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AGRONOMY AND SOILS

Cotton Growth and Yield Response to Short-Term Tillage Systems and Planting Date in North Carolina

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ABSTRACT

Tillage practices, cover crops, and planting dates can influence soil moisture and temperature conditions at planting and cotton (*Gossypium hirsutum* L.) stand establishment and yield. A study was conducted in North Carolina at two locations from 2014 through 2016. Treatments included six tillage systems of fall and spring conventional raised beds and flat strip tillage planted in early and late May, with and without a wheat (*Triticum aestivum* L.) cover crop. Tillage treatments include conventional spring raised beds, fall strip till, stale seedbed, at-plant strip till, pre-plant strip till, and stale seedbed with at-plant strip till. Except for fall strip tillage, no tillage systems reduced plant populations compared to conventionally tilled cotton in any environment. Crop growth rates were similar in conventional and spring strip-till systems and were lower in four planting date environments with stale seedbeds. In 2016, in-row soil resistance was measured from 0- to 30-cm depth using a conical penetrometer both at planting and post-harvest. Plots without any spring tillage had the greatest soil resistance for all measurements and depths. All plots with spring tillage had similar soil resistance to at least the 15-cm depth from which point the conventional spring beds had the least soil resistance through the 30-cm profile. Late planted cotton in 2014 showed inconsistent yield differences among tillage systems between locations. When pooled over location and year for 2015 and 2016, however, tillage system did not influence cotton yield. These data indicate that cotton yields in reduced-till systems are comparable to cotton grown in conventional systems in North Carolina soils.

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Cotton seedlings are susceptible to extended periods of cool, wet soils which can result in reduced and non-uniform stands (Bradow and Bauer, 2010). Imbibing seeds and seedlings are especially sensitive to cool temperatures up to 160 h after planting, and growth can cease when temperatures fall below 16° C (Bauer, 2015; Steiner and Jacobsen, 1992). A reduction in shoot growth of 44% can occur in the first 180 h after planting when soil temperatures are reduced by only 10° C (Bradow and Bauer, 2010; Nabi and Mullins, 2008).

Studies have shown that tillage reduces soil moisture at field capacity by as much as 12% by disturbing the soil surface and increasing macropores through which soil water can drain or potentially evaporate (Karlen et al., 1994; Licht and Al-Kaisi, 2005; Zibilske and Bradford, 2007). Tillage-related reductions in soil moisture allow the soil to increase in temperature more quickly than soil in no-till systems that often conserve soil moisture (Hillel, 1998). Licht and Al-Kaisi (2005) and Radke (1982) both showed that surface tillage can cause an increase in soil temperatures during daytime hours compared to no-till systems though they have little effect during cool weather. It has been well documented that systems with increased tillage typically have greater daily maximum soil temperatures while varying slightly in daily minimum soil temperatures compared to no-till systems (Fortin and Hamill, 1994; Fortin and Pierce, 1990; Kladivko et al., 1986).

The use of cover crops can also play an important role in early-season soil temperatures. Previous crop residue and terminated winter cover crops tend to reduce the daily maximum soil temperature (Dabney et al., 2001; Vos and Sumarni, 1997). Fortin and Hamill (1994) found that cover crops left standing, compared to terminated cover crops flat on the soil surface, can increase daily maximum soil temperatures. Cover crops that are incorporated into the soil however, typically have little impact on soil temperature (Dabney et al., 2001).Toliver et al. (2012) indicated that tillage effects are often dependent on soil texture. The review of over 400 studies in the southeast United States (U.S.), comparing conventional and reduced tillage systems, showed that cotton yields are typically greater in no-till systems on sandy soils, but lower on loams when compared to conventional tillage (Toliver et al., 2012).

A high soil strength layer can develop in many coastal plain soils restricting root growth of various crops (Busscher and Bauer, 2003; Busscher et al., 1995; Busscher et al., 2006; Kashirad et al., 1967). Naturally occurring hardpans and tillage pans are generally associated with structureless soils, low in organic matter, in highly weathered, eluviated horizon in the U.S. These conditions occur in over 50% of coastal plain soils (Busscher et al., 1995; Busscher et al., 2006; Pabin et al., 1998). Busscher and Bauer (2003) reported penetration resistance (PR) values as high as 4.4 MPa in coastal plain soils. The authors also observed reduced cotton root growth with PR values as low as 2.5 MPa and a 50% reduction in root growth at values of 3.5 MPa, although the reduction in roots did not influence final lint yield (Busscher and Bauer, 2003). Gerard et al. (1982) determined that at soil strength values of 6.0 to 7.0 MPa in coarse-textured soils and 2.5 MPa in clay soils, root growth is limited. To alleviate the high strength layers, generally occurring just below the plow layer, in-row subsoiling is often required annually as hardpans typically begin to reform within one year (Busscher et al., 1995; Threadgill, 1982). Several studies have recently shown that the effects of subsoiling or deep slit tillage may result in an acceptable reduction of hardpan soil strength over multiple years (Busscher and Bauer, 2003; Busscher et al., 1995; Busscher et al., 2006; Laboski et al., 1998).

Maintaining adequate crop growth in clay soils requires PR and bulk densities of less than 2.5 MPa and 1.2 Mg m^{-3}, respectively (Gerard, 1982; Snider and Oosterhuis, 2015). Because clay soils include fine particles, increasing bulk density would reduce macropores by forcing small particles into the available macropores. Increasing bulk density in clay soils can reduce porosity to the point that water is held too tightly to be available to the plant or root growth is restricted as the soil strength is too high. A high bulk density in clay soils can also prevent gas exchange with the atmosphere possibly leading to inadequate oxygenation of the soil. Jones (1983) reported critical bulk density for root growth restriction is inversely related to clay content. As clay content increases, a lower bulk density must be maintained to prevent restriction of root growth. Tillage typically breaks up clay aggregates and reduces organic matter, and over time, intensive tillage can increase the bulk density in clay soils (Brady and Weil, 2010; Meijer et al., 2016). A balance must be reached in soils with high clay content to not decrease soil structure with tillage, which could lead to an increase of bulk density, while still controlling the effects of compaction over time.

Minimizing tillage can reduce a grower's ability to adequately supply nutrients to the root zone, particularly immobile soil nutrients such as phosphorus (P) and potassium (K). Without incorporation of these immobile nutrients, P and K can build up in the surface layers and remain deficient in the root zone (Robbins and Voss, 1991). Phosphorus and K concentrations were 3.5 times higher in the top 5 cm than from 5- to 15-cm depth in no-till systems (Robbins and Voss, 1991). Meijer et al. (2016) recommended correcting all nutrient deficiencies and pH concerns before implementing a no- or reduced-till system.

Tillage also has many indirect effects on cotton growth by influencing plant pests and diseases (Koenning et al., 2004; Parajulee et al., 2006; Rothrock, 2012). In wet years, cotton yields can be reduced when planting on flat, reduced or no-till land. Drainage away from the seed, and subsequent roots, is increased when planting on conventionally-tilled raised beds compared to no-till systems, especially in soils with poor drainage (Kargas et al., 2012; Schwartz et al., 2010). Excess soil moisture at planting in reduce-tilled systems can lead to increased incidence of seedling disease (Colyer and Vernon, 2005; Keonning and Collins, 2016; Minton and Garber, 1983; Rothrock et al., 2012). Reduced tillage can also cause an increase in seedling disease complex causal pathogens due to the pathogens overwintering in remaining root residues (Bell, 1999; Colyer and Vernon, 2005; Rothrock et al., 2012; Sumner et al., 1995). Insect and nematode pests can also be influenced by tillage systems. Conservation tillage and the use of winter cover crops have been shown to reduce thrips pressure in early season cotton (Knight et al., 2015; Parajulee et al., 2006; Toews et al., 2010). Tillage practices to manage nematodes, on the other hand, vary by species, in that higher populations of some species of nematode are found in conventional tillage systems while cotton injury to other species is reduced in conventional tillage (Jordan et al., 2008; Keonning and Collins, 2016; Keonning et al., 2004; Lock et al., 2013).

Multiple comparisons exist in the literature comparing reduced and conventional tillage. However, data are limited for these comparisons across planting dates, especially in North Carolina. The objective of this study was to evaluate short-term tillage systems implemented either in the fall or spring, under different environmental conditions, planting dates, and locations and their influence on cotton growth and development in North Carolina.

MATERIALS AND METHODS

Research was conducted from 2014 to 2016 in North Carolina at the Peanut Belt Research Station (PBRS) located near Lewiston-Woodville, NC on a Norfolk sandy loam (Fine-loamy, kaolinitic, thermic Typic Kandiudults) in 2014, a Goldsboro sandy loam (Fine-loamy, siliceous, subactive, thermic Aquic Paleudults) in 2015, and a Rains sandy loam (Fine-loamy, siliceous, semiactive, thermic Typic Paleaquults) in 2016. The experiments were also conducted at the Upper Coastal Plain Research Station (UCPRS) near Rocky Mount, NC on an Aycock very fine sandy loam (Fine-silty, siliceous, subactive, thermic Typic Paleudults) in 2014, a Rains fine sandy loam in 2015, and a Norfolk loamy sand in 2016. Treatments were arranged in a split plot design with planting date serving as whole plot units and a factorial arrangement of tillage system and presence of a wheat (*Triticum aestivum* L.) cover (with and without cover crop) serving as subplot units. Plot size for experimental units was four rows (91-cm row spacing) by 12 m in length, with each combination replicated four times. Plots were planted with Stoneville 4946 GLB2 (Bayer Crop Science, Raleigh, NC) at a rate of 9.8 seed per m row (108,160 seed ha^{-1}) with 112 kg ha^{-1} of 18-46-0 starter fertilizer. Cotton was maintained using North Carolina extension recommendations in regard to all pest management, fertility, and harvest decisions (Edmisten, 2016).

Planting dates represent both early and late planted cotton in eastern North Carolina and ranged from 2 May to 9 May for the early planting, and from 21 May to 29 May for the late planting (Table 1). Six tillage systems were implemented in either the fall or spring and consisted of two bedded systems at varying times, three strip-tilled systems at varying times, and one system including fall bedding followed by strip tillage in the spring (Table 2). All bedded systems were subsoiled at a depth of 30 cm and bedded and strip-till systems were applied with a strip tillage implement consisting of two sets of coulters and basket attachments following in-row subsoiling at 30-cm depth. Two spring strip-till systems were included in the spring, one implemented the day of planting and one implemented two weeks prior to planting. In all years, tillage was implemented directly into corn (*Zea mays* L.) residue from the previous season at the PBRS. The field at UCPRS was prepared by both disking and field cultivating in the fall before any tillage system treatments were implemented.

Table 1. Dates of implementation of fall tillage, cover crop planting, pre-plant spring tillage, and planting date at Peanut Belt Research Station (PBRS) and at Upper Coastal Plain Research Station (UCPRS) for both early and late planted cotton from 2014 to 2016.

		PBRS			UCPRS		
		Fall Till & Cover	Pre-Plant† Spring Till	Plant Date	Fall Till & Cover	Pre-Plant Spring Till	Plant Date
2014	Early	18 Nov	28 Apr	5 May	19 Nov	28 Apr	9 May
	Late		20 May	28 May		19 May	29 May
2015	Early	2 Dec	23 Apr	6 May	4 Dec	23 Apr	8 May
	Late		6 May	21 May		8 May	22 May
2016	Early	7 Dec	18 Apr	5 May	18 Nov	18 Apr	2 May
	Late		10 May	24 May		11 May	25 May

† All spring tillage was implemented the day of planting with the exception of pre-plant strip till which was implemented two weeks prior to the day of planting.

Table 2. Description of short-term tillage systems evaluated at the Peanut Belt Research Station and at the Upper Coastal Plain Research Station from 2014 to 2016.

Tillage System	Fall Tillage	Spring Tillage
Conventional	-	Bed
Fall Strip Till	Strip Till	-
Stale Seedbed	Bed	-
At-Plant Strip Till	-	Strip Till
Pre-Plant Strip Till§	-	Strip Till
Fall Bed/Spring Strip	Bed	Strip Till

† All spring tillage was implemented the day of planting with the exception of pre-plant strip till which was implemented two weeks prior to the day of planting.

Each of the tillage systems was included with and without wheat cover crop drilled each fall on the date of fall tillage implementation (Table 1). The cover crop consisted of the wheat variety NC Yadkin drilled at a rate of 145 kg ha^{-1}. The cover crop was controlled two weeks prior to tillage in spring with glyphosate (840 kg ae ha^{-1}) and was either left standing or incorporated into the soil depending on the tillage system. Residue from dessicated wheat or native vegetation was left standing and not rolled flat.

Beginning in 2015, soil temperatures at a five-cm depth were measured at planting directly beneath the seed furrow within three days of planting between 1000 h and 1100 h for all environments with the exception of the early planting at the UCPRS in 2016. Soil temperatures at that time were measured in the afternoon hours on the day of planting, between 1500 h and 1600 h because of impending poor weather.

Measurements of soil PR were recorded from the center of the row in 2016, using a Fieldscout SC900 Soil Compaction Meter (Spectrum Technologies, Inc., Aurora, Illinois) with a 12.5-mm diameter cone. Penetration resistance values are presented in 5-cm depth increments from 0- to 30-cm depth. Penetration resistance measurements were recorded at PBRS and UCPRS both at planting and post-harvest, and each location and measurement timing are presented separately due to the influence of soil characteristics and soil moisture at the time of the measurement.

Early season plant samples were taken by cutting plants at the soil surface from 0.5 m of row from each of the two outside rows for a total of 1 m at 15, 25, and 35 days after planting (DAP). Plant samples were then dried at 100° C for 48 h. These data were used to calculate the mean crop growth rate (CGR) for the three intervals beginning at emergence (DW = 0). Crop growth rate was calculated using the following relationship: $CGR = (DW_2 - DW_1)/days$, where DW_2 is the dry weights at the second date and DW_1 is the dry weight at the first sampling date. Plant population was determined two weeks after emergence by recording emerged plants from the two center rows for a length of three m. Precipitation totals for the period from one week prior to planting until three weeks following planting, are presented in Figure 1 (CRONOS, 2016).

The two center rows of each plot were machine harvested from late October through early November in each season and seed cotton samples from each plot were ginned to determine turnout lint percentage. Data were analyzed as a split plot design and subjected to analysis of variance using the PROC GLM in SAS 9.4 (SAS Institute Inc., Cary, North Carolina) with corrected error terms for fixed and random effects. Means were separated using Fisher's Protected LSD test at $P \leq 0.05$ (Carmer et al., 1989; Moore and Dixon, 2015). Lint percentage of each sample was analyzed as described, and it was determined that lint percentage did not differ due to main effects when pooled over 2014 and 2016 environments. Therefore, these seed cotton yields were converted to lint yield with the average lint percentage of 42%. When pooled over both locations in 2015, lint percentage was influenced by the main effect of planting date. Seed cotton yields for these environments were converted to lint yield using the average lint turnout of 47% for the early planting date and 44% for the late planting date.

RESULTS AND DISCUSSION

The rainfall total during the period surrounding the early planting date in 2014 at PBRS was over 12 cm; however, 8.5 cm of this total came in one precipitation event that occurred two weeks after planting (Figure 1). Locations for the early planting date in 2016 received over 17 cm and 10 cm during this four-week period at PBRS and UCPRS, respectively. During this period surrounding the early planting date, measurable rainfall was received at PBRS on 17 of 28 days and on 15 of 28 days at UCPRS.

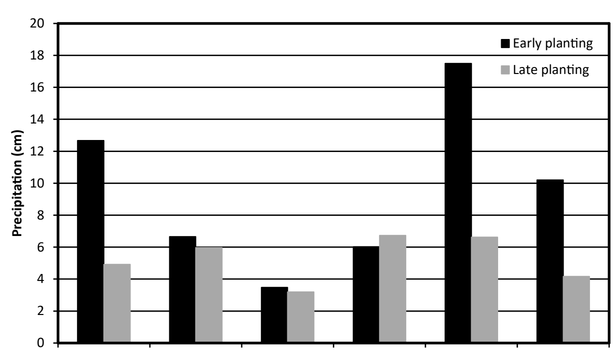

Figure 1. Figure 1. Precipitation totals for the period from one week prior to until three weeks following each planting date by location and year. During this period surrounding the early planting date, measureable rainfall occurred at Peanut Belt Research Station (PBRS) on 17 of 28 days, and on 15 of 28 days at Upper Coastal Plain Research Station (UCPRS).

With the exception of soil PR, the interaction of planting date and tillage was significant for most of the data measured. Therefore, data are presented by planting date. In 2015, the interaction of environment and tillage was significant for soil temperatures taken at the late planting date but was not significant for soil temperatures taken at the early planting date (Table 3). Plots without any spring tillage had the greatest soil temperatures and plots with conventional tillage had the lowest soil temperatures at planting. In 2016, the interaction of environment and tillage was significant for soil temperatures taken at the early planting date but was not significant for soil temperatures taken at the late planting date (Table 3). Trends in 2016 were similar to those observed in 2015. Plots without spring tillage had the greatest soil temperatures and conventional tillage plots had the lowest, with the exception of the early planting date at UCPRS in which conventionally-tilled plots had greater soil temperatures. The measurements taken for the early planting at UCPRS in 2016 were taken on the afternoon of planting between 1500 h and 1600 h, compared to all other measurements which were taken between 1000 h and 1100 h. This is similar to previous findings in that increasing tillage intensity will yield a greater daily variability in soil temperatures during daytime hours (Kladivko et al., 1986; Licht and Al-Kaisi, 2005; Radke, 1982).

The presence of a cover crop increased soil temperatures when pooled across year, location, and planting date with no interactions (Table 3). The cover crop was either left standing or incorporated, depending on the tillage system, and the findings were similar to those previously reported in that standing cover crops can increase soil temperatures (Fortin and Hamill, 1994)

The interaction of environment and tillage was significant for plant population as was the interaction between planting date and tillage with the exception of plant populations measured at UCPRS in 2016 (Table 4). The early planting date tended to have greater plant populations than the late planted in all environments except in 2016 when PBRS received 17 cm of precipitation around the early planting date, reducing the plant population of early planted cotton. Plant populations were the lowest in fall strip tillage systems in three of six environments. Fall strip tillage systems reduced plant populations an average of 26% compared to the plots with the greatest plant populations. With the exception of fall strip till systems, all strip till and stale seedbed systems had plant populations as great, or greater than conventional tillage systems in all environments when differences were observed. The presence or absence of a cover crop did not influence plant populations.

Table 3. Influence of six tillage systems and cover crop on soil temperatures for early and late planted cotton in 2015 and 2016 at both the Peanut Belt Research Station (PBRS) and the Upper Coastal Plain Research Station (UCPRS). Early planting means in 2015 and late planting means in 2016 were pooled across location as there was no significant interaction between location and tillage. Cover crop means were pooled across location, year, and planting date as there was no significant interaction.

Tillage System	Early Plant			Late Plant			2015-2016
	2015	2016		2015		2016	
		PBRS	UCPRS	PBRS	UCPRS		
	Temperature (°C)						
Conventional	17.98 c†	17.22 cd	26.17 a	24.86 bc	24.17 c	22.87 b	-
Fall Strip Till	18.76 a	17.43 a	25.59 b	24.93 bc	24.43 a	23.91 a	-
Stale Seedbed	18.65 a	17.15 de	26.04 b	25.21 a	24.36 ab	23.66 a	-
At-Plant Strip Till	18.34 b	17.30 bc	25.29 b	24.83 c	24.38 ab	22.78 b	-
Pre-Plant Strip Till	18.25 b	17.38 ab	24.79 c	24.96 bc	24.28 bc	23.00 b	-
Fall Bed/Spring Strip	18.30 b	17.05 e	25.29 b	25.09 ab	24.19 c	22.94 b	-
LSD (0.05)	0.14	0.122	0.38	0.23	0.14	0.41	-
Cover Crop	-	-	-	-	-	-	21.94 a
Bare	-	-	-	-	-	-	21.86 b
LSD (0.05)	-	-	-	-	-	-	0.07

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at p ≤ 0.05.

Table 4. Influence of six tillage systems and planting date on plant populations at the Peanut Belt Research Station (PBRS) and at the Upper Coastal Plain Research Station (UCPRS) for both early and late planted cotton in 2015 and 2016.

Tillage System	PBRS				UCPRS		
	2015		2016		2015		2016
	Early	Late	Early	Late	Early	Late	
	------------plants ha^{-1}------------						
Conventional	94592 a†	75763 b	60745	81815 a	82264 b	82264 cd	94368 abc
Fall Strip Till	77109 b	45727 c	59176	46848 b	96610 a	77333 d	82152 d
Stale Seedbed	93920 a	67246 b	58504	43261 b	93023 a	92799 ab	90670 bc
At-Plant Strip Till	91678 a	74643 b	52452	74195 a	94144 a	86299 bc	95153 ab
Pre-Plant Strip Till	97731 a	88764 a	65677	73970 a	100869 a	97730 a	89773 c
Fall Bed/Spring Strip	97282 a	71953 b	57831	80919 a	96386 a	78677 cd	97170 a
LSD (0.05)	7054	10150	-	9336	8351	7947	5133
Planting Date							
Early	92052		59064		93883		96759
Late	70683		66835		85850		86336

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at p ≤ 0.05.

Penetration resistance was measured only for the late planting date at PBRS and only the early planting date at UCPRS. Due to the influence of soil water content and soil type on PR measurements, comparisons were made only within location and measurement timing. At-planting measurements taken at UCPRS tended to have lower PR throughout the profile than that measured post-harvest, most likely due to the shorter interval between the date of tillage implementation and the date of PR measurement (Figure 2). These differences were not as apparent at PBRS, with three tillage systems having greater PR at planting, at various depths throughout the profile, when compared to those measured post-harvest (Figure 3). Unlike UCPRS, the lack of differences between the at-planting and post-harvest measurement at PBRS is most likely due to increased soil water content after harvest, though this was not measured.

Soil PR at PBRS was greatest through all depths in plots without any spring tillage both at planting (Table 5) and post-harvest (Table 6). At UCPRS, for both at-planting (Table 7) and post-harvest measurements (Table 8), plots without spring tillage had the greatest PR through the 15-cm depth. From 15 to 30 cm, both at-plant and pre-plant strip till had high PR similar to plots without spring tillage. In all measurements, plots with some form of spring tillage had similar PR through at least 15-cm depth, from which point conventional tillage had the least PR throughout the remainder of the profile.

Early planting CGR means from emergence to 15 DAP were pooled across all 2014 and 2016 environments as there was no significant interaction between environment and tillage. Crop growth rate means from 2015 are presented by location due to a significant interaction of location and tillage (Table 9). Late planting means were pooled across all environments, except for UCPRS in 2014 when measurements were not taken, due to the lack of significant interactions of environment and tillage. Cotton grown under fall strip tillage was the only cotton to be among the lowest averaging CGR in every environment. This tillage system reduced emergence to 15 DAP CGR by an average of 17% compared to the plots with the greatest CGR. Pre-plant, strip-till systems had the greatest emergence to 15 DAP CGR in all but one environment and did not differ from the greatest CGR in this environment.

Similar trends were observed in mean CGR from 15 to 25 DAP CGR because the fall strip-till system reduced CGR by an average of 42% compared to tillage systems with the greatest CGR (Table 10). With the exception of only PBRS in 2016, all mean CGR values from 15 to 25 DAP were pooled as there were no significant interactions between planting date, environment, or tillage. There was no difference in CGR between tillage systems at the early planting date at PBRS in 2016. This lack of differences is most likely due to the excess precipitation received around the early planting date at this site, as previously discussed. Plots without any spring tillage at the late planting date, however, had reduced 15 DAP to 25 DAP CGR compared to plots including some form of spring tillage. When pooled across all remaining environments, the fall strip-till system had the lowest CGR while no form of spring tillage differed from the greatest.

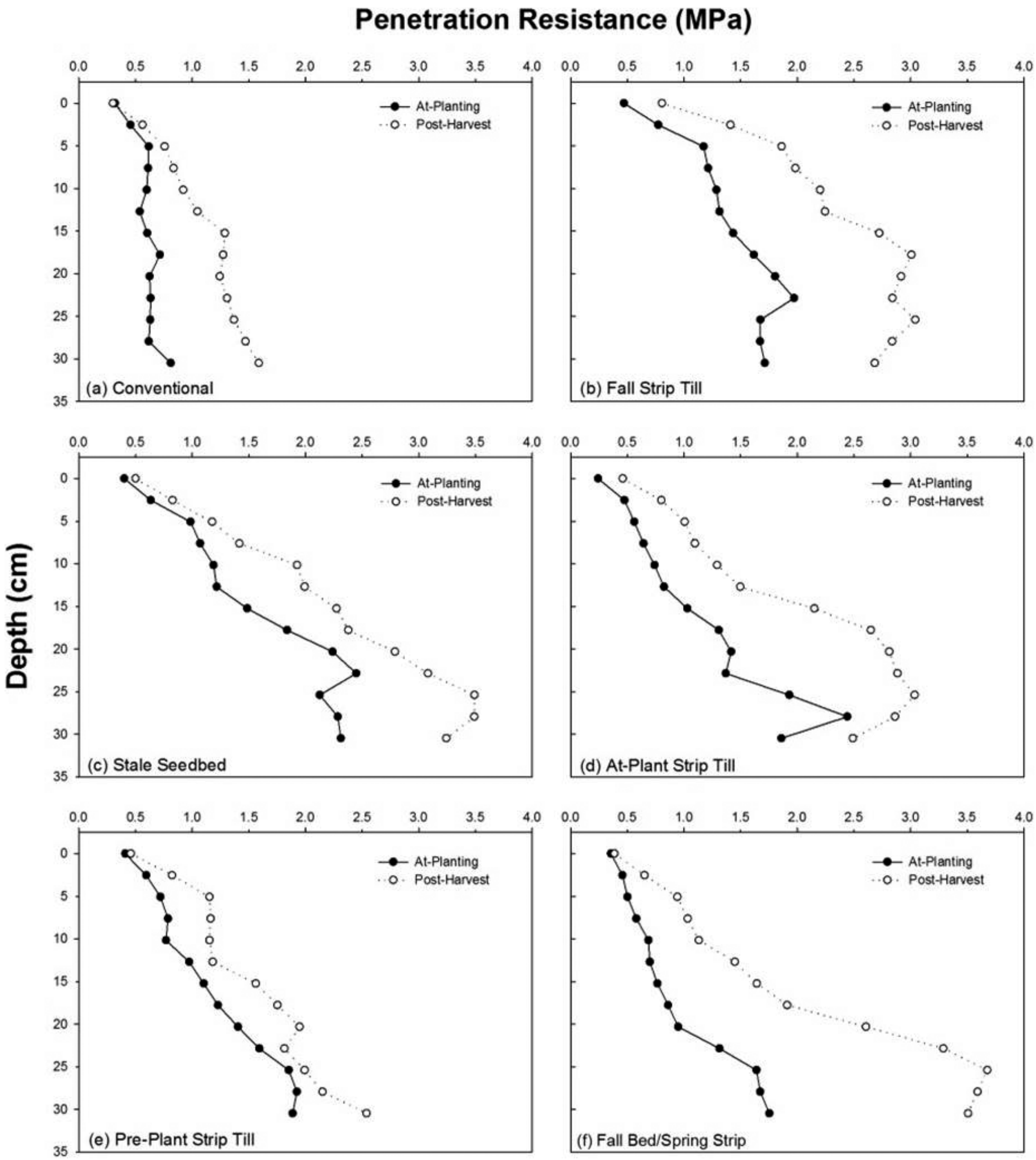

Figure 2. Observed penetration resistance plotted against soil depth per tillage system at the Upper Coastal Plain Research Station both at planting and post-harvest of which soil water contents were not equal.

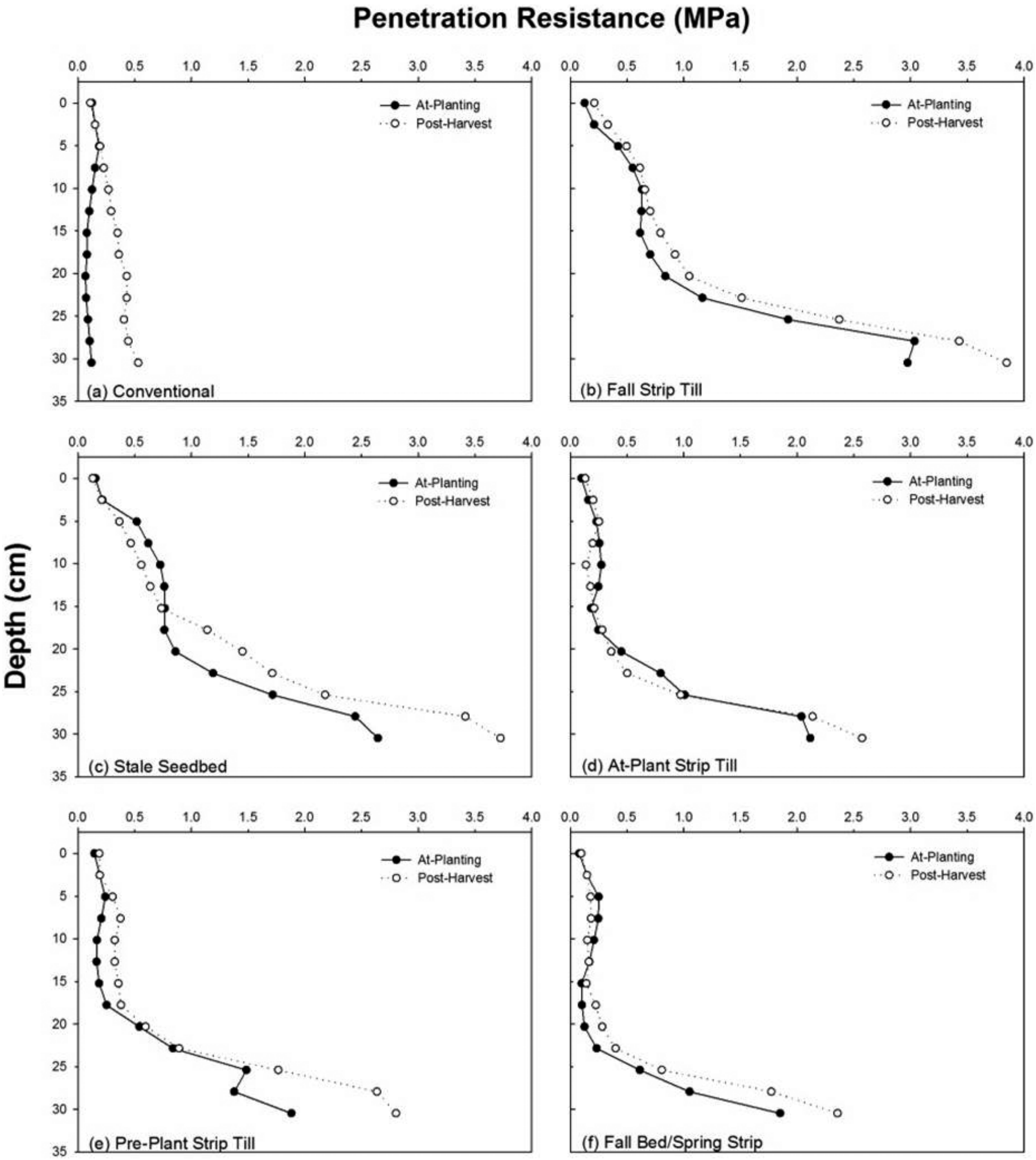

Figure 3. Observed penetration resistance plotted against soil depth per tillage system at the Peanut Belt Research Station both at planting and post-harvest of which soil water contents were not equal.

When pooled across all environments in 2014 and 2016 no differences in 25 to 35 DAP mean CGR values were observed between tillage treatments in early planted cotton, nor were differences observed in late planted cotton at UCPRS in 2014 (Table 11). When differences were observed in all remaining environments, the fall strip-till system had among the lowest mean CGR values.

Across all three CGR values calculated, the pre-plant strip-till system was the only tillage system to not differ from the greatest CGR in every environment when differences were observed. Stale seedbeds and strip-till systems did however, have CGR values as great, or greater than, conventional-till systems in 26 of 30 and 30 of 30 comparisons, respectively. Although the late planted cotton tended to have a greater average CGR due to increased temperatures as the seasons progressed, the presence, or absence, of a cover crop influenced the average CGR in only two environments. The absence of a cover crop increased emergence to 15 DAP CGR in early planted cotton at PBRS in 2015 (Table 9) and increased 15 DAP to 25 DAP CGR by 20% in the late planted cotton at PBRS in 2016 (Table 10). The lack of a response in CGR to the presence of a cover crop in most environments is similar to previous findings, especially when high residue levels are not achieved (Price et al., 2016; Reddy et al., 2004).

Table 5. Influence of six tillage systems on at-planting soil penetration resistance from 0- to 30-cm depth at the Peanut Belt Research Station.

Tillage	Soil Depth (cm)					
	0-5	5-10	10-15	15-20	20-25	25-30
	Penetration Resistance (MPa)					
Conventional	0.13	0.17 b†	0.11 c	0.07 c	0.06 d	0.08 c
Fall Strip Till	0.16	0.49 a	0.63 a	0.66 a	1.00 a	2.31 a
Stale Seedbed	0.18	0.57 a	0.74 a	0.76 a	1.03 a	2.05 a
At-Plant Strip Till	0.13	0.25 b	0.26 b	0.20 b	0.49 bc	1.46 b
Pre-Plant Strip Till	0.11	0.20 b	0.16 bc	0.17 bc	0.55 b	1.36 b
Fall Bed/Spring Strip	0.11	0.25 b	0.18 bc	0.09 bc	0.11 cd	1.14 b
LSD	-	0.12	0.14	0.12	0.38	0.55

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 6. Influence of six tillage systems on post-harvest soil penetration resistance from 0- to 30-cm depth at the Peanut Belt Research Station.

Tillage System	Soil Depth (cm)					
	0-5	5-10	10-15	15-20	20-25	25-30
	Penetration Resistance (MPa)					
Conventional	0.13 b†	0.21 cd	0.27 bc	0.34 b	0.43 b	0.46 e
Fall Strip Till	0.27 a	0.56 a	0.68 a	0.86 a	1.28 a	2.91 ab
Stale Seedbed	0.16 b	0.42 b	0.60 a	0.94 a	1.58 a	3.11 a
At-Plant Strip Till	0.17 b	0.23 cd	0.14 c	0.24 b	0.43 b	1.89 cd
Pre-Plant Strip Till	0.18 b	0.34 bc	0.33 b	0.37 b	0.72 b	2.40 bc
Fall Bed/Spring Strip	0.12 b	0.18 d	0.14 c	0.18 b	0.34 b	1.65 d
LSD	0.08	0.14	0.15	0.21	0.39	0.62

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 7. Influence of six tillage systems on at-planting soil penetration resistance from 0- to 30-cm depth at the Upper Coastal Plain Research Station.

Tillage System	Soil Depth (cm)					
	0-5	5-10	10-15	15-20	20-25	25-30
	Penetration Resistance (MPa)					
Conventional	0.39 b†	0.61 b	0.57 c	0.66 b	0.63 c	0.69 b
Fall Strip Till	0.62 a	1.19 a	1.30 a	1.53 a	1.89 ab	1.69 a
Stale Seedbed	0.52 ab	1.03 a	1.20 ab	1.66 a	2.24 a	2.24 a
At-Plant Strip Till	0.36 b	0.60 b	0.78 c	1.13 ab	1.39 abc	2.03 a
Pre-Plant Strip Till	0.50 ab	0.75 b	0.87 bc	1.16 ab	1.50 abc	1.89 a
Fall Bed/Spring Strip	0.41 b	0.54 b	0.69 c	0.81 b	1.13 bc	1.69 a
LSD	0.18	0.23	0.41	0.68	0.87	0.76

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 8. Influence of six tillage systems on post-harvest soil penetration resistance from 0- to 30-cm depth at Upper Coastal Plain Research Station.

Tillage	Soil Depth (cm)					
	0-5	5-10	10-15	15-20	20-25	25-30
	Penetration Resistance (MPa)					
Conventional	0.43 c†	0.80 c	0.99 c	1.28 c	1.28 c	1.48 c
Fall Strip Till	1.11 a	1.92 a	2.22 a	2.87 a	2.88 a	2.85 ab
Stale Seedbed	0.66 b	1.30 b	1.96 ab	2.33 ab	2.94 a	3.41 a
At-Plant Strip Till	0.63 bc	1.05 bc	1.40 bc	2.40 ab	2.72 ab	3.59 a
Pre-Plant Strip Till	0.64 bc	1.16 bc	1.17 c	1.66 bc	1.88 bc	2.23 bc
Fall Bed/Spring Strip	0.52 bc	0.99 bc	1.29 c	1.78 bc	2.95 a	3.59 a
LSD	0.22	0.42	0.60	0.77	0.91	0.88

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 9. Influence of six tillage systems and presence of a cover crop on average crop growth rate (CGR) from emergence to 15 days after planting for early and late planted cotton from 2014 to 2016 at both Peanut Belt Research Station (PBRS) and Upper Coastal Plain Research Station (UCPRS). Early planting means were pooled across all 2014 and 2016 environments as there was no significant interaction between environment and tillage while 2015 means are presented by location. Late planting means were pooled across all environments except for UCPRS in 2014 when measurements were not taken.

Tillage System	Early Plant			Late Plant
	2014, 2016	2015		2014 - 2016
		PBRS	UCPRS	
	CGR (g m^{-2} d^{-1})			
Conventional	0.146 bc†	0.925 b	0.963 a	0.448 b
Fall Strip Till	0.148 bc	0.855 c	0.900 b	0.365 c
Stale Seedbed	0.164 ab	0.940 ab	0.897 b	0.465 b
At-Plant Strip Till	0.126 c	0.930 ab	0.899 b	0.454 b
Pre-Plant Strip Till	0.177 a	0.975 a	0.944 a	0.536 a
Fall Bed/Spring Strip	0.138 bc	0.954 ab	0.929 ab	0.470 a
LSD	0.028	0.148	0.034	0.44
Cover Crop	0.153	0.913 b	0.918	0.452
Bare	0.146	0.946 a	0.926	0.470
LSD	-	0.026	-	-

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 10. Influence of six tillage systems and presence of a cover crop on average crop growth rate (CGR) from 15 days after planting to 25 days after planting for early and late planted cotton from 2014 to 2016 at both Peanut Belt Research Station (PBRS) and Upper Coastal Plain Research Station. With the exception of PBRS 2016, all means were pooled across year, location, and planting date as there were no significant interactions. There was an interaction of planting date and tillage at PBRS in 2016 and means are presented for each planting date separately.

Tillage System	2014-2016	PBRS 2016	
		Early Plant	Late Plant
	CGR (gram m^{-2} day^{-1})		
Conventional	0.518 ab†	0.06	1.205 ab
Fall Strip Till	0.317 c	0.049	0.907 bc
Stale Seedbed	0.471 b	0.052	0.791 c
At-Plant Strip Till	0.512 ab	0.062	1.441 a
Pre-Plant Strip Till	0.603 a	0.098	1.304 a
Fall Bed/Spring Strip	0.574 ab	0.052	1.375 a
LSD	0.104	-	0.339
Cover Crop	0.499	0.062	1.060 b
Bare	0.508	0.063	1.281 a
LSD	-	-	0.196

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at $p \leq 0.05$.

Table 11. Influence of six tillage systems on average crop growth rate (CGR) from 25 days after planting to 35 days after planting at Peanut Belt Research Station (PBRS) and at Upper Coastal Plain Research Station (UCPRS) for both early and late planted cotton from 2014 to 2016. Early planting means were pooled across locations and years for 2014 and 2016 and only across locations in 2015. Late planted means are pooled across location for each year with the exception of 2014 which is presented by location.

Tillage System	Early Plant		Late Plant			
	2014,2016	2015	2014		2015	2016
			PBRS	UCPRS		
	CGR (g m^{-2} day^{-1})					
Conventional	0.674	0.503 bc†	1.918 b	0.605	1.567 cd	4.233 a
Fall Strip Till	0.805	0.278 d	2.367 b	1.056	1.173 d	2.395 b
Stale Seedbed	0.733	0.656 ab	2.358 b	1.143	1.867 bc	2.649 b
At-Plant Strip Till	0.710	0.813 a	1.732 b	0.812	2.213 ab	4.177 a
Pre-Plant Strip Till	0.875	0.752 ab	3.607 a	0.739	2.462 a	3.697 a
Fall Bed/Spring Strip	0.805	0.723 ab	2.619 ab	1.233	1.525 cd	4.211 a
LSD	-	0.291	1.067	-	0.590	0.830

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at p ≤ 0.05.

Table 12. Influence of six tillage systems and presence of a cover crop on cotton lint yield for early and late planted cotton from 2014 to 2016 at both Peanut Belt Research Station (PBRS) and Upper Coastal Plain Research Station (UCPRS). Early planted cotton yields were pooled across both locations in 2014 while late planted cotton is presented by location due to a significant interaction of tillage and location. Cotton lint yields in all 2015 and 2016 environments are pooled across year, planting date and location.

Tillage System	2014			2015-2016
	Early Plant	Late Plant		
		PBRS	UCPRS	
	Lint yield (kg ha^{-1})			
Conventional	1895	1987 ab†	1132 b	1239
Fall Strip Till	1879	1580 c	1349 a	1194
Stale Seedbed	1910	1864 ab	1362 a	1178
At-Plant Strip Till	1845	1842 b	1257 ab	1258
Pre-Plant Strip Till	1784	2046 a	1365 a	1214
Fall Bed/Spring Strip	1828	1979 ab	1181 b	1244
LSD	-	184	167	-
Cover Crop	1832	1901	1267	1245 a
Bare	1881	1865	1286	1198 b
LSD	-	-	-	34

† Means followed by the same letter within each column are not significantly different according to Fisher's Protected LSD at p ≤ 0.05.

Similar to previous research, tillage and planting date did not influence lint percentage when pooled across 2014 and 2016 (O'Berry et al., 2008; Pettigrew and Meredith, 2009; Wrather et al., 2008). However, early planted cotton in 2015 had greater lint percentage compared to that of the late-planted cotton.

In the first year of the study, a significant interaction between planting date and tillage system was observed for cotton lint yield (Table 12). Early planted cotton yield was not influenced by tillage system or cover crop. Minor and inconsistent differences in late planted cotton were observed at both locations. Cotton grown under the pre-plant strip-till system had the greatest yield at both locations, while fall strip till plots and conventional till plots had the lowest yields at PBRS and UCPRS, respectively. Cotton lint yield did not differ as influenced by tillage or planting date in all of 2015 and 2016 environments (Table 12). This lack of difference due to planting date is not uncommon for the dates used in this study. Edmisten and Collins (2016) reported that on average, late planted yields did not tend to fall below early planted yields unless planting extends past 10 June in North Carolina.

Although the influence of cover crop on most of the data observed during this study was inconsistent, presence of a cover crop did increase cotton lint yields in 2015 and 2016 (Table 12). Although not quantified in this study, greater lint yield may have been associated with increased soil water retention in plots with a cover crop as described by Fortin and Hamill (1994) and Radke (1982), although it is questionable as to whether the cover crop biomass achieved in this study could significantly affect soil water content. Cover crops can also reduce thrips abundance in early in the season in cotton, although there were no symptoms of increased thrips injury in any plots.

CONCLUSIONS

With the exception of the fall strip-till system, stale seedbeds and strip-till systems rarely differed from the conventional-till system in most of the measured data. Soil temperatures were lower in plots with spring tillage and most often lowest in conventional-till, although these temperatures were taken in the morning hours and soil temperatures would most likely increase throughout the day. As shown by the soil temperatures recorded between 1500 h and 1600 h at UCPRS in 2016, it is possible that plots with spring tillage would have higher maximum daily soil temperatures compared to plots without spring tillage. This could be due to a reduced heat capacity in the soil and the influence of air temperatures on shallow soil temperatures as discussed by Licht and Al-Kaisi (2005). Plant populations were similar in tillage systems compared to conventional-till, except for fall strip till. Early season CGR was reduced by stale seedbeds in only three planting date environments while never being reduced by any spring strip tillage system. Penetration resistance was the lowest in conventional-till. Busscher and Bauer (2003) reported that reduced soil strength did not always lead to an increase in yields. Yields did not differ, with the exception of late planted cotton in 2014, in which conventional-till cotton had the lowest yields at one location. These results indicate that these reduced-till systems are comparable to conventional tillage in eastern North Carolina cotton production.

While Toliver et al. (2012) suggested that cotton does not respond equally to tillage on all soils, our data on soils common in the North Carolina coastal plain responded similarly to tillage. However, there are other soils in North Carolina with different characteristics that could influence cotton response to tillage. This study is also limited in the evaluation of cotton response to the presence of a cover crop. Although planting of the cover crop was as timely as possible, due to the timing of the previous crop harvest, the cover crop was not established early enough, nor managed, to ensure the presence of a high residue cover for cotton planting.

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DISCLAIMER

Mention of a trademark, warranty, proprietary product or vendor does not constitute a guarantee by North Carolina State University and does not imply approval or recommendation of the product to the exclusion of others that may be suitable.

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