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Soil strength, cotton root growth and lint yield in a southeastern USA coastal loamy sand

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Abstract

Inverse linear relationships between soil strength and yield in Coastal Plain soils that have subsurface genetic hard layers have previously been developed for corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), and wheat (*Triticum aestivum* L.) grown under management systems that include annual or biannual non-inversion deep tillage. In a field study in the southeastern Coastal Plains of the USA, we tested this relationship for cotton (*Gossypium hirsutum* L.) grown in wide (0.96 m) rows, hypothesizing that root growth and lint yield of cotton would increase with a decrease in soil strength associated with annual deep tillage or cover crop. Root growth and yield were evaluated for treatment combinations of surface tillage or none, deep tillage or none, and rye (*Secale cereale* L.) cover crop or none. Root growth increased (r^2 = 0.66–0.68) as mean or maximum soil strength decreased. Cotton lint yield was not significantly affected by the treatments. Lack of yield response to tillage treatment may have been the result of management practices that employed a small (3 m wide) disk in surface-tilled plots and maintained traffic lanes, both of which help prevent re-compaction. These results indicate that less than annual frequency of subsoiling might be a viable production practice for cotton grown in traditionally wide (0.96 m) rows on a Coastal Plain soil (fine loamy Acrisol–Typic Kandiudult). Thus, annual subsoiling, a practice commonly recommended and used, need not be a blanket recommendation for cotton grown on Coastal Plain soils.
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Keywords: Compaction; Reduced tillage; Deep tillage; Subsoil hardpan; Loamy sand; Penetration resistance; Cover crop; Cotton

1. Introduction

Recent studies have shown inverse linear relationships between soil strength and yield of corn, soybean, and wheat grown on southeastern USA Coastal Plain soils that have subsurface hard layers (Frederick et al., 1998; Busscher et al., 2000). Yield increases were attributed to planting in narrow rows and to the use of deep tillage with a Paratill® (Bingham Brothers, Lubbock, TX), that disrupted the hard layer. These results were in agreement with earlier, more general recommendations that Coastal Plain soils be deep tilled annually (Threadgill, 1982). Recommendations by Frederick et al. (1998) went a step further by showing that deep tillage twice a year increased yield for double-cropped wheat and soybean production. They also quantified the amount of yield reduction that compaction would cause and developed a

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relationship between yield and strength. High strengths were reduced (Baumhardt and Jones, 2002) and yield improved through deep tillage here as it had been in other studies on similar soils (Reeves and Mullins, 1995; Raper et al., 2000).

Though residual effects of deep tillage may be seen for years afterward (Munkholm et al., 2001), incomplete reconsolidation between growing seasons of the paratilled plots was enough to increase soil strengths and reduce maize, soybean, and wheat yields (Frederick et al., 1998). For other forms of deep tillage on these soils, such as slit tillage and in-row subsoiling (Busscher et al., 1995), residual deep tillage effects diminished with time and were no longer seen after about three years, without controlled traffic under conditions of normal rainfall. The southeastern USA Coastal Plain is humid subtropical with an average rainfall of about 1100 mm per year (a 15-year average).

Deep tillage improves yield by increasing the amount of the soil that the plant roots can explore for water and nutrients (Zou et al., 2001; Rosolem et al., 2002). Though most root systems respond to loosened hard layers by improving growth, not all respond in the same way because of inherent differences, such as varieties that are shallow rooted (Bodhinayake et al., 1998) or varieties that have differences in their tolerance of compaction (Rosolem et al., 2002). Additionally, changes in rooting patterns, such as deeper penetration of roots (Hamilton-Manns et al., 2002), do not always lead to improved yield.

Cover crops, such as rye, have been reported to prevent or reduce the severity of compaction. Cover crops appeared to reduce compaction or re-compaction by minimizing the effects of machinery traffic or by perforating hard layers with deep root growth when water contents were favorable for growth within the hard layer (Ess et al., 1998; Raper et al., 2000; Rosolem et al., 2002).

The relationship between soil strength and cotton yield in controlled traffic systems with traditionally wide row (0.96 m) management is unknown, but we hypothesized that root growth and lint yield would increase as soil strength decreased. We tested this hypothesis in a 2-year study using surface tillage with a disk, deep tillage with a commonly used straight-shank in-row subsoiler, and rye cover crop treatments to provide a range of soil strengths.

2. Materials and methods

2.1. Treatments and experimental design

In 1990, rye cover crop plots for cotton production were established at the Clemson Pee Dee Research Center near Florence, SC. Between 1990 and 1992, half of the plots were grown with conventional tillage and half with conservation tillage (Bauer and Busscher, 1996). In 1993, all plots were subsoiled and planted to cotton, which was not harvested because of drought. In 1994 and 1995, the plots were split to accommodate deep tillage treatments (in-row subsoiling and not subsoiling). Treatments included fallow or rye winter cover, disked or non-disked surface tillage, and deep tillage or no deep tillage.

The experimental design was split-split plot, randomized complete block with three replicates. Main plot treatments were winter cover, subplot treatments were surface tillage, and subsubplot treatments were deep tillage. Subsubplots were 3.9 m wide (four 0.96 m wide rows) and 15.5 m long.

The plots were located on a Norfolk loamy sand (fine, loamy, Acrisol or fine, loamy, siliceous, thermic, Typic Kandiudult) that had an E horizon below the plow layer that can have high soil strength even at high water contents (Busscher et al., 2000). For proper root growth, the Norfolk's E horizon is usually disrupted annually with some form of deep tillage, such as subsoiling. Norfolk is a moderately permeable, well-drained soil that formed in Coastal Plain sediments. It typically has Ap and E horizons that are 0.36 m deep, 20–80 g kg^{-1} in clay content, 5–20 g kg^{-1} organic matter, and 1–3 cmol kg^{-1} cation exchange capacity. Rainfall totals for the two growing seasons of the experiment were similar; but distributions throughout the seasons differed (Fig. 1).

2.2. Treatment management

In October 1993 and 1994, after cotton stalks were shredded, half of the plots were seeded to rye at 125 kg seed ha^{-1} in 0.19 m rows using a John Deere 750 grain drill. In early May of the following year, plots that were to be surface-tilled were disked to approximately 15 cm depths with a 3 m wide disk harrow (Tufline Mfg. Co., Columbus, GA); plots that

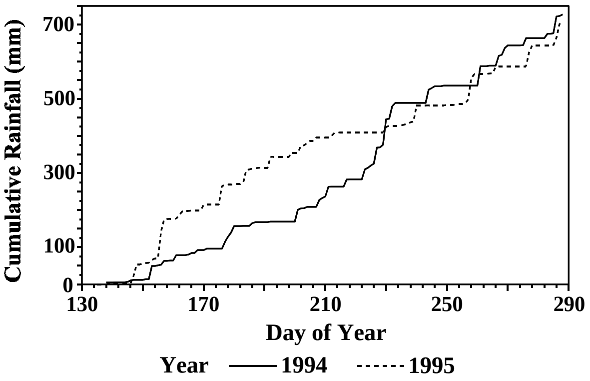

Fig. 1. Cumulative amounts of rainfall for the cotton growing seasons of 1994 and 1995.

did not receive surface tillage were desiccated with paraquat (1,1′-dimethyl-4,4′-bipyridinium).

In a separate operation prior to planting, half of the subsubplots were deep tilled by subsoiling to approximately the 0.40 m depth within 0.15 m of the previous year's row position with a KMC four-row subsoiler (Kelley Manufacturing Co., Tifton, GA) that had 45° forward angled 2.5 cm wide straight shanks. On 18 May 1994 and 15 May 1995, plots were seeded to cotton ('DES 119') over the subsoiled areas with a four-row Case-IH 900 series planter equipped with Yetter wavy coulters. Wheel tracks and row positions were maintained from year to year by centering equipment within plots guided by range poles.

Nitrogen (90 kg N ha^{-1} as ammonium nitrate) was applied in a split application—half at planting and half 1 month later. Nitrogen was banded approximately 50 mm deep and 0.15 m from the rows. Lime, P, K, S, B, and Mn were applied as needed, based on soil test results and Clemson University Extension recommendations. Weeds were controlled with a combination of herbicides, cultivation in only the disked plots, and hand-weeding. Insects were controlled by applying aldicarb (0.85 kg ai ha^{-1} of 2-methyl-2-(methylthio)propionaldehyde-*O*-methyl-carbamoyloxime) in furrow for thrips (*Frankliniella occidentalis* (Pergande)); other insecticides were applied as needed.

2.3. Soil strength and root measurements

Soil cone index was measured in each subsubplot in early June with a 12.5 mm diameter, 30° solid angle cone tip attached to a hand-operated, recording penetrometer (Carter, 1967). Soil cone index was measured to a depth of 0.55 m at nine equally spaced positions across a 0.96 m wide mid-plot row (from non-traffic mid-row to traffic mid row). At each position, measurements were the mean of three probings that were about 4 cm apart in the direction of the row. Cone indices in the form of analog data were recorded on index cards and subsequently digitized at 5 cm depth intervals. Data were normalized using a $\log_{10}$ transformation before making any statistical analyses (Cassel and Nelson, 1979).

While cone index data were collected, gravimetric soil water contents were collected at 0.1 m depth increments within non-wheel track mid-row positions and in-row positions by combining two 25 mm diameter cores. These measurements were considered representative of water contents for each subsubplot.

In early September, in-row root growth was measured by collecting two 25 mm diameter core samples from each plot to a depth of 0.96 m using a hand sampler. The two cores from each plot were combined and subjected to hydropneumatic elutriation, which used flowing water and compressed air to separate roots from soil and to deposit them on a fine screen (Smucker et al., 1982). Roots were then stained methyl violet blue, floated on water in a transparent tray, and counted with an automated digitizer (Delta-T Devices, Burwell, Cambridge, England). All roots, primary and laterals, were counted together. Root data were not lengths but associated counts based on digitization of the root image (Harris and Campbell, 1989; Busscher et al., 2001) where each count corresponded to approximately 4–5 mm of root length.

2.4. Yield measurements

In mid-October, cotton was chemically defoliated. On 31 October 1994 and 9 November 1995, seed cotton yield was harvested from the two interior rows of each subsubplot using a two-row spindle picker and bagged. Each harvest bag was subsampled, and the subsample was saw-ginned to measure lint percent. Lint percentage was multiplied by seed cotton yield to estimate lint yield.

2.5. Statistical analyses

All data were analyzed using ANOVA and the LSD mean separation procedure (SAS Institute, 2000). Differences were considered statistically significant at the 5% level unless otherwise specified. Cone indices were regressed against water content and root growth using either GLM or TableCurve v3.05 (Jandel Scientific of SPSS, Chicago, IL).

3. Results and discussion

3.1. Soil water contents

For both years, water contents differed only for depth and for the three-way interaction of depth by cover by surface tillage. Water contents generally increased with depth (Table 1). The interaction of depth by cover by surface tillage showed differences only at the 0.35–0.55 m depths. At those depths, the two-way parts of the interactions that were fallow by disked and rye by non-disk had greater water contents than the two-way parts of the interactions that were rye by disked and fallow by non-disked.

When analyses of water contents were limited to only the upper half of the profile, they differed only by depth. All other effects were not significant. Therefore, to minimize the complication of cone index differences that might have been caused by water content differences, analyses of tillage and root growth with cone index were limited to the upper half of the profile (0–0.30 m depths), unless otherwise specified.

Though water content data did not generally vary with treatments, when all depths were averaged together, water content and soil strength were correlated (Fig. 2). This relationship provided a way to compare cone indices measured at different water contents, by permitting adjustment of cone indices to values they would have had if measured at a single water content, to help explain cone index differences.

Yield for 1995 was significantly lower than it was for 1994. The low yield of 1995 was probably related to the low amount of rainfall in early August (day of year ∼215 in Fig. 1), which would be a critical time for this cotton crop because that was the time of flowering. By contrast, in 1994, rainfall was plentiful during this period.

3.2. Cone indices

Cone indices differed among years because of differences in water content. In 1994, cone indices were higher because water contents were lower.

3.2.1. Depth

For both years, cone index increased with depth down to the hard layer at about 0.35 m. Below the hard layer, cone index decreased with depth (Table 1 and Fig. 3). Increases in cone indices with depth above the hard layer (above 0.35 m) would have remained increases even if corrected for differences in water contents because they were accompanied by increasing or minimally decreasing (>1 kg per 100 kg soil) water contents. Decreases in cone indices below the hard layer were also accompanied by increases in

Table 1
Cone indices, water contents on a dry weight basis, and cone indices adjusted to a water content of 0.1 kg kg^{-1} soil, listed by depth for the top 0.55 m of the horizon

Depth[a] (m)	Cone index (MPa)		Water content (%)		Adjusted cone index (MPa)	
	1994	1995	1994	1995	1994	1995
0.05	1.03 f[b]	0.89	5.8	10.6 c	0.75	0.93
0.15	2.17	1.86 d	6.0 de	10.0 d	1.6	1.86
0.25	3.61 d	2.45 c	6.8 c	10.0 d	2.83	2.45
0.35	5.71 a	3.85 a	6.6 cd	10.2 cd	4.41	3.91
0.45	4.60 b	3.03 b	8.3 b	11.6 b	4.04	3.42
0.55	4.16 c	3.13 b	10.3 a	12.9 a	4.26	3.9
Mean	3.25 a	2.41 b	7.3 b	10.9 a	2.98	2.75

[a] Depth readings based on samples taken for 0.10 m intervals where depth readings are the middle depth interval values.
[b] Means by year with the same letter are not different at 5% using the LSD mean separation procedure.

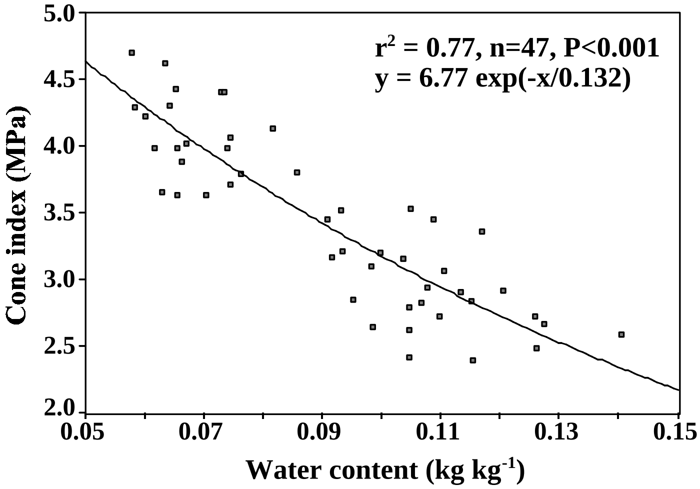

Fig. 2. Regression of soil cone index as a function of water content on a dry weight basis. The ratio of the relationship of cone indices at a water content of 0.1 kg kg^{-1} (or 10%) and at the measured water content was used to adjust cone indices to a common water content for Table 1.

water content with depth. Therefore, there was a possibility that these cone index decreases may have been due to the increasing water content. However, after cone indices were adjusted to values that they would have had if they had been measured at a common water content, they still decreased below the hard layer at 0.35 m (Table 1 and Fig. 2). The adjusted values show that the hard layer had higher strengths at depths above or below it, irregardless of the water content. Corrections to the cone indices (Busscher et al., 1997) were made by taking the ratio of the equation in Fig. 2 at the adjusted and unadjusted values giving $y_c = y_o \exp((x - 0.1)/0.132)$, where y_c was the adjusted cone index, y_o was the

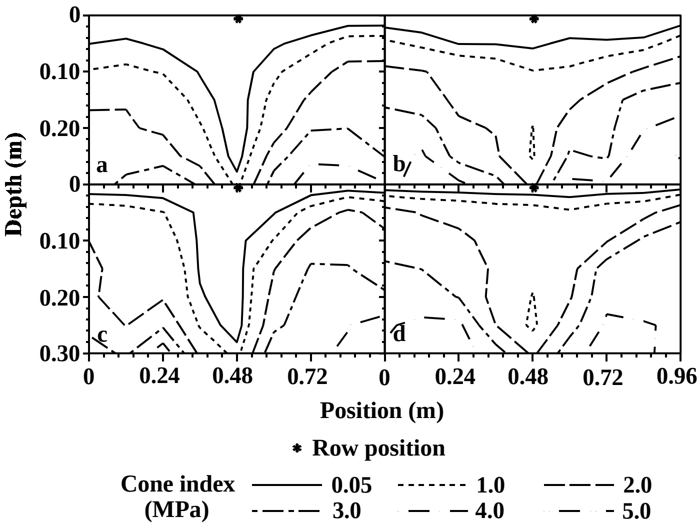

Fig. 3. Contours of cone index as a function of depth into the profile and position across the row averaged over cover crop treatments. Treatments shown were (a) deep tilled and disked, (b) disked only, (c) deep tilled only, or (d) not tilled in 1995.

original cone index, x the original water content in kg water per 100 kg soil, and 0.1 the arbitrarily chosen water content ($0.1\,kg\,kg^{-1} = 10$ kg water per 100 kg soil) to which values were adjusted.

3.2.2. Position

Cone indices within the top half of the horizon varied with position across the row. Cone indices were lower under the non-wheel track mid-row (Fig. 3, position = 0 m) than under the wheel track mid-row (position = 0.96 m). Differences between non-wheel track and wheel track mid-rows were greater for tilled treatments than for non-tilled treatments (Fig. 3). Presumably, tilled treatments would loosen and re-compact annually while the non-tilled treatments compacted continuously from year to year (Busscher et al., 2001), where most of its compaction was in the first year after tillage and additional compaction was less in the following years. As expected, the lowest cone indices were found under the rows (position = 0.48 m) because of soil loosening associated with deep tillage or residual loosening from tillage of previous years.

3.2.3. Tillage

Within the top half of the profile, cone indices were lower for treatments that were disked or deep tilled than for those that were not tilled (Table 2). Cone indices decreased from treatment to treatment as more tillage was practiced. Deep tilled treatments had lower cone indices than non-deep tilled treatments; disked treatments had lower cone indices than non-disked treatments. Disked and deep tilled treatments had the lowest cone indices. Cone indices were not different for disked vs. deep tilled treatments. Also, in the top half of the profile, soil cone indices were not different for the cover crop vs. fallow treatments.

More tillage and lower cone indices did not lead to different yields (Table 3; Busscher and Bauer, 1998). One reason for this could be the residual effect of the previous year's tillage. The residual effect of the tillage may have been sufficient to maintain a suitable environment for cotton root growth. The residual loosening can be seen in the center of the zone of measurement of Fig. 3, even in the treatments that had not been deep tilled for 2 years. In most cases, residual loosening would not be enough to maintain proper growth as seen by standard recommendations for annual tillage in these soils (Threadgill, 1982). However, in this study, there appeared to be less reconsolidation than in other studies (Busscher et al., 1995). This may have occurred because we used the same wheel tracks to prevent re-compaction by traffic and because we used a relatively small disk that did not produce a disk pan (Fig. 3).

Table 2
Mean cone index (MPa) by tillage treatment (subsoiled vs. none and disked vs. none) for the top 0.3 m of the soil profile across a 0.96 m wide row

Tillage	1994			1995		
	Disked	None	Mean	Disked	None	Mean
Subsoiled	2.08	2.18	2.13 b[a]	1.41	1.62	1.51 b
None	2.29	3.06	2.65 a	2.08	2.52	2.29 a
Mean	2.18 b	2.58 a		1.72 b[b]	2.02 a	

[a] Means with the same letter are not significantly different at 5% using the LSD mean separation procedure.
[b] Means with the same letter are not significantly different at 10% using the LSD mean separation procedure.

Table 3
Cotton lint yield ($kg\,ha^{-1}$) as a function of surface tillage, deep tillage, and cover

Tillage		1994[a]		1995	
Surface	Deep	Fallow	Rye	Fallow	Rye
Disked	Subsoiled	1060	1200	665	724
	None	1110	1210	695	619
None	Subsoiled	1299	1010	567	724
	None	1240	1000	624	838

[a] Using an LSD test at 5%, yield analyzed by year was not significantly different except for the non-disked rye cover treatments in 1994 which were lower than other treatments because of the large amount of cover (an estimated $5.8\,Mg\,ha^{-1}$) that made planting difficult.

3.2.4. Root growth

Root growth was correlated with soil strength. Though root growth was measured only under the row, it correlated better with mean cone index across the whole profile ($r^2 = 0.66$, $P < 0.001$, Fig. 4) than with the cone index measured only under the row ($r^2 = 0.59$, $P < 0.001$).

We also correlated root growth with maximum cone index that the root would encounter because research (Mulholland et al., 1999) has shown that plant growth can be related to that maximum. When developing the

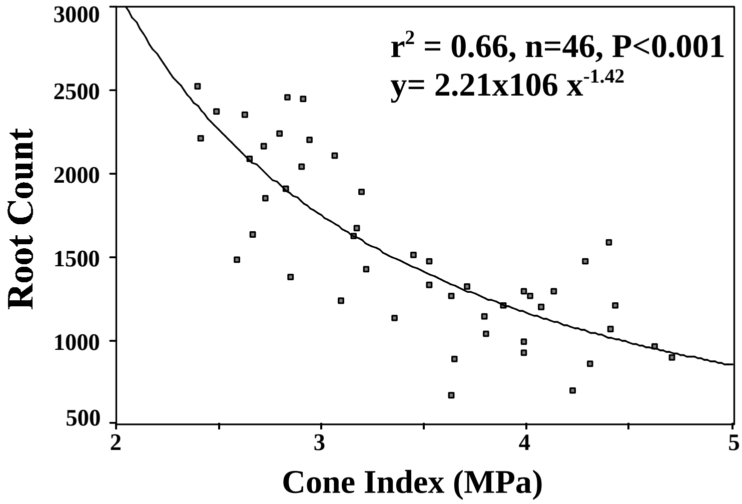

Fig. 4. Root count as a function of mean profile soil strength. Roots were measured in the row and mean strengths were taken over the top 0.55 m of the profile and across a 0.96 m wide row. An outlier with a root count of 2600 and mean cone index of 3.5 MPa was deleted before analyses.

maximum cone index, we used the 95th percentile of cone index rather than the maximum measured data point because it was a more stable number. The maximum measured data point was the result of only one measurement while the 95th percentile was the result of all the data, calculated by adding the mean and two standard deviations. Root growth was marginally better correlated to the 95th percentile of cone index ($r^2 = 0.68$, $P < 0.001$) than to mean profile cone index. With similar correlations to both the mean cone index and the surrogate maximum, we could not tell which one was likely causing the reduction in root growth. Correlation of growth with cone index across the profile was consistent with recent findings where roots encountering high soil strength slowed shoot growth (Mulholland et al., 1999; Roberts et al., 2002). It is not surprising that root growth might be slowed as well. Although increased root growth is usually associated with higher yields, in our study, root growth was not correlated to yield.

3.3. Cover crop

In 1994, cotton yield was higher for fallow cover in the non-disked treatment and for rye cover in the disked treatment than for the other treatments (Table 3). Observations made at the time of growth led us to believe that this was a result of the large amount of cover in 1994 that made planting difficult in the non-disked rye cover and added a significant amount of organic matter to the rye cover disked treatment. There were no other yield differences.

The rye cover crop could have increased soil water content by increasing infiltration and decreasing evaporation, or it could have decreased soil water content by using it for transpiration. Neither were a concern for this study. Cover crop did not have a significant effect on soil water content (data not shown), presumably because of rainfall for 1994 and 1995 (1295 and 1448 mm compared to the 15-year mean of 1100 mm). In 1994, the rainfall total for the 2 months just before killing the cover crop was 210 mm. Between killing of the cover crop and planting of the cotton, it was 76 mm. In 1995, the rainfall total for the 2 months just before killing the cover crop was only 66 mm. However, between killing of the cover and planting of the cotton, it was 170 mm. For these reasons, soil water content interactions that might be associated with rye cover were not seen here.

When cone index data were limited to the upper half of the profile, where we would expect to see cover crop treatment differences, there were no consistently significant differences between the treatments. Cover crops have a number of known advantages: reducing erosion, reducing leaching of nutrients, and increasing organic matter. It is advantageous to know that they can be used to benefit the soil and environment without adversely affecting yield or strength.

4. Conclusions

Rye winter cover crop had no effect on soil strength or yield under conditions of this study. This response differed from previous studies where rye cover increased yield within conservation tillage on these same soils during years when rainfall was lower and tillage was different (Bauer and Busscher, 1996).

Cone index was greater if soils were not deep tilled. Root growth decreased as soil strength increased. The reduction in root growth had the best statistical relationship with either the mean soil strength across the whole profile or the 95th percentile of soil strength, which acted as a stabilized, surrogate measure of the maximum strength that the cotton roots would encounter.

Yield was not related to soil strength or tillage in this study, suggesting that omitting deep tillage from management for at least 2 years may be a viable production practice for cotton grown in traditionally wide rows using controlled traffic. Yield limiting soil strengths may have been partially prevented by our use of a small disk harrow; use of heavier equipment may compact the soil and produce different results. Additional research on the frequency of deep tillage and the degree of re-compaction that reduces cotton lint yield are needed to ensure that this is a reliable production practice.

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