

Cotton management in a compacted subsurface microirrigated coastal plain soil of the southeastern US

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Abstract

A loamy sand Acrisol (Aquic Hapludult) that had been microirrigated for 6 years became so severely compacted that it had root limiting values of soil cone index in the Ap horizon and a genetic hardpan below it. Deep and surface tillage systems were evaluated for their ability to alleviate compaction. Deep tillage included subsoiling or none. Both deep tillage treatments were also surface tilled by disking, chiseling, or not tilling. Subsoiling was located in row or between rows to avoid microirrigation tubes (laterals) that were buried under every other mid row or every row. Cotton (*Gossypium hirsutum*) was planted in 0.96-m wide rows. Cotton yield was improved by irrigation from 485 to 1022 kg ha⁻¹ because both 2001 and 2002 were dry years. Tillage loosened the soil by an average of 0.5–1.3 MPa; but compacted zones remained outside tilled areas. Subsoiling improved yield by 131 kg ha⁻¹ when performed in row where laterals were placed in the mid rows; but subsoiling did not improve yield when it was performed in mid rows. For subsurface irrigation management in these soils, the treatment with laterals buried under every other mid row was able to accommodate in-row subsoiling which improved yield; and this treatment was just as productive as and had been shown to be less expensive to install than burying laterals under every row.

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1. Introduction

In the southeastern US Coastal Plains and similar areas, several factors combine to cause severe water stress and limit cotton (*Gossypium hirsutum*) yield; they include sandy soils with low water holding capacity, short periods of drought, and shallow high-strength root-restricting subsurface layers. Sandy soils of the southeastern US Coastal Plain hold small amounts of water, only about 0.08 m of water per meter of depth (Campbell et al., 1974). This amount of water is not enough to sustain plant growth through frequent 5–20

days droughts that occur seasonally (Sadler and Camp, 1986); at peak bloom, cotton can use 0.01 m per day or more (Tennakoon and Milroy, 2003; Singh, 2004).

Water uptake is also restricted by shallow subsurface hard layers because they restrict root growth and uptake (Busscher et al., 1986). Hard layers, such as these, can have root-restricting penetration resistances that affect yield (Boland et al., 2000) even at water contents as high as field capacity and as soon as a year after disruption by tillage (Busscher et al., 2001). Hard layers recompact as a result of natural settling under the influence of gravity and rain water infiltrating through the soil (Busscher et al., 2001). Recompaction is exacerbated by traffic (Runion et al., 2004).

Southeastern US Coastal Plain producers typically increase access to the soil water supply for plants by subsoiling. Subsoiling loosens the soil down to horizons

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that have structure and greater water holding capacities, both of which can encourage root growth and yield (Adeoye and Mohamed-Saleem, 1990; Akinici et al., 2004). However, subsoiling requires large tractors with power requirements of 14–20 kW per subsoil shank which use 20–25 l of fuel and 0.3–0.7 h of labor ha⁻¹ (Karlen et al., 1991). These requirements are expensive for an operation that is not persistent (Carter et al., 1996) and may need to be performed annually (Busscher et al., 2001). Less expensive and more permanent, alternative solutions are desirable.

Buried microirrigation tubes (laterals) have been successfully used in the southwestern US to provide water to cotton (Tollefson, 1985; Henggeler, 1995). In the southeastern Coastal Plains, irrigation from buried microirrigation laterals has also been studied for a number of crops (Camp et al., 1998) including cotton (Khalilian et al., 2000a). If laterals are not buried in the row, soil can be in-row subsoiled prior to planting allowing roots to grow into the softened layer; but if laterals are buried in the row, soil cannot be in-row subsoiled limiting roots to the zone above the hard layer. Even keeping the hard layer wet does not reduce its strength enough to promote root growth into it (Khalilian et al., 2000b). In addition to consolidation of the hard layer, soils above laterals (and above hard layers) consolidate becoming hard when no tillage is used; this comes about as a result of settling and traffic when laterals remain buried for several years (Camp et al., 1999).

If laterals are buried just below the Ap horizon, they can provide water directly to the root zone. And though one would expect water from laterals to encourage root growth below them, this does not appear to be the case in these soils (Busscher et al., 1993). It is possible that the wet area in the vicinity of the tubes could cause aeration problems; however this is unlikely because when tubes in a similar soil were dug up, roots were wrapped around them in the zone where one would expect the highest water content and least air-filled pore space (Busscher et al., 1993). Though there is some information that adding oxygen through subsurface irrigation systems can increase yields (Bhattarai et al., 2004), this was with a different soil. Other research on adding oxygen showed mixed results (Walter et al., 2004). Regardless of whether aeration or high strength caused poor growth, it should improve with tillage.

Our objective was to increase yield by loosening surface and subsurface microirrigated soil that had recompacted over the years; it had not been loosened previously for fear of ruining the buried tubes. We hypothesized that disruption of the soil by subsoiling between buried microirrigation tubes and chiseling or

disking above the tubes would loosen soil and increase yield.

2. Materials and methods

This study was conducted in 2001 and 2002 on an Eunola sandy loam at the Pee Dee Research Center near Florence, SC, USA. The Eunola soil is an Acrisol (fine loamy thermic Aquic Hapludult) (Soil Survey Staff, 2005). It is a nearly level, deep, moderately well drained, moderately permeable soil with a sandy loam Ap horizon (sand–silt–clay contents, 65%, 32%, 3%) that extends to about 0.15-m depth, sandy loamy eluviated (E) horizon (sand–silt–clay contents, 60%, 35%, 5%) that extends to about 0.30-m depth, and below that a sandy clay loam Bt horizon (sand–silt–clay contents, 56%, 21%, 23%) with predominantly kaolinite clay and seasonally high water tables ranging from 0.5 to 1-m depths. The soil is typically low in organic matter with <1.5% in the Ap and <0.5% in lower horizons. Some other properties of the soil include cation exchange capacities for exchangeable bases of 2, 1, and 1 cmol kg⁻¹ for the Ap, E, and Bt horizons; base saturations of 20%, 20%, and 15%; exchangeable aluminum of 0.1, 0.1, and 0.2 cmol kg⁻¹; and pH's of 5.7, 5.5, and 5.3. The E horizon can develop strength that prevents root growth as it dries.

The experimental design was randomized complete block of 16, 7.6 m × 15 m plots in each of four replicates. Of the 16 plots, 12 were irrigated with buried microirrigation laterals (Geoflow Rootguard, Corte Madera, CA, USA¹) installed at a depth of 0.3 m. Laterals had in-line labyrinth emitters 0.6 m apart that delivered water at 1.7 l h⁻¹. Of the 12 irrigated plots, six had laterals buried under each of eight rows at 0.96-m spacings and six had laterals buried under alternate mid rows at 1.93-m spacings. Of the 16 plots in each replicate, four had no irrigation.

On each plot, treatments imposed were subsoiling to a depth of about 0.3 m or no subsoiling. Subsoiling was performed in mid rows for plots with laterals buried below each row; it was performed in rows for plots with laterals buried in every other mid row. Irrigated subsoiled and non-subsoiled treatments were also surface tilled: disked to a depth of about 0.15 m, chiseled to a depth of about 0.20 m, or not surface tilled. Non-irrigated subsoiled and non-subsoiled

¹ Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture.

treatments were chiseled or not tilled. Because there were only four non-irrigated treatments in each replicate while there were six treatments for each of the buried lateral spacings, non-irrigated plots did not include a disked treatment. The experiment had been set up in 1991 when the number of irrigated and non-irrigated plots was set and this could not be modified.

The recommended practice for this soil includes in-row subsoiling each year. But because of buried laterals, plots had not been regularly subsoiled. In 1991, prior to lateral installation, all plots had been cross subsoiled in the row direction and perpendicular to the rows (Camp et al., 1998) and concern for soil strength led to an attempt in 1996 and 1997 to break up hard soil. However, in this previous study, tillage was performed at shallow depths to be sure to not affect the buried tubes; it did not affect productivity (Camp et al., 1999).

In this experiment, tillage equipment included: a 4.6-m wide John Deere disk (Deere Inc., Moline, IL, USA) in 2001 or the same size Case-IH disk (Case-IH, Racine, WI, USA) in 2002; a KMC (Kelley Manufacturing Co., Tifton, GA, USA) straight 45° forward angled subsoiler; and a 2.15-m wide seven shank chisel.

Plots were planted to cotton (var Delta Pine 458BRR) in summer and flax (*Linum usitatissimum* var Laura) in winter. Cotton was planted in 0.96-m wide rows at 13 plants m⁻¹ on 4 June 2001 and 15 May 2002 using a four-row Case-IH 900 series planter equipped with Yetter wavy coulters. Flax was drilled as a winter cover at 115 kg ha⁻¹ using a John Deere 750 no-till grain drill. Flax fiber was removed from plots.

Soil strength measurements were taken in cotton plots after tillage. Because of buried irrigation laterals, soil strength data could not be collected at positions in the row for some plots and in the mid row for others. Soil strength data (cone index) were taken with a 0.0125-m-diameter cone-tipped penetrometer on 6 June 2001 and 20, 21 May 2002. Cone indices were measured by pushing the penetrometer into the soil to a depth of 0.55 m at nine positions spaced 0.12 m apart starting at the middle of the plot (a relatively non-trafficked mid row) and moving outward to a wheel track mid row; measurements excluded positions where laterals were located when appropriate. Cone index data were digitized into the computer at 0.05-m depth intervals and log transformed before analysis according to the recommendation of Cassel and Nelson (1979).

Gravimetric soil water content samples were taken at the first and fifth positions of cone index readings along with cone indices. Since tubes were buried at the first and fifth positions for the mid-row and in-row tube

placements respectively, samples were taken at either the second or fourth positions respectively in these treatments. Water contents were measured at 0.1-m depth intervals to 0.6-m depth. These water contents were taken as representative of the water contents of the plot.

Fertilizer was applied based on soil test results and Clemson University (2001) extension recommendations. In 2001, 2 months before planting, 20 kg P ha⁻¹, 34 kg K ha⁻¹, plus 2.25 kg B ha⁻¹ and 11.5 kg S ha⁻¹ was broadcast applied. Nitrogen (135 kg N ha⁻¹ as ammonium nitrate) was applied in a split application, one-third at planting and two-thirds 1 month later. In 2002, because of residual fertilizer from low winter flax yields, less nitrogen (90 kg N ha⁻¹) was added: one half at 3 weeks after planting and one half at 6 weeks after planting. No other fertilizer was applied in 2002. Nitrogen applications were all banded approximately 0.05-m deep and 0.15-m to the side of the rows.

Weeds were controlled with a combination of herbicides pendimethalin [*N*-(1-ethylpropyl)-2,6-dinitro-3,4-xylidine] and fluometuron [1,1-dimethyl-3-(α,α,α -trifluoro-*m*-tolyl)urea] at planting and MSMA (sodium hydrogen methylarsonate), glyphosate [*N*-(phosphonomethyl)glycine] and sethoxydim 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one; each were applied one to three times a season as needed, applied at labeled rates. Thrips [*Frankliniella occidentalis* (Pergande)] were controlled by applying Temik [0.5 ai kg ha⁻¹ (2-methyl-2-(methylthio) propionaldehyde *O*-(methylcarbamoyl)oxime)] at planting.

In mid to late October, cotton was chemically defoliated with thidiazuron (*N*-phenyl-*N'*-1,2,3-thiadiazol-5-ylurea), *S,S,S*-tributyl phosphorothioate, and ethephon [(2-chloroethyl) phosphonic acid]. On 7 November 2001 and 28 October 2002, seed cotton yield was harvested from the two interior rows of each plot using a two-row spindle picker and bagged. Each harvest bag was subsampled; the subsample was saw-ginned to determine lint percent. Lint percentage was multiplied by seed cotton yield to calculate lint yield.

Cone index, water content, and yield data were analyzed using the ANOVA and the least square mean separation procedures (SAS Institute, 1990). Yield data were analyzed using a randomized complete block design. Other data were analyzed using a split-split plot randomized complete block design with cone index and water content as main effects, position across the rows as sub plot, and depth as sub-sub plot. Data were tested for significance at the 5% level.

3. Results and discussion

3.1. Soil water content

Soil water content differences affect cone index readings, masking strength differences among treatments. To avoid this, we took cone index measurements when water contents were uniform after a rainfall and before irrigation began. Both years, soil water content differences were not significant for treatment or year; the only significant differences were with depth. Soils were moist near the surface where they averaged (over both years at the time of cone index measurement) 0.11 g g^{-1} on a dry weight basis at 0.05-m depth, slightly dryer under that where they averaged 0.10 g g^{-1} at 0.15-m, 0.10 g g^{-1} at 0.25-m, and 0.10 g g^{-1} at 0.35-m, and increased slightly below that where they averaged 0.12 g g^{-1} at 0.45-m, and 0.13 g g^{-1} at 0.55-m (LSD at 5% = 0.01). Because of the lack of difference, soil water contents were not included in analyses, except where listed.

3.2. Soil strength

Cone indices were analyzed separately for irrigated and non-irrigated treatments because non-irrigated did not have a disked treatment, an effect that had been studied previously (Busscher et al., 2001). Additionally, since the non-irrigated treatments had no buried tubes, they lent themselves to more traditional annual-subsoiling management systems for previous experiments performed in these plots.

For irrigated treatments: since mean soil cone indices for the 2 years (2.31 MPa in 2001 and 2.23 MPa in 2002) were not significantly different and no interactions with years were significant, data for both years were analyzed together (Table 1). Cone index data were also not significantly different for irrigation tube

placements because the two basically had the same treatments; and although the two would have had different wetting patterns causing different soil strength patterns, cone indices were taken before irrigation was started. Data for both tube placements were also analyzed together. Combining these data had the distinct advantage of filling in missing data points where we could not probe the soil because buried laterals were located at the probe position.

Cone indices differed by depth and position across the row because different tillage treatments disrupted soil to different depths and at different positions across the row to avoid buried laterals (Fig. 1). Of course, some positional cone index differences were eliminated when data for the two buried lateral placements were combined by shifting data of treatments subsoiled in the mid row to match that of treatments subsoiled in the row. The shift was anticipated ahead of time by centering data collection on tillage rather than on buried laterals; it allowed us to focus on tillage rather than lateral placement and showed that the only cone index difference between the two tube spacings was tillage position. After the shift, cone indices differed with position as a result of higher values caused by more wheel traffic in some mid rows as seen at the right side of the contour plots (e.g. positions 0.72 and 0.96 m as seen in Fig. 1).

Cone indices differed among surface tillage treatments (disking, chiseling, and no-surface-tillage), subsoiled treatments, and their interaction (Table 1 and Fig. 1). Disking and chiseling had shallower, wider zones of disruption than deep, narrow subsoiling. Subsoiling significantly reduced cone indices in the disked and no surface tillage treatments, but not in the chiseled treatments. In the disked and no surface tillage treatments, subsoiling reduced high soil strength caused by the tillage or genetic pan that developed in the E horizon and prevented root proliferation in these soils

Table 1
Mean profile cone indices (MPa) for irrigated and non-irrigated treatments averaged over years and lateral placement

Tillage	Irrigated			Non-irrigated		
	Subsoiled	Non-subsoiled	Mean	Subsoiled	Non-subsoiled	Mean
Chisel	1.95c ^a (12 ^b)	2.15c (13)	2.05c ^b (12)	2.10c ^a (12)	2.20c (12)	2.15b ^c (12)
Disk	2.04c (11)	2.55b (12)	2.28b (12)	–	–	–
None	2.09c (12)	3.08a (11)	2.52a (12)	2.74b (11)	3.45a (11)	3.08a (11)
Mean	2.02b ^c (12)	2.56a (12)		2.40b ^c (12)	2.80a (12)	

^a Means for the interaction of surface tillage with subsoiling with the same letter are not significantly different for LSD mean separation procedure at 5%.

^b The numbers in parentheses are water contents as percent on a dry weight basis ($\text{g g}^{-1} \times 100$) taken at the time of cone index measurement. Means for water content had no consistent significant differences with LSD = 1 at 5%.

^c Means within columns or rows with the same letter are not significantly different for LSD mean separation procedure at 5%.

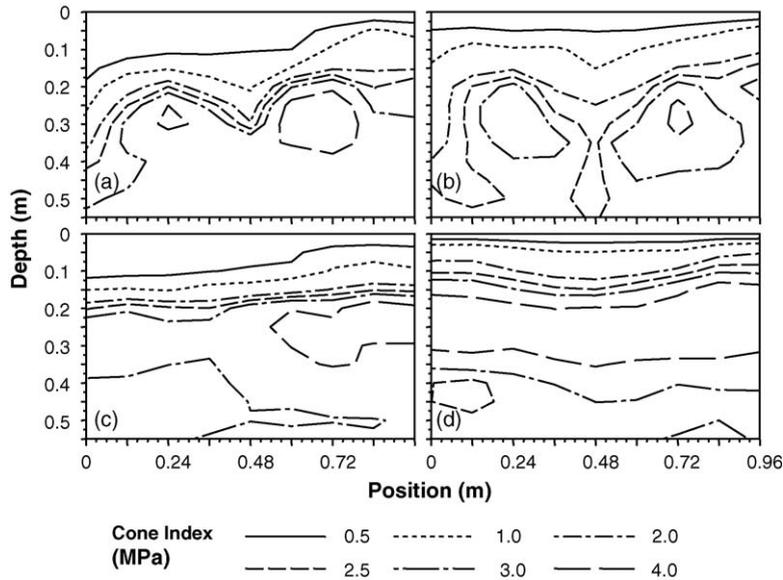


Fig. 1. Profile cone indices for irrigated treatments averaged over both years and four replicates for treatments that were subsoiled and chiseled (a), subsoiled (b), chiseled (c), or not tilled (d). Data were adjusted to center the zone of deepest tillage in the contour plots because it was performed in either the row or mid row to avoid buried irrigation tubes.

(Fig. 1), as seen by Box and Langdale (1984) and Raper et al. (2000). Subsoiling the chiseled treatment reduced cone indices lower than the chiseled only treatment; however, differences were not statistically significant probably because chiseling and subsoiling were performed at depths that differed by only about 10 cm. This lack of significance was also observed in non-irrigated treatments.

For non-irrigated treatments: cone indices differed significantly in magnitude by year at 2.48 MPa for 2001 and 2.90 MPa for 2002. Though they differed in magnitude, cone index differences between years had no significant interactions with any treatments; so data

for the 2 years were analyzed together (Table 1). Cone indices differed for subsoiled treatments, chiseled treatments, and for the interaction of the two. Cone indices were lower for treatments that were chiseled and/or subsoiled versus those that were not. Chiseled treatments had a shallower and wider zone of disruption than subsoiling, as was seen with the irrigated treatments.

The non-tilled treatment still had remnants of deep tillage from previous experiments on these plots (Camp et al., 1999); this may have been enough residual loosening to provide adequate root growth (Busscher and Bauer, 2003) unlike irrigated treatments where buried laterals prevented deep tillage (Fig. 1).

Table 2

Lint yield (kg ha^{-1}) of different lateral spacings, surface tillage, subsoiling and irrigated and non-irrigated treatments for both 2001 and 2002 analyzed together

Tillage	Alternate furrow			In-row			Non-irrigated		
	Subsoiled	Non-subsoiled	Mean	Subsoiled	Non-subsoiled	Mean	Subsoiled	Non-subsoiled	Mean
Chisel	1070 ^a	990	1029a ^b	987 ^a	1032	1010a ^b	489 ^c	482	486a
Disk	1098	901	999a	1071	1123	1097a	–	–	–
None	1085	970	1027a	906	1029	963a	503	466	484a
Mean	1084a ^b	953b		988ab	1062ab		496a ^b	474a	

^a The mean separation for the interaction using the LSD mean separation procedure at 5% was 298 kg ha^{-1} . One interaction (in-row, subsoiled with no surface tillage vs. in-row, non-subsoiled disked) was significantly different.

^b Means within columns or rows with the same letter are not significantly different for LSD mean separation procedure at 5%.

^c The mean separation for the interaction using the LSD mean separation procedure at 5% was 230 kg ha^{-1} . None of the interactions were significantly different.

3.3. Yield

For irrigated treatments, location of tillage affected yield. For mid-row lateral placement, yield improved with subsoiling regardless of surface tillage; for in-row lateral placement, yield of subsoiled treatments did not differ from non-subsoiled treatments (Table 2). Yield of mid-row buried lateral placement increased with subsoiling because tillage loosened soil under the row where most of the roots would be located (Busscher et al., 2001). Yield of the in-row buried lateral placement did not increase as a result of subsoiling because mid-row tillage did not loosen soil under the row (Busscher et al., 1993). Nevertheless, roots were able to get water because irrigation tubes were immediately below the plants in the row; and as a result, though yields were not significantly higher than the non-subsoiled mid-row treatment, they were also not significantly lower than the subsoiled mid-row treatment. Surface tillage treatments did not affect yield probably because they did not disrupt the soil deep enough to eliminate all compaction above buried laterals.

For non-irrigated treatments, rainfall affected yield. Rainfall was lower than the normal of 1145 mm y^{-1} both years but especially low in 2002 (Fig. 2). As a result, yields were lower for non-irrigated (485 kg ha^{-1}) than for irrigated treatments (1022 kg ha^{-1}). Yields for non-irrigated treatments averaged 609 kg ha^{-1} for 2001 and 352 kg ha^{-1} for 2002, the dryer year. Non-irrigated yields were unaffected by subsoiling or chiseling.

Since non-irrigated plots did not have buried tubes, plots were conventionally managed; even plots that were not subsoiled for this study had been subsoiled

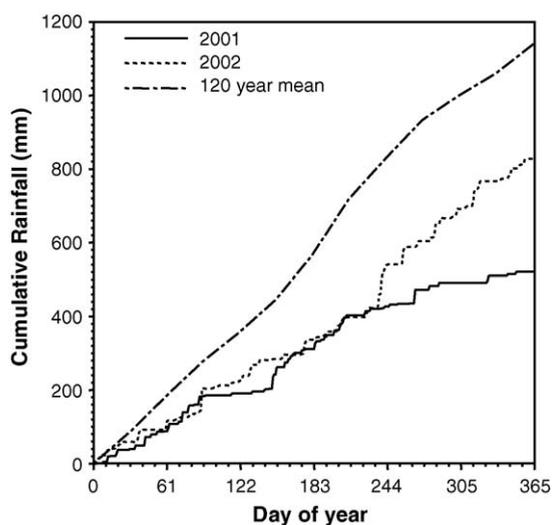


Fig. 2. Cumulative rainfall for 2001 and 2002. Both years were drier than the mean 120-year cumulative annual rainfall of 1145 mm.

within the past 2–3 years for previous experiments. Lack of difference among treatments (Table 2) supports the conclusions of Busscher and Bauer (2003) that subsoiling is not needed every year for in-row subsoiled cotton grown in conventional row widths and using controlled traffic.

Finally, when laterals were buried under every other mid row, subsoiling in the row could be performed to improve yield for subsurface irrigation management in these soils. This treatment is just as productive as and only about two thirds as expensive as installing buried laterals under every row (Camp et al., 1998). As a caveat, water from the buried laterals could move up to the surface as noted by wet areas above the laterals; but in other soils where water cannot move upward, it may not be as available to the plant especially for germination and seedling growth.

4. Conclusions

For irrigated treatments: cone indices were essentially the same for in-row and mid-row subsoiled treatments with the exception that they were shifted laterally one half row width with respect to each other. Cone indices were lower in disked and chiseled treatments than in the no-surface-tillage treatment and the disked and chiseled treatments had shallower, wider zones of disruption than subsoiling. Subsoiling reduced cone indices in disked and no-surface-tillage treatments, but not in the chiseled treatments.

Yields for treatments subsoiled in mid rows (when buried laterals were in the rows) were no higher than non-subsoiled or no worse than subsoiled treatments. Yields increased for treatments subsoiled in row when buried laterals were in mid rows.

Non-irrigated treatment cone indices were lower when treatments were chiseled and/or subsoiled than when they were not. Though non-irrigated treatment yields increased with rainfall, they were unaffected by tillage. This conclusion supports a previous study (Busscher and Bauer, 2003) that subsoiling is not needed every year for non-irrigated in-row subsoiled cotton grown in conventional (0.96 m) row widths.

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