SOIL DRYING EFFECTS ON SPATIAL VARIABILITY OF SOIL HARDPAN ATTRIBUTES ON PACOLET SANDY LOAM SOIL

M. Z. Tekeste, R. L. Raper, E. B. Schwab, L. Seymour

ABSTRACT. *Soil hardpans found in many of the southeastern U.S. soils reduce crop yields by restricting the root growth. Site-specific soil compaction management to alleviate this problem requires determination of the spatial variability and mapping of soil hardpans. The objective of this study was to determine the spatial variability of soil hardpan as influenced by soil moisture. Geo-referenced soil cone index measurements were taken in 200 grid cells (10 m × 10 m grid cell size) on Pacolet sandy loam soil (fine, kaolinitic, thermic Typic Kanhapludults) in Auburn, Alabama, on 29 June and 25 August 2004, representing "wet" and "dry" soil measurement dates. Core samples were also taken in 5 cm depth increments up to a depth of 65 cm for soil moisture and bulk density determinations. Statistical and geostatistical methods were used for the data analysis. In the 0-35 cm depth, the soil moisture had dried significantly by 25 August 2004 (dry) as compared to the soil moisture on 29 June 2004 (wet; $P < 0.0001$). An isotropic spherical semivariogram model best fit the semivariances of the peak cone index for wet ($R^2 = 0.98$) and dry ($R^2 = 0.97$) soil conditions. Soil drying increased the peak cone index and the maximum semivariance value (sill). Small but statistically significant differences ($P < 0.0001$) were also observed on the depth to the peak cone index as the soil dried in the 0-35 cm depth. In the dry soil condition, the semivariances of the depth to the peak cone index were nearly constant over the separation distances, suggesting that the depth to the hardpan did not exhibit substantial spatial dependence.*

Keywords. *Bulk density, Cone index, Hardpan, Semivariogram, Soil compaction, Soil moisture.*

Soil compaction has been recognized as one of the major problems in crop production (Soane and Van Ouwerkerk, 1994). Soil hardpan layers found in many southeastern U.S. soils restrict root growth, which in turn limits crop yield, especially during drought (Taylor and Gardner, 1963; Camp and Lund, 1968). These excessively compacted layers may also reduce soil aeration and soil water infiltration and could accelerate erosion and runoff.

Farmers annually apply uniform-depth tillage to disrupt this root-restricting layer for optimum root growth (Raper et al., 2005b; Busscher et al., 2005). Many researchers have found that the soil hardpan layers exhibit spatial variability within a field (Fulton et al., 1996; Kilic et al., 2003; Raper et al., 2005a). Studies have also shown that site-specific tillage has potential for reducing tillage energy and fuel consumption as compared to conventional uniform-depth tillage (Fulton et al., 1996; Raper et al., 2000; Gorucu et al., 2001; Raper et al., 2005b). Raper et al. (2000) estimated about 50% reduction in energy requirements for shallow tillage (approx. 18 cm) as compared to deep tillage (approx. 33 cm). Gorucu et al. (2001) found that approximately 75% of the test area required tillage operations shallower than the commonly used tillage depth for Coastal plain soils.

Site-specific tillage is a component of precision agriculture management strategy that employs detailed site-specific soil and crop information to precisely manage the production inputs (Zhang et al., 2002). Site-specific tillage management requires accurate soil compaction records and within-field variability, hence optimizing the tillage input within the field zones where root-limiting soil compaction exists. The success of site-specific tillage depends on the availability of economical, rapid, easy, and precise soil strength sensing technology, management of within-field variability, accuracy of field positioning, and controlling the application of real-time or prescribed site-specific tillage.

The soil cone penetrometer has been used widely to assess soil compaction and root penetration resistance, and to predict trafficability and bearing capacity for foundations (Perumpral, 1987; Raper et al., 2005b). The soil cone penetrometer measures the soil penetration resistance, reported as cone index, as a function of depth (*ASAE Standards*, 2004a, 2004b). The influence of soil factors, mainly soil moisture, on the cone index reading and the difficulty of data interpretation in layered soils of varying soil moisture and soil strength are the main challenges in using the soil cone penetrometer for site-specific tillage (Gill and VandenBerg, 1968; Sanglerat, 1972; Mulqueen et al., 1977; Ayers and Perumpral, 1982; Clark, 1999; Raper et al., 2005a). Ayers and Perumpral (1982) studied the relationships of soil moisture, bulk density, and cone index on artificial soils obtained by mixing different quantities of zircon, sand, and clay. According to their report, the cone index decreased with increasing

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Table 1. Descriptive statistics for the soil physical and chemical properties of a Pacolet sandy loam soil.

Soil Parameter	Depth (cm)	Mean	Median	SD	CV (%)	Min.	Max.	95% CI	Kurtosis	Skewness
Soil moisture (% d.b.)										
29 June 2004	0-35	11.25	11.01	2.30	20.40	8.54	17.52	10.42-12.08	2.57	1.59
	35-65	15.80	15.51	3.39	21.46	14.58	17.03	10.71-22.02	0.36	-0.72
25 August 2004	0-35	9.83	9.11	2.17	22.08	7.36	14.84	9.05-10.61	0.40	1.02
	35-65	17.82	17.09	4.43	24.88	16.22	19.42	11.13-23.23	-0.08	-1.58
Cone index (MPa)										
29 June 2004	0-35	2.61	2.63	0.54	20.56	1.75	4.00	2.42-2.81	0.74	1.11
	35-65	3.93	3.86	0.76	19.25	2.86	5.78	3.65-4.20	0.91	0.65
25 August 2004	0-35	2.87	2.83	0.72	25.15	1.62	4.56	2.61-3.13	0.50	0.38
	35-65	2.97	2.91	0.90	30.23	1.48	4.72	2.64-3.29	0.20	-0.40
Bulk density (Mg m^{-3})	0-35	1.39	1.41	0.04	3.11	1.29	1.48	1.38-1.41	-0.67	-0.03
	35-65	1.36	1.37	0.08	6.01	1.22	1.50	1.33-1.39	0.06	-1.07
Soil organic carbon (%)	0-35	0.70	0.72	0.13	19.01	0.42	0.90	0.65-0.75	-0.24	-1.21
	35-65	0.37	0.31	0.14	36.89	0.23	0.71	0.32-0.42	0.94	0.06
Clay (%)	0-35	8.63	6.79	5.36	62.11	2.14	26.07	6.70-10.56	1.20	1.90
	35-65	25.74	27.29	12.80	49.74	3.33	45.83	21.12-30.36	-0.30	-0.87
Silt (%)	0-35	14.76	14.73	2.01	13.62	10.18	18.21	14.03-15.48	-0.40	0.17
	35-65	13.08	12.92	3.86	29.49	5.00	18.96	11.67-14.47	-0.33	0.03
Sand (%)	0-35	76.61	77.86	5.92	7.73	59.11	84.11	74.48-78.75	-0.80	0.71
	35-65	61.18	59.27	12.96	21.19	42.71	91.67	56.51-65.85	1.00	0.97

soil moisture content. The effect of bulk density on cone index was dependent on soil moisture; cone index increased with bulk density at low soil moisture, but at high soil moisture cone index was less dependent on bulk density. Gill and VandenBerg, (1968) and Mulqueen et al. (1977) also found that a soil wedge formed in front of the cone could erroneously increase the soil penetration resistance. In precision tillage, a precise detection of soil hardpan is important because errors of a few centimeters could cause large variations in accurately locating the soil hardpan and recommending site-specific tillage depth.

Spatial variability analysis of soil compaction and application of site-specific tillage management has not progressed like the precision/site-specific application of fertilizers and chemicals due to lack of appropriate technology or procedures to characterize soil physical properties. Hence, research is needed to accurately characterize the soil hardpan and define its spatial pattern as influenced by soil moisture at the landscape level for site-specific tillage applications. Analysis of spatial variability and mapping of soil hardpans may further improve our understanding of soil compaction variability and the precision tillage decision making process for southeastern U.S. soils.

Therefore, our objectives were to: (1) determine the effect of soil moisture on the peak cone index and its depth and (2) to determine the field spatial variability and spatial structure of the peak cone index and the depth to the peak cone index as influenced by soil moisture.

Materials and Methods

Site Description

The experiment was conducted during summer 2004 at the Auburn University experimental field plot in Auburn, Alabama, located at 32° 21′ 15″ N and 85° 17′ 30″ W. The field was in a fallow period with no tillage applied for the previous three years. Pacolet sandy loam (fine, kaolinitic, thermic Typic Kanhapludults) is the dominant soil series in the site. The area receives an average annual precipitation of 1339 mm, and the mean annual temperature is 18°C (Mitchell et al., 2008). The soil physical and chemical properties of the site are shown in table 1.

Experimental Design

The field was divided into 200 grid cells of 10 m × 10 m each, covering an area of 2 ha. Because the objective of the experiment was to determine the spatial variability of soil hardpan, sampling patterns associated with crop management and trafficking were not considered. A tractor-mounted multiple-probe soil cone penetrometer (MPSCP) that has five probes was used to acquire cone index data at 25 Hz sampling rate (*ASAE Standards*, 2004a, 2004b; Raper et al., 1999). Two sets of cone index measurements were obtained in each of the grid cells using the tractor-mounted MPSCP equipped with GPS for field positioning. A dual-frequency RTK GPS receiver (AgGPS 214, Trimble Navigation Ltd., Sunnyvale, Cal.) was also used to obtain elevation data across the field. Soil core samples for soil moisture and bulk density determinations were also collected at 5 cm depth increments to a depth of 65 cm in two replicates at 54 randomly selected grid cells near where the cone indices were sampled (fig. 1)

The soil core samples were oven dried at 105°C for 72 h to determine gravimetric soil moisture and bulk density. Soil particle size distributions and soil organic matter were also analyzed on 32 soil cores, which were randomly selected subsamples of the total soil cores. The soil particle size distributions analysis was carried out at the Auburn University Soil Testing Laboratory (Auburn, Ala.) using the hydrometer method. The soil organic carbon (SOC) was analyzed at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama, using the dry combustion method for total carbon and nitrogen (Truspec model 2003, Leco Corp., St. Joseph, Mich.). The cone index measurement and the soil core sampling were carried out simultaneously within an approximate 24 h period. Within this sampling period, there were no rainfall events, so the risk of soil moisture differences was minimized. The measurements were obtained on 29 June and

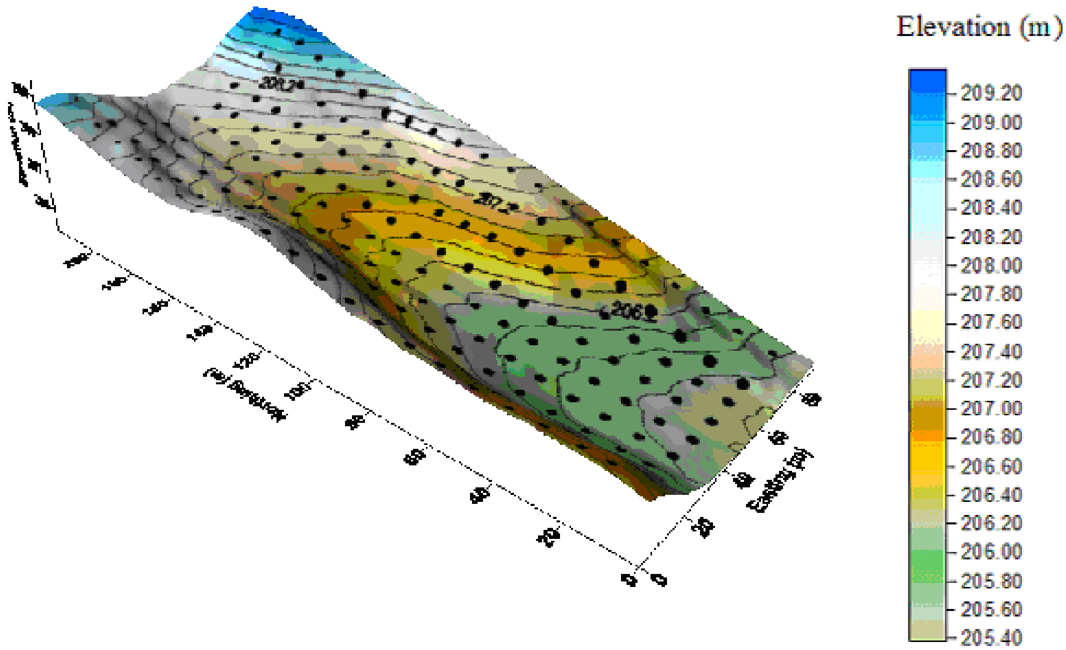

Figure 1. Elevation of the sampling field of Pacolet sandy loam soil. Dots indicate the sampling points for cone index measurement.

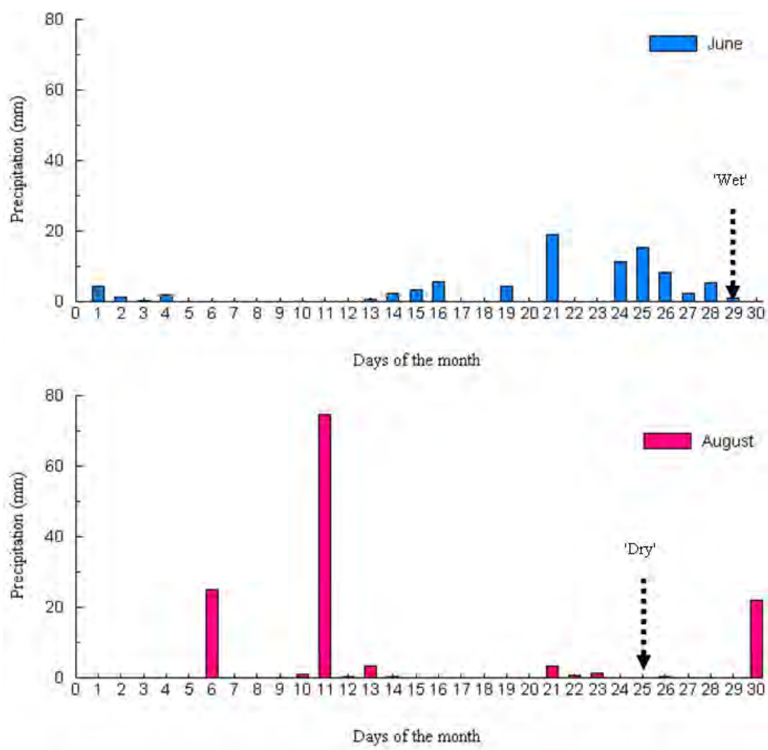

Figure 2. Precipitation data for June 2004 (wet measurement date) and August 2004 (dry measurement date) for Auburn, Alabama.

25 August 2004, representing “wet” and “dry” soil moisture conditions, respectively. The sampling dates were chosen based on rainfall data obtained from the Auburn University weather experimental station located near the field site (fig. 2).

Peak cone index and depth to the peak cone index were considered as soil hardpan characterizing attributes and were determined by analyzing the change in cone index values with depth. In a previous study, using the depth to maximum (peak) cone index as an indicator for soil hardpan depth appeared to provide effective site-specific tillage in terms of improved corn yield, reduced draft, and lower fuel consumption on southeastern soils (Raper et al., 2005b). The analyses for hardpan detection were carried out on the cone index data averaged over the five-probe data set interpolated at 1 cm depth increments. Visual inspection of the 200 cone index-depth profile data revealed there were two peaks. The first peak cone index that occurred in the depth range of 0 to 35 cm was considered as the root-restricting layer in the soil profile. A maximum value of the cone index-depth profile within this depth range (0-35 cm) was determined for the peak cone index.

In developing the algorithm program written in MATLAB code to define the peak cone index in the shallow depth (0-35 cm), instantaneous slope values (change in cone index per depth) were calculated. As the slope values changed abruptly from increasing to decreasing (negative) trend, the peak cone index and its depth were determined based on the following algorithm procedures: (1) if three consecutive negative slope values were obtained, then the cone index and depth value at the first slope value were considered as peak cone index and its depth; (2) if the first test failed, then two negative slopes were considered in deciding the peak cone index, with the data values of the first negative value being used to define the soil hardpan; and (3) if the second test failed, three consecutive zero slope values were considered. These zero slope values indicated that the cone index increased until it reached the soil hardpan characterizing the peak cone index value, and the cone index profile curve flattened with depth. The data set at the first zero slope value characterized the peak cone index and depth to peak cone index. Statistical comparisons of soil drying effects on soil hardpan attributes were made using the GLM procedure with an alpha (α) level of 0.05 in SAS (Release 8.02, SAS Institute, Inc., Cary, N.C.).

Geo-statistical procedures PROC VARIOGRAM and PROC NLIN were used to quantify the isotropic spatial variability and to construct theoretical semivariogram models for the soil hardpan attributes, and maximum bulk density and its depth.

A semivariogram function was determined for each variable according to equation 1 (Isaaks and Srivastava, 1989):

$$\gamma(h) = \frac{1}{2N(h)} \left\{ \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 \right\} \quad (1)$$

where $\gamma(h)$ is the semivariance for interval class h, $N(h)$ is the number of pairs separated by lag distance (separation distance between sample positions), $Z(x_i)$ is a measured variable at spatial location i, and $Z(x_i + h)$ is a measured variable at spatial location $(i + h)$. The spatial structure, $(\gamma(h) = C_0 + C)$, of a semivariogram can be described by three basic parameters: nugget effect (C_0), sill ($C_0 + C$), and range. The nugget effect is the variations occurring at a scale finer than the sampling interval that could be due to sampling errors, microscale variability, and/or measurement errors. The sill (total variance) is the asymptote of the semivariogram model. The range is a distance at which the semivariogram levels off at the sill, and it indicates the distance over which the pairs of values of the variable are spatially dependent.

Spherical, exponential, and linear variogram models were considered in selecting the best-fitting model based on the values of weighted residual sums of squares, regression coefficient (R^2), and relative spatial structure indicator (scale/sill). Scale is the amount of semivariance after the nugget is removed (sill-nugget). A model with the largest R^2 value, the smallest weighted residual sums of squares at the end of the iteration procedure, and a value of the spatial structure indicator close to 1.0 was considered the best-fitting semivariogram model. A scale to sill ratio close to 1 indicates that the nugget effect is negligible, implying a better spatial structure (Raper et al., 2005a). Once the best theoretical semivariogram model was selected, ordinary kriging was used to interpolate values at unsampled locations. Using the gridded data, contour maps were created in Surfer (version 8.00, Golden Software, Inc., Golden, Colo.).

Results and Discussion

Soil Moisture

The soil moisture distribution varied by depth (fig. 3; P < 0.0001). The normality of residuals assumption, a requirement for analysis of variances, was fairly maintained on soil moisture and other soil variables for soil depth classes of 0-35 and 35-65 cm separately. At the soil depth range of 0-35 cm, the soil moisture sampled on 29 June 2004 (11.25%) was significantly higher than the soil moisture (9.83%) sampled on 25 August 2004 (P < 0.0001). For convenience, the soil moisture conditions were assumed "wet" and "dry" for the measurement dates of 29 June and 25 August 2004, respectively. At the deeper profile (35-65 cm), the soil moisture trend was reversed (fig. 3). The soil moisture (17.82%) for the second measurement date (25 August 2004) was significantly higher than the soil moisture (15.80%) for 29 June 2004 (table 1, P < 0.0001). This may indicate a wetting front moving downward through the soil profile. The skewness value (table 1) and frequency distribution (not shown) showed that the soil moisture variability for the shallow depth appeared to be skewed to the left, and the skewness was higher in the wet soil than in the dry soil. In the wet condition, the skewness and coefficient of variation values at the deeper profile were relatively small, indicating that the subsoil soil moisture distribution tended to be symmetrically distributed around the mean.

Bulk Density and Cone Index Descriptive Statistical Results

Bulk Density

The average bulk density profile for the field is shown in figure 4. The bulk density varied by depth significantly (P < 0.0001), with the maximum bulk density (1.54 Mg m^{-3}) located at 20.94 cm depth (table 2). There was one outlier from the bulk density samples due to a large stone found inside the cylinder, and thus maximum bulk density based hardpan characterization was done on 53 bulk density data points. The skewness (−0.49) and coefficient of variation (0.1) showed that the distribution of bulk density was nearly symmetrical around the mean. There were no statistically significant differences in the bulk density values by measurement dates (P = 0.056), indicating that the variations in cone index values were not attributed to the differences in bulk density between the two measurement dates.

Peak Cone Index and Depth to Peak Cone Index

The cone index-depth slope algorithm was able to identify the hardpan layers on 200 cone index profile samples for the dry soil moisture condition; however, for the wet soil condition, the algorithm missed peak cone index (table 3). The average peak cone index was significantly higher for the dry soil condition than for the wet soil condition (table 3, P < 0.0001). As shown in figure 5a, the relative frequency distribution of the peak cone index for the dry soil condition appeared to shift to the right as compared to the peak cone index distribution for the wet soil condition. By taking cone index measurements at the drier soil condition (25 August 2004), the average peak cone index increased by 28%. This signifi-

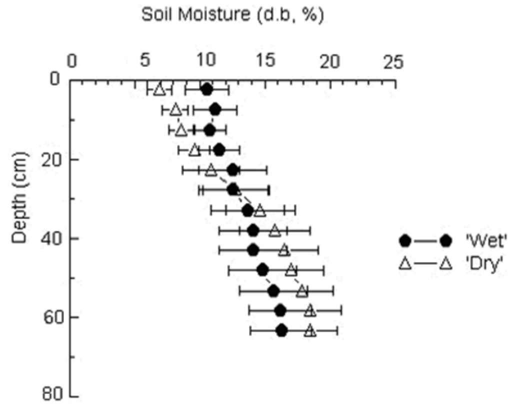

Figure 3. Soil moisture profile for the two measurement dates of 29 June 2004 (wet) and 25 August 2004 (dry). The horizontal bars indicate standard deviations.

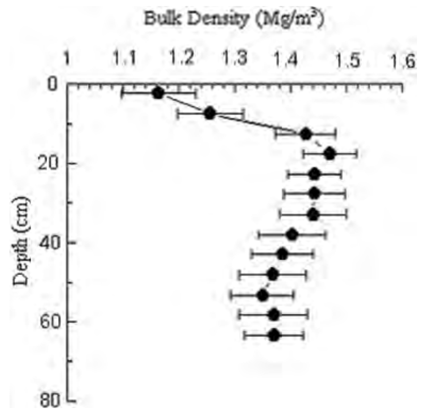

Figure 4. Bulk density profile averaged over the two measurement dates of 29 June and 25 August 2004. The horizontal barsindicate standard deviations.

cant increase in the soil strength was attributed to soil drying effects as the bulk density, another soil variable that can also influence cone index (Ayers and Perumpral, 1982), did not vary by measurement dates.

The relative frequency distribution of the depth to the peak cone index (fig. 5b) indicated a slight shift to the left (small depth values) as a result of soil drying. Even though the differences in the depths appeared to be small, there was strong statistical evidence that the depth to the peak cone index decreased by soil drying (table 3, $P < 0.0001$). The depth to the

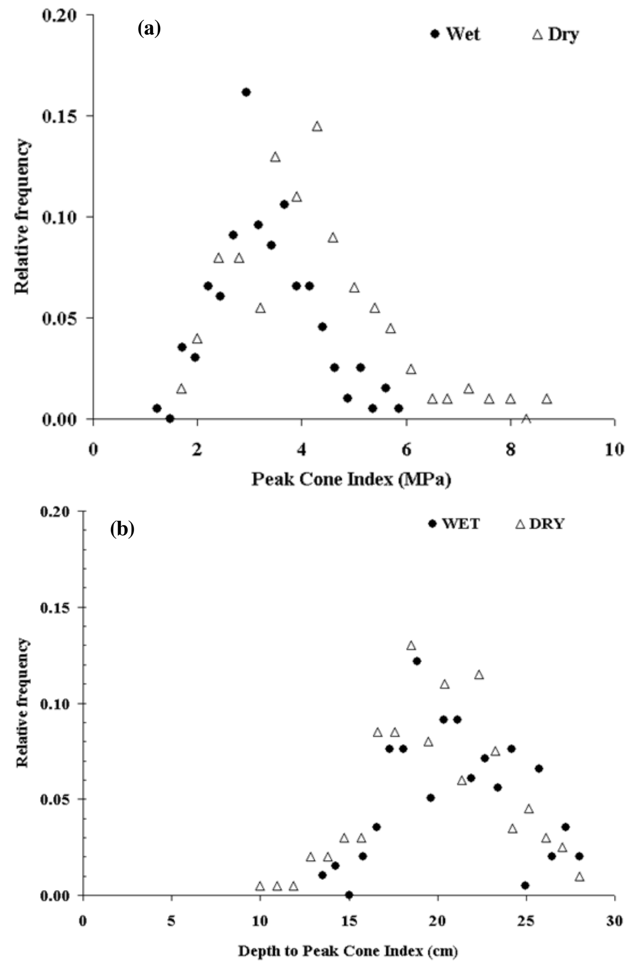

Figure 5. Relative frequency distribution of (a) peak cone index (MPa) and (b) depth to peak cone index for the twomeasurement dates of 29 June 2004 (circles) and 25 August 2004 (triangles).

peak cone index occurred within the shallow depth range (0-35 cm) where the soil moisture significantly decreased by sampling date (table 3). Tekeste et al. (2008) reported similar influences of soil drying on the peak cone index and the soil hardpan depth in a Norfolk sandy loam soil bin study.

The hardpan layer in the Pacolet sandy loam soil was detected from the bulk density and cone index measurements. From the descriptive statistical analysis shown in tables 2 and

Table 2. Descriptive statistics for the maximum bulk density and the depth to the maximum bulk density.

	No. of Values	Mean	Median	SD	CV	Min.	Max.	95% CI	Kurtosis	Skewness
Maximum bulk density (Mg m^{-3})	53	1.54	1.54	0.06	0.04	1.43	1.65	1.52-1.55	-1.00	0.05
Depth to maximum bulk density (cm)	53	20.94	5.66	0.27	31.99	12.7	27.94	19.38-22.50	-1.36	-0.06

Table 3. Descriptive statistics of the peak cone index and the depth to the peak cone index for the two measurement dates of 29 June and 25 August 2004.

	No. of Values	Mean	Median	SD	CV	Min.	Max.	95% CI	Kurtosis	Skewness
29 June 2004										
Peak cone index (MPa)	198	3.29	3.2	0.88	0.27	1.23	5.86	3.23-3.36	0.11	0.42
Depth to peak cone index (cm)	198	21.08	21	3.36	0.16	13.5	28	20.84-21.31	-0.70	0.14
25 August 2004										
Peak cone index (MPa)	200	4.12	3.99	1.36	0.33	1.68	8.69	4.03-4.23	0.81	0.78
Depth to peak cone index (cm)	200	20.08	20	3.56	0.18	10	28	19.83-20.33	-0.04	-0.06

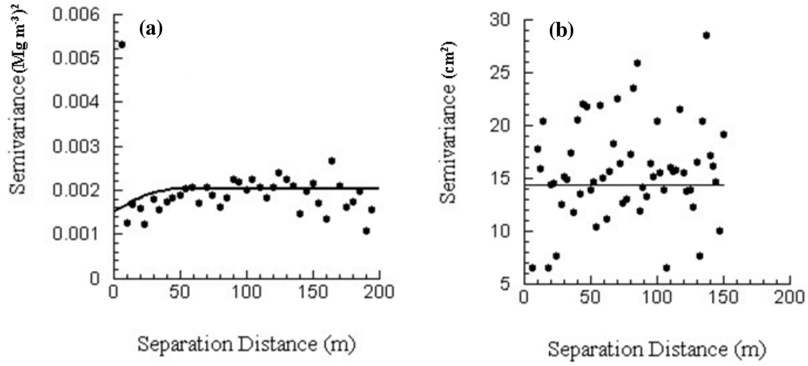

Figure 6. Semivariances for (a) maximum bulk density with theoretical exponential semivariogram model fit and (b) depth to maximum bulk density with pure nugget semivariogram model fit.

3, the depth to the peak cone index determined from the cone index data both in the wet and dry soil conditions fell within the 95% confidence interval of the depth to the maximum bulk density [lower limit (LL) = 19.38 cm ; upper limit (UL) = 22.50 cm]. Conventionally, farmers in the southeastern U.S. subsoil to a depth of 30 to 50 cm (Raper et al. 2000); however, the average hardpan depth was detected at 21.08 ±3.36 cm under wet conditions and 20.08 ±3.56 under dry conditions on Pacolet sandy loam soils. Application of site-specific variable depth tillage to such shallow hardpan layers on Pacolet sandy loam soils can help to save draft and energy consumption. Raper et al. (2000) reported shallow depth of tillage (18 cm) resulted approximately 50% saving in draft and energy as compared to deep tillage (33 cm). Varying tillage depth to account for the small differences (<3 cm) in the hardpan depth resulting from soil drying effects may not provide substantial benefits. The result on Pacolet sandy loam soils suggested cone index measurement for hardpan depth detection can be carried out in both wet and dry soil moisture conditions. Interpretation of the magnitude of cone index of hardpan layer (peak cone index) obtained at wet and dry soil moisture conditions; however, should consider the effect of soil drying.

Bulk Density and Cone Index Geospatial Analysis Results

Selection of sampling distance intervals is important in ensuring the quality of spatial variability analysis and interpolation of points for unsampled locations using geostatistical techniques (Nielsen and Wendroth, 2003). A sampling interval distance less than the range, or the distance over which pairs of observations exhibit spatial dependence, was considered appropriate in grid sampling. The 10 m transect distance used in the cone index sampling was less than the minimum spatial range (12.4 m) that Raper et al. (2005a) estimated for the depth to soil hardpan on silty upland soils of northern Mississippi.

Maximum Bulk Density and Depth to Maximum Bulk Density

The variability of the maximum bulk density (fig. 6a) was best fit by the exponential semivariogram model (R^2 = 0.96 and a spatial structure indicator of 0.3). A pure nugget semivariogram model best fit the semivariances of the depth to the maximum bulk density with a sill value (14.3) nearly half of the sample variance (31.99) (fig. 6b). The semivariances appeared to be nearly constant over the entire separation distances, indicating that the variability of the depth to the maximum bulk density was spatially independent. The depth to the soil hardpan, as determined from the depth to the maximum bulk density, varied across the field (fig. 7).

Peak Cone Index and Depth to Peak Cone Index

The spherical semivariogram was the best-fitting model to the estimated semivariances of the peak cone index for both the wet and dry soil conditions (table 4 and fig. 8). The sill for the dry soil condition was nearly twice the value for the wet soil condition. At a distance greater than the range, the square of the differences between pairs of peak cone index values would be approximately the same as the sample variance (twice the sill). Isaaks and Srivastava (1989) explained that increasing the sill has less effect on the value of kriging

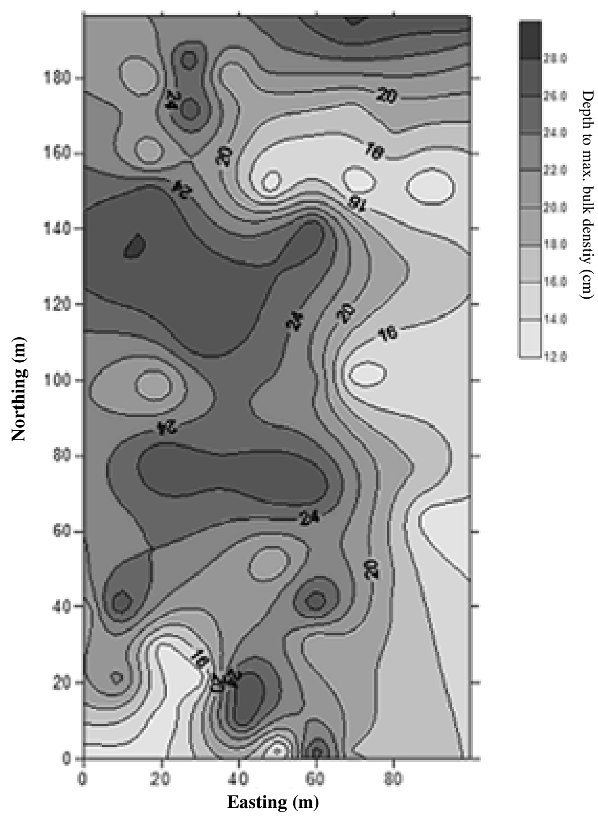

Figure 7. Contour map of the depth to the maximum bulk density on Pacolet sandy loam soil.

Table 4. Descriptive semivariogram statistics for the peak cone index and the depth to the peak cone index for the two measurement dates of 29 June and 25 August 2004.

	Model	Nugget[a]	Sill[a]	Range (m)	Regression Coefficient (R)	(Sill-Nugget)/Sill Coefficient	WSS[b]
29 June 2004							
Peak cone index (MPa)	Spherical	0.26	0.4	44	0.98	0.36	322
Depth to peak cone index (cm)	Exponential	0	5.73	47	0.99	1	259
25 August 2004							
Peak cone index (MPa)	Spherical	0.15	0.93	26	0.97	0.84	505
Depth to peak cone index (cm)	Pure Nugget	5.8			0.98	0.15	151

[a] Units for nugget and sill are MPa^2 for peak cone index and cm^2 for depth to peak cone index.
[b] WSS = Weight Residual Sums of Squares.

estimates for the sample site. The range for the dry soil condition (26 m) was smaller than for the wet soil (44 m). The smaller range value indicates that soil drying reduced the distance over which pairs of peak cone index values remain spatially dependent. At the dry soil condition, the spatial continuity of the magnitude of soil hardpan on Pacolet sandy loam could be captured by having sampling distances less than 26 m. The maps for the peak cone index of the field (not shown) indicate that the values exceeded the critical root-limiting cone index value of 2 MPa (Taylor and Gardner, 1963) in most parts of the field, with the values being higher for the dry soil condition. In conditions where a maximum cone index is found within 35 cm of the soil surface and higher cone index (>2 MPa) re-occurs below 35 cm, application of site-specific tillage on shallower depth hardpan appeared to be beneficial, as found by Raper et al. (2005b). They found that application of site-specific subsoiling to break a soil hardpan located at the 25-35 cm depth provided reduced draft (26%) and fuel (27%) consumption as compared to deep tillage (45 cm) on the same field plots.

Similar to the peak cone index spatial variability, the different soil moisture levels also affected the estimated semivariances and the semivariogram models for the depth to the peak cone index (table 3 and fig. 9). An exponential semivariogram model explained the spatial variability of the depth to the peak cone index with a scale to sill ratio of 1, which indicates a well-defined spatial structure. For the dry soil condition, the semivariances appeared to be spatially uncorrelated in that the values were nearly similar over the separation distances (fig. 9b). The contour maps in figure 10

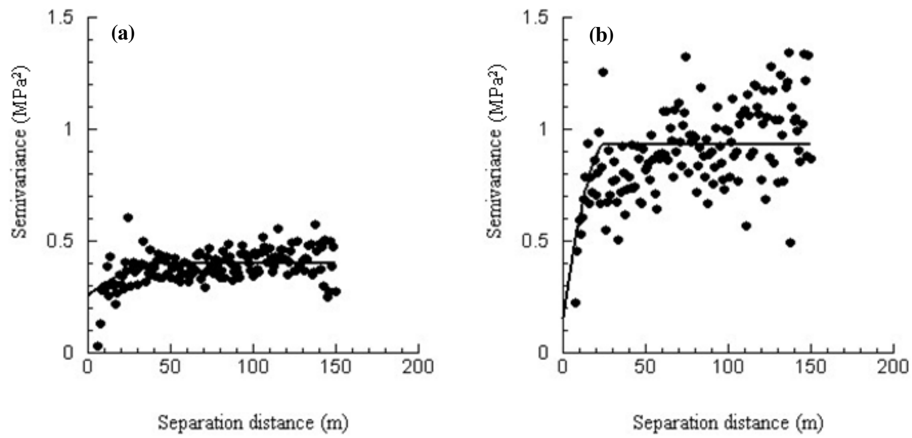

Figure 8. Semivariances for the peak cone index and spherical theoretical model fits for the two measurement dates of (a) 29 June 2004 and (b) 25 August 2004.

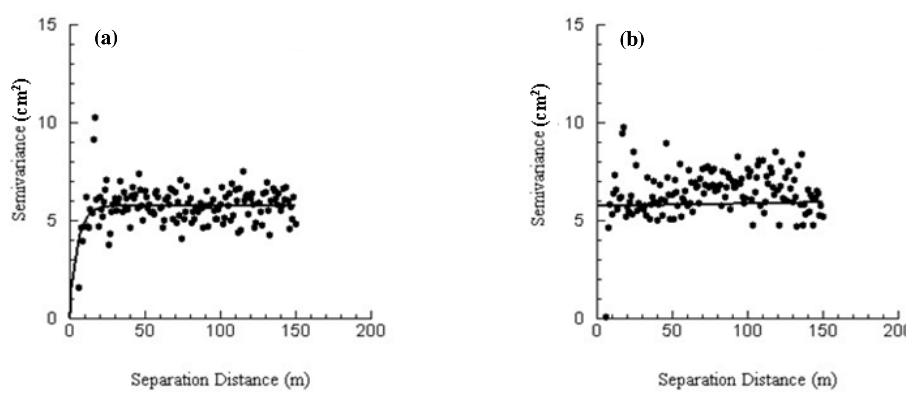

Figure 9. Semivariances for the depth to peak cone index and exponential theoretical model fit and pure nugget model fit for the measurement dates of (a) 29 June 2004 and (b) 25 August 2004.

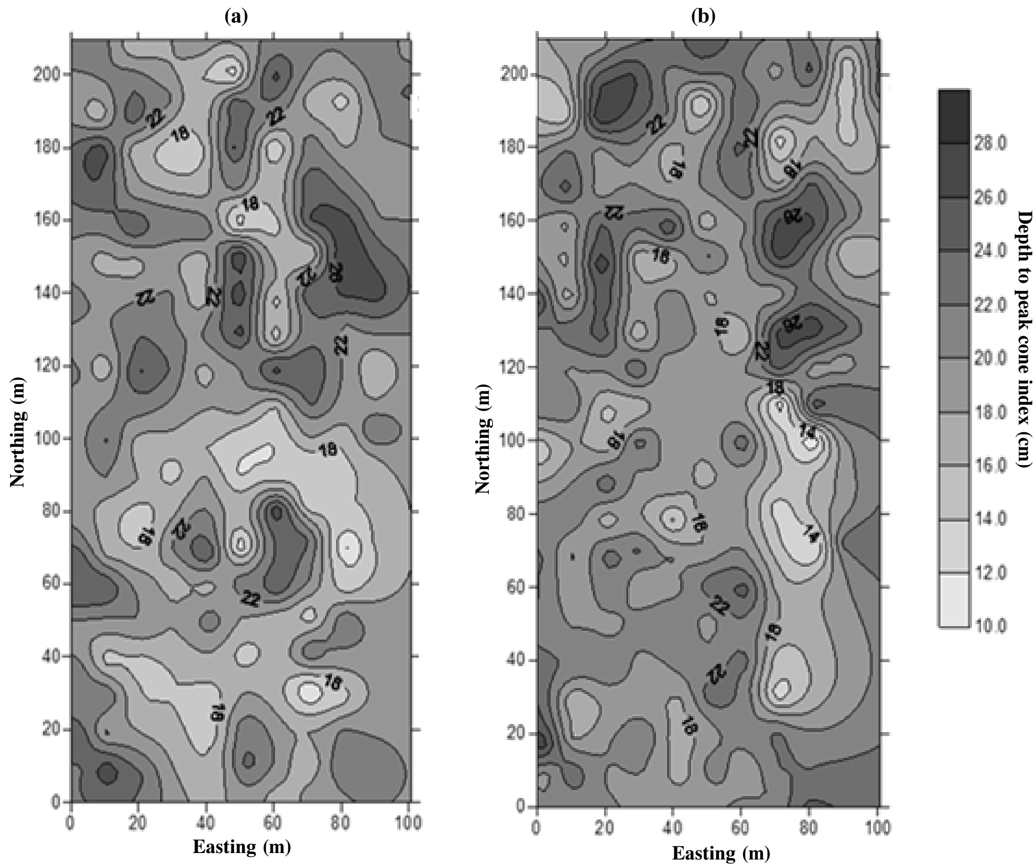

Figure 10. Contour map of the depth to peak cone index on Pacolet sandy loam soil for the two measurement dates of (a) 29 June 2004and (b) 25 August 2004.

show that the depths to the peak cone index appeared to be shallower for the dry condition in most parts of the field.

CONCLUSIONS

Soil drying increased the magnitude and spatial variability of the peak cone index on Pacolet sandy loam soil. The spatial pattern of the peak cone index was explained by a spherical semivariogram model for wet and dry soil conditions. An exponential semivariogram model best fit the spatial variability of the depth to the peak cone index in the wet soil condition; however, in the dry soil condition, the variability in the depth to the peak cone index was nearly constant over the separation distances. The results suggested that soil moisture variations not only affected the values of the soil hardpan attributes (peak cone index and depth to the peak cone index) but also their estimated spatial structures, which in turn may affect the prediction and soil sampling procedure.

The large relative frequency of peak cone index values that exceeded 2 MPa, a root-limiting value, indicated that most of the field on Pacolet sandy loam soils required tillage. However, considerable spatial variation in the soil hardpan depth was observed within the field, as shown from the depth to the maximum bulk density or the depth to the peak cone index values. Thus, application of depth-specific tillage according to within-field variation of soil hardpan depths might be advantageous. Further research may be needed to evaluate the effects on crop yield and fuel consumption of variable depth-specific tillage that varied on the soil hardpan depths in wet and dry soil moisture conditions.

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