



Deep tillage management for high strength southeastern USA Coastal Plain soils

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Abstract

Southeastern USA production is limited in Acrisols (Paleudults and Kandiodults) because they have high strengths and low water holding capacities. Production systems with crop rotations or deep tillage before planting were compared with less intensive management. Production systems included double-crop wheat (*Triticum aestivum* L.) and soybean (*Glycine max* L. Merr.) that were drilled in 0.19 m-row widths and grown in 15 m wide, 150 m long plots with soils of varying hardpan depths. Treatments included surface tillage (disked or none), deep tillage (paratilled or none), deep tillage with winter fallow and maize (*Zea mays* L.) in rotation, and disked/deep tillage with an in-row subsoiler where soybean was planted in conventional 0.76 m-wide rows. Cone indices were measured near the ends of each plot (120 m apart) to assess soil strength differences among soil types and among treatments. Cone indices were 1.50 MPa higher for non-deep tilled treatments than for deep tilled treatments and 0.44 MPa higher in wheel-track mid rows than in non-wheel-track mid rows. Cone indices were also 0.28 MPa higher for soils with shallower Bt horizons. Cone indices were not significantly different for subsoiled treatments and paratilled treatments. Rainfall was erratic throughout the 5-year experiment with dry periods lasting more than 2 weeks at a time and with annual totals ranging from 520 to 1110 mm. Wheat yields were 0.67 Mg ha⁻¹ greater for deep-tilled soils (subsoiled and paratilled) than for non-deep-tilled soils. Soybean yields were 0.36 Mg ha⁻¹ greater for paratilled than for subsoiled or non-deep-tilled treatments partly as a result of the more complete disruption of the paratill and partly because paratilled treatments were managed with narrow rows. Yields did not vary significantly among the soil types despite the fact that they had different cone indices. Tillage was a more dominant factor than soil type. For wheat, lower cone indices from tillage led to higher yields. For soybean, management of uniform loosening from deep tillage and narrow rows led to higher yields.

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1. Introduction

Soils in the USA southeastern Coastal Plain, like many other agricultural areas, can develop high

strength layers that prevent root growth and reduce yield (Arvidsson et al., 2001; Radford et al., 2001; Lapen et al., 2001). High strengths build up naturally because of low organic matter (Pabin et al., 1998); strengths can also be increased by traffic (Busscher et al., 2002). High strengths in the southeastern Coastal Plain are often associated with a subsurface eluviated horizon, located just below the plow layer. The eluviated layer is found in 50–60% of the soils in the southeastern Coastal Plain (Campbell et al., 1974).

Yields can increase when strengths are reduced. For wheat and soybean in narrow row management (0.19 m-wide rows) and for relatively complete subsoil disruption (Busscher et al., 2000), yields of wheat increased 1.6 Mg ha^{-1} and yields of soybean increased 1.5 Mg ha^{-1} for each 1 MPa decrease in mean profile cone index. These results were shown on a loamy sand; but other soils can exhibit similar properties (Stenitzer and Murer, 2003; Strock et al., 2001).

Typical management for these soils utilizes deep tillage to break up high strength layers (Schwab et al., 2002). For these soils, management involves non-inversion tillage 0.3–0.4 m deep to disrupt the hard layer. Though residual effects of tillage can remain for years afterward as seen by Munkholm et al. (2001) and Baumhardt and Jones (2002), tillage is still performed annually on these southeastern USA Coastal Plain soils because annual re-compaction can reduce root growth and yield even though it is not complete (Porter and Khalilian, 1995). A recent study (Frederick et al., 1998) showed that deep tillage significantly increased yield when it was performed twice a year, before double-cropped wheat and drilled soybean.

Since southeastern USA Coastal Plain soils are sandy, yields are limited not only by high soil strength but also by low water holding capacities ($\sim 0.08 \text{ g g}^{-1}$ on a dry weight basis). Low water holding capacities can be especially detrimental when rainfall is low, even though the long term average rainfall is 1140 mm (<http://www.dnr.state.sc.us/climate/>). When rainfall is limiting, low water holding capacities lead to yield-reducing crop stresses especially when crops experience periods of no rain for 2 weeks or more (Sadler and Camp, 1986). Unfortunately, limited rainfall is not uncommon in the SE Coastal Plain (Sheridan et al., 1979). If soil water is available throughout the profile, deep tillage can alleviate some water stress by expanding the soil profile available for root exploration.

Southeastern Coastal Plain fields are variable and can have different soil types with varying production potentials (Sadler et al., 2000). The varying production potentials can be caused by differences in soil strength or soil properties related to strength such as macroporosity, oxygen diffusion, or structure (Lipiec and Hatano, 2003). Despite differences among soil types in a field, management can override other factors, masking differences and leading to more uniform production (Schafer-Landefeld et al., 2004).

Our objectives were to compare intensive management systems with less intensive management. The intensively managed systems were deep tilled before every crop or rotated between wheat–soybean double-crop and fallow–maize. Our comparisons were soil strengths, water contents, and yields measured at two places within plots to determine differences among soil types and to quantify the effects of tillage, soil type, and management on wheat and soybean yields.

2. Materials and methods

2.1. Crops and soils

In fall of 1996, 15 m-wide, 150 m-long plots were established to grow a wheat–soybean double-crop using Northrup King Coker 9134¹ soft red winter wheat and Hagood soybean. Plots were located in a field that had soils Bonneau (loamy, siliceous, subactive, thermic Arenic Paleudult), Norfolk (Fine-loamy, kaolinitic, thermic Typic Kandiudult), and Rains (fine-loamy, siliceous, semiactive, thermic Typic Paleaquult) at one end and Goldsboro (fine-loamy, siliceous, subactive, thermic Aquic Paleudult), Noboco (fine-loamy, siliceous, subactive, thermic Oxyaquic Paleudults), and Norfolk at the other end.

All of these soils were similar. They were all typically loamy sands (Table 1) and Acrisols in the FAO classification and all had E horizons below the plow layer that restricted root growth (<http://soils.usda.gov/technical/classification/osd/index.html>). All soils had an Ap horizon that had been tilled over the

¹ Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or Clemson University and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

Table 1

General soil characteristics for Ap and E horizons based on mapping soils and collecting information from <http://soils.usda.gov/technical/classification/scfile/>; differences between the Ap and E horizons are based mainly on previous tillage that mixes surface organic matter into the Ap

Characteristics	Soil types				
	Bonneau	Rains	Norfolk	Goldsboro	Noboco
Texture	Loamy sand	Loamy sand	Loamy sand	Loamy sand	Loamy sand
Water table ^a (m)	1.1–1.5	0.0–0.3	1.2–1.8	0.5–0.75	0.75–1.0
CEC (cmol kg ⁻¹)	1–4	1–5	1–3	1–3	4–10
OM (g kg ⁻¹)	5–20	10–60	5–20	5–20	5–20
Clay ^b (g kg ⁻¹)	50–150	20–100	20–80	20–80	20–80
Depth ^c (m)	0.50–1.00	0.18–0.46	0.23–0.48	0.20–0.45	0.25–0.40

^a Seasonally high water table.

^b Clay content of Ap and E horizons.

^c Depth to E–Bt interface.

years to a depth of about 0.20 m. All had eluviated E horizons to depths of 0.30–1.0 m overlaying a sandy clay loam or sandy loam Bt horizon that extended beyond 0.6 m depth. Bt horizons typically had less than 10 g kg⁻¹ organic matter, 2–8 cmol kg⁻¹ cation exchange capacity, and 130–400 g kg⁻¹ clay content. All soils formed in Coastal Plain marine sediments. For this experiment, a significant factor appeared to be deeper and thicker E horizons in the Bonneau, Norfolk, and Rains at the lower end of the field.

2.2. Treatments and yield

Plots had two surface tillage and two deep tillage treatments in three randomized complete block replicates. The two surface tillage treatments were either disked twice or not disked before planting. Each surface tillage treatment also had a deep tillage treatment that was either paratilled (Bingham Brothers Inc., Lubbock, TX, USA) or not paratilled before planting both wheat and soybean. The two deep tillage treatments were duplicated; the duplicated set was rotated with winter fallow and maize during the second and fourth years of the experiment. A final treatment was in-row subsoiled at planting of soybean in 0.76 m-row widths.

For wheat and soybean treatments, surface tillage, deep tillage to 0.35 m, and planting were performed separately, unless stated otherwise. Before planting, surface tillage was performed with a 4.6 m-wide John Deere Disk (Deere Inc., Moline, IL, USA) or Case-IH Disk (Case-IH, Racine, WI, USA). Surface tillage disrupted the soil to a depth of approximately 0.15 m.

Deep tillage was performed with a paratill that had six shanks, three on each side bent inward and with tips spaced at 0.65 m; the paratill had a roller attached behind it to firm the seed bed. Subsoiling was performed with a 45° forward-angled, 0.025 m-wide, straight subsoil shank (Kelley Manufacturing Co. (KMC), Tifton, GA, USA), a common management technique for the southeastern Coastal Plain. Deep tillage by both the paratill and the KMC disrupted soil at 0.35–0.40 m depths.

Wheat was drilled in 0.19 m-row widths with a 3 m-wide John Deere 750 no-till drill. Soybean were either drilled in narrow rows with the no-till drill or planted in 0.76 m-wide rows with 6-row John Deere 7100 Maxi-Emerge planters preceded by the subsoiler in the same operation. Wheat was drilled in mid November at a rate of 65 seeds m⁻¹ and harvested in late May or early June. Soybean were planted in early June at a rate of 13 seeds m⁻¹ for drilled plots or 30 seeds m⁻¹ for wide-row plots and harvested in early November with a 2366 Axial Flow Case IH Combine with 4.5 m-wide headers.

In the second and fourth years of the experiment, maize (var. Dekalb 687) was rotated into the extra set of deep-tilled treatments, after a fallow winter. Maize was deep-tilled and planted in one operation with 6 John Deere Maxi-Emerge planters on 0.76 m-row widths preceded by the KMC subsoiler. Maize was planted in late March at a rate of 4.5 seeds m⁻¹. It was harvested in late August with a 6-row header on a 2366 Axial Flow Case IH Combine.

All tillage and harvesting equipment followed the same wheel tracks as closely as possible. All plots were

fertilized following Clemson soil test recommendations (Clemson University, 1982). Weeds were controlled with disking, pre-emerge alachlor [2-chloro-2',6'-diethyl-*N*-methoxymethylacetanilide] 2.6 kg a.i. ha⁻¹, glyphosate [*N*-(phosphonomethyl)glycine] 1.1 kg a.i. ha⁻¹, chlorimuron ethyl [2-(4-chloro-6-methoxypyrimidin-2-ylcarbamoylsulfamoyl)benzoate] 0.013 kg a.i. ha⁻¹, or sethoxydim [2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one] 0.21 kg a.i. ha⁻¹ as required and according to labeled instructions.

2.3. Soil strength and rainfall data

Within 2 weeks after planting either wheat or soybean and several weeks after planting maize, soil strength data were taken with a 12.5 mm diameter 30° cone-tipped penetrometer (Carter, 1967). Cone indices were measured to a depth of 0.55 m at 0.05 m intervals across the rows at nine positions for a width of 0.76 m. Measurements began between wheel tracks, centered on the zone of maximum disruption of a deep tillage shank whenever appropriate, and ended in a wheel track. Cone indices were taken at two locations 15–30 m from either end of each 150 m-long plot. Data were digitized into the computer and log transformed for analysis (Cassel and Nelson, 1979). Soil water contents were taken along with cone indices. They were measured at the first and fourth positions across the row and at 0.10 m-depth intervals from the surface to 0.6 m and used as representative water contents of each plot.

Rainfall data were obtained from South Carolina site number 2037 of the Soil Climate Analysis Network of the US Department of Agriculture Natural Resources Conservation Service located approximately 2 km from the experimental site <http://www.wcc.nrcs.usda.gov/scan/site.pl?site-num=2037&state=sc>. At that site, rainfall was measured with a tipping-bucket rain gauge in a Campbell Weather Station (Campbell Scientific Inc., Logan, Utah, USA).

2.4. Data analyses

Data were analyzed using ANOVA and the least significant difference mean separation procedure (SAS Institute Inc., 2000). Cone index and water

content data were analyzed using a split-split plot randomized complete block design where main effects were disking and deep tillage. The first split was on position across the row; the second, on depth. All data were tested for significance at the 5% level unless otherwise specified. Wheat and soybean yield data were corrected to 13% moisture and maize to 15.5%.

3. Results and discussion

3.1. Water contents and cone indices

Soil water contents (data not shown) were, generally, unaffected by tillage treatment and did not affect soil cone indices except as mentioned below. Cone indices were consistently lower for treatments that had been deep tilled with either the paratill or subsoiler than for treatments that were not deep tilled (Tables 2 and 3). Cone indices did not differ between paratilled and subsoiled treatments after disking, though patterns of disruption were different (Fig. 1). Differences in patterns of disruption were manifested statistically in the interactions of the cone index data analyses for three-way interaction of treatment by depth by position. This interaction showed that the subsoiler disrupted a narrower zone with low strengths near the surface, while the paratill disrupted a larger

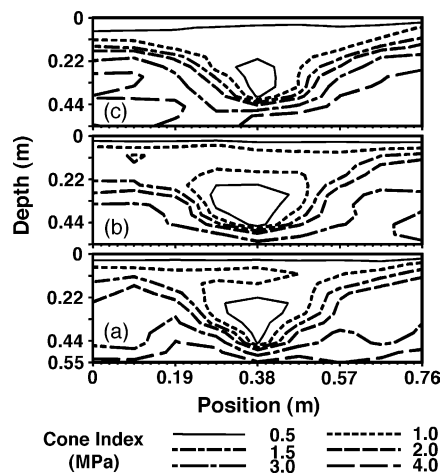


Fig. 1. Cone indices in spring of 2001 as a function of depth and position across the rows for the treatments that were subsoiled after disking (a), paratilled without disking (b), and paratilled after disking (c).

Table 2

Mean^a soil strengths for the top 0.55 m of the profile for 0.76 m across the rows for readings taken in fall under wheat or fallow

Tillage		Cone index (MPa)							
Deep	Surface	1996	1997	1998	1999	2000	Overall	Not rotated	Rotated
Paratill	Disked	1.47 b ^b	1.44 c	1.59 b	0.97 de	1.80 bc	1.43 cd	1.61 bc	1.18 c
Paratill	None	1.42 b	1.45 c	1.55 b	0.83 e	1.96 b	1.40 d	1.63 bc	1.10 c
None	Disked	2.25 a	2.69 a	3.19 a	2.17 ab	3.25 a	2.67 a	2.86 a	2.42 a
None	None	2.40 a	2.78 a	3.15 a	2.57 a	3.09 a	2.78 a	2.86 a	2.67 a
Rotated ^c	Disked	1.51 b	1.98 b	1.57 b	1.58 bc	1.83 bc	1.68 b	1.63 bc	1.77 b
Rotated ^c	None	1.52 b	1.95 b	1.31 b	1.23 cd	1.74 c	1.53 c	1.51 c	1.55 b
Subsoil	Disked	1.64 b	1.59 c	1.74 b	0.83 e	1.87 bc	1.48 cd	1.75 b	1.16 c
Mean		1.71 c	1.93 b	1.90 b	1.33 d	2.15 a			

^a Means for all years (overall), for years when the treatments were not rotated (not rotated: 1996, 1998, 2000) or for years when they were rotated (rotated: 1997, 1999).

^b Means with the same letters are not significantly different.

^c Paratilled treatments rotated among soybean, wheat, fallow, maize.

fraction or wider zone of the profile with higher strengths near the surface. The higher strengths near the surface were caused by the roller that followed the paratill and by the grain drill. The roller was used with the paratill to improve seed-soil contact and trafficability. The grain drill provided down-pressure of 500–2000 N per opener.

Cone index differences for the three-way interaction of treatment by depth by position interaction were also significant for disked versus non-disked treatments. Cone indices of the disked treatment increased rapidly with depth, indicating compaction by surface tillage (Fig. 1) as also seen by Baumhardt and Jones (2002). This compaction was seen in the section of the profile that was not disrupted by deep tillage. Compaction near the surface could also be seen in

the cone index differences by position. These data revealed lower strengths at non-wheel track mid-row (0 m in Fig. 1) than for the wheel track mid-row positions (0.76 m in Fig. 1).

Cone indices differed by depth when they were compared for the different measurement locations, that is the measurements taken in different soil types at either end of each plot. At one end of the plots, cone indices for Goldsboro and Noboco soils were lower above 0.2 m and higher below 0.2 m than the cone indices for the Bonneau and Rains soils at the other end of the plots. The difference was first noted at the time of measurement because the Bt horizons for the Goldsboro and Noboco soils appeared to be harder and closer to the surface than those for the Bonneau and Rains as mentioned in soil descriptions. The difference was not a

Table 3

Mean^a soil strengths for the top 0.55 m of the profile for 0.76 m across the rows for readings taken in spring under soybean or maize

Tillage		Cone index (MPa)							
Deep	Surface	1997	1998	1999	2000	2001	Overall	Not rotated	Rotated
Paratill	Disked	1.37 b ^b	2.21 b	1.21 bc	1.74 bcd	1.77 bc	1.62 cd	1.43 bc	1.95 d
Paratill	None	1.30 bc	2.20 b	0.90 cd	1.50 d	1.64 bc	1.45 d	1.24 cd	1.82 d
None	Disked	2.85 a	3.01 a	2.26 a	3.11 a	3.98 a	2.99 a	2.95 a	3.06 a
None	None	2.69 a	2.90 a	2.72 a	3.07 a	3.91 a	3.03 a	3.06 a	2.98 a
Rotated ^c	Disked	1.51 b	3.36 a	1.16 bcd	2.08 b	1.76 bc	1.85 b	1.46 bc	2.65 b
Rotated ^c	None	1.16 c	2.77 a	0.84 d	1.94 bc	1.53 c	1.52 cd	1.14 cd	2.32 c
Subsoil	Disked	1.43 b	1.87 b	1.31 b	1.72 cd	1.95 b	1.64 c	1.54 b	1.79 d
Mean		1.66 d	2.57 a	1.37 e	2.09 c	2.19 b			

^a Means for all years (overall), for years when the treatments were not rotated (1997, 1999, 2001) or for years when they were rotated (1998, 2000).

^b Means with the same letters are not significantly different.

^c Paratilled treatments rotated among soybean, wheat, fallow, maize.

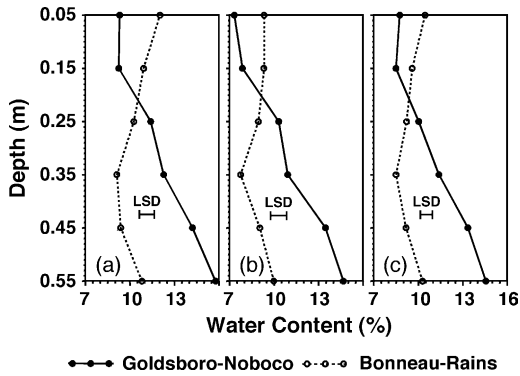


Fig. 2. Examples of higher water contents at the top of the measured profile for Bonneau and Rains and higher water contents at the bottom of the profile for Goldsboro and Noboco. LSDs at 5% are 1.0 for fall 1996 (a), 1.1 for spring 1997 (b), and 0.76 for all years of the experiment (c).

result of softening of the soil caused by increased water content because harder soils, above 0.2 m in the Bonneau and Rains and below 0.2 m in Goldsboro and Noboco, were also wetter (Fig. 2).

The main reason for breaking up the soil was to loosen the subsoil hard layer associated with the E horizon; remnants of the hard layer can be seen between the bottom of the Ap horizon (~ 0.22 m) and 0.44 m depths in the disked treatments of Fig. 1. While surface-tilled treatments at times had higher or lower cone indices than non-tilled treatments, deep-tilled treatments always had significantly lower cone indices than non-tilled treatments. Deep tillage or alleviation of subsoil compaction has been the focus of many studies, recently reported in a special issue of this journal (Van

den Akker et al., 2003), including studies that reported increased compaction by traffic and reduced yield with increased subsoil compaction (Trautner and Arvidsson, 2003; Stenitzer and Murer, 2003).

3.2. Yield

Yields generally increased with deep tillage treatment. For both disked and non-disked treatments, wheat and soybean yields improved with paratillage over no deep tillage (Table 4, all years). For the non-disked treatments, wheat yields improved with subsoiling over no deep tillage. However, it did not improve for disked treatments and soybean yields did not improve with subsoiling for disked or non-disked treatments. Increased yields for the paratill and not the subsoiler were not caused by differences in cone indices because they were similar for paratilled, disked and subsoiled, disked treatments. Increased yields in the paratilled treatments were probably a result of its broadcast deep tillage and the narrow-row planting which was part of its management system. This system was effective in increasing yield in these large scale plots, as it had been when it was developed earlier in small scale plots (Frederick et al., 1998).

Yields were not different for various soil types. Though we had expected soil type to be a determining factor, yields for these years were dominated by other factors such as tillage and rainfall. The cumulative rainfall curves have relatively flat sections on them, such as days 122–143 in 1996 or 120–165 in 1999 in Fig. 3, indicating times of drought. If droughts last for several days in these sandy, low-water-holding-

Table 4

Yields of wheat and soybean averaged over all growing seasons that were appropriate for that crop and over all years that were not rotated

Tillage		Crop yields (Mg ha^{-1})					
Deep	Surface	All years		Non-rotated years		Rotated years	
		Wheat	Soybean	Wheat	Soybean	Wheat	Soybean
Paratill	Disked	2.63 a ^a	1.95 ab	2.52 b	1.74 abc	2.81 a	2.26 ab
Paratill	None	2.41 a	2.10 a	2.34 b	1.84 a	2.51 ab	2.50 a
None	Disked	2.02 b	1.77 bc	1.85 c	1.54 bcd	2.28 bc	2.11 ab
None	None	1.79 b	1.65 c	1.68 c	1.48 cd	1.97 c	1.94 b
Rotated ^b	Disked	–	–	2.98 a	1.81 ab	–	–
Rotated ^b	None	–	–	2.78 ab	1.88 a	–	–
Subsoil	Disked	2.68 a	1.66 c	2.69 ab	1.44 d	2.77 a	1.98 b

^a Means with the same letters are not different.

^b Paratilled treatments rotated. For the 5 years of the experiment, treatments were in maize in the second and fourth years.

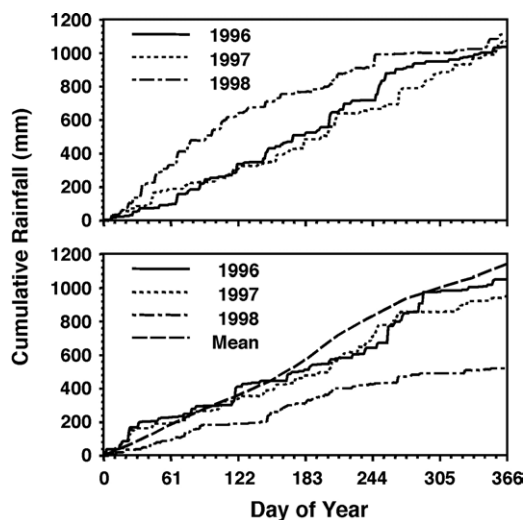


Fig. 3. Cumulative rainfall throughout the year showing times of relative drought, the flat sections of the curves. The mean is over the 120-year period from 1882 to 2001. The 2 years when corn was grown in rotation were 1998 and 2000.

capacity soils, crop stresses can reduce yields (Sadler and Camp, 1986). Deep tillage, especially the broadcast deep tillage of the paratill, helps alleviate plant water stress by making more of the profile available for root exploration and water extraction.

In 1998, maize yields were low (1.74 Mg ha^{-1}) because of drought during the maize growing season which was at approximately 90–220 days of the year (Fig. 3). In 2000, maize yields were 4.37 Mg ha^{-1} . There were no maize yield differences based on tillage treatment or soil type.

3.3. Management and rotation

For the 3 years when there were no rotations (1997, 1999, and 2001), all plots were in wheat and soybean. For these 3 years, cone indices were non-significantly higher for most disked versus non-disked treatments; they were similar for subsoiled and paratilled plots; and they were lower for deep-tilled plots when compared to non-deep-tilled plots (Tables 2 and 3). Wheat yields (Table 4) were related to soil cone indices. They were higher for lower cone index, deep-tilled treatments and lower for the higher cone index, non-deep-tilled treatments.

For the other 2 years (1998 and 2000), selected plots were in maize. For plots that were not rotated

during these years, wheat yields were higher for deep-tilled treatments, though this was only significant for the paratilled, disked treatment. Soybean yields were also generally higher for paratilled treatments than for non-deep-tilled treatments, though only significantly higher for the non-disked treatment. Soybean yields were also non-significantly higher for paratilled than for subsoiled treatments because, as discussed above, more uniform loosening (Fig. 1), allowed roots to explore more of the profile. Soybean yields were not significantly different for other treatments.

When rotated treatments were compared with non-rotated treatments (paratill versus rotated in Table 4), wheat yields improved with rotation. Soybean yields did not improve, even though their 1999 yield would have been positively affected by residual fertility as a result of low maize yields in 1998.

4. Conclusions

High soil strengths and low water holding capacities limit production in southeastern USA Acrisols. Crop rotations and deep tillage before each planting were compared with less intensive management for double-crop wheat and soybean, which in some treatments were rotated with maize. Cone indices were measured at the two ends of each plot (120 m apart) to assess soil strength differences among soil types and among treatments. Cone indices differed among treatments and soil types. They were lower for deep-tilled versus non-deep-tilled treatments and in non-wheel tracks versus wheel tracks. Cone indices of the different deep-tilled treatments, subsoiling or paratilling, did not differ when means throughout the profile were compared; but they differed in distribution throughout the profile with paratilling having more thorough disruption across the profile and subsoiling having lower strengths below the row.

Cone indices were lower for soils that had shallower B horizons. Despite this, yields did not differ by soil type, probably because the B horizons tended to have some structure that allowed the roots to grow along ped faces even though their cone indices were higher. In this study, tillage treatment and management affected yield more than soil type. Rainfall was erratic throughout the 5 years of the

experiment with long dry periods and with the last year of the experiment being one of the driest years on record (<http://www.dnr.state.sc.us/climate/>).

Wheat yields had the only difference related to rotation; it was a 0.46 Mg ha^{-1} increase for the disked, deep-tilled rotated versus non-rotated treatments. Wheat yield differences were similar (0.44 Mg ha^{-1}) 1) for non-disked, deep-tilled rotated versus non-rotated wheat treatments but it was not statistically significant. Soybean differences were less than 0.1 Mg ha^{-1} and not significant.

For wheat, lower cone index generally led to higher yield. For soybean, other factors such as drilling in narrow rows and more uniform deep tillage of the paratill led to higher yields verifying that the innovative management as reported in Frederick et al. (1998) can lead to higher yields in large scale plots as it had earlier in small scale plots.

References

- Arvidsson, J., Trautner, A., van den Akker, J.J.H., Schjønning, P., 2001. Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden. II. Soil displacement during wheeling and model computations of compaction. *Soil Till. Res.* 60, 79–89.
- Baumhardt, L., Jones, O.R., 2002. Residue management and paratillage effects on some soil properties and rainfall infiltration. *Soil Till. Res.* 65, 19–27.
- Busscher, W.J., Bauer, P.J., Frederick, J.R., 2002. Recompaction of a coastal loamy sand after deep tillage as a function of subsequent cumulative rainfall. *Soil Till. Res.* 68, 49–57.
- Busscher, W.J., Frederick, J.R., Bauer, P.J., 2000. Timing effects of deep tillage on penetrometer resistance and wheat and soybean yield. *Soil Sci. Soc. Am. J.* 64, 999–1003.
- Campbell, R.B., Reicosky, D.C., Doty, C.W., 1974. Physical properties and tillage of Paleudults in the southeastern Coastal Plains. *J. Soil Water Conserv.* 29, 220–224.
- Carter, L.M., 1967. Portable penetrometer measures soil strength profiles. *Agric. Eng.* 48, 348–349.
- Cassel, D.K., Nelson, L.A., 1979. Variability of mechanical impedance in a tilled one hectare field of Norfolk sandy loam. *Soil Sci. Soc. Am. J.* 43, 450–455.
- Clemson University, 1982. Lime and fertilizer recommendations based upon soil test results. Cooperative Extension Service Cir. #476, Clemson, SC.
- Frederick, J.R., Bauer, P.J., Busscher, W.J., McCutcheon, G.S., 1998. Tillage management for doublecropped soybean grown using narrow and wide row-width culture. *Crop Sci.* 38 (3), 755–762.
- Lapen, D.R., Topp, G.C., Gregorich, E.G., Hayhoe, H.N., Curnoe, W.E., 2001. Divisive field-scale associations between corn yields, management, and soil information. *Soil Till. Res.* 58, 193–206.
- Lipiec, J., Hatano, R., 2003. Quantification of compaction effects on soil physical properties and crop growth. *Geoderma* 116, 107–136.
- Munkholm, L.J., Schjønning, P., Rasmussen, K.J., 2001. Non-inversion tillage effects on mechanical properties of a humid sandy loam. *Soil Till. Res.* 62, 1–14.
- Pabin, J., Lipiec, J., Wlodek, S., Biskupski, A., Kaus, A., 1998. Critical bulk density and strength for pea seedling root growth as related to other soil factors. *Soil Till. Res.* 46, 203–208.
- Porter, P.M., Khalilian, A., 1995. Wheat response to row spacing in relay intercropping systems. *Agron. J.* 87, 999–1003.
- Radford, B.J., Yule, D.F., McGarry, D., Playford, C., 2001. Crop responses to applied soil compaction and to compaction repair treatments. *Soil Till. Res.* 61, 157–166.
- Sadler, E.J., Bauer, P.J., Busscher, W.J., 2000. Site-specific analysis of a droughted corn crop. I. Growth and grain yield. *Agron. J.* 92, 395–402.
- Sadler, E.J., Camp, C.R., 1986. Crop water use data available from the southeastern USA. *Trans. ASAE* 29, 1070–1079.
- SAS Institute Inc., 2000. SAS/STAT User's Guide Version 8. SAS Institute Inc., Cary, NC.
- Schafer-Landefeld, L., Brandhuber, R., Fenner, S., Koch, H.J., Stockfisch, N., 2004. Effects of agricultural machinery with high axle load on soil properties of normally managed fields. *Soil Till. Res.* 75 (1), 75–86.
- Schwab, E.B., Reeves, D.W., Burmester, C.H., Raper, R.L., 2002. Conservation tillage systems for cotton in the Tennessee Valley. *Soil Sci. Soc. Am. J.* 66, 569–577.
- Sheridan, J.M., Knisel, W.G., Woody, T.K., Asmussen, L.E., 1979. Seasonal variation in rainfall and rainfall-deficit periods in the Southern Coastal Plain and Flatwoods Regions of Georgia. *Georgia Agric. Exp. Stat. Res. Bull.* 243, 73.
- Stenitzer, E., Murer, E., 2003. Impact of soil compaction upon soil water balance and maize yield estimated by the SIMWASER model. *Soil Till. Res.* 73, 43–56.
- Strock, J.S., Malzer, G.L., Porter, P.L., 2001. Spatial variability of corn yield affected by landscape position and mechanical impedance. In: *Proceedings of the Fifth International Conference on Precision Agriculture*, Bloomington, MN, USA, 16–19 July, pp. 1–11.
- Trautner, A., Arvidsson, J., 2003. Subsoil compaction caused by machinery on a Swedish Eutric Cambisol at different soil water contents. *Soil Till. Res.* 73, 107–118.
- Van den Akker, J.J.H., Arvidsson, J., Horn, R., 2003. Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. *Soil Till. Res.* 73, 1–8.