Spatial Variability of Soil Cone Penetration Resistance as Influenced by Soil Moisture on Pacolet Sandy Loam Soil in the Southeastern United States

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Abstract

Soil hardpans found in many of the Southeastern USA 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 X 10 m^2 grid cell size) on Pacolet sandy loam soil (*Fine, kaolinitic, thermic Typic Kanhapludults*) in Auburn, AL (USA) on June 25, 2004 and August 29, 2004 representing wet and dry soil measurement dates. Core samples were also taken in 5.08 cm depth increments up to a depth of 66.04cm for soil moisture and bulk density determinations. Statistical and geostatistical methods were used for the data analysis. In the 0-30 cm depth, the soil moisture had dried significantly by August 29, 2004 (Dry) as compared to the soil moisture on June 25, 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 predicted depth to the peak cone index as the soil dried in the 0-30 cm depth. In the dry soil condition, the semivariances of the predicted depth to the peak cone index were nearly constant over the separation distances suggesting that the depth to the hardpan did not exhibit spatial dependence.

Introduction

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 US soils restrict root growth that in turn limits crop yield, especially during drought (Taylor and Gardner, 1963; and Camp and Lund, 1968). These excessively compacted layers may reduce soil aeration and soil water infiltration that could accelerate erosion and runoff. Farmers annually apply uniform depth tillage to disrupt this root restricting layer for optimum root growth environment (Busscher and Bauer, 2003 and Raper et al., 2004a). Many researchers have found that the soil hardpan layers exhibit spatial variability within a field (Fulton et al., 1996; Kenan et al., 2003; Raper et al., 2004b). Studies have also suggested that site-specific tillage has potential in reducing tillage energy and fuel consumptions as compared to the conventional uniform depth tillage (Fulton et al., 1996; Raper et al., 2000; Gorucu et al., 2002; Raper et al. 2004a). Raper et al. (2000) estimated about 50% reduction in energy requirements for shallow tillage (approximately 18cm) as compared to deep tillage (approximately 33cm). Gorucu et al. (2002) 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 (Naiqian et al., 2000). Site-specific tillage in particular is geared towards achieving the goals of sustainable agriculture by determining within field variability and providing more accurate soil compaction records, and optimizing the tillage input within the field 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.

A soil cone penetrometer has been used widely to asses soil compaction, root penetration resistance; and to predict trafficability and bearing capacity for foundations (Perumpral, 1987 and Raper et al., 2004b). The soil cone penetrometer measures the soil penetration resistance, reported as cone index, as a function of depth (ASAE 1999a; 1999b). The influence of soil factors, mainly soil moisture, on the cone index reading and the difficulty in data interpretation in layered soils varying by soil moisture and soil strength, are the main challenges in using the soil cone penetrometer for site-specific tillage (Gill, 1968; Sanglerat, 1972 and Mulqueen et al., 1977). Gill (1968) and Mulqueen et al. (1977) showed 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 site-specific tillage depth recommendations.

Spatial variability analysis of soil compaction and application of site-specific tillage management has not progressed as the precision/site specific application of fertilizers and chemicals due to lack of appropriate technology or procedures to characterize soil physical properties. Hence, a research was needed to accurately characterize the soil hardpan and define its spatial pattern as influenced by soil moisture on 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 US soils.

Therefore, our objectives were to:

- determine the effect of soil moisture on the peak cone index and its depth, and 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

The experiment was conducted during summer 2004 at the Auburn University experimental field plot located in Auburn, AL. Pacolet sandy loam (*Fine, kaolinitic, thermic Typic Kanhapludults*) is the dominant soil series in the experimental site. The field was divided into 200 grid cells each with a 10 X 10 m^2 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. In the north and east directions of the field, a 10 meter transect distance was used for cone index sampling. 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, 1999 a, b and 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 Trimble ® 4600 L.S. Surveyor Total Station with DGPS was also used to obtain elevation data across the field. Soil core samples for soil moisture and bulk density determinations were also collected at every 5.08 cm depth increments to a depth of 66.04 cm in two replicates at 54 randomly selected grid cells near where the cone indices were sampled. The soil core samples were oven dried at 105 ^{0} C for 72 hrs to determine gravimetric soil moisture and bulk density. The cone index measurement and the soil core sampling were carried out simultaneously within an approximate 24- hrs period. With in this sampling period there were no rainfall events that minimized the risk of soil moisture differences. The measurements were obtained on June 25, 2004 and August 29, 2004 representing 'wet' and 'dry' soil moisture conditions, respectively. The sampling dates were chosen based on climatic data obtained for the Auburn University weather experimental station located near the field site.

Peak cone index and depth to the peak cone index were considered as soil hardpan characterizing attributes that were predicted by analyzing the change of cone index values with depth. The analyses were carried out on the cone index data averaged over the five probe data set interpolated at every 1 cm depth increments. Visual inspection on the 200 cone index-depth profile data revealed there were two peaks. The first peak cone index that occurred in depth range of 0 – 30 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 (0-30 cm) was determined for the peak cone index. In developing, the algorithm to define the peak cone index in the shallow depth (30 cm), instantaneous slope values (change in cone index per depth) were calculated and the values were tested in the following priorities, (1). If three consecutive negative slope values were obtained, 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 fails, 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 hardpan; and (3) If the second test fails, three consecutive zero slope values were considered. These zero slope values indicated that the cone index increased till it reached the root restricting peak cone index value and the cone index depth profile curve flattened with depth. The data set at the first zero slope value characterized peak cone index and depth to peak cone index.

Geo-statistical procedures PROC VARIOGRAM and PROC NLIN (SAS. Release 8.02 SAS Institute Inc., Cary, NC, 2001) were used to quantify the isotropic spatial variability and to construct theoretical variogram models for the soil hardpan attributes, and maximum bulk density and its depth. 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 reduced (Sill-Nugget). A model with the largest R^2 value, the smallest weighted residual sums of squares at the end of 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 the nugget effect is negligible implying a better spatial structure (Raper et al., 2004). After selecting the best theoretical semivariogram model, point kriging was used to interpolate values for un-sampled locations. Contour maps were created using Surfer (Surfer version 8.00 Golden Software Inc., 2002). All statistical comparisions were made using PROCGLM procedure (an alpha (α) level of 0.05) in SAS.

RESULTS AND DISCUSSION

Soil Moisture

The soil moisture distribution varied by depth (Fig.2; $P < 0.0001$). At the soil depth range of 0-30 cm depth, the soil moisture sampled on June 25, 2004 (11.97 %) was significantly higher than the soil moisture (10.09 %) sampled on August 29, 2004 ($P < 0.0001$). For convenience, the soil moisture conditions were assumed 'wet' and 'dry' for the measurement dates of June, 25

2004 and August 29, 2004, respectively. At the deeper profile (30 – 66 cm), the soil moisture trend was reversed (Fig. 2). The soil moisture (17.10 %) for the second measurement date (August 29, 2004) was significantly higher than the soil moisture (15.23%) for the first measurement date (June 25, 2004) (Table 1 and $P < 0.0001$). 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 dry soil than in the wet soil. At the deeper soil depth, the skewness and coefficient of variation values (Table 1) were relatively small indicating the subsoil soil moisture distribution tends to be symmetrically distributed around the mean.

Table 1. Descriptive statistics of soil moisture for the depths of 0-30 cm and 30 – 66 cm at the two measurement dates.

	Depth -cm-	Number of values	Mean	Median	Standard deviation	Coefficient of variation	Variance	Minimum	Maximum	95% Confidence interval	Kurtosis	Skewness
June 25,2004	0-30	378	11.97	10.94	3.82	0.34	16.56	5.05	5.86	11.60-12.38	2.34	1.49
	30-66	324	15.23	15.11	4.89	0.3	22	6.72	28	14.88-15.90	-1.06	0.19
August,29 2004	0-30	378	10.09	9.03	4.21	0.41	17.73	4.21	8.69	9.67-10.52	2.63	1.66
	30-66	324	17.1	16.96	4.89	0.29	23.88	7.45	28	16.57-17.63	-0.99	0.11

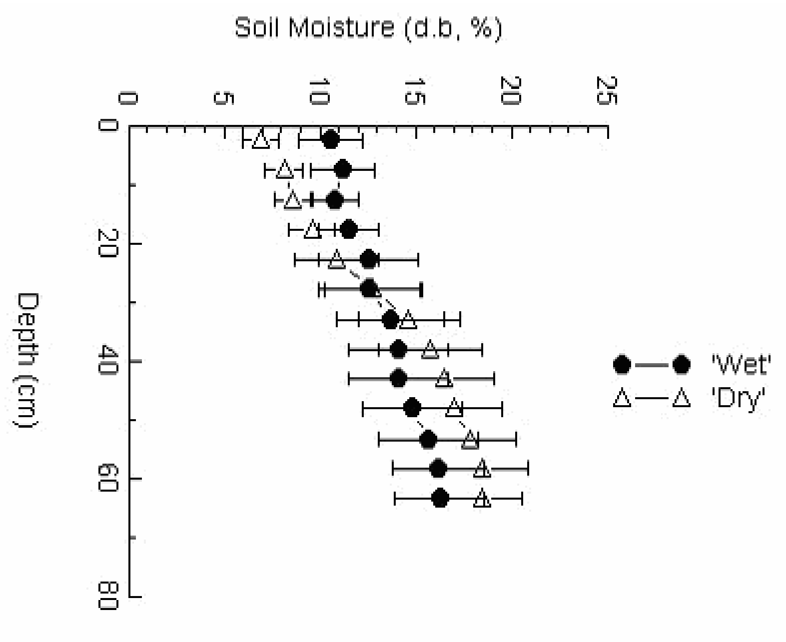


Fig. 2. Soil moisture profile for the two measurement dates of June 25, 2004 (‘Wet’) and August 29, 2004 (‘Dry’). The horizontal bars indicate standard deviations.

Bulk Density

The average bulk density profile for the field is shown in fig. 3. The bulk density varied by depth significantly ($P < 0.0001$). There were not statistically significant differences in the bulk density values by measurement dates (P < 0.0001). The skewness (-0.49) and coefficient of variation (0.1) showed that the distribution of bulk density was nearly symmetrical around the mean.

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

	Number of values	Mean	Median	Standard deviation	Coefficient of variation	Variance	Minimum	Maximum	95% Confidence interval	Kurtosis	Skewness
Maximum bulk density (Mgm^{-3})	53	1.54	1.54	0.06	0.04	0.004	1.43	1.65	1.52-1.55	-1	0.05
Depth to the maximum bulk density (cm)	53	20.94	22.86	5.66	0.27	31.99	12.7	27.94	19.38-22.50	-1.36	-0.06

As shown in fig. 4 (A), the variability of the maximum bulk density showed spatial dependence that was best fit by the exponential semivariogram model ($R^2 = 0.96$ and a spatial structure indicator of 0.3). A linear semivariogram model best fit the semivariances of the predicted depth to the maximum bulk density with a sill value (14.3) nearly half of the sample variance (31.99) (Fig. 4, B). 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. Contour map of the depth to the maximum bulk density showed that the predicted soil hardpan depth seems to vary across the field (Fig. 5).

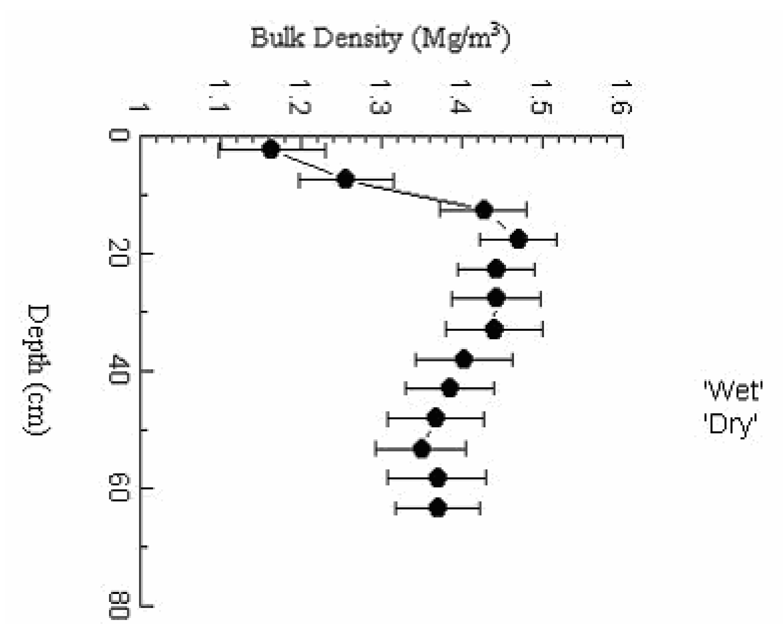


Fig. 3. Bulk density profile averaged over the two measurement dates of June, 25 2004 and August, 29 2004. The horizontal bars indicate standard deviations.

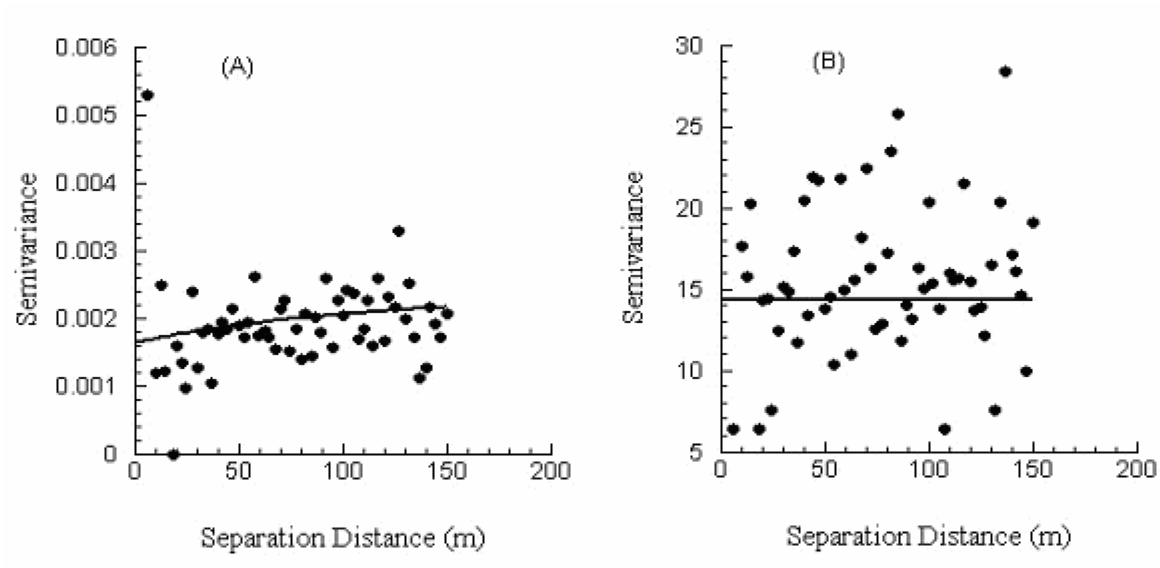


Fig.4. Semivariances (A) for the maximum bulk density with theoretical exponential semivariogram model fit and (B) depth to the maximum bulk density with theoretical linear semivariogram model fit.

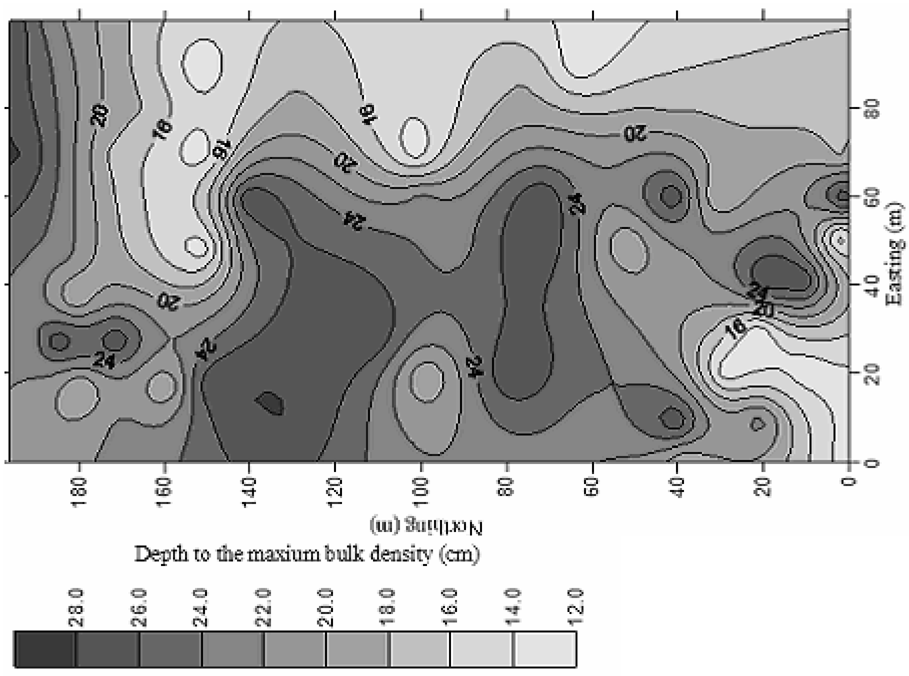


Fig. 5. Contour map of the depth to the maximum bulk density on Pacolet sandy loam soil.

Peak Cone Index and Depth to the Peak Cone Index

The average peak cone index was significantly higher for the dry soil condition than the value for the wet soil condition (Table 3 and $P < 0.0001$). By taking cone index measurements at the drier soil condition (August 29, 2004), the peak cone index increased by 28 %. As shown in fig. 6 (A), the relative frequency distribution of the peak cone index for the dry soil condition appeared to shift to the right as compared to the wet soil condition. For the dry soil condition, the relative frequency distribution of the depth to the peak cone index (Fig. 6 B) indicated a slight shift to the left (small depth values). Even though the difference in the depths appeared to be small, there was strong statistical evidence that the predicted depth to the peak cone index decreased by soil drying (Table 3 and $P < 0.0001$). The predicted depth occurred within the shallow depth range (0-30cm) where the soil moisture significantly decreased by sampling date.

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

		Number of values	Mean	Median	Standard deviation	Coefficient of variation	Variance	Minimum	Maximum	95% Confidence interval	Kurtosis	Skewness
June 25, 2004	Peak cone index (MPa)	198	3.29	3.2	0.88	0.27	0.78	1.23	5.86	3.23-3.36	0.11	0.42
	Depth to the peak cone index (cm)	198	21.08	21	3.36	0.16	11.29	13.5	28	20.84-21.31	-0.7	0.14
August 29, 2004	Peak cone index (MPa)	200	4.12	3.99	1.36	0.33	1.84	1.68	8.69	4.03-4.23	0.81	0.78
	Depth to the peak cone index (cm)	200	20.08	20	3.56	0.18	12.65	10	28	19.83-20.33	-0.04	-0.06

Tekeste et al. (2004) reported similar influences of soil drying on the peak cone index and the predicted depth of soil hardpan on Norfolk sandy loam soil. Comparing the soil hardpan depth prediction using the cone index and maximum bulk density method, the depths predicted at the wet and dry soil conditions from cone index data lies within the 95 % confidence interval of the depth to the maximum bulk density (Table 3).

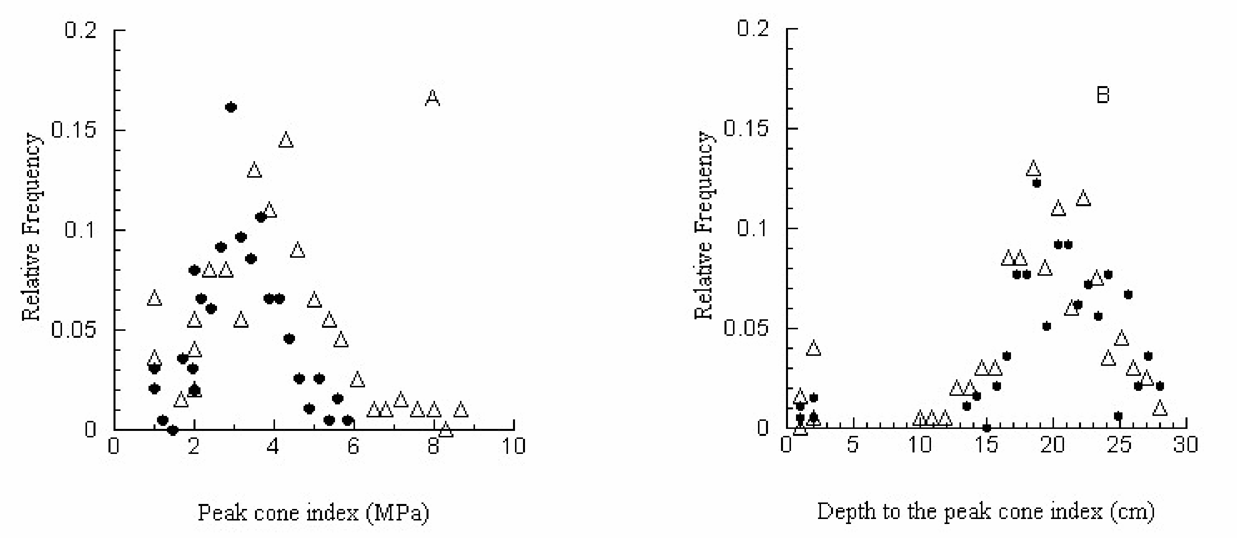


Fig. 6. Relative frequency distribution of (A) the peak cone index (MPa) and (B) the depth to the peak cone index for the two measurement dates of June 25, 2004 ('Triangle') and August 29, 2004 ('Circle').

Spatial Variability Analysis

Selection of sampling distance intervals is important in ensuring the quality of spatial variability analysis and interpolation of points for un-sampled locations using geostatistical techniques (Donald and Ole, 2003). A sampling interval distance less than a range, a distance over which pairs of observations exhibit spatial dependence, was considered appropriate in grid sampling. The ten-meter transect distance used in the cone index sampling was less than a range that Raper et al. (2004b) estimated for the depth of the soil hardpan on silty upland soils of Northern Mississippi.

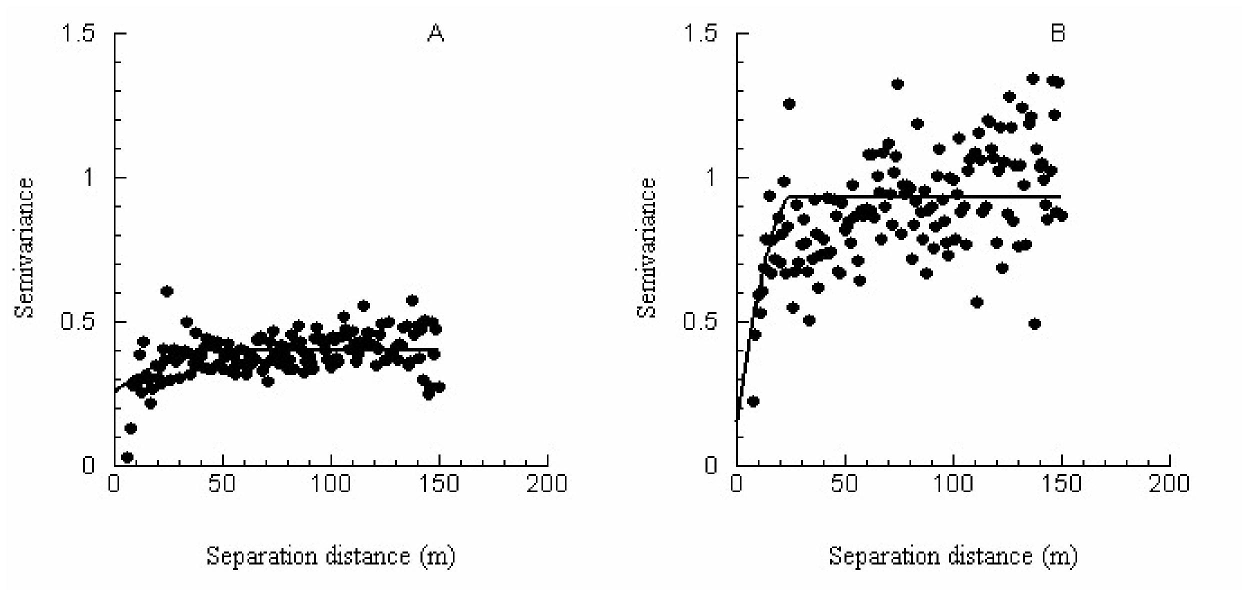
Table 4. Descriptive semivariogram statistics for the peak cone index and the depth to the peak cone index for the two measurement dates of June 25, 2004 and August 29, 2004.

		Model	Nugget u	Sill	Range	Regression coefficient	(Sill-Nugget)/Sill	WSS v
				--MPa^2--	--m--			
June	Peak cone index (Mpa)	Spherical	0.26	0.4	44	0.98	0.36	322
25, 2004	Depth to the peak cone index (cm)	Exponential	0.00	5.73	47	0.99	1.00	259
August	Peak cone index (Mpa)	Spherical	0.15	0.93	26	0.97	0.84	505
29, 2004	Depth to the peak cone index (cm)	Linear	5.80			0.98	0.15	151

u Nugget units are MPa^2 for the peak cone index and cm^2 for the depth to the peak cone index.
v WSS= Weighted Residual Sums of Squares

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.7). 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 estimates for the sample site. The range for the dry soil condition (26 m) was smaller than for the wet soil (44 m). Smaller range value indicates that soil drying reduced the distance over which pairs of peak cone index values remain spatially dependant. 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 that may improve the efficiency of future cone index sampling procedure. The maps for the peak cone index of the field (not showen) 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.

Fig. 7. Semivariances for the peak cone index and spherical theoretical model fits for the two measurement dates of June 25, 2004 (A) and August 29, 2004 (B).



Similar to the peak cone index spatial variability, soil moisture variation also affected the estimated semivariances and the semivariogram models for the depth to the peak cone index (Table 4 and Fig. 8). Exponential semivariogram model explained the spatial variability of the depth to the peak cone index with a scale to sill ratio of 1 that indicates a well defined spatial structure. For the dry soil condition, the semivariances appeared to be spatially uncorrelated that the values were nearly similar over the separation distances (Fig. 8 B). The contour maps in fig. 9 (A and B) show that the predicted depths to the peak cone index appeared to be shallow for the dry condition in most parts of the field.

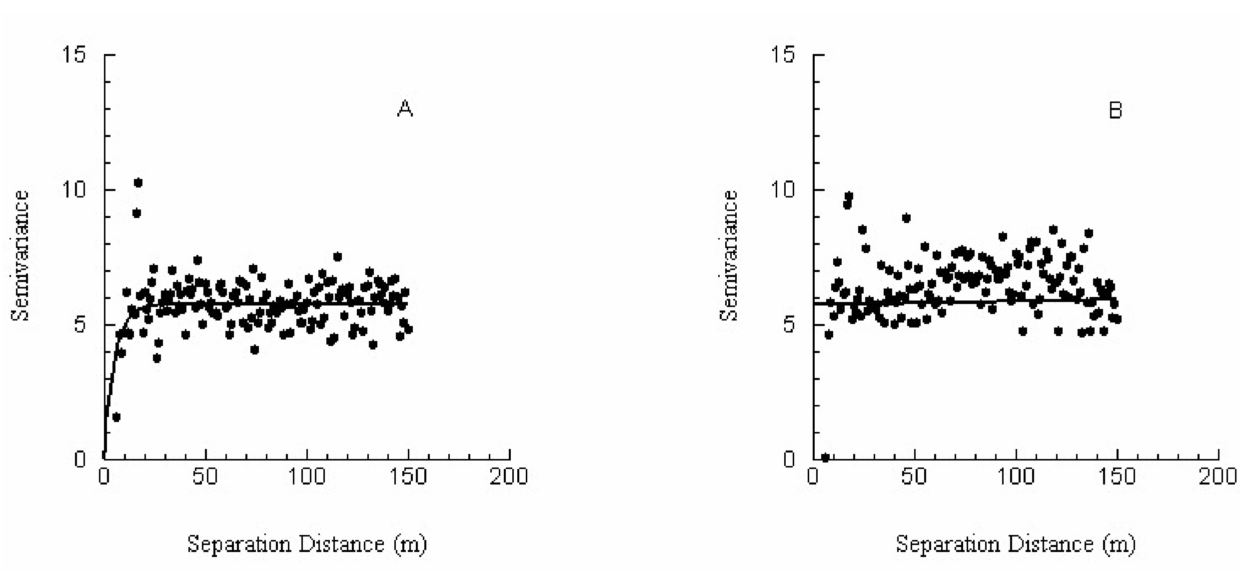


Fig. 8. Semivariances for the depth to the peak cone index and exponential theoretical model fit and linear theoretical model fit for the measurement dates of June 25, 2004 (A) and August 29, 2004 (B), respectively.

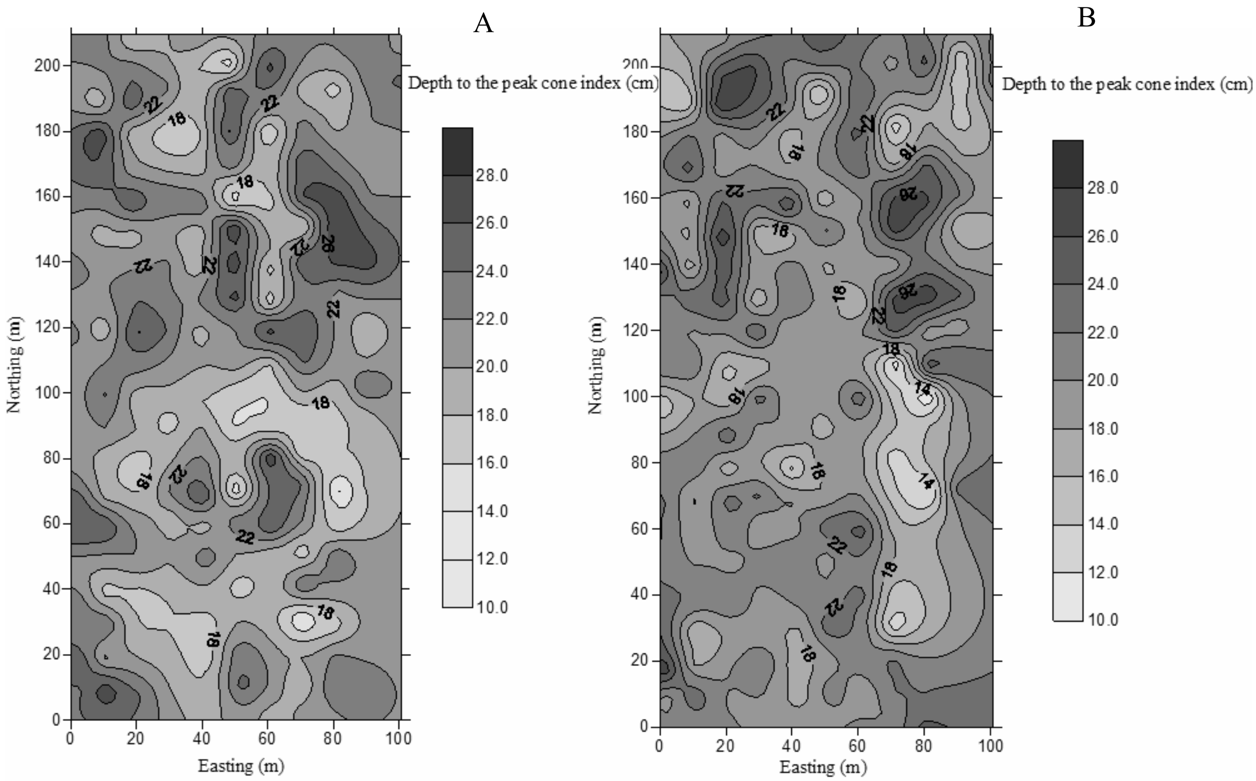


Fig. 9. Contour map of the depth to the peak cone index on Pacolet sandy loam soil for the two measurement dates of June 25, 2004 (A) and August 29, 2004 (B), respectively.

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 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 on the wet soil condition; however, in the dry soil condition the variability in the predicted 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.

Generally the distribution pattern of the soil hardpan depths across the field seems similar as predicted by the depth to the maximum bulk density or the depth to the peak cone index values. Maps of peak cone index values indicate that most part of the field requires deep tillage. The depths of tillage, however, need to vary according to the predicted soil hardpan depths. This indicates that applications of depth-specific tillage on Pacolet sandy loam soils may improve the sustainability of crop management.

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