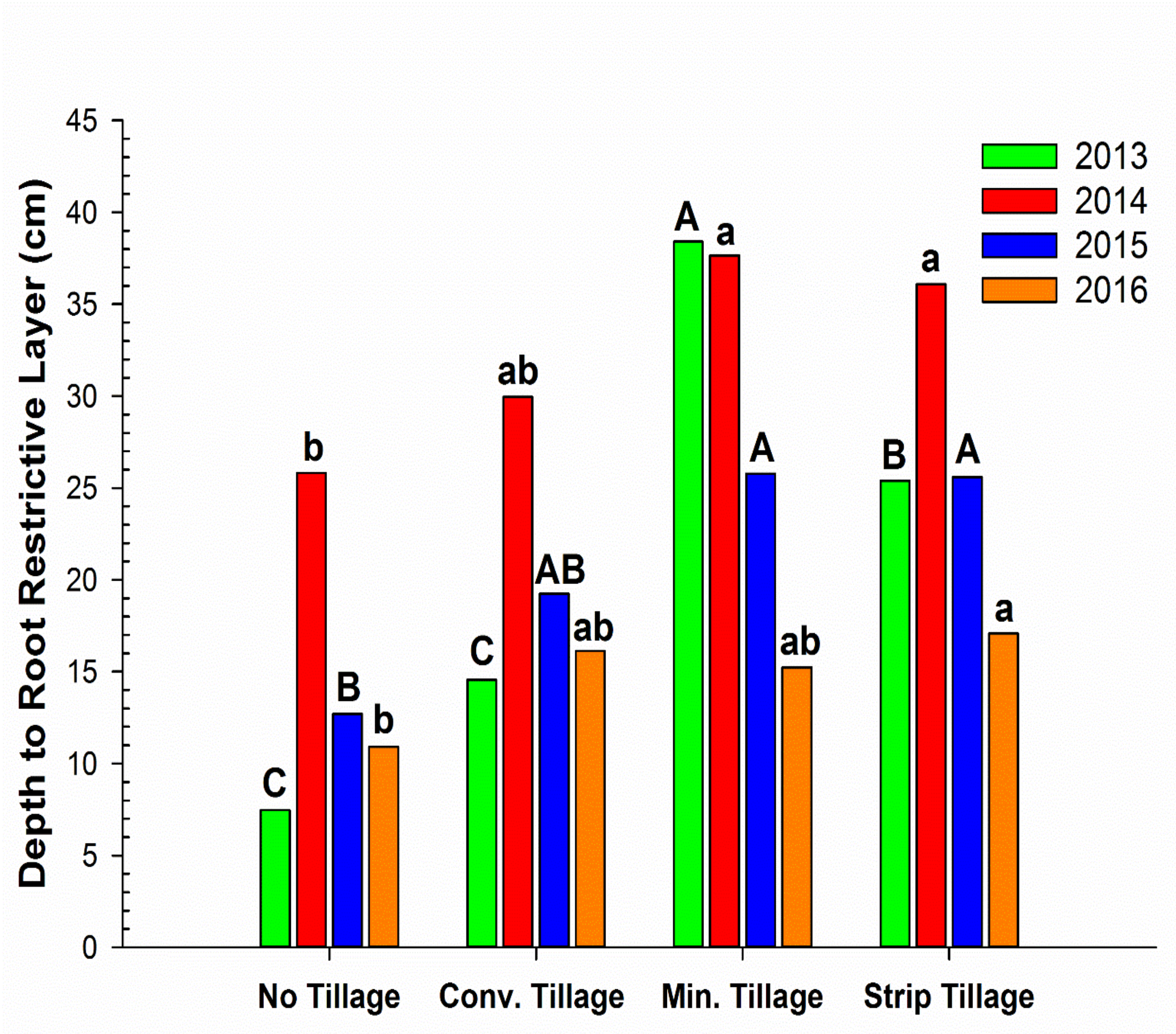

Figure 3.1: In-season penetrometer measurements for each tillage treatment by year measuring depth to a root restricting layer of 2,068 kPa. *Values within year with different letters are significantly different at α = 0.05.

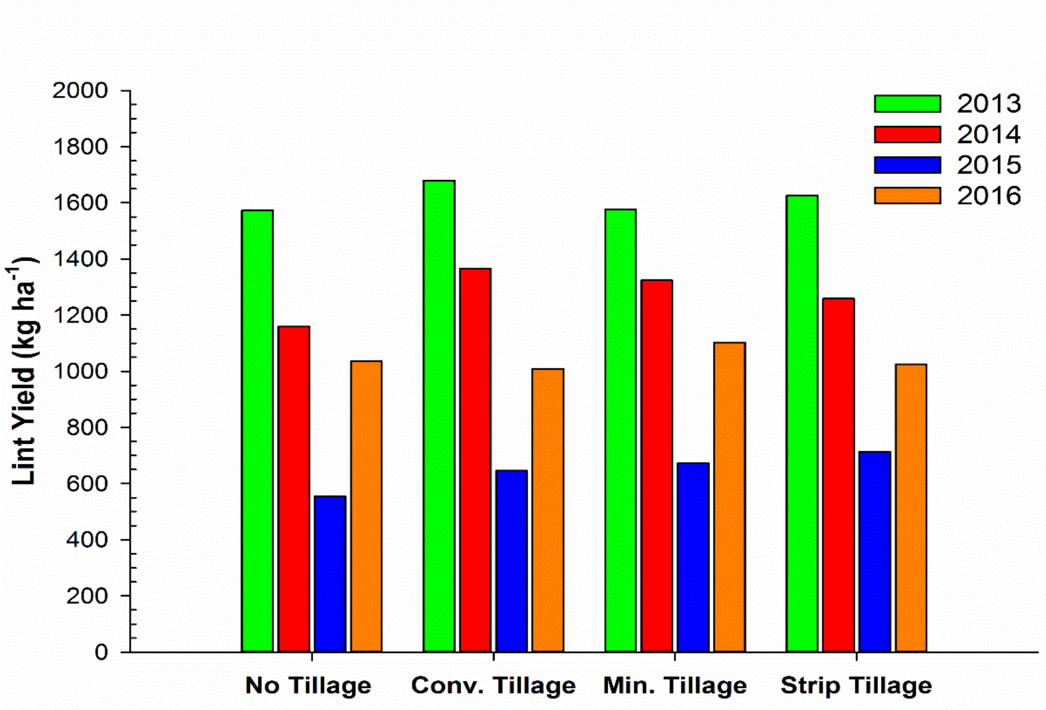

Figure 3.2: Lint yields for tillage treatments in each year.* No significant differences were observed in any year with α = 0.05.

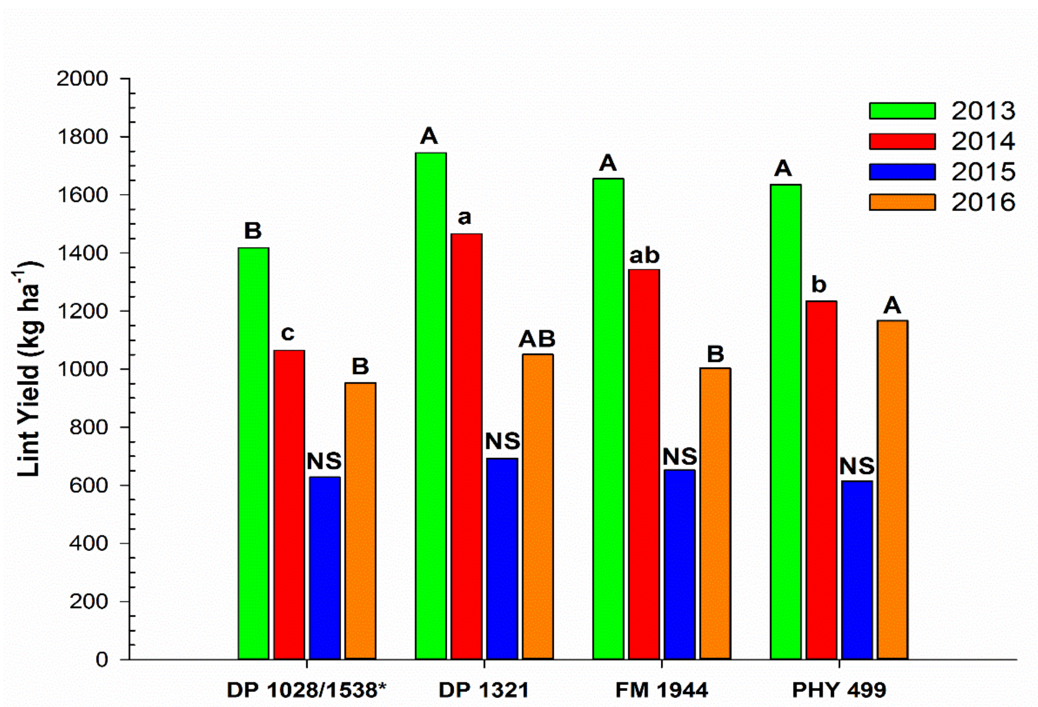

Figure 3.3: Lint yields for varietal treatments in each year. * Values within year with different letters are significantly different at α = 0.05, and DP 1028 was used 2013-2015, and replaced with DP 1538 in 2016.

Table 3.1: Study site information by location and year.

Location	Year	Soil Type	Latitude	Longitude	Planted	Tillage Occurrence
3	2016	Eunola loamy fine sand	36.66263	-76.73599	5/27/2016	5/26-27/2017
2	2015/2014	Suffolk loamy sand	36.68293	-76.75793	6/11/2015 6/2/2014	5/28/2015 6/2/2014
1	2013	Eunola loamy fine sand Kenansville loamy sand	36.66356	-76.73528	5/31/2013	5/31/2013

Table 3.2: Stand establishment for tillage and variety treatments during 2013-2016.

Tillage System	Plant Population (plants / 3 m row)				Variety	Plant Population (plants / 3 m row)			
	2013	2014	2015	2016		2013	2014	2015	2016
No Till	30.0	32.2	29.3	28.6	DP 1028/1538ǂ	30.0 bc*	30.2	28.8	29.9
Conventional Tillage	30.0	30.4	30.7	29.6	DP 1321	32.0 a	30.8	29.8	30.3
Minimum Tillage	31.0	30.4	27.2	29.3	FM 1944	29.0 c	32.1	28.9	28.8
Strip Tillage	31.0	31.6	28.2	30.9	PHY 499	31.0 ab	31.6	27.9	29.3
ANOVA Pr>F	**NS**	**NS**	**NS**	**NS**		**0.0004**	**NS**	**NS**	**NS**

*Values with different letters within sampling interval are significantly different at α=0.05.

ǂ DP 1028 was used in 2013, 2014, and 2015 and was replaced with DP 1538 in 2016.

Table 3.3: Plant heights (cm) during the 4th through 8th week after planting for tillage treatments during 2013-2016.

Tillage System	Plant Height (cm)				
	4th ǂ	5th	6th	7th	8th
2016					
No Till	14	21	34	49	63
Conventional Tillage	13	20	33	48	63
Minimum Tillage	13	21	33	51	65
Strip Tillage	14	23	39	58	71
ANOVA Pr>F	**NS**	**NS**	**NS**	**NS**	**NS**
2015					
No Till	18	21	26	39	48
Conventional Tillage	21	25	31	44	54
Minimum Tillage	20	25	33	46	57
Strip Tillage	20	25	33	45	57
ANOVA Pr>F	**NS**	**NS**	**NS**	**NS**	**NS**
2014					
No Till	32	47 b*	60 b	75 b	84 b
Conventional Tillage	37	55 a	69 a	86 a	92 a
Minimum Tillage	36	55 a	69 a	86 a	94 a
Strip Tillage	35	52 ab	67 ab	82 ab	89 ab
ANOVA Pr>F	**NS**	**0.0271**	**0.0210**	**0.0195**	**0.0207**
2013					
No Till	13	20 b	32 b	51 b	69 b
Conventional Tillage	14	22 ab	37 a	57 a	74 ab
Minimum Tillage	14	22 ab	37 a	56 a	75 a
Strip Tillage	15	23 a	39 a	59 a	77 a
ANOVA Pr>F	**NS**	**0.0226**	**0.0113**	**0.0070**	**0.0085**

ǂ Weeks after planting.
*Values with different letters within sampling interval are significantly different at α=0.05.

Table 3.4: Plant heights (cm) during the 4th through 8th week after planting for variety treatments during 2013-2016.

Variety	Plant Height (cm)				
	4th ǂ	5th	6th	7th	8th
2016					
DP 1538	12 c*	20 b	34 bc	51 a	68 a
DP 1321	15 a	24 a	37 a	55 a	69 a
FM 1944	12 c	19 b	32 c	46 b	59 b
PHY 499	14 b	23 a	36 ab	54 a	67 a
ANOVA Pr>F	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
2015					
DP 1028	20 a	24 a	31 a	45 a	56 a
DP 1321	21 a	26 a	33 a	47 a	56 a
FM 1944	18 b	22 b	27 b	38 b	47 b
PHY 499	20 a	24 a	32 a	45 a	57 a
ANOVA Pr>F	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
2014					
DP 1028	33 b	49 c	62 c	81 b	88 b
DP 1321	38 a	56 a	71 a	85 a	92 a
FM 1944	34 b	51 c	65 bc	79 b	85 c
PHY 499	36 a	53 b	67 b	85 a	93 a
ANOVA Pr>F	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
2013					
DP 1028	14 b	22	36	55	74
DP 1321	15 a	23	37	58	76
FM 1944	14 b	21	35	54	71
PHY 499	14 b	22	37	55	74
ANOVA Pr>F	**0.0028**	**NS**	**NS**	**NS**	**NS**

ǂ Weeks after planting.

*Values with different letters within sampling interval are significantly different at α=0.05.

Table 3.5: Total node counts for tillage treatment and variety for the 1st and 2nd week following MHS during 2013-2016.

Tillage System	Total Nodes		Variety	Total Nodes	
	1st‡	2nd		1st	2nd
			2016		
No Till	10.1	11.1	DP 1538	9.4 c*	11.4 b
Conventional Tillage	9.8	11.7	DP 1321	10.3 a	12.5 a
Minimum Tillage	9.8	12.0	FM 1944	9.7 bc	11.6 b
Strip Tillage	9.8	12.7	PHY 499	10.0 ab	11.9 b
ANOVA Pr>F	**NS**	**NS**		**<0.0001**	**<0.0001**
			2015		
No Till	6.6	8.3	DP 1028	6.4	8.5 b
Conventional Tillage	7.4	8.7	DP 1321	7.0	9.0 a
Minimum Tillage	6.7	9.0	FM 1944	6.9	8.6 ab
Strip Tillage	6.5	9.0	PHY 499	6.9	9.0 a
ANOVA Pr>F	**NS**	**NS**		**NS**	**0.0077**
			2014		
No Till	9.2 b	10.9 b	DP 1028	8.9 b	10.5 c
Conventional Tillage	10.3 a	11.4 ab	DP 1321	10.4 a	12.1 a
Minimum Tillage	9.7 a	11.7 a	FM 1944	9.9 a	11.5 b
Strip Tillage	9.9 a	11.4 ab	PHY 499	10.1 a	11.4 b
ANOVA Pr>F	**0.0077**	**0.0446**		**<0.0001**	**<0.0001**
			2013		
No Till	9.2	11.0	DP 1028	8.7 b	10.9 b
Conventional Tillage	9.5	11.3	DP 1321	9.8 a	11.5 a
Minimum Tillage	9.4	11.5	FM 1944	9.6 a	11.4 ab
Strip Tillage	9.6	11.5	PHY 499	9.7 a	11.5 a
ANOVA Pr>F	**NS**	**NS**		**<0.0001**	**0.0104**

*Values with different letters within sampling interval are significantly different at α=0.05.

‡ Week of sampling after the Matchhead Square (MHS) growth stage was reached.

Table 3.6: Weather data by month including rainfall (mm) and GDD totals for 2013-2016.

	Month													
Year	May		June		July		August		September		October		November	
	Rainfall (mm)	GDD*	Rainfall (mm)	GDD	Rainfall (mm)	GDD	Rainfall (mm)	GDD	Rainfall (mm)	GDD	Rainfall (mm)	GDD	Rainfall (mm)	GDD
2013	85.34	244	206.25	480	88.14	620	163.83	488	51.31	293	114.81	154	153.92	17
2014	76.45	339	75.18	492	101.09	556	175.51	510	133.10	429	39.62	147	114.05	12
2015	13.97	348	189.99	583	117.35	611	66.55	535	135.38	438	87.88	121	120.65	58
2016	211.07	224	88.65	471	215.39	669	62.74	639	310.90	464	258.06	171	19.30	22

*Growing Degree Days (GDD) calculated using a base of 60°F (16°C).

Table 3.7: Lint turnout for tillage and variety treatments during 2013-2016.

Tillage System					**Variety**				
	Lint (g. lint / kg. seed cotton)					**Lint** (g. lint / kg. seed cotton)			
	2013	2014	2015	2016		2013	2014	2015	2016
No Till	410 a*	430	440	430	DP 1028/1538ǂ	400 b	430 b	440 a	440 a
Conventional Tillage	410 a	430	430	440	DP 1321	420 a	430 b	440 a	430 b
Minimum Tillage	400 b	430	440	430	FM 1944	380 c	410 b	420 b	410 c
Strip Tillage	400 b	430	440	430	PHY 499	420 a	450 a	440 a	440 a
ANOVA Pr>F	**0.0113**	**NS**	**NS**	**NS**		**<0.0001**	**0.0004**	**0.0001**	**<0.0001**

*Values with different letters within sampling interval are significantly different at α=0.05.

ǂ DP 1028 was used in 2013, 2014, and 2015 and was replaced with DP 1538 in 2016.

Table 3.8: Lint quality measurements for tillage treatments during 2013-2016.

Tillage System	Lint Quality			
	Micronaire	Length (cm)	Strength (g / tex)	Uniformity (%)
2016				
No Till	5.2	3.00	31.4	84.0
Conventional Tillage	5.2	2.97	31.6	84.1
Minimum Tillage	5.1	3.02	32.5	84.8
Strip Tillage	5.1	3.05	32.1	84.7
ANOVA Pr>F	**NS**	**NS**	**NS**	**NS**
2015				
No Till	4.7	3.02	29.3	85.3
Conventional Tillage	4.8	2.97	29.7	84.5
Minimum Tillage	4.7	3.02	29.5	85.1
Strip Tillage	4.7	3.02	29.4	84.9
ANOVA Pr>F	**NS**	**NS**	**NS**	**NS**
2014				
No Till	4.8	2.87	31.0	84.4
Conventional Tillage	4.6	2.87	31.3	83.4
Minimum Tillage	6.6	2.87	30.7	83.6
Strip Tillage	4.7	2.90	30.5	84.1
ANOVA Pr>F	**NS**	**NS**	**NS**	**NS**
2013				
No Till	4.3 a*	3.02	30.5	84.6
Conventional Tillage	4.3 a	3.02	30.4	84.7
Minimum Tillage	4.0 b	3.02	30.4	84.4
Strip Tillage	4.1 ab	3.02	30.7	84.5
ANOVA Pr>F	**0.0064**	**NS**	**NS**	**NS**

*Values with different letters within sampling interval are significantly different at $\alpha=0.05$.

Table 3.9: Lint quality measurements for varietal treatments for 2013-2016.

Variety	Lint Quality			
	Micronaire	Length	Strength	Uniformity
		(cm)	(g / tex)	(%)
2016				
DP 1538	5.0 b *	2.92 b	29.7 c	84.2
DP 1321	5.1 ab	3.00 b	31.5 b	84.4
FM 1944	5.1 ab	3.12 a	33.3 a	84.4
PHY 499	5.2 a	2.97 b	33.2 a	84.7
ANOVA Pr>F	**0.0112**	**<0.0001**	**<0.0001**	**NS**
2015				
DP 1028	4.5 b	2.95 b	28.3 c	84.2 b
DP 1321	5.0 a	2.97 b	28.9 b	84.8 ab
FM 1944	4.5 b	3.15 a	30.4 a	85.3 a
PHY 499	4.9 a	2.97 b	30.3 a	85.6 a
ANOVA Pr>F	**<0.0001**	**<0.0001**	**<0.0001**	**0.0005**
2014				
DP 1028	4.6 b	2.84 c	28.8 d	83.7
DP 1321	4.7 b	2.87 b	30.8 c	83.6
FM 1944	4.5 b	2.97 a	32.3 a	84.5
PHY 499	4.9 a	2.82 d	31.6 b	83.6
ANOVA Pr>F	**<0.0001**	**<0.0001**	**<0.0001**	**NS**
2013				
DP 1028	4.0 b	3.00 b	28.8 c	84.6
DP 1321	4.4 a	2.97 b	30.2 b	84.5
FM 1944	4.0 b	3.12 a	31.7 a	84.3
PHY 499	4.1 b	3.00 b	31.3 a	84.8
ANOVA Pr>F	**<0.0001**	**<0.0001**	**<0.0001**	**NS**

*Values with different letters within sampling interval are significantly different at α=0.05.

4 Conclusion

Precision annual strip-tillage to a depth of 30-40 cm in-row provided minimal benefits over biennial strip-tillage. Plant population was not affected by tillage occurrence. Early season plant growth from the 4th through 8th WAP showed minimal differences, however there seems to be a minor penalty in plant height associated with biennial strip-tillage. This may be explained by the soil reconsolidation within the biennial treatment subsoil tillage passes. Early season soil compaction measured 10-15 cm from the row show that both vertical and lateral effects are occurring due to in-row subsoiling. Biennial strip-tillage resulted in greater early season and harvest soil compaction at the depths of 7.5 cm through 15 cm at three of four locations, with Barlow B showing no statistical differences within the 30 cm sampling depth. This location had a lighter textured soil type than the other locations, and suggests that there are no differences in early season soil compaction between annual and biennial strip-tillage in this soil type. Soil compaction at MHS was significantly greater in-row for biennial strip- tillage at three out of four locations, resulting in a shallower depth to a root restricting layer, and decreased as distance from the row increased to 46 cm. Soil compaction increased from early season to harvest for two sites, and decreased at the other two sites, suggesting that soil compaction begins to increase within a single growing season, but subsoil tillage benefits may persist for at least two growing seasons. Annual strip-tillage still resulted in significantly less soil compaction and deeper depths to a root restricting layer in-row at harvest for all locations except Barlow A. Harvest compaction data also showed that for the depths of 7.5-15 cm, annual strip-tillage had less soil compaction at two locations. No location had differences below 25 cm early season, and only one location resulted in differences below this depth at harvest, suggesting that below 25 cm, annual nor biennial strip-tillage are different. Lint yields were only significantly higher for annual strip-tillage at one location, but over all locations, annual-strip tillage produced 66 kg ha^{-1} more lint than biennial strip-tillage. Interest in adoption of biennial strip-tillage using precision GPS guidance has emerged which would potentially increase sustainability and profitability by saving time and resources. Findings from this work suggest that this is feasible, and minimal reductions in yield and plant growth should be expected under similar conditions and soil types.

No-till systems resulted in minimal negative effects on plant growth and lint yield as compared to conventional, minimal, and strip-tillage systems in a single growing season. All tillage systems resulted in similar plant populations, however no-till resulted in shorter plant heights during the 5^{th} through 8^{th} WAP in 2013 and 2014. Total node production was only effected by tillage in one season (2014) with no-till resulting in significantly less nodes than the other three tillage systems. No-till was observed in every year to have higher levels of soil compaction than other tillage systems, resulting in shallower depths to a root restricting layer. Across all study years, no-till had the lowest average depth to root restricting layer of 14 cm, while minimum tillage had the greatest of 29 cm. The decreased early season plant growth measurements which were observed in the no-till system, coupled with the greater soil compaction measurements did not correlate to any consistent significant differences in lint yield or fiber quality that was explained by tillage systems. Across all years, the relative yield of no-till was 0.78, compared to the other tillage systems of 0.86, resulting in an average 8% reduction in lint yield associated with no-till, though this was not statistically significant at $\alpha = 0.05$.

Varietal differences were observed to result in more differences than tillage systems in plant heights, total nodes, lint yield, lint turnout, and lint quality. Shorter plant heights were consistently observed across years for FM 1944 GLB2, and taller plant heights were observed for DP 1321 B2RF, across all tillage systems. Deltapine 1028 B2RF produced fewer nodes in every year, and DP 1321 B2RF was amongst the varieties with the most nodes each year, supporting the plant heights data. Deltapine 1028 B2RF consistently had lower lint strength than the other varieties, while FM 1944 GLB2 had the lowest lint turnout in each year. Varietal effects on lint yield occurred in three out of four years, with DP 1028 B2RF yielding significantly lower than all of the other varieties in both 2013 and 2014.

These findings suggest that in a single growing season, there are minimal differences associated with these tillage systems. Growers wishing to increase profitability by cutting tillage costs and saving time may be able to adopt no-till for single growing seasons without any significant plant growth or yield penalties. Further research is needed to determine the longevity of these tillage systems and their associated effects on plant growth, soil compaction, and lint yield, and if these systems can be adopted for more than one growing season. Long term tillage studies in the same location, coupled with more rooting depth measurements obtained through root digging would potentially provide further insight into the effects these tillage systems and varieties would have on cotton growth, yield, and soil compaction.