SARE Project LS88-9

MEASUREMENT OF MECHANICAL IMPEDANCE IN TILLED AND NO-TILL GRAVELLY SOILS OF THE SOUTHERN PIEDMONT

R. Stolf, D.K. Cassel*, L.D. King, C.R. Crozier
and K. Reichardt

INTRODUCTION

Tillage practices, crop rotation, and use of green manure crops can have a large impact on the physical condition of the soil (Power, 1990; Culley et al., 1987; NeSmith et al., 1987). The degree of soil disruption or compaction varies with the kind and frequency of tillage and wheel traffic. Characterizing soil strength is useful when evaluating the effects of tillage systems on soil properties (Cassel, 1983) and crop yield (Vepraskas, 1988). Conceptionally, measuring soil resistance with a cone penetrometer is simple, but one problem associated with its use is the difficulty in penetrating "hard" (high soil strength) soils, the very soils we wish to use them on.

Manually-operated penetrometers are difficult to push into hard soils and they frequently bend if the clay content is high, or if gravel or small pebbles are present. The majority of soils in the Piedmont region of the southeastern U.S. fall in this category. Hydraulically-driven penetrometers also have limited use on these soils because the penetrometer shaft often bends when hard zones, gravel, or rocks are encountered.

An impact penetrometer is designed to penetrate the soil in response to repeated impacts of a known mass falling through a known distance (Stolf et al., 1983; Stolf and Faganello, 1983). This penetrometer does not require greater instantaneous force to penetrate a hard soil, but needs only a greater number of impacts of a given force. Its simplicity makes it a viable candidate to measure mechanical impedance on gravelly, high strength Piedmont soils.

The objectives of this study were: 1) to determine the feasibility of using an impact penetrometer to assess mechanical impedance in a high-strength soil containing gravel and a high clay content, and 2) to describe and analyze the mechanical impedance patterns for four experimental systems in a sustainable agriculture experiment.

THEORY OF IMPACT PENETROMETER

The Stolf impact penetrometer[1/] and large penetrometers used in civil engineering applications are based on the same principle (Stolf, 1991). The device (Fig. 1), measures the dynamic resistance, R (kg s^{-2} m^{-1}), of the soil given by

$$R = F/A \qquad [1]$$

where F is the force (m kg s^{-2}) per unit basal area of the cone (A)(m^{2}) that the soil offers against the movement of the penetrometer. The mass of the impact cylinder (M) is 4.000 kg and the combined mass (m) of the shaft, cone, and handle is 3.200 kg. The falling distance (h) for mass M is 40.0 cm. The basal area of the cone is 1.29 x 10^{-4} m^2 according to instrumentation standards adopted by the American Society of Agricultural Engineers (ASAE, 1976).

To determine R, the impact cylinder is raised to the initial position h cm above the impact plate (Fig. 1b). Upon falling, the cylinder impact drives the penetrometer cone distance x into the soil. Consequently, the impact cylinder falls a distance of h + x. Important to this analysis is the fact that the impact also moves penetrometer frame distance x below its original position (Fig. 1c). The maximum gravitational energy available for penetration of the cone is Mgh + Mgx + mgx where g is gravitational acceleration (9.80 m sec^{-2}). However a portion of this energy is converted to heat during the impact. The work done in advancing the penetrometer distance x into the soil is given by

$$w = F\,x = mgx + fMgh + Mgx \qquad [2]$$

where f is the coefficient of elasticity of the collision. For a totally elastic impact f is equal to 1. For a totally inelastic impact, Newton’s third law states that the coefficient is

$$f = M/(M + m) \qquad [3]$$

Although neither case exists in practice, we assume the impact of the steel cylinder against the steel impact ledge approaches that of an inelastic collision. Substitution of [3] into [2] and solving for F gives

$$F = [M + m]g + M^2gh/[x(M + m)] \qquad [4]$$

Substitution of equation [4] into [1] and using the appropriate numeric values for the penetrometer, we obtain the following expression for R (kPa)

$$R = 550 + 6750/x \qquad [5]$$

where x is the penetration in cm/impact.

In practice, it is convenient to define N as the number of impacts required to drive the penetrometer some arbitrary depth into the soil. If we choose N = 10, for example, then

$$x = 1/(10\,N) \qquad [6]$$

Substituting [6] into equation [5] gives

$$R = 550 + 675\,N \qquad [7]$$

where R is the resistance in kg s^{-2} m^{-1} and N is the number of impacts/dm.

MATERIALS AND METHODS

The field study was conducted in 1991 at the North Carolina State University Research Unit 9, Raleigh, on selected plots of a long-term study evaluating various crop and soil management systems (King and Buchanan, 1992). The management systems were established in September 1985 on a Cecil gravelly loam (clayey, kaolinitic, thermic typic Kanhapludults).

The four systems studied, all of which were planted to corn in 1991, the year of the study, were:

Tilled: Continuous, conventionally tilled corn (*Zea mays*): Chisel plowed and disked prior to seeding.

No-till: Continuous no-tillage corn: Corn seeded directly behind coulters.

No-till/rotation: No-tillage with rotation of corn, wheat (*Tritium vulgare* L.), soybean (*Glycine max* L. (Merr.)): chronological rotation was wheat, soybean (1985-86); fallow, corn (1986-87); wheat, soybean (1987-88); fallow, corn (1988-89); wheat, soybean (1989-90); fallow, corn (1990-91).

Tilled/green manure: Continuous, tilled corn with "Tibee" crimson clover (*Trifolium incarnatum* L.) as a winter green manure: clover seeded each fall and killed prior to corn planting by chisel plowing and disking.

Corn rows in each 8-m x 30-m plot were spaced 100 cm apart. Two-row tillage equipment pulled by a 2500-kg tractor was used for all plots, thus only alternate interrows were trafficked. The tilled/green manure system received two cultivations after planting.

A 4.00-m-long transect, oriented perpendicular to the rows, was selected in each management system in block one. Soil resistance to a depth of 60 cm was measured with the Stolf penetrometer at 33 equally spaced points (12.5 cm apart) on the transect (Fig. 2). Soil compaction by foot traffic during measurements was prevented by walking on an elevated wooden plank parallel to the transect. To begin, the penetrometer was held vertically and the cone was placed on the soil surface; the impact cylinder rested on the impact plate at this time (Fig. 1c). The penetration depth of the cone was recorded. Then the impact cylinder was raised to a height of 40 cm (Fig. 1b), and released repeatedly until the penetrometer penetrated an additional 5 cm (approximately). The number of impacts and the depth of penetration were recorded. This procedure was repeated until the penetrometer cone was driven to the 60-cm depth. Weighted means for R for each 5-cm increment were calculated giving 396 R values for each transect.

Soil water content in each row and in the centers of each trafficked and non-trafficked interrow (at positions A, E, and I in Fig. 2) were determined in each plot using a time domain reflectometer. Wave guides 15, 30, 45 and 60 cm long were installed at each position. Soil water content for the 15- to 30-cm depth (θ_{15-30}), for example, was calculated by

$$\theta_{15-30} = 2\ \theta_{0-30} - \theta_{0-15} \qquad [8]$$

where θ_{0-15} and θ_{0-30} are the average water contents in the 0- to 15- and 0- to 30-cm depths, respectively.

The computed R values for each transect were plotted using three dimensional graphics to visualize the horizontal and vertical variation. Positions along the transect were assigned identifiers A through I. Identifier E occurs in the corn row whereas, for example, I occurs in the center of trafficked interrows. In our analysis, we assume all factors acting on the soil to affect R are symmetric with respect to the centers of each interrow. For example, the traffic pattern is assumed to be symmetric with respect to the center of the trafficked interrow; hence the amount of compaction and presumably R would be identical at position G on either side of I. A linear regression of R against the 5 distances from the nearest row (0, 12.5, 25, 37.5 or 50 cm) was computed separately for the trafficked and non-trafficked interrows for each transect. All statistical computations were made using Statistical Analysis System software (SAS Institute, 1985). Levels of significance for the regression coefficients were determined according to Pimentel (1970).

RESULTS AND DISCUSSION

The penetrometer performed well during the 2-day period required to make the measurements on the four transects. Even though small rocks, up to 15 mm in size, were present, the penetrometer was able to penetrate the soil. Soil resistance data were obtained to the 60 cm depth at all 33 position for all transects.

Soil resistance as a function of depth and position for the four transects are shown in Figs. 3 to 6. The mean soil resistance, computed by averaging all 33 measurements at a given depth for a given treatment, is plotted versus depth in Fig. 7. Three features can be observed. First, there is a general increase in soil resistance with depth for each transect with the exception of the tilled/green manure system (Fig. 7). The soil water content (not shown) was at in situ field capacity for all systems, except the tilled/green manure system where some of the soil water stored in the 10- to 60-cm depth had been depleted by crimson clover before it was killed and incorporated.

Another feature, shown clearly for the tilled system (Fig. 3), is the pronounced effect of traffic wheeling as indicated by the higher soil resistance at shallow depths in the trafficked interrows. Chisel plowing prior to planting loosened the upper 20 cm of soil, while disking recompacted soil below the 10-cm depth. Wheel traffic during the planting operation markedly compacted the soil in the 0- to 15-cm depth as evidenced by the large increase in soil resistance at the center of the trafficked interrow.

Soil resistance for the no-till system (Fig. 4) was similar for both the trafficked and non-trafficked interrows. This result was surprising because no wheel traffic had occurred in the non-trafficked interrow for 4 years. In general, for no-till, the minimum value of R occurred at the 0- to 5-cm depth in the row, the only location that was loosened by the coulter when the corn was planted.

The soil resistance pattern for the no-till/rotation system (Fig. 5) was similar to those for the tilled and no-tilled systems. However, the pattern for the tilled/green manure system differed from those of the other systems (Fig. 6). Soil resistance for the latter system was low in the 0- to 5-cm depth, which was loosened during the chisel and disk operations, but below this depth, R increased because the soil was dryer. The crimson clover had utilized some of the stored available water prior to being killed.

The relationship between R and distance from the corn row was determined by regressing R on distance for both the trafficked and non-trafficked interrows at all soil depths (data not shown). The only consistent trend found was in the tilled system in the trafficked interrows: regression models were significant ($P = 0.1$ or 0.05 level) at each sampling increment to a depth of 40 cm. Correlation coefficients (r) ranged from 0.83 to 0.95. The slope coefficients from models for the trafficked interrows of all systems are shown in Fig. 8. In the tilled system, the coefficient was relatively high at the surface, then decreased with soil depth and approached values of coefficients of the other systems. Actual values of R from the trafficked interrow of the tilled system are shown in Fig. 9. In the upper 20 cm, R generally increases by a factor of two as sampling location moves from the row to the middle of the interrow.

The tilled and the tilled/green manure systems are similar in that they both are chisel plowed and disked prior to planting corn. Apparently, in the till/green manure system, the partial incorporation of crimson clover during tillage prevents the wheel-track compaction found in the tilled system.

The third feature illustrated by the data in Figs. 3 through 6 is the presence of gravel or small rocks at randomly distributed locations in the subsoil. The effects of these rocks are most pronounced for the tilled and tilled/green manure systems, and are indicated by the abrupt increases in R. The impact penetrometer was capable of penetrating, breaking, or pushing these rocks aside. A manually-operated penetrometer would have stopped when it encountered the rock. A hydraulically-operated penetrometer might have penetrated the rocks, but our experience has been that obstructions below the soil surface often result in bending the penetrometer shaft.

We conclude that the impact penetrometer effectively measures dynamic resistance in soils having high soil strength. Although the penetrometer can be used by one person, it is more efficient and less tiring when two persons work together, especially if a large number of measurements are required. It is particularly tiring to repeatedly lift the 4-kg impact cylinder.

Based on the data from this limited study, it appears that no-tillage will be no more limiting from a soil "hardness" or compaction standpoint than the other three treatments. However, no definitive statement to this effect can be made because soil resistance was not replicated in blocks. However, we have shown that the impact penetrometer can be used to address this question.

SUMMARY

The Stolf impact penetrometer is an effective device for measuring soil resistance in clayey soils containing gravel where difficulties have been encountered using manual and hydraulically driven penetrometers. The soil resistance values measured allowed us to evaluate pictorially and statistically the variation in R with respect to depth and position.

ACKNOWLEDGEMENTS

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LIST OF FIGURES

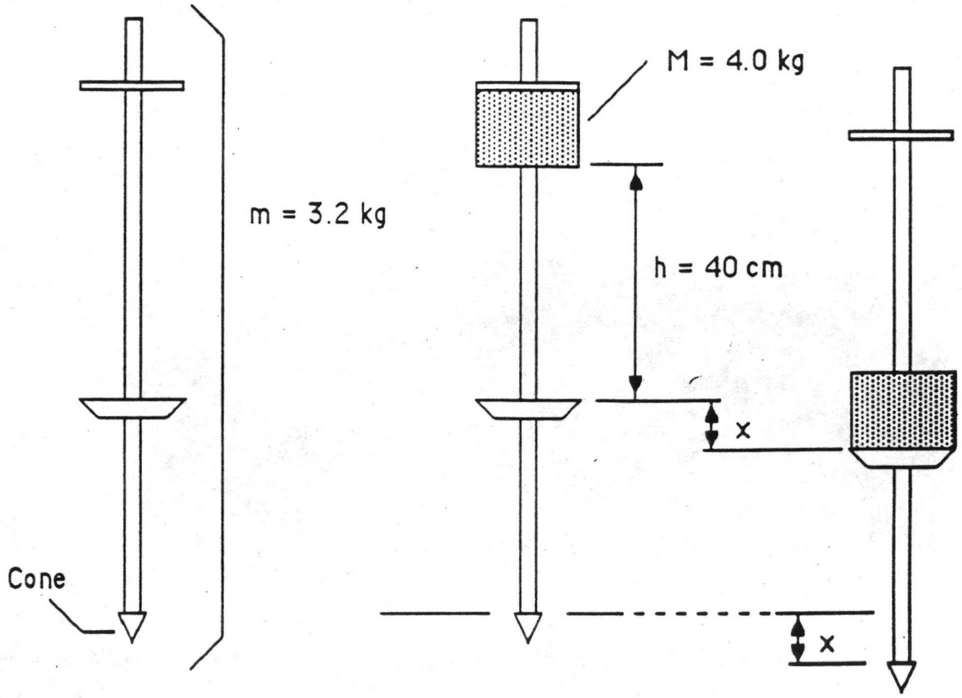

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Figure 1. Position of the penetrometer components in the gravitational field according to Stolf (1991). M moves the distance h + x; m moves the distance x.

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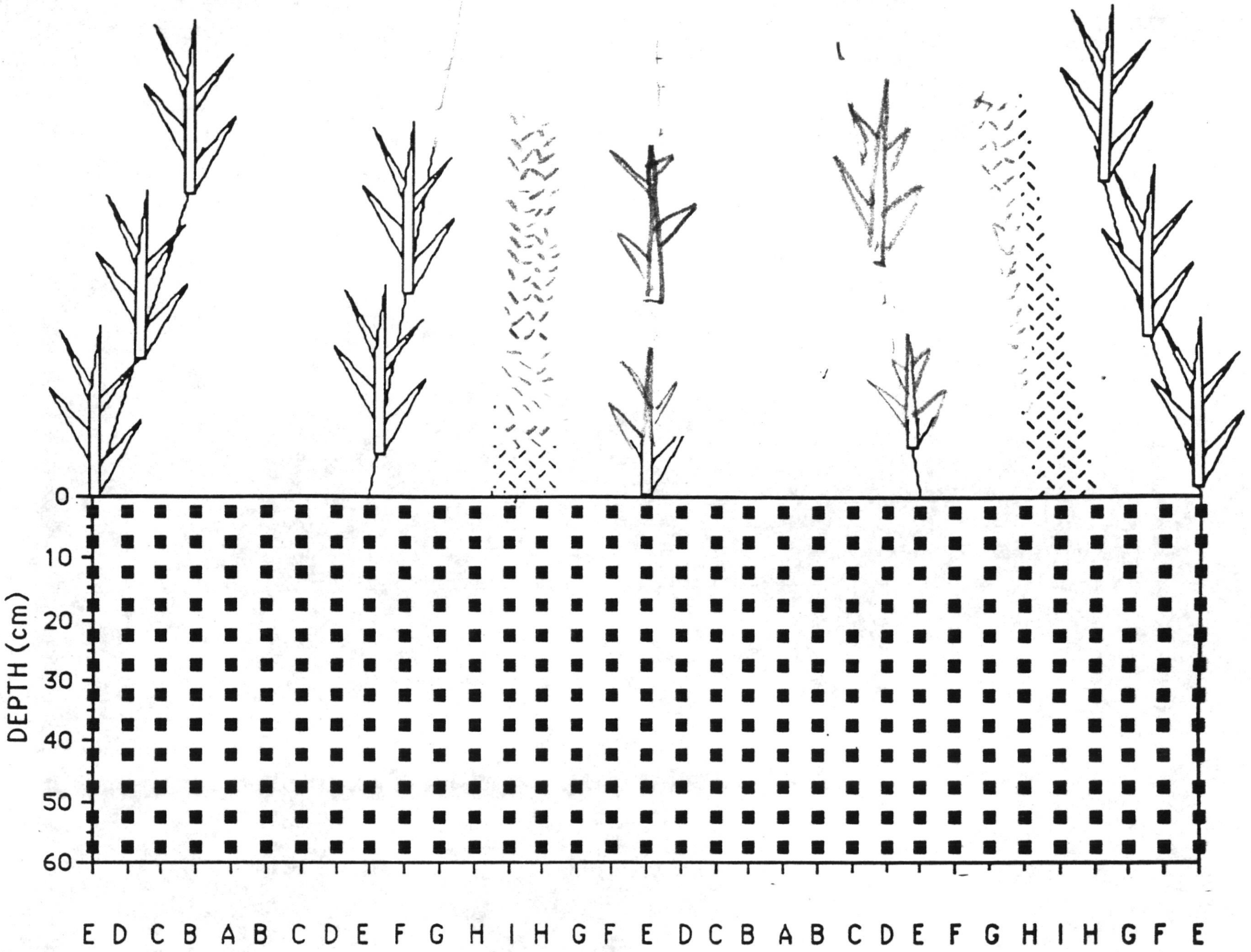

Figure 2. Sampling design: 33 horizontal points 12.5-cm apart and 12 depth increments each 5-cm long. Letters identify sampling points on the transect in relation to distance from the nearest corn row, and to the presence or absence of wheel compaction.

Fig. 2

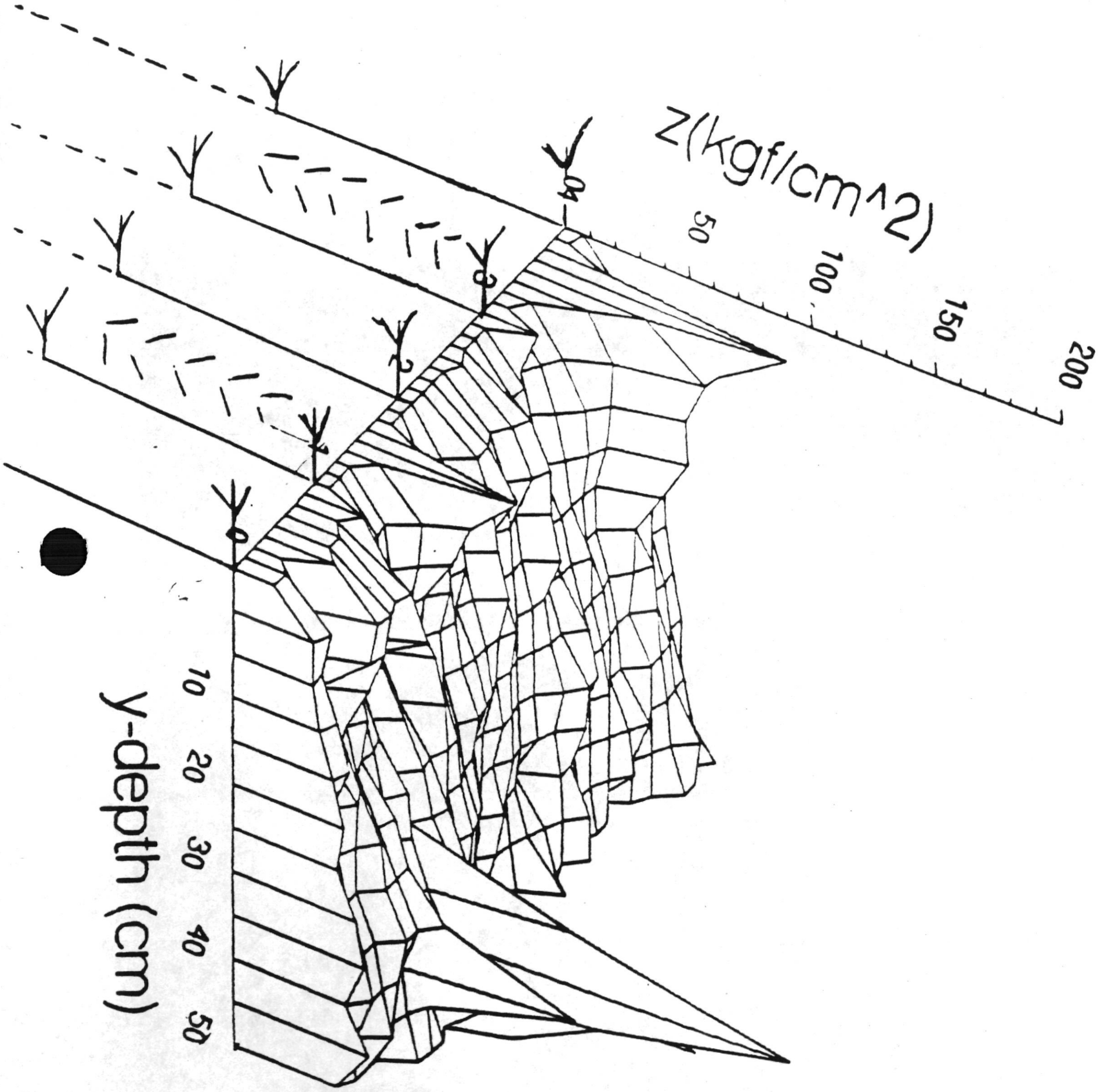

Figure 3. Spatial distribution of 396 measurements of dynamic soil resistance in a vertical section crossing four interrows of the tilled system.

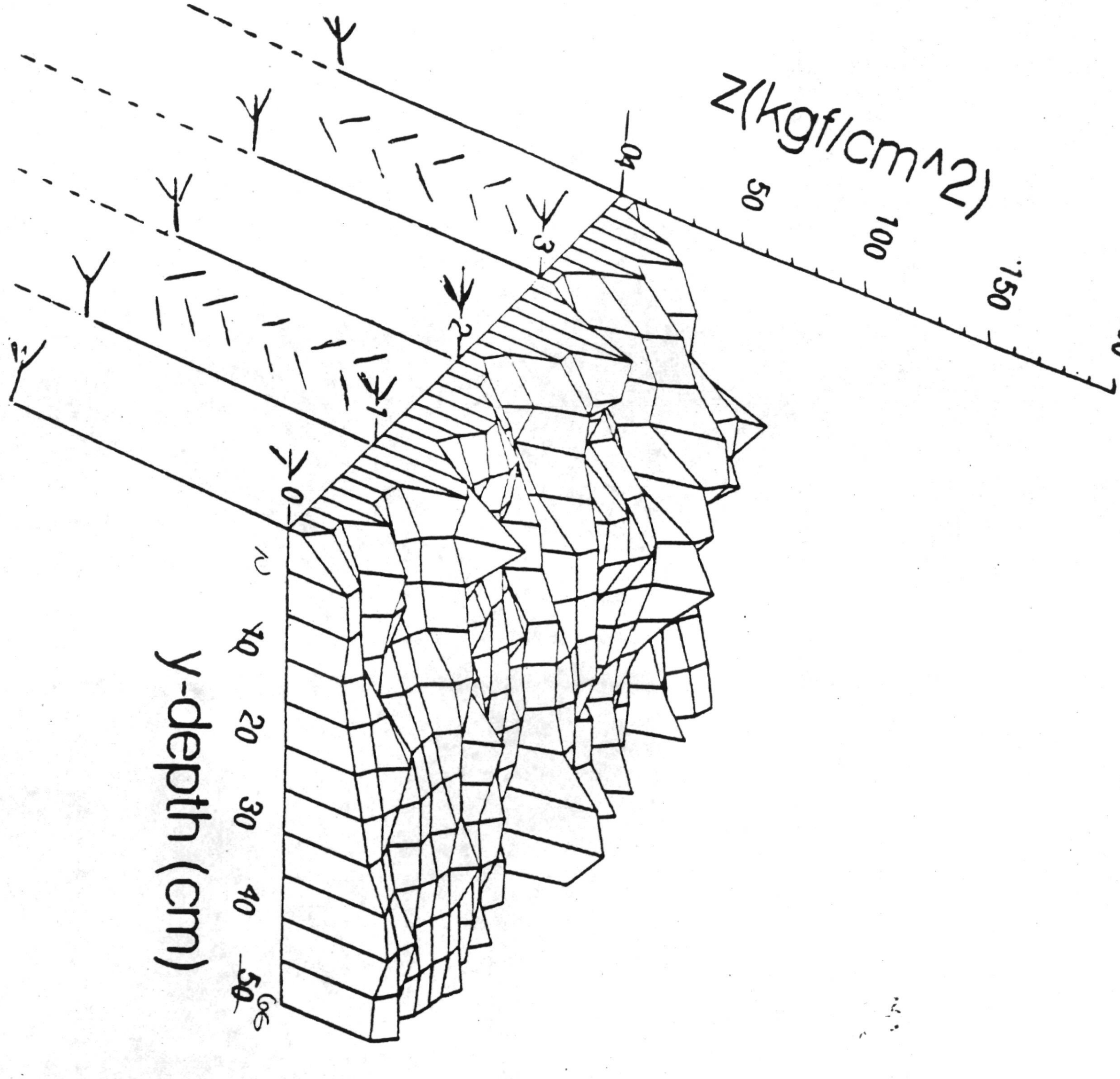

Figure 4. Spatial distribution of 396 measurements of soil resistance in a vertical section crossing four interrows of the no-till system.

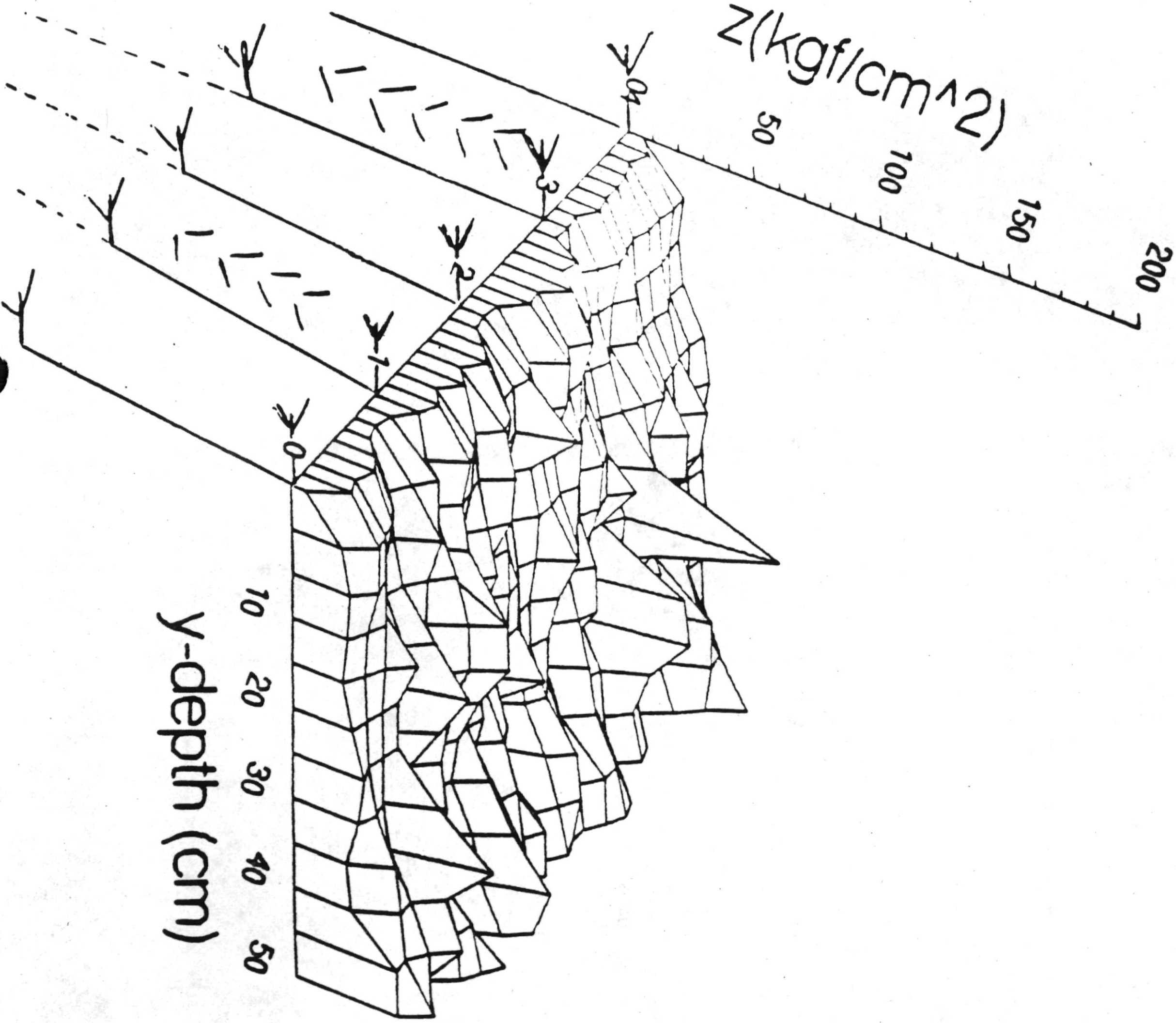

Figure 5. Spatial distribution of 396 measurements of soil resistance in a vertical section crossing four interrows of the no-till/rotation system.

Fig 5,

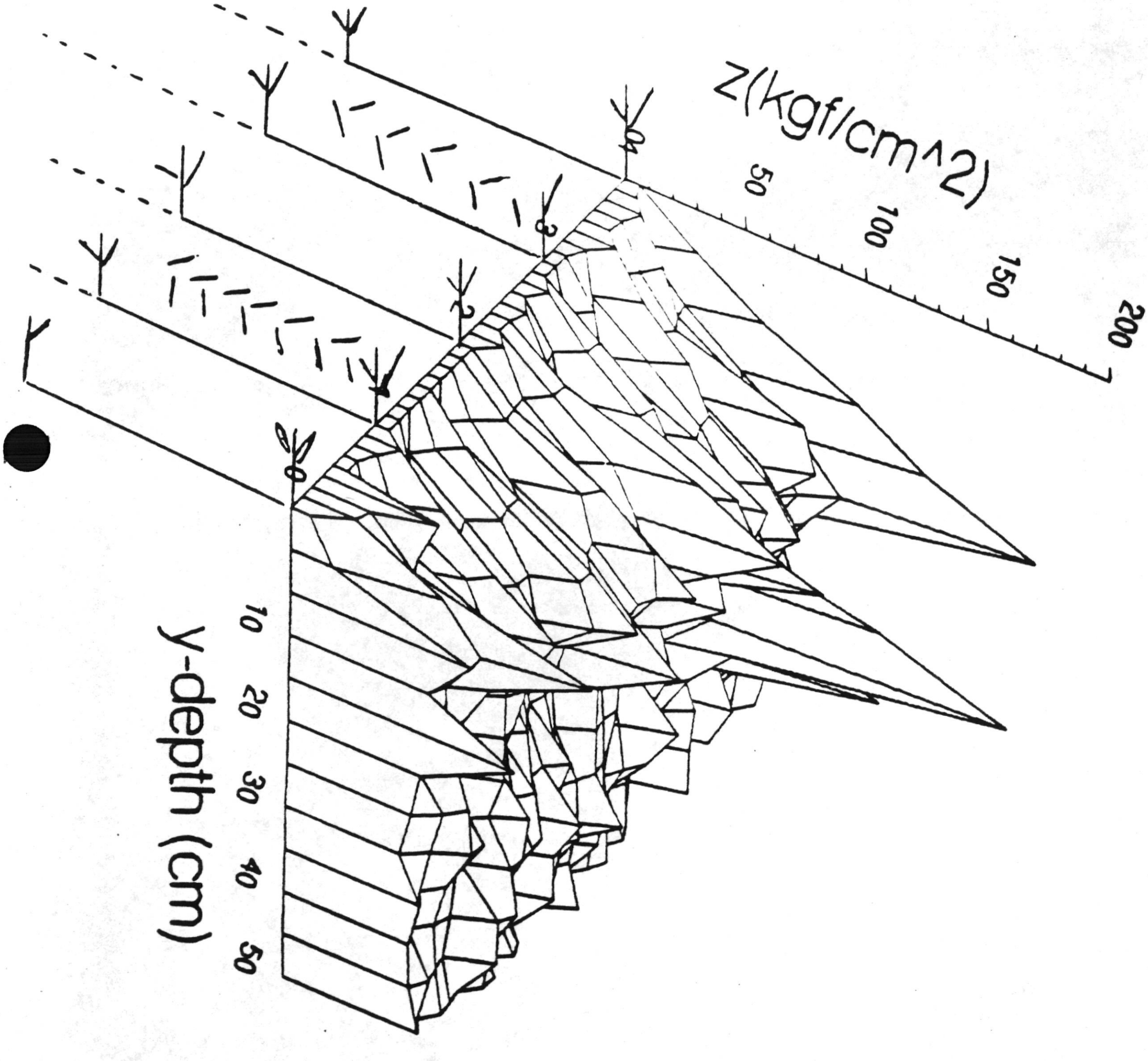

Figure 6. Spatial distribution of 396 measurements of soil resistance in a vertical section crossing four interrows of the tilled/green manure system.

Fig. 6

Fig. 7

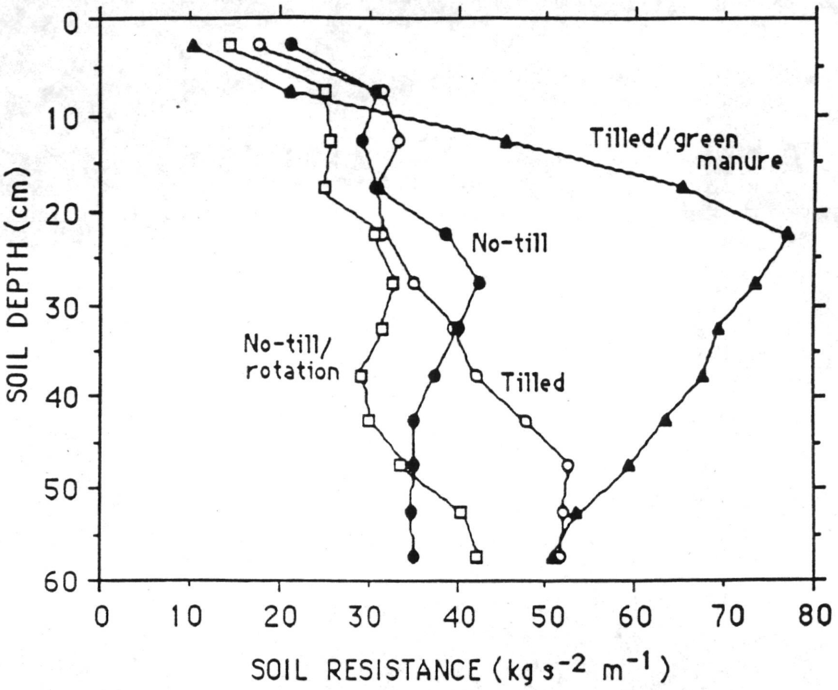

Figure 7. Effect of crop management systems and depth on soil resistance. Each value is the mean of 33 measurements.

Fig 8

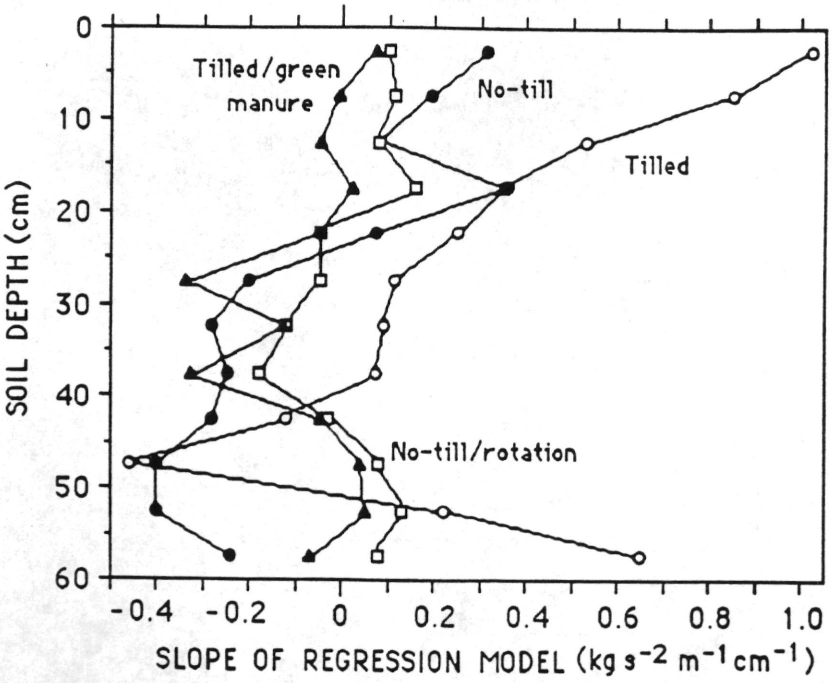

Figure 8. Slope of models of resistance regressed on distance from the corn row in the trafficked interrow.

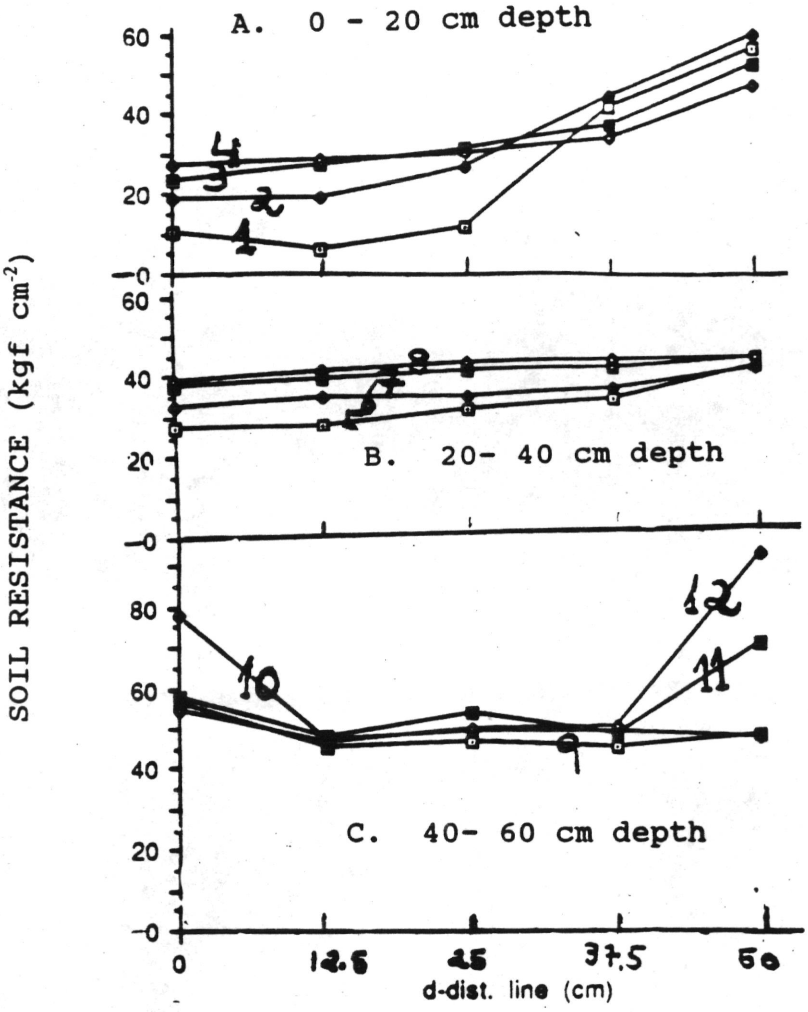

Figure 9. Horizontal variation of soil resistance in the tilled system from the corn row to the center of the trafficked interrow. A) depths from 1 (0 - 5 cm) to 4 (15 - 20 cm); b) depths from 5 (20 - 25 cm) to 8 (35 - 40 cm); c) depths from 9 (40 - 45 cm) to (55 - 60 cm).

Fig. 9