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Measurement and Variation of Site-specific Hardpans

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***Abstract*.** Cone index profiles taken in several Southeastern U.S. fields with upland soils 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, even in no-trafficked row middles and directly beneath the rows. Little difference in depth of hardpan was found between a no-till field subjected to random traffic and a field where traffic was segregated. The least amount of variation in hardpan depth was found in trafficked row middles in a no-till field.

Keywords. Soil compaction, soil cone penetrometer, site-specific, cone index, hardpan, spatial, soil moisture

Introduction

Significant variation in crop yields have been found in many parts of the U.S. 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 (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 Southeast. 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 Southeast 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 *et al*., 2001). 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 x 30 m area immediately after irrigation, 2 hours after irrigation, and 24 hours 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. They 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.

Therefore, the objectives of this study were:

1. To develop an effective procedure to determine the depth of hardpan in a soil prone to 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 selected Southeastern U.S. fields.

Methods and Materials

A multiple-probe soil cone penetrometer (MPSCP; Raper *et al*., 1999) was used to obtain cone index measurements (ASAE, 1999a; 1999b) 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. Fields consisting of upland soils of Grenada silt loam soil type (fine silty, mixed, thermic, Glossic Fragiudalf) near Senatobia, MS were sampled for soil compaction variability. The three fields sampled were managed with (1) no-tillage with drilled soybeans for narrow row production, (2) conventional tillage (chisel, disk twice) for 90-cm row soybean production, and (3) 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). The MPSCP was used to acquire soil strength data of varying grid sizes on each field. For field 1, 2, and 3 the grids sampled were approximately 30 m x 15 m, 30 m x 11 m, and 30 m x 16 m, respectively. Immediately following this procedure, a complete set of 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. A range level was also used to determine the topography and sampling positions more accurately than could be accomplished with GPS (Figs. 1, 2, and 3).

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 fields, a SAS procedure 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 3 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. 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. Segregated row middles were maintained and the cone index measurements were analyzed for differences caused by vehicle 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.

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 due to the limited data that was obtained, 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.

Results and Discussion

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 0.337 m, the soil moisture was found to be 35.5 % for the 0-15 cm depth range and 37.0 % for the 15-30 cm depth range (Table 1). Skewness for the depth to the hardpan was 0.769 which indicates that the data is only slightly asymmetric (Fig. 4). The coefficient of variation for the depth to the hardpan was 0.275 which indicates that the histogram does not have a long tail of values. Much lower values of coefficient of variation were obtained for the soil moisture for the 0-15 cm depth range (0.050), the 15-30 cm depth range (0.027), and for the elevation (0.012). Small values of skewness were also found for soil moisture for the 0-15 cm depth range (0.119), the 15-30 cm depth range (-0.295), and for the elevation (-0.149). The negative values of skewness indicates a slight shift in the histogram to the left.

It was obvious from the data for field 2 that shallower hardpans were found when the row middles were trafficked. Using data collected in the trafficked row middles gave an average depth of hardpan of 0.178 m compared to the data collected in the no-trafficked row middles, which gave an average depth of hardpan of 0.210 m (Table 1). We therefore determined that vehicle traffic may have caused the hardpan profile to move closer to the soil surface by 0.032 m, which could additionally restrict root growth and water movement. However, data obtained directly beneath the row showed the depth to the root-impeding layer to be 0.189 m. 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 1). All coefficients of variation for the depths to the hardpan in the row (0.306), in the trafficked middle (0.269), and in the no-trafficked middle (0.293) were very close and indicated no long tail of values (Fig. 5).

The soil moisture for field 2 was found to be 34.5 % for the 0-15 cm depth range and 35.0 % for the 15-30 cm depth range (Table 1). The shallow soil moisture measurements and the elevation were both slightly negatively skewed while the 15-30 cm depth range showed a slight positive skewness. The coefficients of variation for the shallow soil moisture (0.070) and for the deep soil moisture (0.046) indicated little deviance from a normal distribution. This was also true for the elevation coefficient of variation (0.014).

The depths of the hardpans for field 3 were substantially greater than for field 2. The depth to the hardpan in the no-trafficked row middle was 0.306 m, which was slightly shallower than either of the depth to the hardpan in the trafficked row middle (0.322 m) or the depth to the hardpan in the in-row position (0.354 m). These values were similar to those depths measured in field 1 and probably resulted from the lack of tillage being applied. 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 (0.270), the trafficked middle (0.318), and for the no-trafficked middle (0.291) also indicated no long tails of high values (Fig. 6)

The soil moisture for field 3 was found to be 36.8 % for the 0-15 cm depth range and 36.5 % for the 15-30 cm depth range (Table 1). 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 (0.044) and for the deep depth range (0.050) showed little reason to question normality of the data. This was also true for elevation (0.016) with the value being so close to zero.

Table 2 shows the correlation coefficients between the depth to the hardpan, the soil moisture at 0-15 cm depth, the soil moisture at 15-30 cm depth, and the elevation. For field 1, a strong relationship was obtained between the hardpan depth and the soil moisture at the 15-30 cm depth ($P<0.001$) and between the hardpan depth and elevation ($P<0.07$).

For field 2, table 2 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 15-30 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 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 ($P<0.06$).

When the depth to hardpan data for field 1 was analyzed for spatial dependence (Table 3), we determined that the spherical model was the best fit for this data (Fig. 7). 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 being 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 3). This value indicates that samples to quantify the depth to the hardpan must 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 3 shows that the spherical models most closely fit the depth to hardpan data obtained in the in-row and the trafficked middle. This was evidenced by regression coefficients of 0.46 for the in-row position and 0.224 for the trafficked position (Figs. 9 and 10). However, for the no-trafficked middle, a zero correlation coefficient and visual inspection of the semivariogram indicates a poor fit for the spherical model (Fig. 8). 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 was 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 3). 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 3 and Fig. 11). 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 the in-row position, so this model was also disregarded (Fig. 12). The spherical model was the best fit for the trafficked position with a correlation coefficient of 0.721 being obtained (Fig. 13). 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. 14). 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. Fields 1 and 3 cropping systems consisted of no-tillage. In these fields, the hardpan depths were much deeper. Little difference in hardpan depth was seen between fields 1 and 3, indicating that the random traffic that occurred in field 1 caused equivalent compaction to the relatively controlled traffic that was practiced in field 3.

The predicted range values shown in Fig. 15 may tell a somewhat different story, however. Fields 1 and 3, despite having similar tillage systems, show dramatically different values of range despite having similar 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.

Conclusions

An effective procedure to determine the depth to the hardpan was developed that consisted of analyzing the cone index profile and determining the value of the shallowest peak where multiple peaks occurred.

Conventional tillage systems were found to bring the hardpan significantly closer to the soil surface, even in no-trafficked row middles and directly beneath the rows. Hardpan depths in a no-till field subjected to random traffic and in a field where traffic was segregated showed little difference.

Significantly reduced variation in hardpan depth was found in trafficked row middles in a no-till field. A randomly trafficked no-till field exhibited a greater amount of variation in hardpan depth as did a conventionally tilled field.

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Table 1. Descriptive Statistics of Depth to Hardpan, Soil Moisture, Elevation.

	Mean	Standard Deviation	Min Value	Max Value	Number of Values	Coefficient of Variation	Skewness
Field 1 *(no-tillage with drilled soybeans)*							
Depth to Hardpan, (m)	0.337	0.092	0.19	0.59	55	0.275	0.769
Soil Moisture (0-15 cm), (%)	35.5	1.808	32.0	39.2	52	0.050	0.119
Soil Moisture (0-30 cm), (%)	37.0	1.362	34.0	39.4	54	0.027	-0.295
Elevation, (m)	150.9	1.682	146.9	152.7	55	0.012	-0.149
Field 2 *(conventional tillage for 90-cm row soybeans)*							
Depth to No-Trafficked Hardpan, (m)	0.210	0.062	0.105	0.365	50	0.293	0.4669
Depth to In-Row Hardpan, (m)	0.189	0.058	0.085	0.335	53	0.306	0.484
Depth to Trafficked Hardpan, (m)	0.178	0.048	0.105	0.305	57	0.269	0.392
Soil Moisture (0-15 cm), (%)	34.5	2.308	28.9	39.6	60	0.070	-0.397
Soil Moisture (0-30 cm), (%)	35.0	1.347	31.5	37.9	61	0.046	0.0834
Elevation, (m)	150.1	1.917	146.3	152.8	61	0.014	-0.252
Field 3 *(no-tillage for 90-cm row soybeans)*							
Depth to No-Trafficked Hardpan, (m)	0.306	0.089	0.15	0.57	61	0.291	0.741
Depth to In-Row Hardpan, (m)	0.354	0.096	0.17	0.58	55	0.270	0.262
Depth to Trafficked Hardpan, (m)	0.322	0.102	0.13	0.59	57	0.318	0.561
Soil Moisture (0-15 cm), (%)	36.8	1.623	32.3	39.8	66	0.044	-0.595
Soil Moisture (0-30 cm), (%)	36.5	1.809	23.6	39.6	66	0.050	-0.290
Elevation, (m)	153.5	2.401	148.9	157.3	66	0.016	-0.233

Table 2. Correlation Coefficients Between Depth to Hardpan, 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)		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)

Table 3. Descriptive Semivariogram Statistics for Depth to Hardpan.

	Model	Nugget $(m)^2$	Sill $(m)^2$	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*	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*	0.002	0.008	31.2	0.376	0.857
Depth to In-Row Hardpan, (m)	Spherical*	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

*Models disregarded due to poor fit.

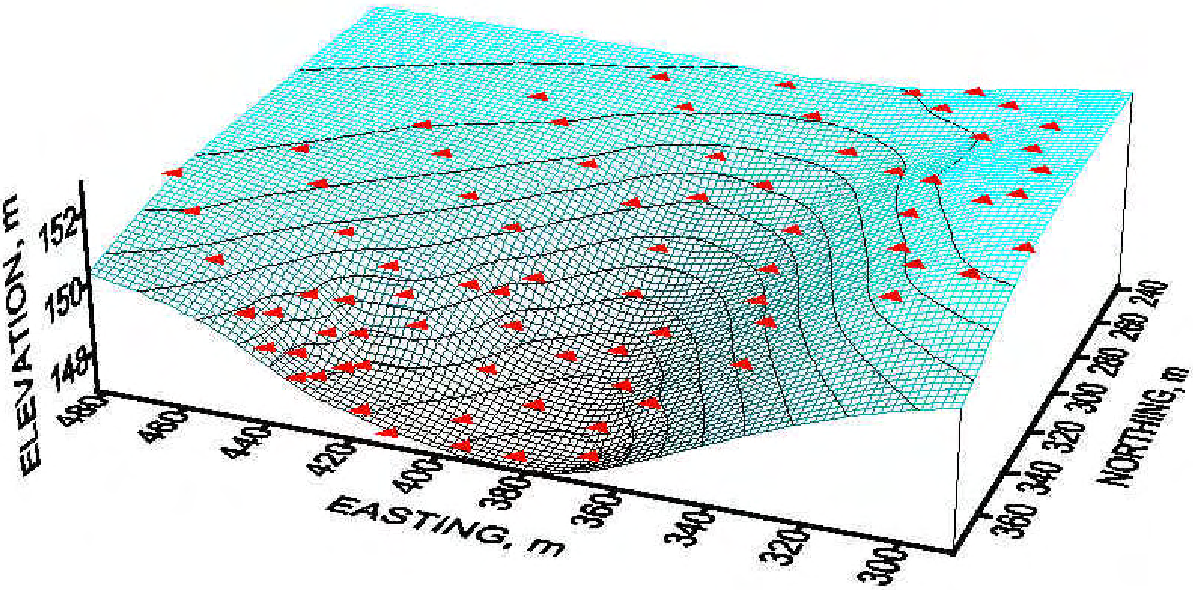

Figure 1. Elevation of field 1 with markers indicating sampling locations.

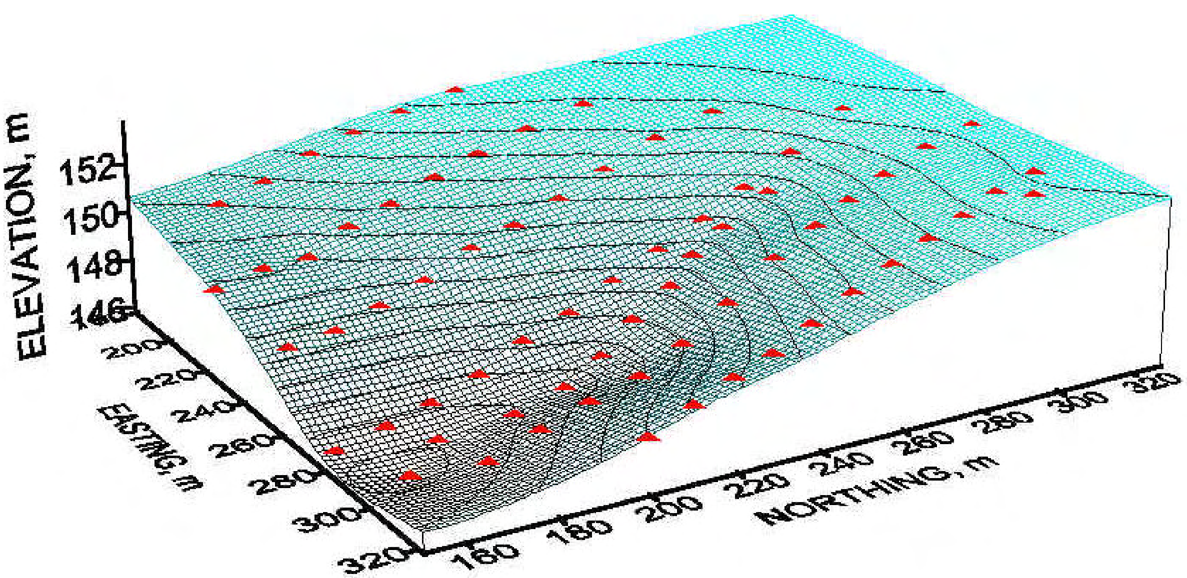

Figure 2. Elevation of field 2 with markers indicating sampling locations.

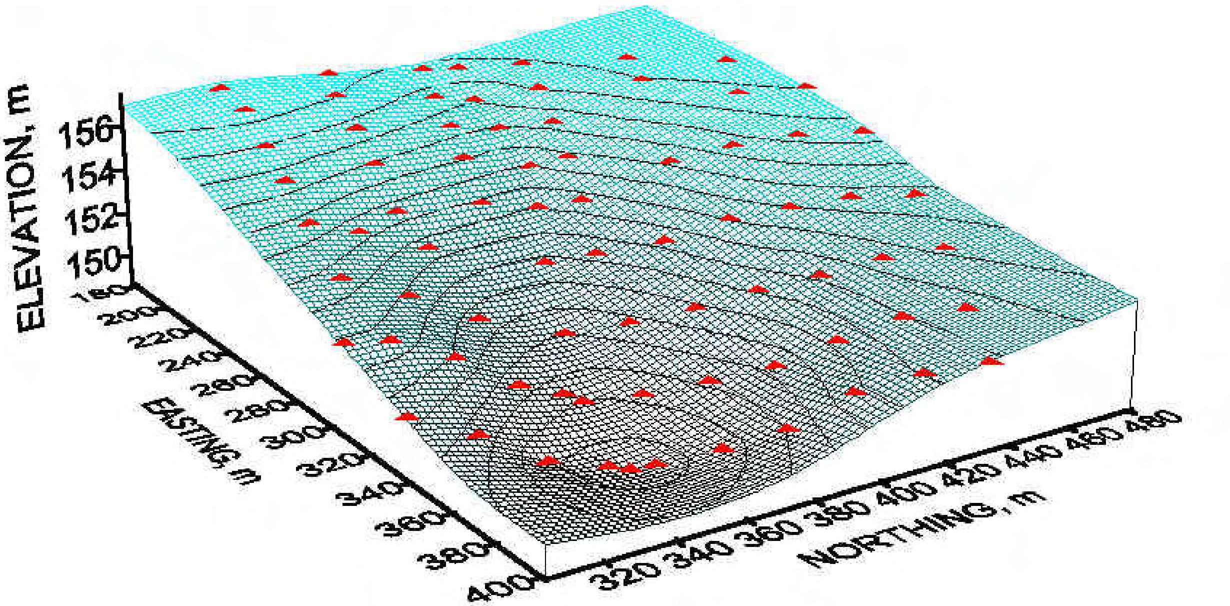

Figure 3. Elevation of field 3 with markers indicating sampling locations.

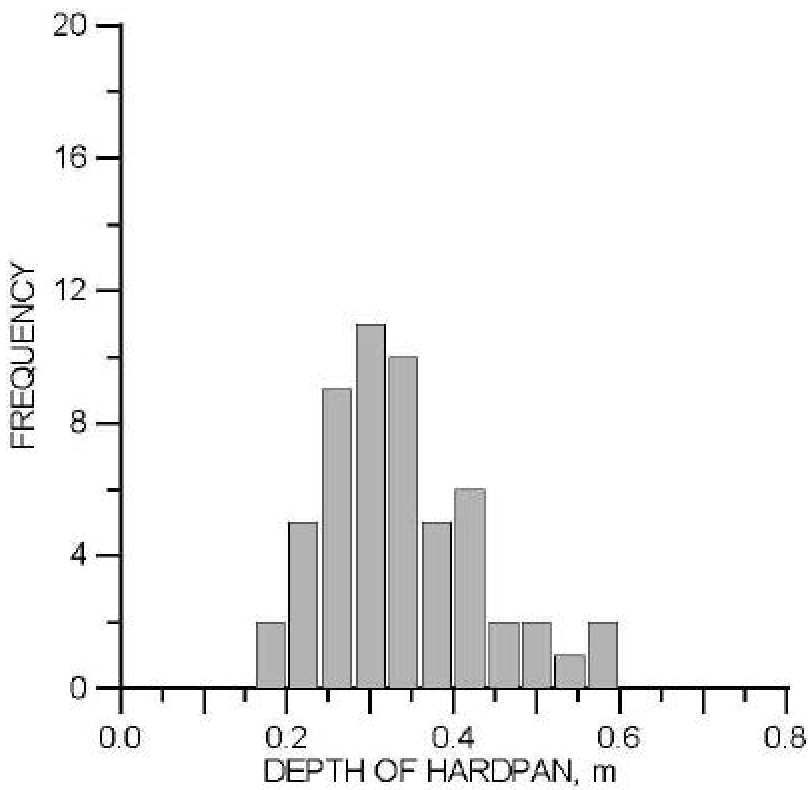

Figure 4. Histogram of hardpan depths for field 1.

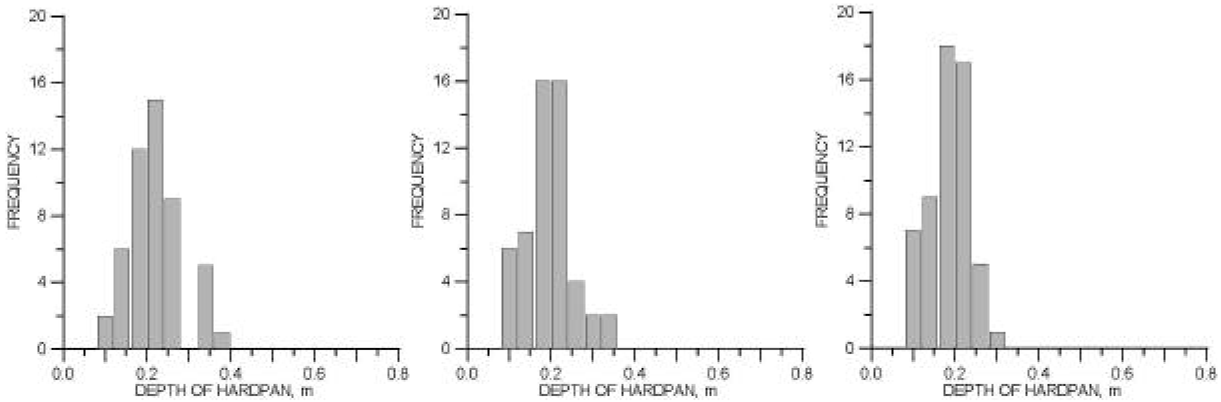

Figure 5. Histogram of hardpan depths for field 2 for no-trafficked area (left), in-row area (center), and trafficked area (right).

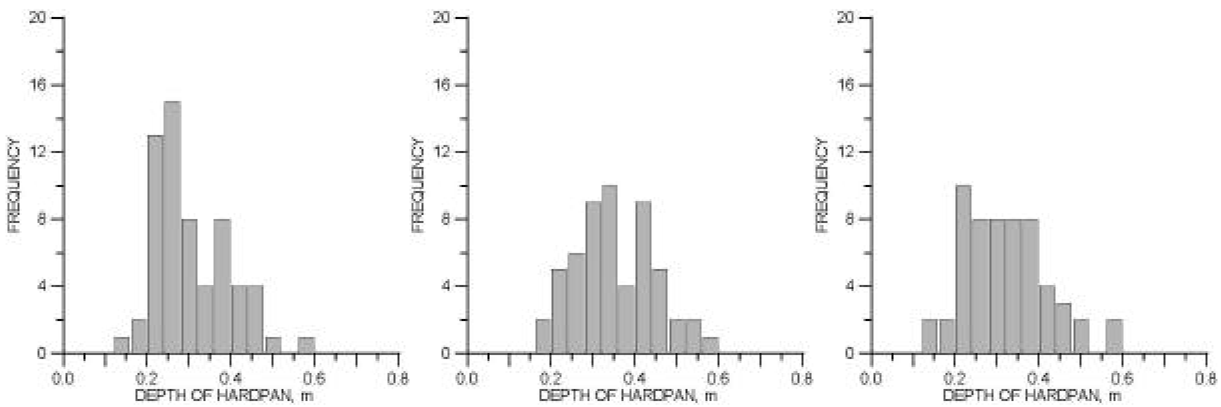

Figure 6. Histogram of hardpan depths for field 3 for no-trafficked area (left), in-row area (center), and trafficked area (right).

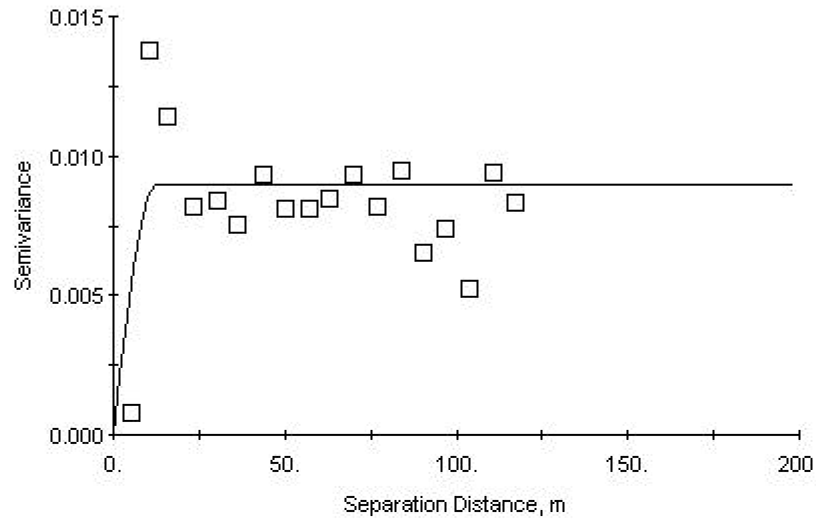

Figure 7. Semivariogram for hardpan depth for field 1 showing fit of spherical model.

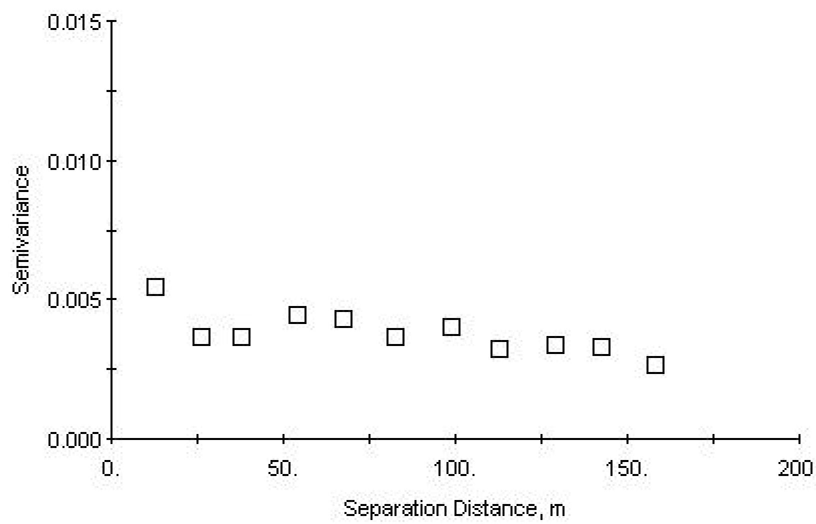

Figure 8. Semivariogram for hardpan depth for no-trafficked row middle for field 2 showing no model fit of data.

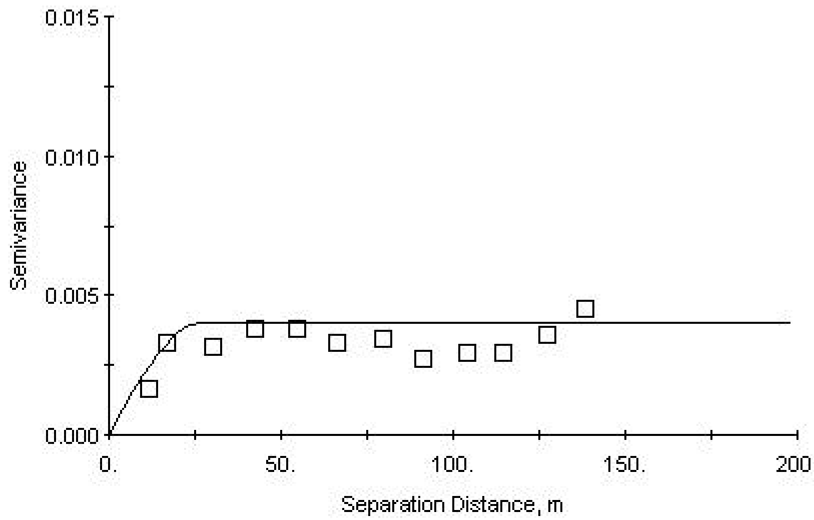

Figure 9. Semivariogram for hardpan depth for inrow position for field 2 showing fit of spherical model.

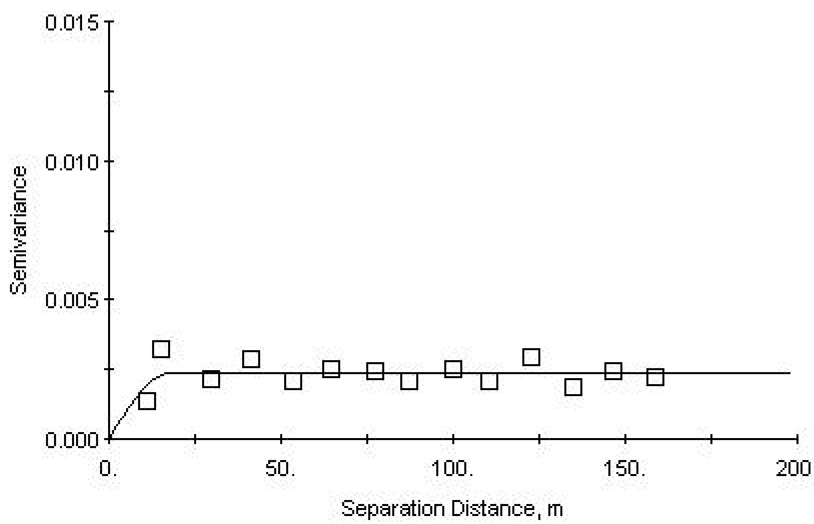

Figure 10. Semivariogram for hardpan depth for trafficked row middle for field 2 showing fit of spherical model.

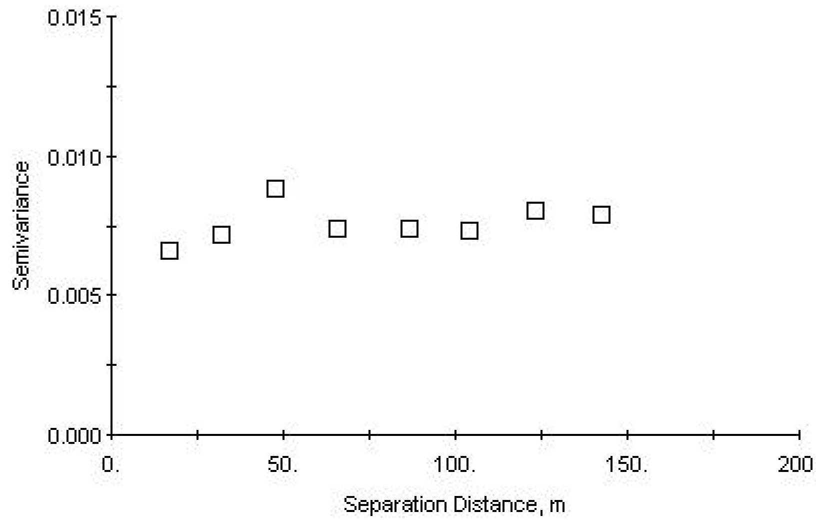

Figure 11. Semivariogram for hardpan depth for no-trafficked row middle for field 3 showing no model fit of data.

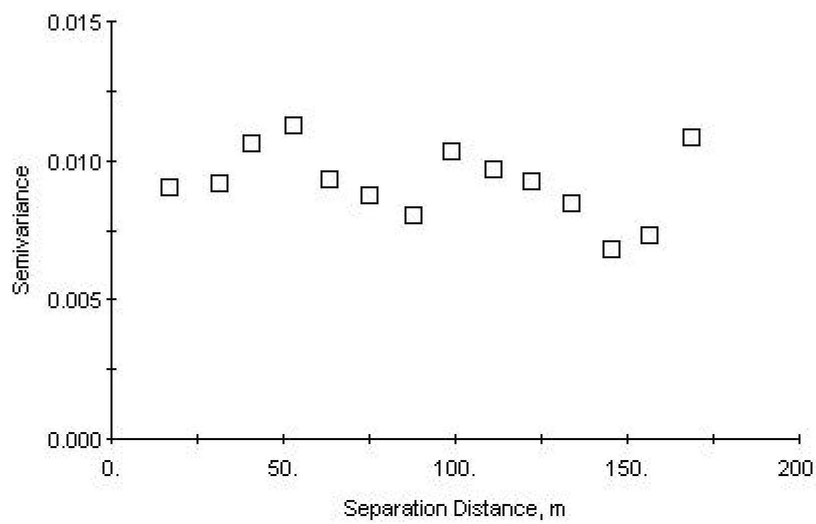

Figure 12. Semivariogram for hardpan depth for inrow position for field 3 showing no model fit of data.

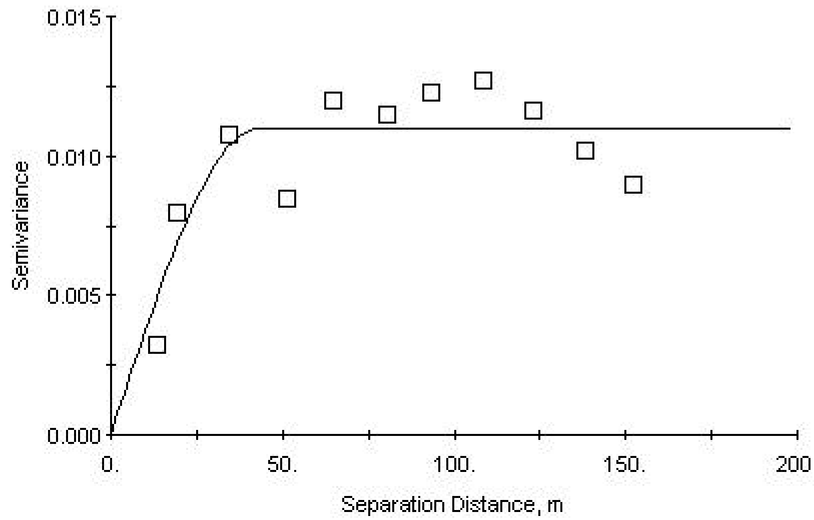

Figure 13. Semivariogram for hardpan depth for trafficked row middle for field 3 showing fit of spherical model.

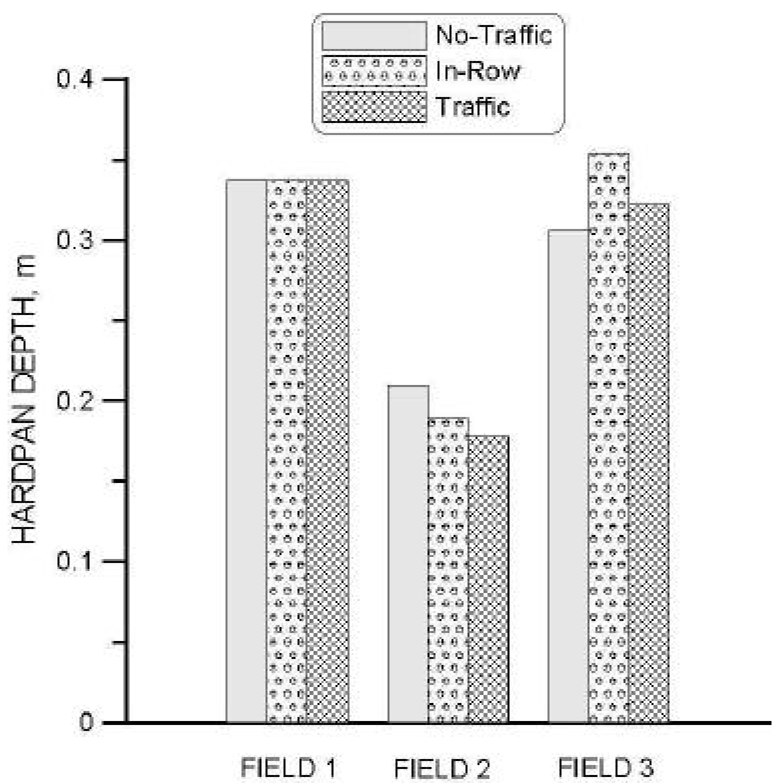

Figure 14. Average hardpan depths measured across the fields for the different sampling positions. (Note: all three positions were averaged for field 1)

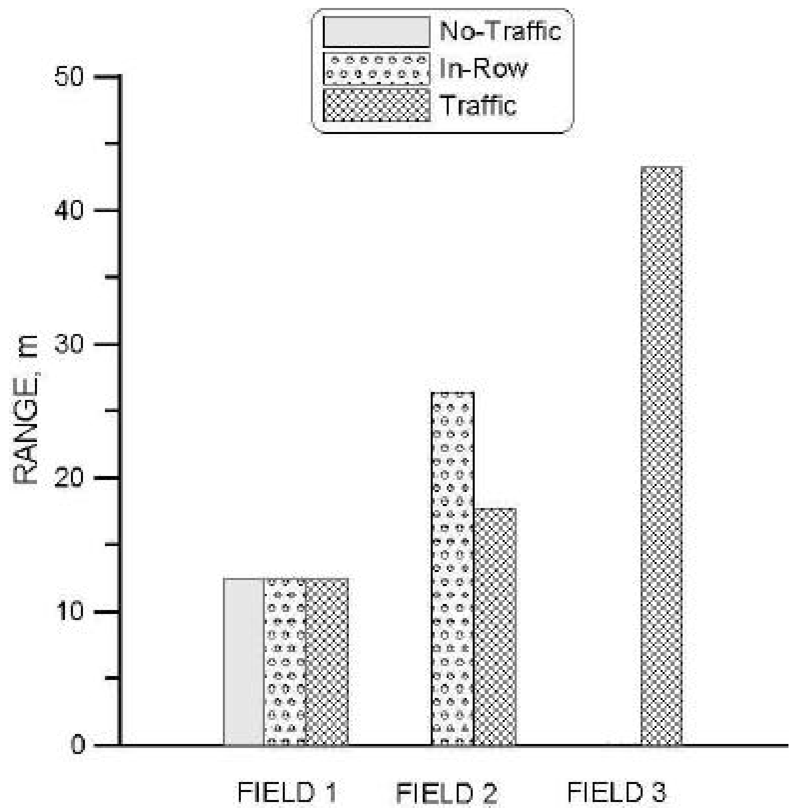

Figure 15. Predicted ranges for the fields for different sampling postions. (Note: all three positions were averaged for field 1)