



# Measurement and variation of site-specific hardpans for silty upland soils in the Southeastern United States

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## Abstract

Soil compaction in the form of a hardpan layer restricts root growth and reduces crop yield throughout the Southeastern United States. However, the depth of this compacted soil layer varies significantly over landscapes. A sampling procedure was developed and evaluated to determine the depth of the hardpan layer in upland soils of Grenada silt loam soil type in this region. Cone index profiles taken with a multiple-probe soil cone penetrometer in three fields were used to measure the hardpan depth and to predict their spatial variation. Continuous treatments of these fields for several years included conventional tillage, no-tillage, segregated traffic, and random traffic. Conventional tillage systems were found to bring the hardpan significantly closer to the soil surface as compared to no-till systems; in trafficked row middles by 0.144 m, directly beneath the rows by 0.165 m, and in no-trafficked row middles by 0.094 m. Little difference in depth of hardpan was found between a no-till field subjected to random traffic and a field where traffic was segregated. However, the effect of this random traffic was found to dramatically reduce the predicted range (which is a geo-statistical measure of field variability) from 43.2 m for the no-till field in the trafficked row middle as compared to 12.4 m for the randomly trafficked no-till field. This may indicate that the depth of the hardpan layer in these soils is brought uniformly closer to the soil surface by the effect of traffic, especially when annual tillage is not practiced which could alter this hardpan depth. This information about the variation of the hardpan layer will greatly assist researchers who are interested in developing site-specific tillage technologies to remedy this soil compaction condition. Published by Elsevier B.V.

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## 1. Introduction

Significant variation in crop yields have been found in many parts of the US using global positioning systems (GPS) and yield monitors (Yang et al., 1998; Doerge, 1999). Attempts to explain these differences have largely centered on pest and nutrient variability

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(Smith et al., 1998). In many areas of the country, research efforts have been partly successful with site-specific applications of pesticides and/or nutrients, which have helped to increase yields in lower yielding areas of the field (Doerge, 1999). In some cases, abandonment of low-producing areas has also improved producer profitability.

However, soil variability is a likely culprit of extremely variable yields, particularly on highly weathered ultisols with deep sandy surface layers, which are one of the predominate soil orders in the Southeastern United States. In most cases, these soils do not provide adequate moisture storage for successful crop production. Inadequate amounts of topsoil create limited reservoirs of moisture. Soil compaction caused by natural processes or by vehicle traffic also limits the ability of plant roots to penetrate to depths of soil that could sustain plants during common short-term droughts. Soil compaction has long been noted to cause root restrictions and yield reductions for many crops in the Southeastern United States (Kashirad et al., 1967; Cooper et al., 1969).

Many producers in the Southeastern U.S. rely on some form of annual deep tillage to break through this hardpan layer which allows crop roots to penetrate to less compact, more moist horizons (Cooper et al., 1969; Campbell et al., 1974; Box and Langdale, 1984; Hammond and Tyson, 1985; Reeves et al., 1992). Subsoiling densely compacted soil allows deeper rooting for withstanding short-term droughts prevalent during the growing season in the Southeast. This tillage event can be fairly expensive, both in environmental and productivity cost terms. Typically, soils in this region are subsoiled every year to depths of 0.3–0.5 m. Annual subsoiling is recommended because soils recompact quickly due to natural consolidation processes and random wheel traffic (Tupper et al., 1989; Busscher et al., 1986; Busscher and Sojka, 1987). Excessively deep tillage can cover valuable crop residue, which can increase surface erosion and also waste tillage energy (Raper, 2002). Some studies have also found that deep tillage can decrease crop yields, perhaps due to excessive soil disturbance (Raper et al., 2000a). Tillage performed at too shallow of a depth can also result in reduced crop yields if not performed to a depth adequate to disrupt the hardpan.

Several recent studies (Raper et al., 2000b; Goodson et al., 2000) have shown that the depth of this root-restricting layer varies greatly from field to field and also within the field. They also showed that the depth and strength of a soil hardpan varied significantly both down into the soil and across the field in very short distances, such as between a crop row and a trafficked row middle. Fulton et al. (1996) assessed the spatial variation of bulk density and cone index in a Maury silt loam soil. Their results showed very little correlation between these two parameters at field capacity soil moisture content.

Utset and Greco (2001) determined the penetrometer resistance on a Rhodic Ferralsol over a 30 m × 30 m area immediately after irrigation, 2 h after irrigation, and 24 h after irrigation. They found that the penetration resistance was considerably affected by the soil moisture condition and was substantially affected by bulk density and topographical variation. Utset and Greco (2001) estimated that penetrometer resistance was correlated in this soil type at distances of up to 10 m. However, these results may not be applicable over a large field area because of the small area sampled.

If the depth of subsoiling could be adjusted based on the depth of the hardpan, significant savings in energy and potential reductions in soil erosion could be realized. If maps of the depth of the hardpan layer could be created for entire fields, producers would have information that could prove useful for setting and adjusting their depth of subsoiling. Producers could consider setting up different management zones within the field, which could each require a different depth of subsoiling.

Maps of this root-impeding layer could also contribute to the overall knowledge about the variation of soil parameters. Sampling methodologies could be developed from this information, which would determine the maximum distance between each sample that would be necessary to adequately sample the field. Obtaining too few samples would not adequately describe the variation within the field while obtaining too many samples could allow soil moisture to change, thus affecting the measurements of soil strength data.

Therefore, the objectives of this study were: (1) to develop an effective procedure to determine the depth of hardpan in a soil prone to hardpan and fragipan

formation; (2) to determine if typical traffic and cropping systems conducted over a long period of time had an effect on the depth of hardpan over a field scale, and; (3) to determine the variation in depth of hardpan of an uplands soil in the Southeastern U.S.

## 2. Methods and materials

### 2.1. Experimental background

A multiple-probe soil cone penetrometer (MPSCP; Raper et al., 1999) was used to obtain cone index measurements (ASAE, 1999a,b) in several fields in the Southeastern U.S. This measurement device was used to sense the soil strength and to determine the depth of the root-impeding or hardpan layer. It has five soil cone penetrometers that are simultaneously forced into the soil resulting in five measurements of soil cone index. The instrumentation system acquired five force values and one depth measurement at approximate depth increments of 5 mm. Fields consisting of upland soils of Grenada silt loam soil type (fine silty, mixed, active, thermic Oxyaquic Fraglossudalfs; FAO designation of Dystric Podzoluvisols) near Senatobia, MS were sampled for soil compaction variability. The three fields sampled were managed in the following manner. Field 1 was managed with no-tillage with drilled soybeans (*Glycine max* (L.) Merr.) for narrow row production, field 2 was managed with conventional tillage (chisel, disk twice to shallow depths of less than 20 cm) for 90-cm row soybean production, and field 3 was managed with no-tillage for 90-cm row soybean production. All three fields were adjacent and were 2 to 3 hectares in size with slopes averaging 4%. These three fields have been used extensively for measurement of rainfall and soil erosion (Dabney et al., 2000).

### 2.2. Soil measurements

The MPSCP was used to acquire soil strength data of varying grid sizes on each field. For fields 1, 2, and 3 the grids sampled were approximately 30 m × 15 m, 30 m × 11 m, and 30 m × 16 m, respectively. This sampling strategy allowed the fields to be sampled within a 1-day period. Closer grid spacings would have required additional days which would have also

allowed soil moisture to change and would have potentially masked differences between fields. Immediately following the acquisition of the cone index data, a complete set of volumetric soil moisture data was collected at the same locations at depths of 0–15 and 0–30 cm using a time-domain reflectometry (TDR) probe (Topp et al., 1980). A range level was also used to determine the topography and sampling positions more accurately than could be accomplished with standard GPS (Fig. 1).

Soil strength data showed two peak values of cone index that required discrimination. The upper peak that occurred at depths of approximately 20–40 cm was considered a hardpan while the second peak that occurred at a depth of approximately 50 cm was considered a fragipan. These soils typically possess fragipans at this approximate depth. Throughout these

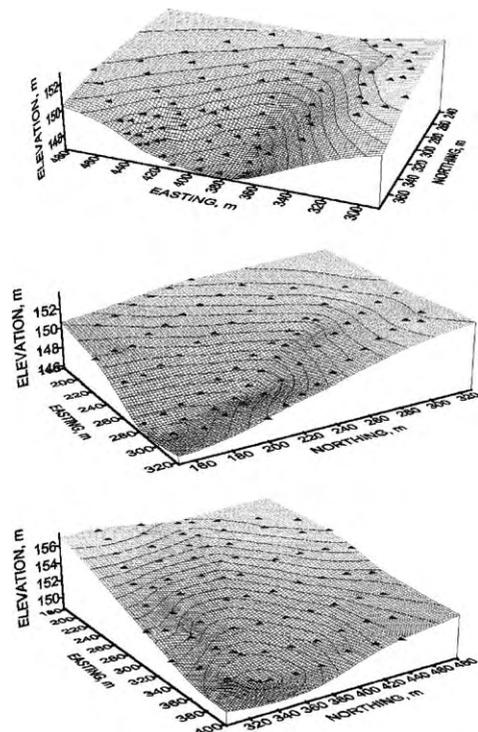


Fig. 1. Elevation of fields: 1 (top), 2 (center), and 3 (bottom) with markers indicating sampling locations. Field 1 was managed with no-tillage with drilled soybeans for narrow row production, field 2 was managed for conventional tillage (chisel, disk twice to shallow depths of less than 20 cm) for 90-cm row soybean production, and field 3 was managed for no-tillage for 90-cm row soybean production.

fields, a SAS procedure (SAS Institute, 1998) was used to sort the data and determine hardpan depth based on searching for the peak value as the criteria for the hardpan. The criteria used to locate these depths of hardpans consisted of locating at least three consecutive data points that were less than 0.05 MPa from previous data points and ensuring that the magnitude of cone index was greater than 1.0 MPa. Locating three consecutive data points that differed by 0.05 MPa criteria was selected as a criterion to eliminate single spikes that sometimes occur with cone index data due to electronic noise. A lower limit of 1.0 MPa was selected to ensure that a root would be significantly impeded by contact with a layer with this soil strength. These criteria should indicate the depth at which the peak value of the hardpan occurred. In some locations within each field, a single hardpan depth was not found and the entire force–depth graph was discarded. In other locations, a visual assessment showed a clear hardpan when the computer failed to discern this depth. For example, in field 1, 80 locations were sampled for cone index, but the hardpan depth was only successfully found in 55 locations using the computer method. Twenty-five locations did not contribute to the overall analysis of the field.

Because the data was collected with the MPSCP, we retained the ability to discriminate between depths of hardpan caused by wheel traffic. For fields 2 and 3, segregated row middles were maintained and the cone index measurements were analyzed for differences caused by vehicle traffic. Therefore, three separate data sets were created for each of these fields: (1) trafficked row middle position, (2) in-row position, and (3) non-trafficked row middle position. Each of these data sets were analyzed independently for fields 2 and 3. For field 1, all of the sampling positions were averaged together due to the lack of row position and random wheel traffic.

Statistical analyses were made using SAS software using Proc Univariate (SAS Institute, 1998). The data was split into rows and columns and each set of data analyzed independently to check for extreme skewness or kurtosis. This method allowed outliers to be found and eliminated from the data set. Stem-leaf plots were prepared for the remaining data to determine if the data was normally distributed.

### 2.3. Semivariograms

The depths to the hardpan layers were checked for spatial variability by constructing semivariograms. These graphs of separation distance versus the semivariance provide methods of determining the spatial patterns of a variable (Isaaks and Srivastava, 1989). Omnidirectional semivariograms were constructed using GS+ (Gamma Design Software, 1999). Several models were fit to each semivariogram, including linear, spherical, and exponential. All semivariograms were checked for anisotropy, but no directional differences could be determined. The model which best fit the data was identified based on the regression coefficient and the (sill-nugget)/sill parameter. The nugget is defined as the vertical jump from the value of zero at the origin to the value of the semivariance at extremely small separation distances. The sill is defined as the plateau that the semivariance reaches.

## 3. Results and discussion

### 3.1. Soil measurements

In field 1, all five values of cone index obtained from the MPSCP were averaged together because there was no row orientation and no method of segregating traffic from no-trafficked regions. In this field, the average depth of the hardpan was found to be 0.34 m, the soil moisture was found to be 35.5% for the 0–15 cm depth range and 37.0% for the 0–30 cm depth range (Table 1) with a 90% confidence interval of 0.32–0.36 m. Skewness for the depth to the hardpan was 0.77, which indicates that the data is only slightly asymmetric (Fig. 2). The coefficient of variation for the depth to the hardpan was 0.28, which indicates that the histogram does not have a long tail of values and the arithmetic mean is appropriate to characterize the sampled data. A coefficient of variation greater than one may indicate the presence of some erratic high values (Nielson and Wendroth, 2003). Much lower values of coefficient of variation were obtained for the soil moisture for the 0–15 cm depth range (0.05), the 0–30 cm depth range (0.03), and for the elevation (0.01). Small values of skewness were also found for soil moisture for the 0–15 cm depth range (0.12), the

Table 1  
Descriptive statistics of depth to hardpan, volumetric soil moisture, and elevation for field 1 (no-tillage with drilled soybeans)

	Mean	90% Confidence interval	Standard deviation	Minimum value	Maximum value	Number of values	Coefficient of variation	Skewness
Depth to hardpan (m)	0.34	0.32–0.36	0.09	0.19	0.59	55	0.28	0.77
Soil moisture (0–15 cm) (%)	35.5	35.1–35.9	1.8	32.0	39.2	52	0.05	0.12
Soil moisture (0–30 cm) (%)	37.0	36.7–37.3	1.4	34.0	39.4	54	0.03	–0.30
Elevation (m)	150.4	150.0–150.8	1.7	146.9	152.7	55	0.01	–0.15

0–30 cm depth range (–0.305), and for the elevation (–0.15). These values agree with Nielson and Wendroth (2003) who indicate that soil water content measurements are mostly symmetrical because air-dryness and water saturation are far outside the range of potential observations. The negative values of skewness indicate a slight shift in the histogram to the left.

It was obvious from the data for field 2 that shallower hardpans were found with conventional tillage. Using data collected in the trafficked row middles gave an average depth of hardpan of 0.18 m compared to the data collected in the no-trafficked row middles, which gave an average depth of hardpan of 0.21 m (Table 2). The 90% confidence interval for the trafficked hardpan only extended to 0.19 m, which was less than the lower end of the 90% confidence interval for the no-trafficked row middle (0.20 m). We therefore determined that vehicle traffic might have caused the hardpan profile to move closer to the soil surface by an average value of 0.03 m, which could additionally restrict root growth and water movement.

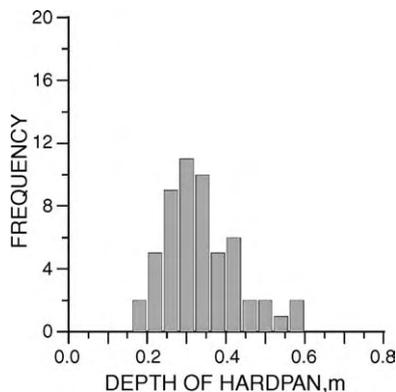


Fig. 2. Histogram of hardpan depths for field 1.

However, data obtained directly beneath the row showed the depth to the root-impeding layer to be 0.19 m. The 90% confidence interval for directly beneath the row intersects both confidence intervals for the no-trafficked row middle and the trafficked row middle further showing the likely influence of both areas on this zone. This area lies between the tracked and no-tracked row middle and was likely influenced by traffic applied to the trafficked row middle. Skewness for all three positions of depth to the hardpan was minimal indicating somewhat positive normal distributions (Table 2). All coefficients of variation for the depths to the hardpan in the row (0.31), in the trafficked middle (0.27), and in the no-trafficked middle (0.29) were very close (Fig. 3).

The soil moisture for field 2 was found to be 34.5% for the 0–15 cm depth range and 35.0% for the 0–30 cm depth range which was similar to that found in field 1 (Table 2). The shallow soil moisture measurements and the elevation were both slightly negatively skewed while the 0–30 cm depth range showed a slight positive skewness. The coefficients of variation for the shallow soil moisture (0.07) and for the deep soil moisture (0.05) indicated little deviance from a normal distribution. This was also true for the elevation coefficient of variation (0.01).

The depths of the hardpans for field 3 were substantially greater than those measured in field 2 but were similar to the hardpan depths measured in field 1. The depth to the hardpan in the no-trafficked row middle was 0.31 m (Table 3), which was slightly shallower than either of the depth to the hardpan in the trafficked row middle (0.32 m) or the depth to the hardpan in the in-row position (0.35 m). These values were similar to those depths measured in field 1 and probably resulted from the lack of conventional tillage

Table 2

Descriptive statistics of depth to hardpan, volumetric soil moisture, and elevation for field 2 (conventional tillage for 90-cm row soybeans)

	Mean	90% Confidence interval	Standard deviation	Minimum value	Maximum value	Number of values	Coefficient of variation	Skewness
Depth to no-trafficked hardpan (m)	0.21	0.19–0.23	0.06	0.10	0.36	50	0.29	0.47
Depth to in-row hardpan (m)	0.19	0.18–0.20	0.06	0.08	0.34	53	0.31	0.48
Depth to trafficked hardpan (m)	0.18	0.17–0.19	0.05	0.10	0.30	57	0.27	0.39
Soil moisture (0–15 cm) (%)	34.5	34.0–35.0	2.3	28.9	39.6	60	0.07	–0.40
Soil moisture (0–30 cm) (%)	35.0	34.7–35.3	1.3	31.5	37.9	61	0.05	0.08
Elevation (m)	150.1	149.7–150.5	1.9	146.3	152.8	61	0.01	–0.25

being applied. The 90% confidence intervals for the depths to the hardpan between the no-trafficked row position (0.29–0.32 m) and the trafficked row position (0.29–0.34 m) were very similar with the trafficked row position indicating slightly higher variation (Table 3). The 90% confidence interval for the depth to the hardpan in the in-row position (0.33–0.38 m) was deeper and did not intersect with the hardpan depth in the no-trafficked row position due to the decreased variation of this measurement. Values of skewness were all less than one, indicating symmetry. The coefficients of variation for the depth to the hardpan for the in-row position (0.27), the trafficked middle (0.32), and for the no-trafficked middle (0.29) also indicated no long tails of high values (Fig. 4).

The soil moisture for field 3 was found to be 36.8% for the 0–15 cm depth range and 36.5% for the 0–30 cm depth range (Table 3). The skewness was found to be slightly negative, indicating a slight shift to the left but with very little asymmetry. The coefficients of variation for the soil moisture for the shallow depth range (0.04) and for the deep depth range (0.05) showed little reason to question normality of the data.

This was also true for elevation (0.02) with the value being so close to zero.

### 3.2. Correlation coefficients

Table 4 shows the correlation coefficients between the depth to the hardpan, the soil moisture at 0–15 cm depth, the soil moisture at 0–30 cm depth, and the elevation. For field 1, a strong relationship was obtained between the hardpan depth and the soil moisture at the 0–30 cm depth ( $P < 0.001$ ) and between the hardpan depth and elevation ( $P < 0.07$ ).

For field 2, Table 4 shows the correlation coefficients between the depth to the hardpan as measured in the three positions across the row, the soil moisture at 0–15 cm depth, the soil moisture at 0–30 cm depth, and elevation. A strong inter-relationship was obtained for all three of the positions at which the hardpan was obtained ( $P < 0.05$ ). The depth to the in-row hardpan and the depth to the no-trafficked hardpan were also found to be highly related to the soil moisture at the 0–15 cm depth.

For field 3, a strong inter-relationship was obtained for all three of the positions at which the hardpan was

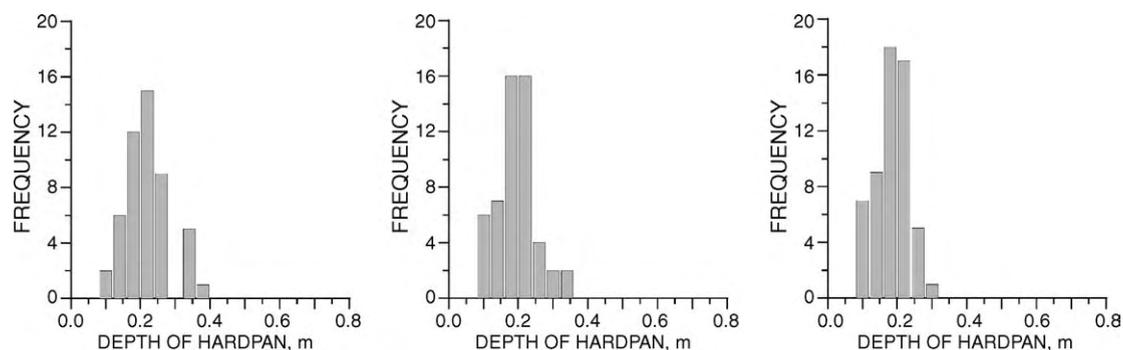


Fig. 3. Histogram of hardpan depths for field 2 for no-trafficked area (left), in-row area (center), and trafficked area (right).

Table 3  
Descriptive statistics of depth to hardpan, volumetric soil moisture, and elevation for field 3 (no-tillage for 90-cm row soybeans)

	Mean	90% Confidence interval	Standard deviation	Minimum value	Maximum value	Number of values	Coefficient of variation	Skewness
Depth to no-trafficked hardpan (m)	0.31	0.29–0.32	0.09	0.15	0.57	61	0.29	0.74
Depth to in-row hardpan (m)	0.35	0.33–0.38	0.10	0.17	0.58	55	0.27	0.26
Depth to trafficked hardpan (m)	0.32	0.29–0.34	0.10	0.13	0.59	57	0.32	0.56
Soil moisture (0–15 cm) (%)	36.8	36.5–37.1	1.6	32.3	39.8	66	0.04	–0.60
Soil moisture (0–30 cm) (%)	36.5	36.1–36.9	1.8	23.6	39.6	66	0.05	–0.29
Elevation (m)	153.5	153.0–154.0	2.4	148.9	157.3	66	0.02	–0.23

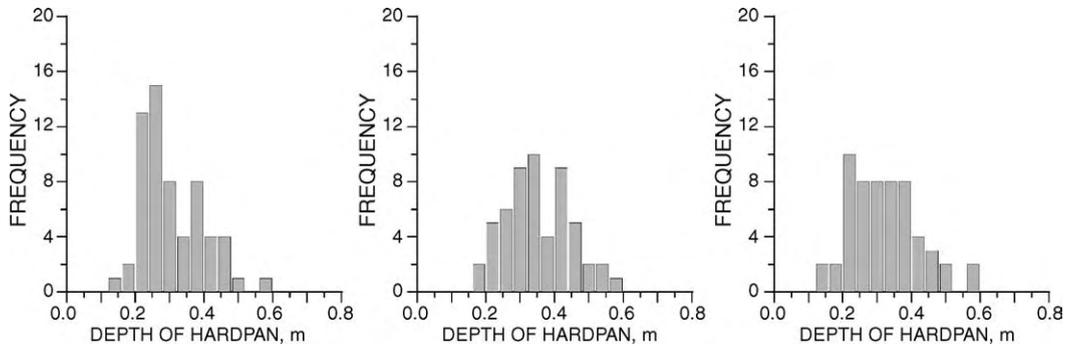


Fig. 4. Histogram of hardpan depths for field 3 for no-trafficked area (left), in-row area (center), and trafficked area (right).

obtained ( $P < 0.05$ ). The only other relationships that were found were between the depth to the hardpan in the no-trafficked middle and the soil moisture at the 0–15 cm depth ( $P < 0.10$ ) and elevation ( $P < 0.06$ ).

It is interesting to note that elevation was strongly correlated with hardpan depth for field 1 and depth to no-trafficked hardpan for field 3. Both of these fields

were no-tilled and may have had reduced soil erosion as compared to field 2 which was conventionally tilled.

### 3.3. Spatial dependence

When the depth to hardpan data for field 1 was analyzed for spatial dependence (Table 5), we

Table 4  
Correlation coefficients between depth to hardpan, volumetric soil moisture, and elevation

	Depth to in-row hardpan (m)	Depth to no-trafficked hardpan (m)	Depth to trafficked hardpan (m)	Soil moisture (0–15 cm) (%)	Soil moisture (0–30 cm) (%)	Elevation (m)
Field 1 (no-tillage with drilled soybeans)						
Depth to hardpan (m)				–0.19 (0.18)	–0.38 (0.00)	0.25 (0.07)
Field 2 (conventional tillage for 90-cm row soybeans)						
Depth to no-trafficked hardpan (m)	0.33 (0.03) <sup>a</sup>		0.35 (0.02)	–0.29 (0.04)	–0.03 (0.84)	–0.16 (0.27)
Depth to in-row hardpan (m)		0.33 (0.03)	0.37 (0.01)	–0.29 (0.04)	–0.18 (0.19)	–0.20 (0.15)
Depth to trafficked hardpan (m)	0.37 (0.01)	0.35 (0.02)		–0.16 (0.24)	–0.06 (0.67)	0.01 (0.91)
Field 3 (no-tillage for 90-cm row soybeans)						
Depth to no-trafficked hardpan (m)	0.42 (0.00)		0.30 (0.03)	–0.21 (0.10)	–0.03 (0.84)	0.24 (0.06)
Depth to in-row hardpan (m)		0.42 (0.00)	0.31 (0.03)	–0.26 (0.55)	–0.04 (0.76)	0.07 (0.59)
Depth to trafficked hardpan (m)	0.31 (0.03)	0.30 (0.03)		–0.17 (0.21)	–0.05 (0.69)	–0.12 (0.36)

<sup>a</sup> Brackets indicate probability values.

Table 5  
Descriptive semivariogram statistics for depth to hardpan

	Model	Nugget (m) <sup>2</sup>	Sill (m) <sup>2</sup>	Range (m)	Regression coefficient	(Sill-nugget)/sill
Field 1 (no-tillage with drilled soybeans)						
Depth to hardpan (m)	Spherical	0.000	0.009	12.4	0.430	1.000
Field 2 (conventional tillage for 90-cm row soybeans)						
Depth to no-trafficked hardpan (m)	Spherical <sup>a</sup>	0.000	0.004	13.0	0.000	1.000
Depth to in-row hardpan (m)	Spherical	0.000	0.004	26.4	0.460	1.000
Depth to trafficked hardpan (m)	Spherical	0.000	0.002	17.7	0.224	1.000
Field 3 (no-tillage for 90-cm row soybeans)						
Depth to no-trafficked hardpan (m)	Exponential <sup>a</sup>	0.002	0.008	31.2	0.376	0.857
Depth to in-row hardpan (m)	Spherical <sup>a</sup>	0.001	0.009	19.3	0.001	0.889
Depth to trafficked hardpan (m)	Spherical	0.000	0.011	43.2	0.721	1.000

<sup>a</sup> Models disregarded due to poor fit.

determined that the spherical model was the best fit for this data (Fig. 5). The regression coefficient provides an indication of how well the model fits the semivariogram data and was 0.43 for these data. Another indicator of spatial structure is the (sill-nugget)/sill value. With most of the models for hardpan depth having nuggets being predicted to be very close to zero, this parameter is mostly predicted to be near 1.0, which indicates a high degree of spatial structure.

One of the most useful items that result from spatial analysis is the range. This value is the approximate distance from one point to another within a field, which would be assumed to be correlated. Therefore, a small value would indicate a great amount of variability within a field. Large values indicate greater distances that samples could be obtained and the data still be correlated. For field 1, a relatively small value of 12.4 m was found (Table 5). This value indicates that samples to quantify the depth to the hardpan must

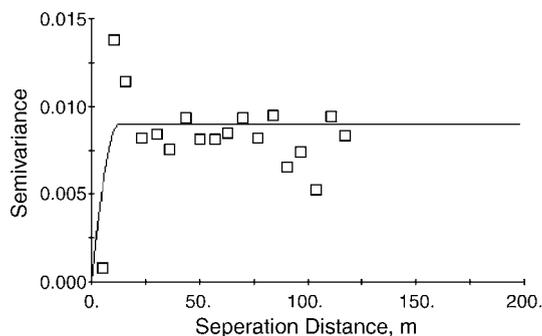


Fig. 5. Semivariogram for hardpan depth for field 1 showing fit of spherical model.

be obtained no greater than 12.4 m from each other. Samples obtained at greater distances than 12.4 m are assumed to not be correlated.

For field 2, Table 5 shows that the spherical models most closely fit the depth to hardpan data obtained in the in-row and the trafficked middle (Fig. 6). This was evidenced by regression coefficients of 0.46 for the in-row position and 0.224 for the trafficked position. However, for the no-trafficked middle, a zero correlation coefficient and visual inspection of the semivariogram indicates a poor fit for the spherical model. The (sill-nugget)/sill values were the same for the in-row position and the trafficked position. These values indicate a high degree of spatial structure and were close to 1.00 for both measurements, which was the best theoretical fit possible.

The range of the depth to hardpan for field 2 in the in-row position was 26.4 m (Table 5). This value is the approximate sampling distance from one point to another within a field from which similar hardpan depths would be expected. This value decreased for the trafficked middle to 17.7 m. These predictions indicate that the effect of in-row tillage likely reduced the natural and man-made variability present in this field to increase the sampling range for the in-row position.

The exponential model best fits the data for the no-trafficked position for field 3 with a correlation coefficient of 0.376 (Table 5 and Fig. 7). However, after visually examining the data, this model was discounted because no data points were found at small separation distances. A very poor correlation coefficient of 0.001 was obtained for a spherical model for

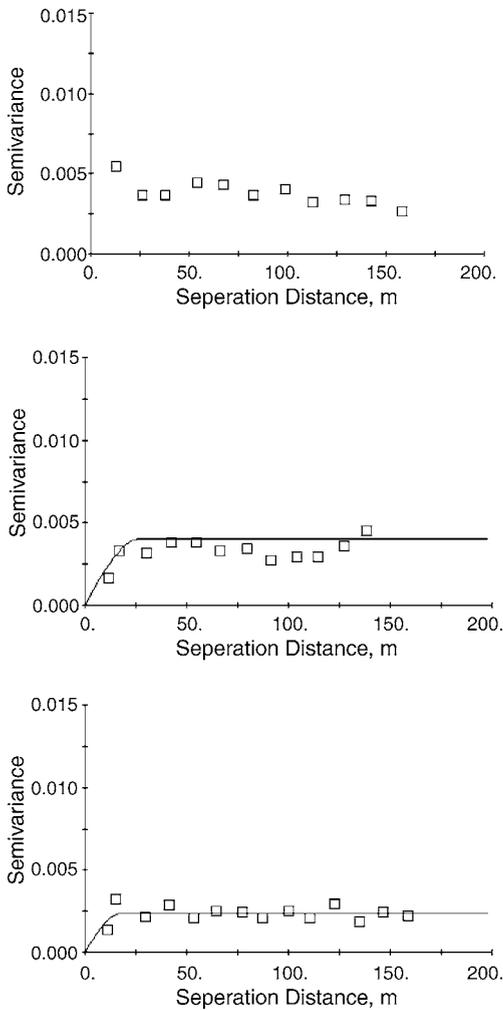


Fig. 6. Semivariogram for field 2 for hardpan depth for no-trafficked row middle showing no model fit of data (top), in-row position showing fit of spherical model (center), and trafficked row middle showing fit of spherical model (bottom).

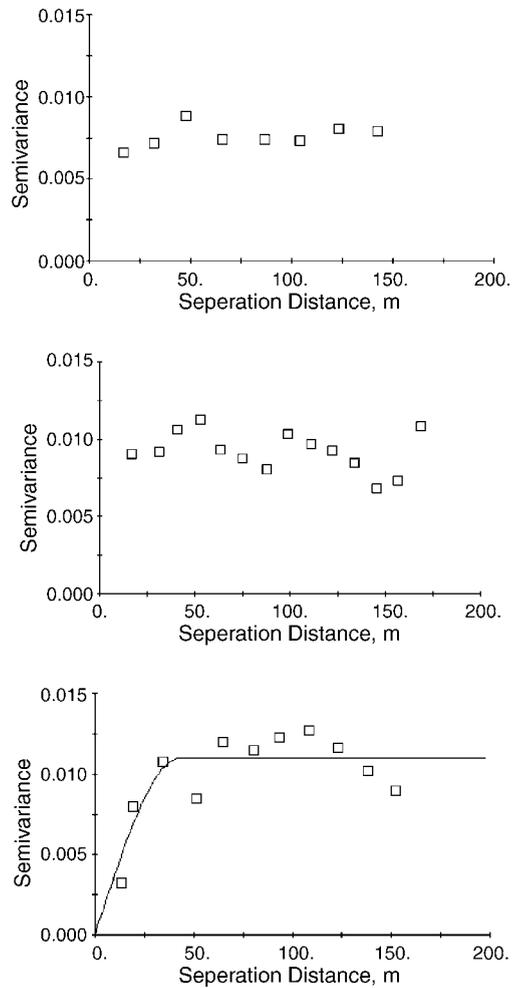


Fig. 7. Semivariogram for field 3 for hardpan depth for no-trafficked row middle showing no model fit of data (top), for in-row position showing no model fit of data (center), and for trafficked row middle for field 3 showing fit of spherical model (bottom).

the in-row position, so this model was also disregarded. The spherical model was the best fit for the trafficked position with a correlation coefficient of 0.721 being obtained. A reasonably high (sill-nugget)/sill ratio was found for the trafficked position. The greatest value of range for all positions and fields were obtained for the trafficked position (43.2 m).

Comparing the hardpan depths across the different fields for the different tillage and traffic conditions shows one obvious trend (Fig. 8). Field 2 has much shallower hardpans than both fields 1 and 3. This fact

is undoubtedly due to the tillage system for field 2, which has annually consisted of chiseling and disking. All surface soil structure was annually destroyed. Surface traffic and natural consolidation moved the hardpan layer significantly closer to the soil surface. These results concur with research reported by Raper et al. (1994) and Reeves et al. (1992) which found that in Coastal Plain soils, conventional tillage systems had shallower and denser hardpan profiles as compared to conservation tillage systems. These studies also found that crop yields were limited by these shallower

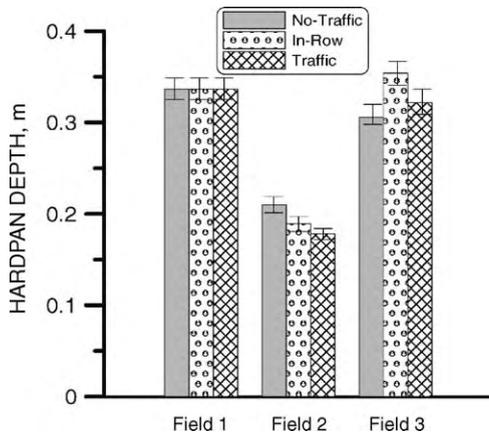


Fig. 8. Average hardpan depths measured across the fields for the different sampling positions with error bars indicating standard error. Note: all three positions were averaged for field 1.

hardpan profiles. In our study, in fields 1 and 3, where the cropping systems consisted of no-tillage, the hardpan depths were much deeper as compared to field 2 with the conventional tillage treatment. Little difference in hardpan depth was seen between fields 1 and 3, indicating that the random row pattern and random traffic that occurred in field 1 caused equivalent compaction to the 90-cm row spacing and relatively controlled traffic that was practiced in field 3.

The predicted range values shown in Fig. 9 may tell a somewhat different story, however. Fields 1 and 3,

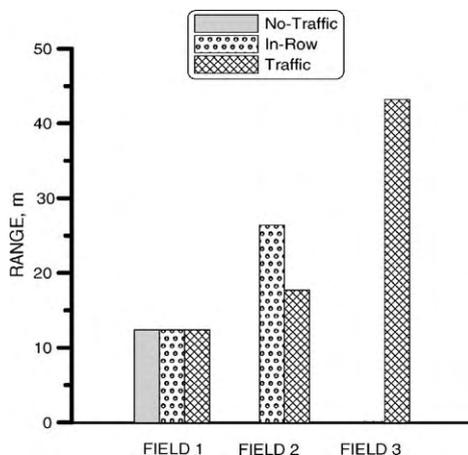


Fig. 9. Predicted ranges for the fields for different sampling positions. Note: all three positions were averaged for field 1.

despite having similar tillage systems, show dramatically different values of range despite having similar average hardpan depths. This may be due to the segregation of traffic that was practiced in field 3. In this field, traffic was routinely located in the same position several times a year, while in field 1, traffic was randomly located. The variation present in field 1 was much greater due to this random application of traffic while in field 3, the variation was minimized and a much larger value of range (43.2 m) was predicted for the trafficked middle. Considering the smaller values of range that were predicted for fields 1 and 2, it may be surmised that the depth to hardpan varied substantially in those fields and they were not likely to have been sampled adequately to determine their hardpan variation.

It may be deduced from modeling of the depth to hardpan that a substantial portion of this data was spatially related, particularly when traffic was segregated. Because of the predicted spatial relationship, it is therefore reasonable to consider altering the hardpan depth with some form of site-specific tillage that may be more efficiently applied than uniform tillage.

#### 4. Conclusions

An effective procedure to determine the depth to the hardpan was developed that consisted of obtaining cone index with the MPSCP, analyzing the cone index profile for shallow peak values, and determining the value of the shallowest peak where multiple excessive values of cone index occurred. However, the distance between samples should be reduced to enable increased precision for fields managed with random wheel traffic or with conventional tillage systems.

Conventional tillage systems were found to bring the hardpan significantly closer to the soil surface in all three row position. In trafficked row middles, conventional tillage moved the hardpan closer to the soil surface by 0.144 m, in no-trafficked row middles, conventional tillage moved the hardpan closer to the soil surface by 0.094 m, and directly beneath the rows, conventional tillage moved the hardpan closer to the soil surface by 0.165 m. Depth to hardpan in no-till fields subjected to random traffic or where traffic was segregated showed little difference.

The effect of traffic on the predicted values of range was minimal for conventional tillage systems. The predicted range for the depth of the hardpan was found to be decreased from the trafficked row position (26.4 m) as compared to the in-row position (17.7 m) for the conventionally tilled field. However, when tillage was not routinely practiced, traffic was found to have a large effect on the predicted range. Comparing the randomly trafficked field and the no-tilled field with 90-cm row patterns showed that a much more uniform soil condition was found in the no-till field in the trafficked row middles with a predicted range of 43.2 m as compared to the predicted range of 12.4 m in the randomly trafficked field.

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