Reprinted from the *Soil Science Society of America Journal*
Volume 64, no. 3, May–June 2000
677 South Segoe Rd., Madison, WI 53711 USA

Timing Effects of Deep Tillage on Penetration Resistance and Wheat and Soybean Yield

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ABSTRACT

In many southeastern Coastal Plain soils, subsoil pans have strengths that restrict root growth. To reduce strengths, soils are deep tilled annually, and perhaps biannually for double cropping. We evaluated the effect of deep tillage in fall, in spring, or at both times on strength of a Goldsboro loamy sand (fine loamy, siliceous, thermic Aquic Kandiudult) and on the yield of wheat (*Triticum aestivum* L.) and drilled soybean [*Glycine max* (L.) Merr.] in a double-cropped system. Treatments consisted of all combinations of surface tillage (disked and not disked) and deep tillage (no deep tillage, paratillage before wheat planting, before soybean planting, and before both) in four replicates. Soil strengths, measured as cone indices, showed that disked, non-deep-tilled treatments resulted in a pan at the 20- to 30-cm depth, generally associated with an E horizon. In more recently and more frequently deep-tilled treatments, mean profile cone indices were 0.31 to 0.36 MPa lower than treatments not deep tilled or deep tilled for the previous growing season. If soil was deep tilled only once a year, it was 0.26 MPa softer when tilled only in spring than when tilled only in fall. Deep tillage at the beginning of either season reduced soil cone indices and improved wheat and soybean yields over other treatments. Deep tillage at the beginning of both seasons maintained the softest soil. For every megapascal decrease in mean profile cone index, wheat yields increased 1.5 to 1.7 Mg ha^{-1} and soybean yields increased 1.1 to 1.8 Mg ha^{-1}.

Because of increased yield, double-cropped soybean following wheat has become popular with producers in the southeastern Coastal Plains. Some of the popularity and increased yield comes from a newer management system (Frederick et al., 1998) that includes soybean drilled in 19-cm row widths and deep tillage. Double-cropped area, 80% of which is narrow row (P.J. Bauer, 1999, personal communication), has risen to about half of all the soybean acreage in the southeastern USA, with 80 000 to 100 000 ha in South Carolina alone (USDA-NASS, http://www.fedstats.gov/index20.html; verified January 31, 2000).

A common deterrent to plant growth in many southeastern Coastal Plain soils is high soil strength. High strength, as measured by cone index, is found throughout the profile but especially in the E horizon, just below the Ap. Strength in the E horizon can restrict root growth even when water content is at field capacity (Campbell et al., 1974) and strength increases as the soil dries. Cone indices up to 20 MPa have been measured in the E horizon (Karlen et al., 1991); this is 10 times the root limiting cone indices reported by Blanchar et al. (1978) and Taylor and Gardner (1963) for soils of similar textures. Though a few roots may find their way through the hard layer (Vepraskas et al., 1995), cone indices of this magnitude generally prevent roots from taking water and nutrients from the E and lower horizons. As a result, yield is reduced (Sojka et al., 1991).

Current practice in the southeastern Coastal Plain is to reduce soil strength by deep tillage. Because the soil reconsolidates between growing seasons (Threadgill, 1982; Busscher et al., 1986), deep tillage is required annually. Deep tillage is recommended either in spring (Threadgill, 1982; Busscher et al., 1986) or fall (Porter and Khalilian, 1995). Though it is not usually recommended twice a year, some producers deep till twice if double cropping. A recommended time and frequency for deep tillage has yet to be established for the southeastern Coastal Plains, and potentially for other similar coastal areas. The timing and effectiveness of deep tillage are important because it is expensive; it requires large tractors (14–20 kw per deep tillage shank), 20 to 25 L of fuel per hectare, and 20 to 40 min labor per hectare (Karlen et al., 1991). Timing, frequency, and effectiveness of deep tillage need to be developed.

We hypothesized that for the narrow-row management system, frequency and timing of deep tillage would affect double-crop productivity and soil strength. Our purpose was to determine whether deep tillage in spring, fall, or both gave the greatest reduction in soil strength and the greatest improvement in soybean and wheat yield. Since we planned to measure both soil strength (cone index) and yield, another purpose was to correlate the effects of soil strength reduced by tillage with yield for the narrow-row, deep-tilled, double-cropped management system.

MATERIALS AND METHODS

In summer 1993, before plot establishment, an experimental field at the Pee Dee Research and Education Center near Florence, SC, was planted to soybean by conventional techniques of 0.76-m-spaced rows with in-row subsoiling. In the fall of 1993, we established wheat-soybean double-cropped plots in the field. Plots were 3 m wide and 15 m long. Plots were located on a Goldsboro loamy sand that had an E horizon below the plow layer.

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Published in Soil Sci. Soc. Am. J. 64:999–1003 (2000).

Abbreviations: N, no deep tillage; S, spring deep tillage (before soybean planting); W, fall deep tillage (before wheat planting); B both spring and fall deep tillage.

Table 1. Water contents with depth averaged over treatments for each date of measurement of cone indices. Water contents were not significantly different among treatments or treatment interactions with date and depth.

Depth	Water content					
	21 June 1994	20 Dec. 1994	16 June 1995	12 Dec. 1995	13 June 1996	Mean
cm	$g\ g^{-1}$					
5	0.08c†	0.11d	0.10d	0.11d	0.11b	0.10d
15	0.07c	0.11d	0.10d	0.11d	0.10c	0.10d
25	0.08c	0.12c	0.11c	0.12c	0.11b	0.11c
35	0.10b	0.14b	0.13b	0.13b	0.13a	0.12b
45	0.13a	0.15a	0.15a	0.14a	0.13a	0.14a
55	0.13a	0.15a	0.15a	0.14a	0.13a	0.14a
Mean	0.10c‡	0.13a	0.12b	0.12b	0.12b	

† Means within the columns with the same letter are not significantly different by the LSD test at $P = 0.05$.
‡ Means within the row with the same letter are not significantly different by the LSD test at $P = 0.05$.

The day before planting either wheat or soybean, we imposed surface tillage and deep tillage treatments onto the plots. The two surface tillage treatments involved not disking (planting into the stubble of the previous season's crop) or disking twice before planting. The four deep tillage treatments included no paratilling (N), paratilling before soybean planting (S), paratilling before wheat planting (W), and paratilling before planting both soybean and wheat (B). Treatments were replicated four times in a randomized complete block design.

Surface tillage, deep tillage, and planting were done in separate operations. All tillage and harvesting equipment followed the same wheel tracks as closely as possible. Surface tillage was done with a 3-m-wide Tufline[1] disk (Tufline Mfg. Co., Columbus, GA) pulled by a John Deere 4230 (Deere and Co., Moline, IL) 75-kw tractor with wheels on 1.6-m centers. Deep tillage was done with a two-shank paratill in fall of 1993 and after that with a four-shank paratill (Tye Co., Lockney, TX). Shanks were set 0.66 m apart. The paratill was pulled with a Case 2670 (now Case-IH, Racine, WI) 165-kw, four-wheel-drive tractor with dual wheels on 1.9-m and 3.1-m centers. Shanks deep-tilled soil to approximately 0.4 m (the bottom of the hardpan).

Plots were planted to soft red winter wheat cultivar Northrup King Coker 9134 and 'Hagood' soybean, a Maturity Group VII cultivar. Both wheat and soybean were drilled in 19-cm-spaced rows with a 3-m-wide John Deere 750 No-till Planter pulled by a Massey Ferguson 398 (Massey Ferguson, Inc., Des Moines, IA) 60-kw tractor with wheels on 1.9-m centers. Wheat was drilled on 18 Nov. 1993, 23 Nov. 1994, and 21 Nov. 1995 at a rate of 66 seeds m^{-1} and harvested on 27 May 1994, 30 May 1995, and 24 May 1996. Soybean were drilled on 30 May 1994, 1 June 1995, and 7 June 1996 at a rate of 13 seeds m^{-1} and harvested on 3 Nov. 1994, 3 Nov. 1995, and 8 Nov. 1996. Whole plant samples for yield of wheat and soybean were harvested from six 1-m sections of row in each plot. Yield data for both were corrected to 130 g kg^{-1} moisture.

When in wheat, grain for the whole plot was harvested with an Allis Chalmers (now Deutz-Allis, Norcross, GA) F3 Gleaner with a 4-m-wide header and wheels on 2.4-m centers. When in soybean, grain from the whole plot was harvested with an IH (now Case-IH, Racine, WI) 1420 axial flow combine with a 4.0-m wide header and wheels on 2.3-m centers.

Following Clemson soil test recommendations (Clemson University, 1982), P and K were preplant broadcast on all plots at rates of 90 kg ha^{-1} each before disking for wheat. Ammonium nitrate was broadcast on all plots at 34 kg N ha^{-1} immediately after planting wheat and at 56 kg N ha^{-1} as a side-dressing in late February or early March (the stem erect wheat growth stage). Fertilizer was applied with a 3-m-wide Gandy spreader (Gandy Co., Owatonna, MN) pulled by a Massey Ferguson 253 tractor with wheels on 1.9-m centers.

To control weeds, non-disked plots were sprayed with glyphosate [*N*-(phosphonomethyl)glycine] at a rate of 1.1 kg a.i. ha^{-1} before wheat planting or Bronco (Monsanto, St. Louis) [glyphosate plus (alachlor) 2-chloro-2′,6′-diethyl-*N*-(methoxymethyl)acetanilide] at a rate of 3.9 kg a.i. ha^{-1} before soybean planting. Disked plots were sprayed with alachlor preemergence at a rate of 2.6 kg a.i. ha^{-1} before soybean emergence. To control annual broadleaf weeds and nutsedge (*Cyperus esculentus* L.), all plots were sprayed with chlorimuron ethyl (2-[[[(4-chloro-6-methoxyprimidin-2-yl)-carbonyl]-amino]sulfonyl]benzoate) at 0.013 kg a.i. ha^{-1} at 21 d after soybean planting. To control annual grasses, all plots were sprayed with sethoxydims (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) at 0.2 kg a.i. ha^{-1} at 30 d after soybean planting.

Cone index data were taken with a 12.5-mm-diameter cone-tipped penetrometer (Carter, 1967) on 21 June 1994, 16 June 1995, and 13 June 1996 in soybean and on 20 Dec. 1994 and 12 Dec. 1995 in wheat. Cone indices were measured by pushing the penetrometer into the soil to a depth of 55 cm at nine positions spaced 9.5 cm apart starting at the middle of the plot and moving outward. Cone index data were digitized into the computer at 5-cm-depth intervals and log transformed before analysis according to the recommendation of Cassel and Nelson (1979). Data for all positions across the plot and depth were combined to produce cross-sectional contours of soil cone indices by the method of Busscher et al. (1986).

In 1993, at the first wheat planting, we did not take cone index data. At that time, we had performed tillage in N and W plots but we could not perform tillage in S and B plots

Table 2. Mean profile cone indices for the different times of tillage averaged over disked and non-disked treatments. The timing of tillage Both, Spring, Fall, and None correspond to treatments B, S, W, and N.

Time of measurement	Mean cone index			
	Both	Spring	Fall	None
	MPa			
21 June 1994	1.10c†	1.14c	1.70b	2.13a
20 Dec. 1994	0.92b	0.96b	1.00b	1.49a
16 June 1995	0.90c	0.88c	1.56b	2.03a
12 Dec. 1995	0.85d	1.20b	1.00c	1.50a
13 June 1996	0.91c	0.94c	1.20b	1.63a
Mean	0.93d	1.01c	1.27b	1.73a

† Means within rows with the same letter are not significantly different by the LSD test at $P = 0.05$.

[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 U.S. Department of Agriculture or Clemson University.

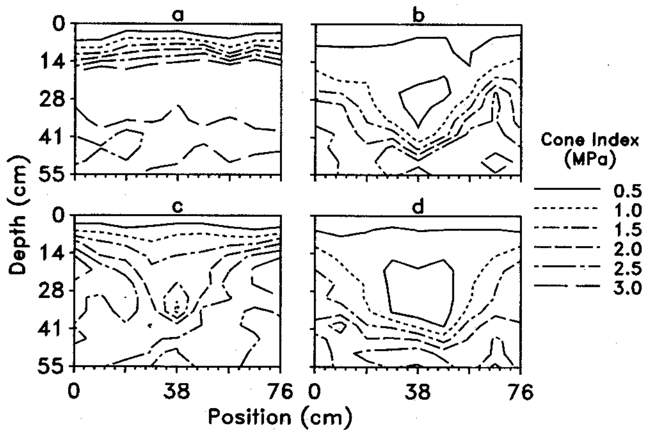

Fig. 1. Cone index contours for the spring 1995 soybean planting (disked treatment). The time of deep tillage is (a) none, (b) spring, (c) fall, or (d) both spring and fall. Readings were taken from non-wheel track position under the center of the tractor to a wheel track.

until the following spring. The first set of cone index data were taken in 1994 after the first soybean planting and after all treatments had been imposed.

Gravimetric soil water content samples were taken along with cone indices. They were taken at the first and fifth positions of cone index readings. Water contents were measured at 10-cm-depth intervals to the 60-cm depth. These water contents were taken as representative of the water contents of the plot.

We analyzed cone index and water content data using the ANOVA and the least square mean separation procedures (SAS Institute, 1990). Data were analyzed by a split-split plot randomized complete block design where the first split was position across the row and the second depth. We analyzed yield as a function of cone index using the linear regression procedure, REG (SAS Institute, 1990). Data were tested for significance at the 5% level.

RESULTS AND DISCUSSION

Water Content

At the beginning of each growing season (June and November), soil in untilled areas was usually dry and hard. As a result, soil strength was high enough that cone indices exceeded our measurement capabilities

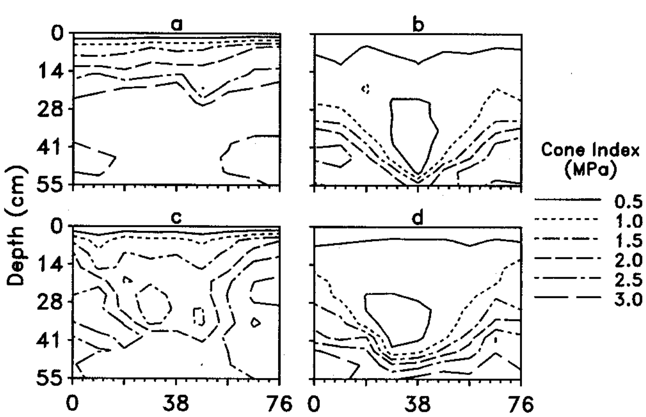

Fig. 2. Cone index contours for the spring 1995 soybean planting (non-disked treatment). The time of deep tillage is (a) none, (b) spring, (c) fall, or (d) both spring and fall.

(Busscher et al., 1997). In order to take cone index readings, we had to wait for rain to wet the profile (Table 1) and soften the soil.

Rain also equalized soil water contents across treatments, and water contents across treatments were not significant. Mean square errors for water contents on each date of measurement ranged from 1.35 to 2.28.

Although water contents did not vary with treatment or treatment interactions with depth and date, they varied with depth and date of measurement (Table 1). Water content generally increased with depth. Water content differences among dates of measurement depended on how thoroughly each rain wetted the profile. Because of its lack of variation with treatment, water content was ignored for the analysis of cone indices, except when considering depth and date.

Cone Index

Deep Tillage Treatments

For the deep tillage treatments, the cone indices were generally lowest in the more recently or more frequently deep-tilled plots (Table 2). Over the course of the experiment, Treatment B, paratilled at the beginning of both seasons, developed the lowest mean cone indices, when averaged over the whole profile that was measured (Fig. 1 and 2). On a season-by-season basis, cone indices for Treatment B were as low as those for the spring-deep-tilled treatment, S, in the spring and as low as (or lower than) those for the fall-deep-tilled treatment, W, in the fall.

Averaged over all dates of measurement (Table 2), spring deep tillage maintained lower mean cone indices than fall deep tillage. Since there were three spring measurements and two fall measurements, we reran the data twice without either the 1994 or 1996 spring readings. Even then, spring readings maintained lower cone indices with about the same means seen in the bottom of Table 2. Also, for each of the measurements taken after spring deep tillage, spring-deep-tilled treatments developed significantly lower mean profile cone indices than fall-tilled treatments. For the two measurements taken after fall deep tillage, one of the two fall-tilled treatments developed a lower mean profile cone index than the spring-tilled treatment. If producers working on the Goldsboro soil were to deep till only once a year, spring appeared to be the preferred time to maintain lower cone indices. The probable reason for this was the lower evapotranspiration in the winter. In an area where rainfall is on the average fairly uniform throughout the year at about 10 cm per month (Sadler and Camp, 1986), more water will percolate through the soil reconsolidating the tilled subsoil more during the winter than during the summer.

In addition to analyzing data for spring tillage vs. fall tillage, we analyzed the data to determine the effects of more recent versus less recent tillage on cone indices. Mean profile cone indices were lower for the more recently tilled treatments. Averaged over all seasons, the treatment with no deep tillage resulted in the highest

Table 3. Comparison of the mean profile cone indices for the dates of measurement and for disked and non-disked treatments averaged over deep-tillage treatments. Means are over date and disked treatment for the whole experiment.

Time of measurement	Mean cone index		
	Disked	Non-disked	Mean
	MPa		
21 June 1994	1.53a†	1.41b	1.47a‡
20 Dec. 1994	1.11a	1.04a	1.07e
16 June 1995	1.28a	1.26a	1.27b
12 Dec. 1995	1.11a	1.11a	1.11d
13 June 1996	1.22a	1.07b	1.14c
Mean	1.24a	1.18b	

† Means within rows for disked and non-disked with the same letter are not significantly different by the LSD at $P = 0.05$.
‡ Means within the column with the same letter are not significantly different by the LSD test at $P = 0.05$.

mean cone index, 1.74 MPa (0.264)[2]. The treatment with last season's deep tillage resulted in the next highest mean cone index, 1.30 MPa (0.145). The treatment with the current season's deep tillage resulted in the third highest mean cone index, 0.99 MPa (0.039). The treatment with deep tillage both seasons resulted in about the same mean cone index, 0.94 MPa (0.015, LSD = 0.025 at $P = 0.05$), as the current season's deep tillage treatment. From this point of view, more recent tillage provides the soil with lower cone indices. Deep tilling in both seasons has no advantage in reducing cone indices over deep tilling in the current (or more recent) season; however, if we continually till in the current season, we will be tilling in both seasons anyway. Also, fall tillage before spring planting a single season crop would not be recommended unless earlier planting, as a result of the earlier tillage, could overcome the potential loss of yield caused by the harder soil.

Surface Tillage Treatments

For the average over the course of the experiment and for two of the five season-by-season measurements, disking compacted the soil more than it loosened it (Table 3). Averaged over the course of the experiment, disked treatments developed 60-kPa higher mean profile soil cone indices than non-disked treatments. On a season-by-season basis, disked treatments in spring 1994 and spring 1996 developed higher mean profile cone indices than non-disked treatments. Disking never reduced mean profile cone index (Table 3). Though disking loosened the top 5 to 15 cm of the profile (Fig. 1), it compacted soil below the disked zone to produce mean profile cone indices that were equivalent to or higher than non-disked treatments.

For all statistical analyses of cone index data, disking was included in the surface-tillage × depth interaction. The disked, no-deep-tillage treatment produced a pan just below the loosened or disked zone (Fig. 1). The non-disked, no-deep-tillage treatment developed no pan, or less of a pan with contour intervals further apart (Fig. 2). Deep tillage eliminated most, if not all, of the disk pan.

[2] Numbers in parentheses are log transforms. Analyses are based on log transforms. For the transform, 0.1 was added to each reading to prevent taking log(0).

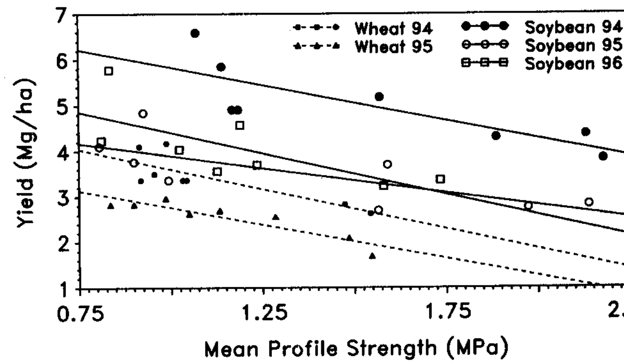

Fig. 3. Yield decrease with increase of cone index analyzed on a season-by-season basis. Data points are means over four replications for each of the eight surface and deep tillage treatments.

When averaged over disked and non-disked treatments, cone indices for deep tilled treatments increased for each 5-cm-depth interval from the soil surface to the 55-cm depth. The cone index averages by 5-cm-depth increment were 0.47 (−0.243), 0.73 (−0.079), 0.93 (0.011), 1.11 (0.084), 1.28 (0.141), 1.40 (0.177), 1.56 (0.221), 1.86 (0.293), 2.20 (0.362), 2.44 (0.406), and 2.56 MPa (0.425, LSD = 0.013 at $P = 0.05$). Since water content also increased with depth, cone index increases were due to increased soil strength, not to water content changes (If water contents had been equal, changes would have been greater.).

Position across the Rows

As also seen by Reeves et al. (1990), Wiermann et al. (1999), and others, cone indices varied significantly with position across the rows. Cone indices below the wheel track (position = 76 cm, Fig. 1 and 2) averaged over depths were 0.14 MPa higher (0.854 difference of the logs, LSD = 0.018 at $P = 0.05$) than below the non-wheel-track (position = 0 cm). Even for the no-till treatments, cone indices below the wheel tracks [1.88 MPa (0.296)] were higher than below the non-wheel-tracks [1.62 MPa (0.235), LSD = 0.028 at $P = 0.05$)].

Cone index differences due to position were also a result of the deep tillage vs. non-deep tillage treatments (Fig. 1 and 2). The interaction between deep tillage treatment and position was significant and was a result of the zone in the middle of the measured area (position = 25.3 to 50.6 cm of Fig. 1 and 2) being either disrupted by deep tillage or not disrupted. Disruption resulted in a mean cone index of 0.80 MPa (−0.043) for the deep-tilled treatments vs 1.73 MPa (0.262) for the non-deep-tilled treatments (LSD = 0.036 at $P = 0.05$). For non-deep-tilled treatments, cone indices in the middle of the measured area are as high in strength as those in the wheel tracks 1.75 MPa (0.267).

Yield

Yield was summarized in Frederick et al. (1998). Briefly, averaged over years, wheat yielded more in the non-disked treatments (3.05 Mg ha^{-1}) than in the disked treatments (2.84 Mg ha^{-1}, LSD = 0.16 at $P = 0.05$). Soybean also yielded more in the non-disked treatments

(4.60 Mg ha^{-1}) than in the disked treatments (3.78 Mg ha^{-1}, LSD = 0.22 at $P = 0.05$). With respect to timing of tillage, wheat yielded more for treatments that were tilled more recently; the order was B (3.29 Mg ha^{-1}) ~ W (3.26 Mg ha^{-1}) > S (2.95 Mg ha^{-1}) > N (2.30 Mg ha^{-1}, LSD = 0.22 at $P = 0.05$). Soybean yielded more for treatments that were tilled more recently or more frequently in the order B (4.98 Mg ha^{-1}) > S (4.32 Mg ha^{-1}) ~ W (4.07 Mg ha^{-1}) > N (3.39 Mg ha^{-1}, LSD = 0.31 at $P = 0.05$).

When both wheat and soybean yields were regressed against mean profile cone indices, shown in Tables 2 and 3, yield decreased with increased cone index. This trend was not significant when data from all seasons were analyzed together. However, the trend was significant at $P < 0.01$ when data for each season were analyzed separately. The regression coefficients (r^2s) ranged between 0.52 and 0.84 (Fig. 3). Within the range of cone indices measured and on the basis of the slopes of these linear regressions, wheat yields were reduced 1.75 Mg ha^{-1} in 1994 for every megapascal increase in mean profile cone index and 1.50 Mg ha^{-1} in 1995. Similarly, soybean yields were reduced 1.55 Mg ha^{-1} in 1994 for every megapascal increase in mean profile cone index, 1.08 Mg ha^{-1} in 1995, and 1.81 Mg ha^{-1} in 1996.

SUMMARY AND CONCLUSIONS

Disked treatments resulted in equal or higher mean profile cone indices than non-disked treatments. Deep tillage treatments resulted in mean profile cone indices in the order non-deep tilled > deep tilled last double-cropped season > deep tilled this season ≥ deep tilled both seasons.

Spring only deep tillage maintained lower cone indices in the following double-cropped growing season than fall only deep tillage.

For season-by-season correlations, yields were reduced by an increase in mean profile cone indices. Wheat yields were reduced 1.75 Mg ha^{-1} in 1994 and 1.50 Mg ha^{-1} in 1995 for every megapascal increase in mean profile cone index, and soybean yields were reduced 1.55 Mg ha^{-1} in 1994, 1.08 Mg ha^{-1} in 1995, and 1.81 Mg ha^{-1} in 1996. On the basis of the mean profile cone indices given in Table 2 and the mean of the regressions of Fig. 3, soybean yield from the treatment with deep tillage in both spring and fall was reduced by 0.03 Mg ha^{-1} if deep tilled only in spring, by 0.73 Mg ha^{-1} if deep tilled only in fall, and by 1.38 Mg ha^{-1} if not deep tilled. Similarly, wheat yield was reduced by 0.18 Mg ha^{-1} if deep tilled only in spring, by 0.30 Mg ha^{-1} if deep tilled only in fall, and by 0.99 Mg ha^{-1} if not deep tilled. If producers deep till only once a year, spring appears to be better for this soil.

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