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INCREASE OF SOIL STRENGTH OVER TIME IN A US SOUTHEASTERN COASTAL PLAIN LOAMY SAND

Warren J. Busscher, Jeff M. Novak, Patrick G. Hunt, and Philip J. Bauer

With rising energy costs, fuel-consumptive soil management practices, such as deep tillage, need to be reassessed to determine whether they need to be performed every year or not. Between 1978 and 1996, conservation (nondisked) and conventional (disked) tillage treatments had been annually deep-tilled with noninversion subsoiling to break up a subsurface layer that had high soil strength, associated with the E horizon of a coastal loam sand. After 1996, treatments were split with half being deep-tilled until 2001, after which no treatments were deep-tilled, although surface tillage continued. By 1999, soybean (*Glycine max* L. Merr.) treatments in which deep tillage ceased in 1996 were significantly higher in cone index (as measured by a penetrometer) than were treatments that had been deep-tilled, suggesting that the effects of deep tillage lasted three years. By 2004, conventional treatments in which tillage ceased in 2001 had reconsolidated to the point that they were not different from conventional treatments where tillage had ceased in 1996. However, conservation tillage treatments were still significantly different, suggesting that conservation tillage can help buffer the effects of reconsolidation. Two competing trends could be observed. On the one hand, although reconsolidation might not be complete, soils with incomplete reconsolidation could be hard enough to reduce production. On the other hand, soils in which tillage ceased still showed the effects of deep tillage even after they reconsolidated to the point that they were statistically different from deep-tilled treatments. (Soil Science 2006;171:519–526)

Key words: Soil strength, cone index, conservation tillage, hardpan.

IN the southeastern US coastal plains and similar areas, several factors can combine to limit productivity; they include sandy soils with low water holding capacity, short periods of drought, and shallow high-strength root-restricting subsurface layers. High strength in many coastal plain soils of the southeastern United States, especially in the E horizon, impedes plant growth; it degrades soil physical properties, reducing the yield of row crops (Arvidsson et al., 2001; Lapen et al., 2001; Radford et al., 2001) like corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L. Merr.). High strengths can be reduced and yield improved through deep tillage (Reeves and Mullins, 1995; Busscher et al., 2000; Raper et al., 2000). Deep tillage of these coastal soils is recommended annually (Threadgill, 1982; Busscher et al., 1986; Porter and Khalilian, 1995) or seasonally for double crops (Frederick et al., 1998) because reconsolidation between growing seasons can increase soil strengths enough to reduce productivity. In some studies, the residual effects of deep tillage were shown to be effective for years (Munkholm et al., 2001; Baumhardt and Jones, 2002), especially if traffic is limited to specific midrows (Frederick et al., 1998), whereas the effects are gone after 3 years or less in other studies (Busscher et al., 1995; Shukla et al., 2003).

Coastal Plains Soil, Water, and Plant Research Center, 2611 W Lucas St, Florence, SC 29501-1242. Warren J. Busscher is corresponding author. E-mail: busscher@florence.ars.usda.gov

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Producers typically till these sandy coastal soils with subsoilers, a noninversion method of deep tillage that breaks up hard subsurface layers. Deep tillage loosens the soil to allow root growth into deeper horizons that have a higher degree of structural development and greater water holding capacities than do shallow horizons; this can encourage root growth and improve yield (Adeoye and Mohamed-Saleem, 1990; Akinci et al., 2004). However, as fuel prices increase, deep tillage may become prohibitively expensive because it requires 14 to 20 kW of power per subsoil shank and uses 20 to 25 L of fuel per hectare (Karlen et al., 1991). High fuel prices and significant energy requirements make deep tillage a significant part of plant production management costs despite the fact that the effect on the soil is temporary (Carter et al., 1996; Busscher et al., 2000). More research needs to be performed to determine soil reconsolidation and frequency of deep tillage.

The objective of this study is to measure the differences between deep-tilled and non-deep-tilled treatments after tillage ceased in conventional (disked) and conservation (non-disked) tillage plots. We hypothesized that plots would recompact to values equivalent to non-deep-tilled plots within three years. We tested the hypothesis by measuring the differences in soil strength either among treatments or between the in-row position, where tillage effect would be maximized, and the midrow position, where tillage effects would be minimized, as they changed over the years after tillage.

MATERIALS AND METHODS

Site and Management Description

This study was conducted on a long-term research site that had conventional (disked) and conservation (nondisked) tillage plots established in 1978 on a Norfolk loamy sand (fine-loamy, siliceous, thermic *Typic Kandiudult*) near Florence, South Carolina. The Norfolk soil formed in coastal marine sediments. It had an Ap horizon that had been tilled over the years to a depth of about 0.20 m. Below the tilled layer, it had an eluviated E horizon that typically varies in depth from 0.30 to 1.0 m and, when recompacted, developed penetration resistance that restricts root growth. Both the Ap and E horizons had less than 5- to 6-g kg^{-1} organic matter, 1- to 4-cmol kg^{-1} cation exchange capacity, and 20- to 80-g kg^{-1} clay content. They overlaid a sandy clay loam Bt horizon that extended beyond 0.6-m depth. The Bt horizon typically had less than 5-g kg^{-1} organic matter, 2- to 5-cmol kg^{-1} cation exchange capacity, and 200- to 400-g kg^{-1} clay content (Soil Survey Staff, 2005).

During the first 18-year period of the experiment (Karlen et al., 1996; Hunt et al., 1997), crops grown on the plots included corn and winter wheat double cropped with soybean or cotton (*Gossypium hirsutum* L.). During that time, organic matter increased to about 14 g kg^{-1} in the top 100 mm of the profile of the conservation tillage plots, whereas it rose to 8 g kg^{-1} at the same depth interval for the conventional tillage plots (Hunt et al., 1996). Subsoils of these treatments were similar, having been uniformly managed with in-row deep tillage throughout the 18-year period (Karlen et al., 1996; Hunt et al., 1997).

Tillage Management

For this study, corn and wheat with double-cropped soybean were grown in a two-year rotation; both phases of the rotation were planted in duplicate sets of plots to allow for investigation of each crop in every year. The study was initiated in November 1997 when wheat was planted in half of the plots. The next spring, corn was planted in the other plots; after wheat harvest, soybean was planted in the wheat plots. Main plot treatments included surface tillage (conventional vs. conservation tillage). Conventional tillage consisted of multiple diskings of the surface at the depth of 0.10 to 0.15 m; conservation tillage consisted of no surface tillage. Subplot treatments included no deep tillage versus noninversion deep tillage of the E horizon with either a ParaTill (AGCO Corporation, Duluth, GA) or a subsoiler (Kelly Manufacturing Co, Tifton, GA). The ParaTill was configured with four subsoiling-legs (0.66 m apart and 25 mm wide); each leg was preceded by a serrated coulter. The legs were 0.94 m long (top to ground) with a 45-degree angle bend (left rows to the right and right rows to the left) at 0.69 m from the top. Each leg had a 64-mm-wide point, which was set to a soil depth of 0.42 m. Each leg had a shatter plate above and behind the point to provide lifting and fracturing of soil with minimal disturbance of the soil surface. The ParaTill was used to provide broadcast deep tillage before drilling soybeans or wheat. The subsoiler was configured with four legs spaced (0.72 m apart and 25 mm wide); each leg was preceded by a serrated coulter. The legs were 45-degree forward-angled straight shanks.

The shanks were attached to a tool bar immediately in front of each planter; thus, in-row subsoiling and planting were performed in one operation. The combination of subsoiling and paratilling resulted in three deep tillage events in each two-year rotation.

Every year, plots continued to be surface-tilled (or not). All plots were deep-tilled until the fall of 1995. Starting in the spring of 1996, surface tillage plots were split into two 60-m-long and 11.4-m-wide deep tillage subplots. The plot and subplot treatments were as follows: (i) no surface and no deep tillage, (ii) no surface tillage with deep tillage, (iii) surface tillage and no deep tillage, and (iv) surface and deep tillage. After 2001, no plots were deep-tilled, whereas surface tillage continued. Subplots consisted of four treatments for each crop in each year. The experimental design was a split plot with four replications. Because of the variety of machinery used in the plots over the years, traffic was not limited to any specific midrows.

Strength Measurements

Soil strength was measured as cone index of a penetrometer in soybean plots on July 29 to August 3, 1998; May 11, 1999; July 31, 2000; August 2, 2001; June 28, 2002; June 25 and 27, 2003; and June 30, 2004. The dates of measurement varied because many of these years were dry; rain was often required to soften the soil and allow measurements to be within the range of the penetrometer. Cone indices were the force required to push the penetrometer into the soil divided by the cross-sectional area of the cone. They were measured up to 9 megapascals (MPa) before going off-scale; cone indices at or above 9 MPa would be well above those considered acceptable for plant root growth in these soils (Busscher et al., 1986). Soil cone index data were obtained with a 12.5-mm diameter, 30-degree solid angle cone tip attached to a hand-operated, recording penetrometer (Carter, 1967). Cone indices were measured near the middle of each tillage subplot to a depth of 0.55 m at nine equally spaced positions along a 0.76-m transect perpendicular to the rows (spacing, 95 mm); these measurements spanned approximately from a position between the shanks that was a non-wheel track across a region that was deep-tilled to a position between shanks that was a wheel track. At each position, the measurements were the means of three probings that were about 4 cm apart and parallel to the row. Until 2002, cone indices in the form of analog data were recorded on index cards and subsequently digitized at 50-mm depth intervals. After 2002, cone indices were measured with a strain gauge; depth was measured with a potentiometer; and data were downloaded to a CR21x or CR23x data logger (Campbell Scientific, Inc, Logan, UT) and transferred to a computer. Automated data were collected at a rate of 100 Hz. Automated data collection produced more data with depth than did the digitized data, and because the data were obtained on the basis of time of probing and not of depth, they were not necessarily at the same depths. To standardize the readings, the automated data for all depths and all positions were calculated for 50-mm depth intervals and 95-mm width positions using bivariate interpolation in the G3GRID procedure of SAS (1999), resulting in less than the original amount of data for the automated sampling but uniform data for all dates of measurement. Soil samples were obtained along with cone indices to measure gravimetric water contents. Soil samples were obtained at 0.1-m intervals to 0.6-m depths.

Crop Management

Corn

Each year in March, growing season weeds in conventional tillage plots were controlled by applying cyanazine (2-[{4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl}amino]-2-methylpropanenitrile) and metolachlor (2-chloro-*N*-[2-ethyl-6-methylphenyl]-*N*-[2-methoxy-1-methylethyl] acetamide). Weeds in the conservation till plots were controlled with an initial burndown of glyphosate (*N*-[phosphonomethyl]glycine), cyanazine, and metolachlor; in May, glufosinate (2-amino-4-[hydroxymethylphosphinyl] butanoic acid) was used. Granular fertilizer was applied at the rate of 15, 10, and 90 kg ha^{-1} for N, P, and K, respectively. Corn (cv. Pioneer 34SA55 Liberty Linked) was planted in late March or early April at a rate of 59,300 seeds per hectare on 0.76-m row spacing. Liquid N (urea ammonium nitrate) was surface-applied in May of each year at the rate of 110 kg of N per hectare. Corn was harvested in August or September with a Case IH Model 2366 combine.

Wheat

Glyphosate was applied at the rate of 0.94 kg a.e. ha^{-1} in October. The conventional tillage plots received multiple diskings. The plots then received N, P, K, and lime fertilizers at 50, 14, 15, and 1120 kg ha^{-1}, respectively. In November, wheat (cv. Coker 9835) was planted with a no-till grain drill (John Deere Model 750) at a seeding rate of 100 kg of seed per hectare on 0.19-m row spacings. Bromoxynil (oclanoic acid ester of bromoxynil [3,5-dibromo-4-hydroxybenzonitrile]) and ammonium nitrate were broadcast in February. Wheat was harvested in June with a Case IH Model 2366 combine.

Soybean

After wheat harvest, the conservation tillage plots were sprayed with 0.41 kg a.e. ha^{-1} of glyphosate; the conventional tillage plots were sprayed with 0.45 kg a.i. ha^{-1} of pendimethalin (n-[1-ethylpropyl]-3-4-dimethyl-2,6-dinitrobenzenamine). Conventional tillage plots received multiple diskings and all plots received fertilizer (10-kg P ha^{-1} and 56-kg K ha^{-1}) before planting. Soybean (cv. Northrup King 573Z6) was planted as soon as practical in June after wheat harvest at the rate of 112 kg ha^{-1} with the no-till grain drill in 0.19-m rows. In July, glyphosate (0.41 kg a.e. ha^{-1}) was applied over-the-top. Soybean was harvested in October or November with a Case IH Model 2366 combine.

Statistical Analyses

Data were analyzed by analysis of variance and a least squares mean separation procedure (SAS, 1999). Cone index data were analyzed using the log transformation as recommended by Cassel and Nelson (1979). Because the data were collected over a 7-year period and because conditions differed from year to year, data were analyzed separately by year. Year-to-year effects were inferred by determining the differences (or similarities) among treatments as they varied from one year to the next. Cone index and water content data were analyzed using a split-plot randomized complete block design where the main plots were surface tillage; the first split was deep tillage; the second, position across the row; and the third, depth. For ease of interpretation, data were also analyzed by surface tillage, which made deep tillage the main plot, and position and depth as the first and the second splits, respectively. The data for main plots and for all splits were tested for significance at the 5% level unless otherwise stated.

RESULTS AND DISCUSSION

Soil Water Content

Soil water content differences affect cone index readings: they can mask the differences

TABLE 1

Water content and cone index means for each year by depth

Depth (m)	Year						
	1998	1999	2000		2002	2003	2004
Water Content ($g\ g^{-1}$)							
0.0–0.1	0.10d*	0.10e	0.10d	0.10c	0.10c	0.11c	0.18a
0.1–0.2	0.09d	0.10e	0.11c	0.08d	0.08e	0.10d	0.19a
0.2–0.3	0.11c	0.12d	0.12b	0.09cd	0.09d	0.12c	0.14c
0.3–0.4	0.14b	0.15c	0.12b	0.12b	0.12b	0.16b	0.10e
0.4–0.5	0.16a	0.17b	0.16a	0.15a	0.13a	0.18a	0.12d
0.5–0.6	0.17a	0.18a	0.16a	0.16a	0.13a	0.19a	0.16b
Mean	0.13	0.14	0.13	0.12	0.11	0.14	0.15
Cone Index (MPa)							
0.05	1.97d	1.07d	1.00d	1.10d	0.53f	0.93e	0.25d
0.15	3.72c	2.64a	2.72b	2.89c	3.12e	3.17b	1.58c
0.25	3.67c	2.41b	3.02a	4.00a	4.10c	3.34a	2.83a
0.35	4.04b	2.00c	2.39c	2.72c	3.62d	2.06d	2.22b
0.45	4.25b	2.36b	2.49bc	2.74c	4.89b	2.14d	2.21b
0.55	4.87a	2.85a	2.99a	3.58b	5.59a	2.54c	2.60a
Mean	3.75	2.22	2.43	2.84	3.64	2.36	1.95

*Means within columns for water index with the same letter are not significantly different for least significance difference test at 5%.

TABLE 2

Mean cone indices of the profile for surface and deep tillage treatments

Tillage Treatment		Year						
Surface	Deep	1998	1999	2000	2001	2002	2003	2004
None	None							
	Paratill							
Disk	None							
	Paratill							
Mean								

Measurements are expressed in megapascals.

*Means within columns with the same letter are not significantly different for least significant difference test at 10%.

†Means within columns with the same letter are not significantly different for least significant difference test at 5%.

among treatments. To avoid this, we waited until water contents were uniform after a rainfall to measure cone indices. Consequently, soil water content differences (data not shown) were generally not significantly different for treatments, although they differed from year to year; in addition, water contents generally increased with depth (Table 1). Because of the similarity among treatments, soil water contents were not included in analyses, except where listed.

Soil Strength

Deep tillage showed more differences than did surface tillage, and the interaction between the two was generally nonsignificant. When cone indices for disked and nondisked surface tillage treatments were analyzed separately in 1998, they did not differ on the basis of deep tillage treatment despite the fact that deep tillage continued in one treatment and ceased two years earlier in the other treatment (Table 2), showing that the residual effects of deep tillage persisted. In later years, cone indices for non–deep-tilled treatments had significantly higher values than for those that continued to be deep-tilled; this was especially evident in 1999 and 2001. This agrees with data showing that the effects of deep tillage last about three years (Busscher et al., 1995) without controlled traffic.

Cone index (Table 1) generally increased with depth, except for the hard layer at the depth of approximately 0.25 m. The hard layer usually exhibited higher cone indices than above and below it. It was the layer that was responsible for reduced root growth and deep tillage management in these soils (Frederick et al., 1998).

Deep tillage ceased on all plots after 2001. As the years passed, cone index differences decreased between plots where deep tillage ceased in 1996 and those where it had just ceased (Table 2). Cone indices differences for disked plots seemed to be decreasing faster than those for nondisked plots, suggesting that the compacting effect of disking without deep tillage was increasing soil reconsolidation. Increased organic matter in the nondisked treatments could also be slowing the reconsolidation of the hard soil (Hunt et al., 1996). But that would be near the surface and would not be effective at maintaining loosening, except for shallow (100 mm) depths.

Another way to analyze reconsolidation was to consider the variation of cone indices by position across rows. Because ParaTill shanks were 0.66 m apart, the zones of maximum loosening would also be 0.66 m apart, with zones of relatively high strength between them. Over time, cone indices in the zones of loosening would increase to the same values as those in the zones of higher strength.

Because the position-by-deep-tillage interaction was significant and the position-by-surface-tillage interaction was not significant, data on deep tillage treatments could be analyzed independently of surface tillage (Table 3). For this analysis, cone indices were also averaged on the basis of depth. Positions of cone index measurement across the rows had been centered at the point of tillage, with position 0 m being in a non–wheel track and position 0.76 m being in a wheel track. These positions were not necessarily related to the narrow row positions because the soybean and wheat (the plots where the data were obtained) were drilled with 0.19-m row spacings. Because positions were centered on tillage, they had lower cone indices at the center (0.38 m; Table 3) and higher at the outer positions (0.0 m and 0.76 m; Table 3), which were approximately midway between the points of tillage. In 1998, cone indices at the center positions for the non–deep-tilled

TABLE 3

Cone indices by position perpendicular to the row centered on deep tillage (position, 0.38) averaged over the top 0.55 m of the soil profile

Year	Tillage	Position (m)								
		0.0	0.10	0.19	0.29	0.38	0.48	0.57	0.67	0.76
1998	None	4.21ab*								
	Deep	3.93a								
1999	None	2.75a								
	Deep	1.88bcd								
2000	None	3.13a								
	Deep	2.08ab								
2001	None	3.65a								
	Deep	2.54ab								
2002	None	3.18a								
	Deep	3.04ab								
2003	None	2.67a								
	Deep	1.92ab								
2004	None	2.08a								
	Deep	1.83a								

For tillage treatment *None*, deep tillage ceased in 1996; for treatment *Deep*, deep tillage continued until 2001, when it ceased. Measurements are expressed in megapascals.

*Means across rows with the same letter are not significantly different for least significant difference test at 5%.

treatments were lower than those at the positions midway between tillage (as observed by using the mean separation procedure comparing the values at the different positions; Table 3) despite the fact that it had been two years since deep tillage was performed. By 1999, three years after deep tillage ceased, there were no differences among these positions for the non–deep-tilled treatments. For the deep-tilled treatments, cone indices showed several levels of difference between the center and the outer positions between 1998 and 2001 (when deep tillage ceased). After 2001, the number of levels of difference among positions for these treatments decreased until 2004, three years after tillage ceased, when there were no differences among positions.

Although the plots had not been tilled for three or eight years, cone index contour plots

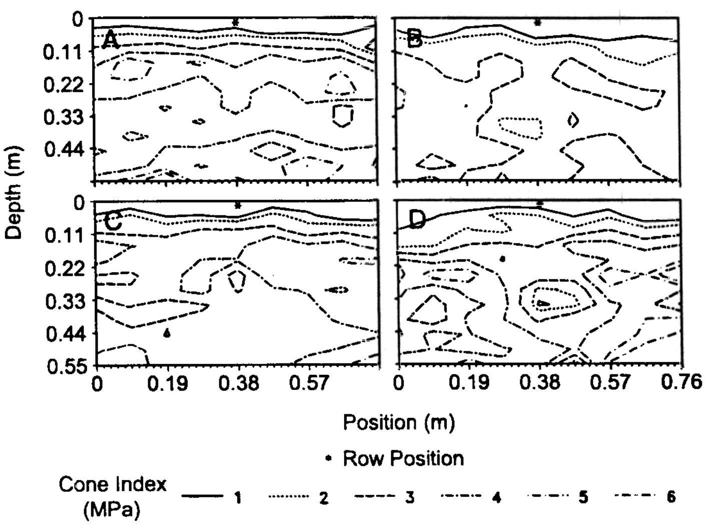

Fig. 1. Cone indices in 2004 of soil profiles for treatments with (A) no surface tillage and no deep tillage since 1996, (B) no surface tillage and no deep tillage since 2001, (C) surface tillage and no deep tillage since 1996, and (D) surface tillage and no deep tillage since 2001.

show that the positions of deep tillage could still be detected near the center of the graphs (Fig. 1). Evidence of deep tillage was more obvious in treatments that were deep-tilled more recently (Fig. 1b, d). Evidence of deep tillage was also more obvious in treatments that had not been disked. The fact that reduced cone indices continued to be detected for several years after tillage supports the work of Munkholm et al. (2001) and Baumhardt and Jones (2002). In a similar coastal soil, evidence of tillage could be seen for 6 years despite the fact that cone indices had built up to yield limiting values every season (Busscher et al., 2000); although cone index and yield differences from year to year may not have been significant, the regression demonstrated a significant change with time.

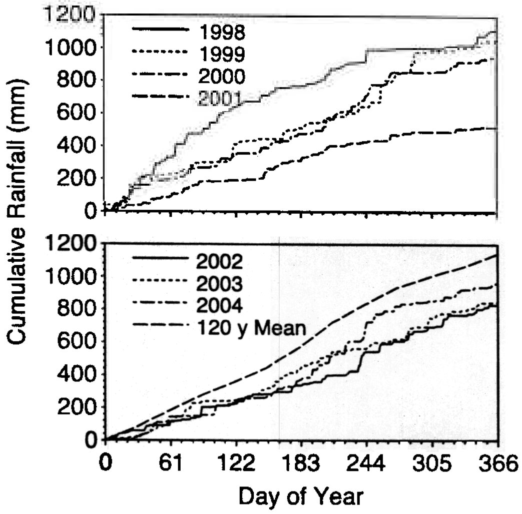

Fig. 2. Cumulative rainfall during the experiment. The Mean is the average for the 120-year period from 1882 to 2001. Total annual values include 1111 mm for 1998, 1051 mm for 1999, 951 mm for 2000, 521 mm for 2001, 828 mm for 2002, 843 mm for 2003, 958 mm for 2004, and 1139 mm for the mean.

Soil Moisture and Rainfall

Soil water contents seem high because we waited for rain to have relatively uniform soil water contents when taking cone index readings. Generally, years with higher water contents (Table 1) had lower cone indices (Table 2) when compared with years with lower water contents, which had higher cone indices. When averaged over years, cone indices averaged over all treatments increased (r^2 = 0.59) as water contents decreased.

For this study, most years were considered droughty, partly because of rainfall deficits of approximately 180 mm or more when compared with the 120-year mean of 1139 mm and partly because of poor rainfall distribution during the growing seasons; for example, see the flat sections of the cumulative rainfall in 2001 (Fig. 2). In 2002, the rainfall deficit was severe during the soybean season (approximately Days 170 to 300 of the year; Fig. 2), with that year receiving only half of the normal annual rainfall; that year, the soybean crop was not harvested. Rainfall deficits were severe enough to cause mean cone indices at the times of measurement to exceed 2 MPa every year except 2004; 2-MPa cone indices were considered root limiting (Taylor and Gardner, 1963; Blanchar et al., 1978). High cone indices (Table 2) were likely related to both the rainfall deficits (especially in 2001 and 2002) and the high-strength nature of the soil profile (Busscher et al., 2000).

For information on cone indices and yield in this experiment, see Hunt et al. (2004). They found that with deep tillage, corn and wheat yields did not differ with disked or nondisked treatments. Yet, when deep tillage ceased, yields were greater for the nondisked treatments. They concluded that the increased organic matter accumulation in the surface layer of the nondisked treatments partially compensated for the need to deep-till; yet, deep tillage was beneficial for corn and wheat yields.

CONCLUSIONS

In 1999, split-plot treatments where deep tillage ceased three years earlier had significantly higher cone indices than treatments where deep tillage was continuous. Additionally, plots that were not being tilled had no differences in cone indices for the positions across the rows.

In 2004, three years after deep tillage ceased on all plots, conventionally tilled plots did not have significantly lower cone indices than plots that had not been tilled for eight years. Plots with conservation tillage still showed reduced cone indices for the plots not tilled since 2001. Additionally, no plots had differences in cone indices for the positions across the rows, suggesting significant soil recompaction.

During most years, cone indices were above 2 MPa, which was considered a root-limiting value. This was attributed to both soil recompaction and rainfall deficits.

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