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SOIL STRUCTURAL FORM AND STABILITY INDUCED BY TILLAGE IN A TYPIC HAPLUDALF

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DALVAN JOSÉ REINERT

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of the requirements for

Ph. D. degree in Crop + Soil Sciences

Major professor

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SOIL STRUCTURAL FORM AND STABILITY INDUCED BY TILLAGE IN A TYPIC HAPLUDALF

By

Dalvan Jose Reinert

A DISSERTATION

Submitted to

Michigan State University

in partial fulfillment of the requirements

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ABSTRACT

SOIL STRUCTURAL FORM AND STABILITY INDUCED BY TILLAGE IN A TYPIC HAPLUDALF.

By

Dalvan Jose Reinert

Changes in soil structure induced by tillage are commonly recognized but the extent and trend of variation in the short and long term are not well known. This work aims to develop a better understanding of dynamics, over space and time, of soil structural changes induced by conventional tillage and no-tillage as compared to a non tilled site. Four studies were conducted. The first study examined spatial variability of soil physical properties related to soil structure. The second and third studies quantified the variation of soil physical properties related to soil structural stability and form over two and four year periods, respectively. The fourth study evaluated compressive properties of soil as indirect measurements of susceptibility to soil compaction.

Selected soil physical properties were measured before the experiment was begun in 1985 and 20 times from June of 1986 to November of 1989 using undisturbed soil cores sampled in non-trafficked interrows. Water stable aggregate size distribution was measured 13 times in the 1988-1989 period. Compression tests were conducted with consolidometers using undisturbed soil

samples from conventional tillage and no-tillage.

Soil physical properties demonstrated a well defined spatial dependence with a range of dependence of about 30 to 40 meters for bulk density and total porosity as compared to 10-20 meters for macroporosity and saturated hydraulic conductivity. This implied a significant effect of management history and soil formation factors and processes on soil physical properties in close distances. Temporal variation induced by tillage on physical properties related to soil structural form was cyclic and appeared to be controlled by the variation of macroporosity for plowed and no-tilled soil and both macro- and microporosity in the never tilled soil. However, aggregate stability had a cyclic pattern in the temporal variation only for conventional tillage and no-tillage. Temporal variation was highest in the 4 to 6.3 aggregate size class which varied from 4 to 63% of the aggregates by weight depending on the date of sampling. The precompression pressure and compression index were similar for conventional tillage and no-tillage but was strongly affected by the initial state of compaction and water saturation. The data suggest the major effect of no-tillage on the compressive behavior of soils in the first few years after cessation of tillage is predominantly due to the effect of increased bulk density.

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Finally, to my parents, Ain and Ivone Reinert, my eternal admiration.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The natural state of soil structural form, stability, and restoration are markedly affected by cropping systems. Degradation and restoration of natural state is a response to regional climatic pattern and to management imposed by several components involved in cropping systems such as soil tillage type and intensity, and the choice of crop.

Soil tillage studies have shown that cultivation profoundly changes the form and reduces stability of soil structure and that such deterioration can be rapid, occuring after only a few years of plowing (Kay, 1989; Low, 1972). No-tillage or direct drilling has been reported to increase aggregate stability (Douglas and Goss, 1982) and soil strength (Culley and Larson, 1987) over plowing. The deterioration of soil structure is a major factor contributing to increased rates of soil degradation by processes such as erosion and compaction with consequent effects on productivity and the environment (Coote et al., 1988; Belvins et al.,1983).

It is not widely recognized that soil structure can have a pronounced spatial variability and a seasonal component with its long term trend of degradation and restoration.

This work aims to develop a better understanding of the dynamics, over space and time, of soil structural changes induced by conventional tillage and no-tillage as compared to a no tilled site. Four studies were conducted. The first study examined spatial variability of soil physical properties related to soil structure. The second and third studies quantified the variation of soil physical properties related to soil structural forms and stability in four and two years period, respectively. The fourth study evaluated compressive properties of soil as indirect measurements of susceptibility to soil compaction.

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CHAPTER 1

SPATIAL VARIABILITY OF SELECTED SOIL PHYSICAL PROPERTIES.

INTRODUCTION

Variability in soil properties results from the natural variation imposed by the soil forming processes operating and interaction at differential rates in space and in time (Trangmar et al., 1985; Cassel and Fryrear, 1990) and from variability imposed on this natural variability by man's management of soil (Cassel and Fryrear, 1990). The natural variability in soils is controlled by the stratigraphy, geomorphology, and hydrology of a particular site (Daniels and Bubenzer, 1990) and is usually longer range with respect to lateral distance then induced variability, following a pattern in concert with geomorphic features (Cassel and Fryrear, 1990). Induced variability in soil properties, such as that induced by tillage and traffic operations, tends to exhibit short range variability (Cassel and Fryrear, 1990).

Conservation tillage systems have been shown to affect soil physical properties quite differently than full width, clean tillage systems such as moldboard plowing (Gantzer and Blake, 1978; Kladivko et al., 1986). It has also been shown the spatial and temporal distribution of soil properties may differ with tillage. Cassel (1983), Cassel and Nelson (1985), and Larney and Kladivko (1989) reported considerable variability over short distances in soil physical properties due to position with respect to crop row within a field (row and interrow), the extent to which that position in the field was trafficked, the time of sampling, and the tillage system. Kachanoski et al. (1985) reported a systematic soil redistribution resulting in higher overall variances for organic carbon and solum mass in cultivated soil compared to an adjacent native site. The temporal variation in soil properties related to structural forms (bulk density, porosity, saturated hydraulic conductivity) was reported by Reinert and Pierce (1990) to be cyclic for management systems with the seasonal fluctuation considerable for the soil managed under a moldboard plowed tillage system but relatively stable under the no-tillage system.

The theory of regionalized variables provides the basis to quantify spatial variation in soils, for estimating properties and mapping them, and for planning purposes (Webster, 1985). The geostatistical approach (see Robertson, 1987; Trangmar et al., 1985; Warrick et al., 1986; Webster, 1985) has been used successfully to quantify the spatial and temporal distribution of soil properties under different tillage systems that are needed to adequately model and predict crop response to tillage system. Cassel et al. (1988) used the theory of regionalized variable to evaluate corn (Zea mays L.) grain yield response to four tillage systems.

Salinity, heavy metals in soil, soil temperature, P-sorbed, pH, Ca, Mg, K, and Si have showed autocorrelation or spatial dependence with different distance ranges (Davidoff, 1986; Miyamoto, 1987: Woopereis, 1988; Yost, 1982a, b). Kachanoski et al. (1985) reported a systematic soil redistribution resulting in higher overall variances for organic carbon and solum mass in cultivated soil compared to the native site. The latter indicates that random sampling should be avoided in both the native and cultivated sites.

Different field measurements have been adopted to study spatial dependence of hydraulic properties of soils. Saturated hydraulic conductivity, volumetric water content, and pore size index were shown to have spatial dependence of 21, 55, and 35 meters, respectively (Russo and Bresler, 1981);

soil water pressure of 6 meters (Yeh, 1986); and soil water pressure head had spatial dependence of approximately 10 meters (Greminger et al., 1985). For soil bulk density, as shown by Gajem et al. (1981), the semi-variance values increased and leveled off to a value approximately equal to the variance with a range of spatial dependence of 25 meters.

The purpose of this study was to quantify the spatial distribution of selected soil physical properties of a field in south-central Michigan prior to the installation of a long term tillage study. The overall objective of the long-term study was to understand how below ground processes within an agroecosystem interact to affect nutrient availability under different management systems (Pierce and Robertson, 1990). The temporal variation in soil structure and differences in compressibility of this soil induced by tillage have been reported (Reinert and Pierce, 1990a, 1990b, 1990c). Understanding the spatial structure of the variation in soil properties will make it possible to have unbiased estimates of these properties and pattern description with statistical confidence needed in evaluating tillage systems.

MATERIAL AND METHODS

The research was conducted at the W. K. Kellogg Biological Station in south-central Michigan. The soil is a Kalamazoo loam formed in glacial outwash material. Selected soil physical properties are reported by Reinert and Pierce (1990a). The main site area is approximately 150 by 120 m (1.8 h) in size and has been in crop production since the land was cleared in the mid 1800's. Prior to the initiation of tillage treatments to the long-term agroecosystem study, a stratified unaligned sample grid was established over the entire area to determine the variability of surface horizon properties of the soils. In order to avoid disturbance, the areas where the no-tillage treatments were to be located were not included in the sampling scheme for the intact soil core sampling. The sampling points for soil physical properties are illustrated in Figure 1. This sampling scheme resulted in three West-East transects corresponding alleyways between replications and two well sampled areas roughly 30 by 100 m each in size located on the West and East sides of the main site area. The site area had been uniformly plowed in the spring of 1985 and seeded to rye (Secale cereale L.) and lightly disked in the fall of 1985.

Undisturbed soil cores (7.6 cm diameter by 7.6 cm height) were sampled in April of 1986 using a double-cylinder sampler for measuring bulk density, total porosity, pore size distribution, and saturated hydraulic conductivity. The soil cores were saturated form the bottom and then weighed so that total porosity could be measured at saturation. Saturated hydraulic conductivity was measured by the constant head method (Klute, 1965). Cores were then equilibrated on a tension table or pressure-plate apparatus at matric potentials of -1, -2, -3, -4, -6, -10, -30, and -100 kPa. These were converted to equivalent pore size diameter (EPSD) of 288, 144, 96, 72, 48, 28, 8, and 3 micrometers (Childs, 1940; Leamer and Shaw, 1941; Richards, 1965). Cores were then oven dried. Bulk density, total porosity, and pore-size distribution were calculated from the above measurements. The pore-size distribution was separated into two major classes: macroporosity representing percent of pores larger than 48 micrometers and microporosity representing pores smaller than 48 micrometers. This limit was chosen based on pore size distribution curves which showed, for most cases, inflexion point around 48 micrometers EPSD (Reinert and Pierce, 1990b).

The statistical analysis was made as recommended by Burgess and

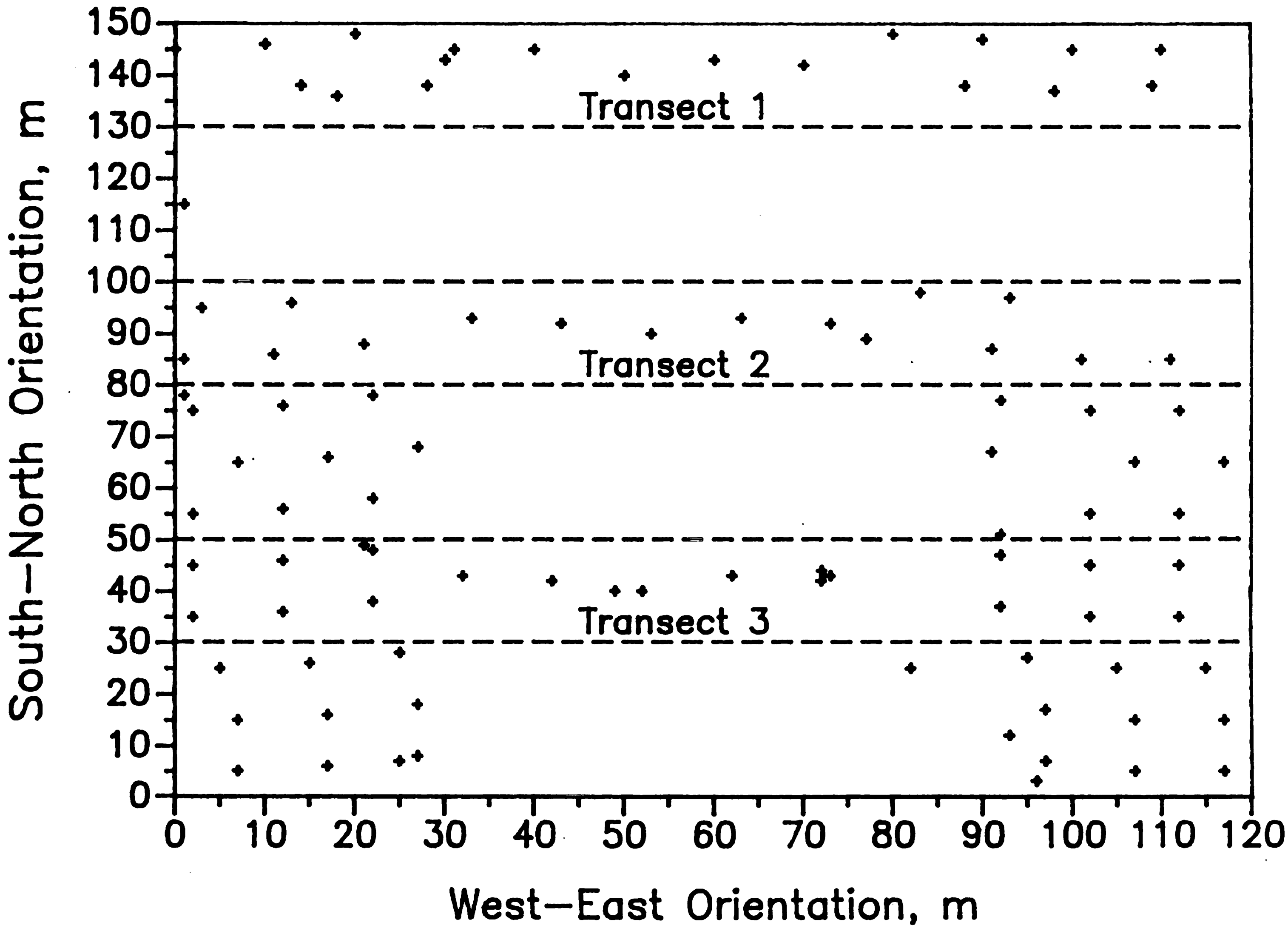

Figure 1.1. Experimental area for spatial variability study showing points representing sampling location distribution and area considered for three West-East transacts.

Webster (1980) following three steps: 1-spatial analysis to compute the semivariograms; 2-choice and fitting a suitable model to the semivariograms; and 3-computation of weights in each location (kriging interpolation). Algorithm cited in Robertson (1987) were used to compute semivariogram and PC-SAS to fit semivariogram models. The four general models, linear, spherical, exponential and gaussian, were fitted using number-of-couples as the weighing factor. The best fit was chosen based on residual sum of squares, R-square and eye approximation. The block kriging interpolation was made using algorithms cited in Robertson (1987) to estimate soil properties at unmeasured locations.

RESULTS AND DISCUSSION

The frequency distribution for the measured parameters for the 1.8 ha experimental area were normally distributed for bulk density, total porosity, macroporosity and microporosity and log-normally distributed for saturated hydraulic conductivity, as reported by Warrick and Nielson (1980) (Figure 1.2 to 1.6). The spatial dependence of these soil properties are summarized in Table 1.1 for the three west-east transects and for the anisotropy for individual directions of South-north, and at 45 and 90 degrees from north direction. The semi-variograms are summarized by three parameters: the nugget variance, sill, and range. The nugget variance is the intercept of the semi-variogram and represents the random components of the variance. The sill is the maximum of the semi-variogram , i.e., where the semi-variance levels out. The sill is the priori variance of the variable and should equal the sample variance given in Table 1.1, column 4 if the model fit is reasonable. The range is the lag at which the sill is reached and marks the limit of spatial dependence.

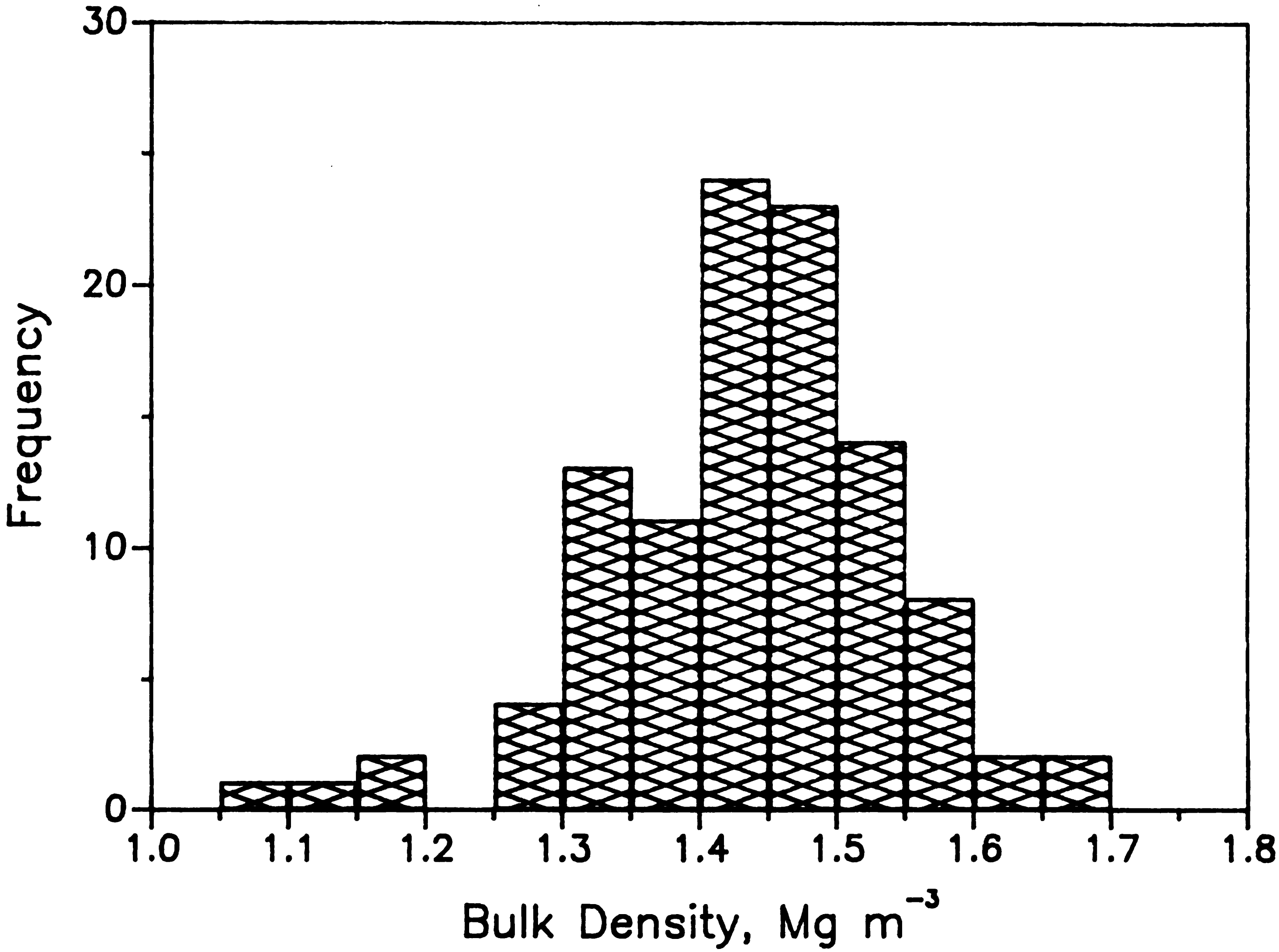

Figure 1.2. Frequency of bulk density values including all points sampled in the experimental area.

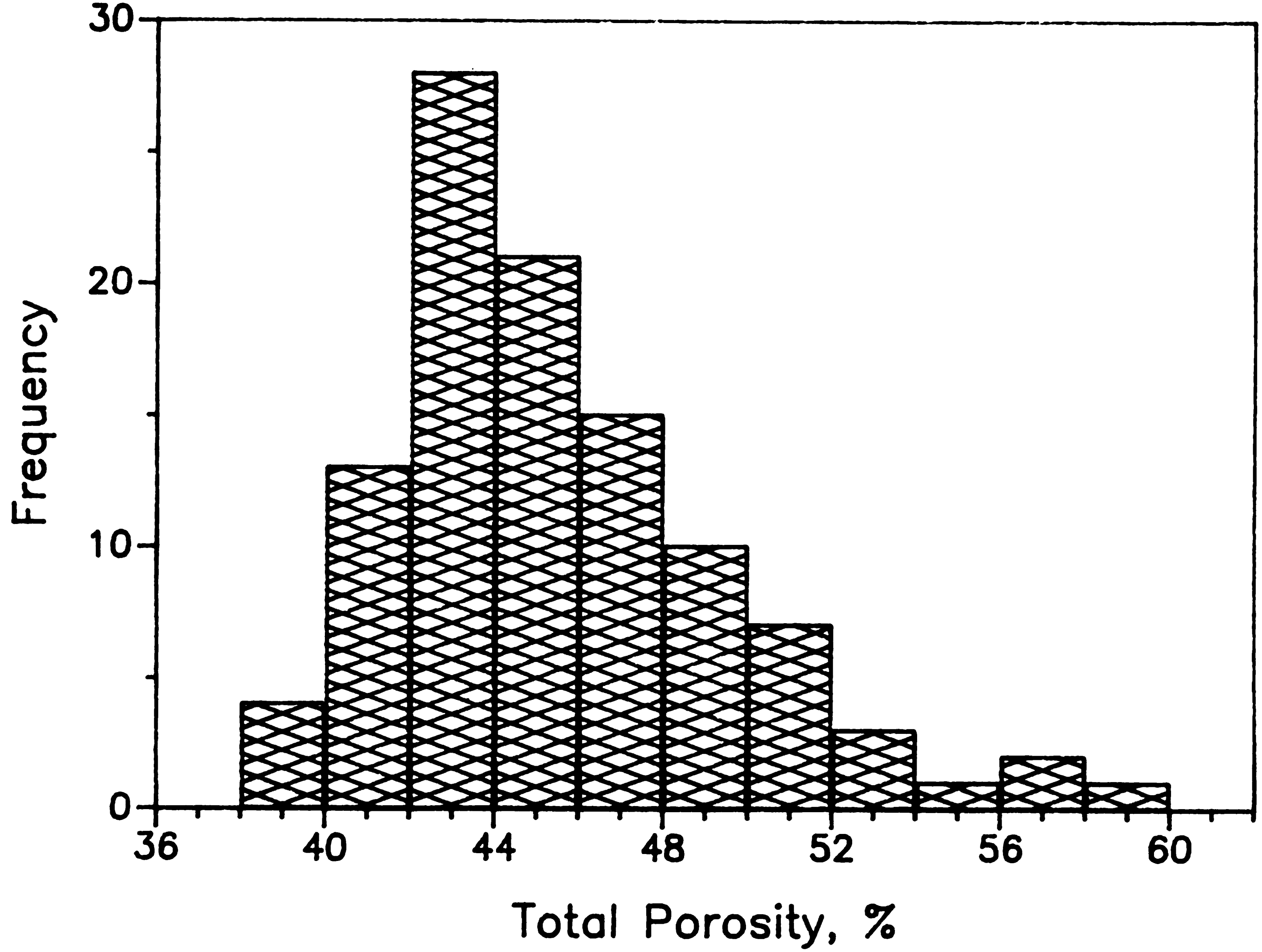

Figure 1.3. Frequency of total porosity values including all points sampled in the experimental area.

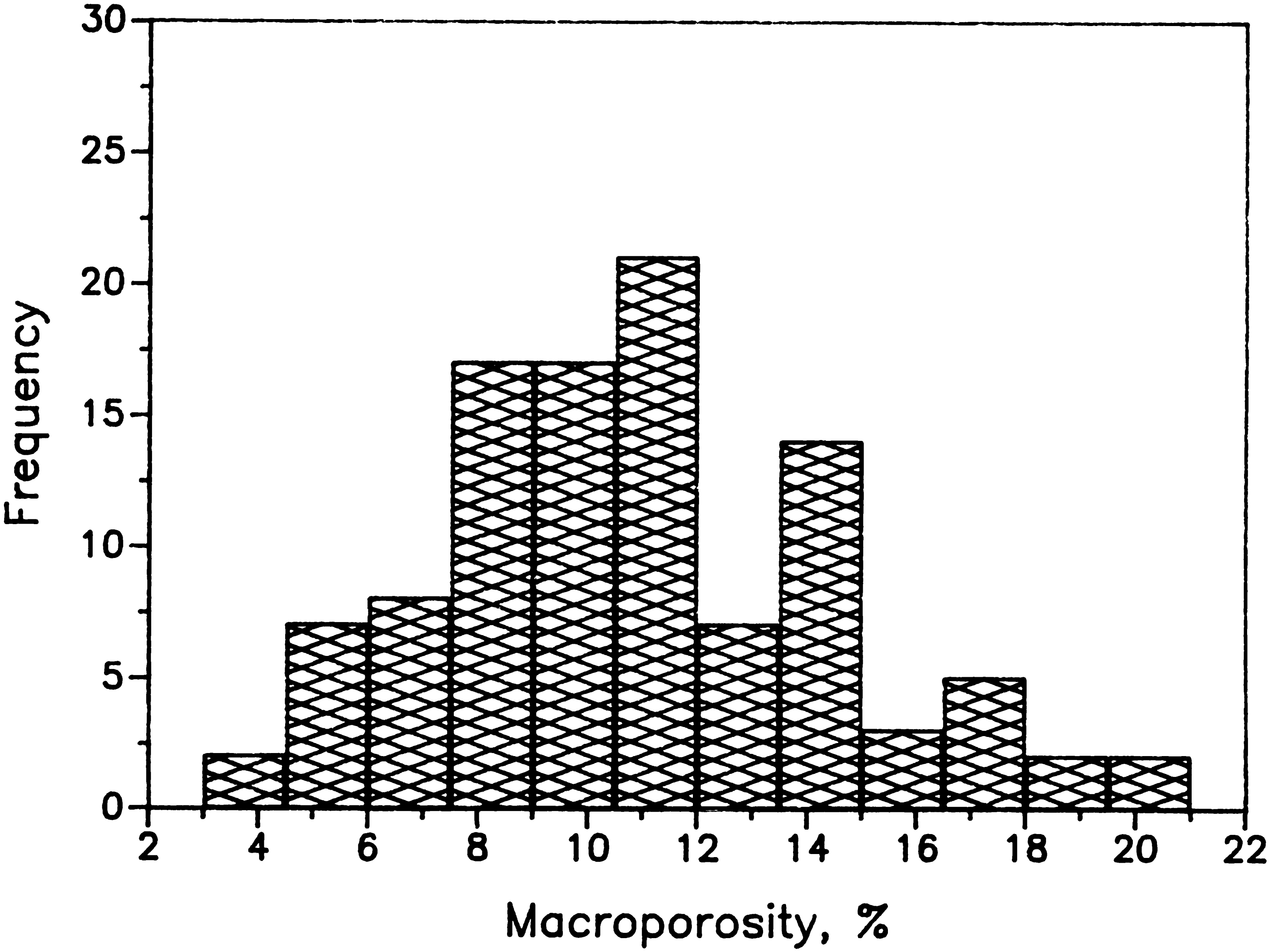

Figure 1.4. Frequency of macroporosity values including all points sampled in the experimental area.

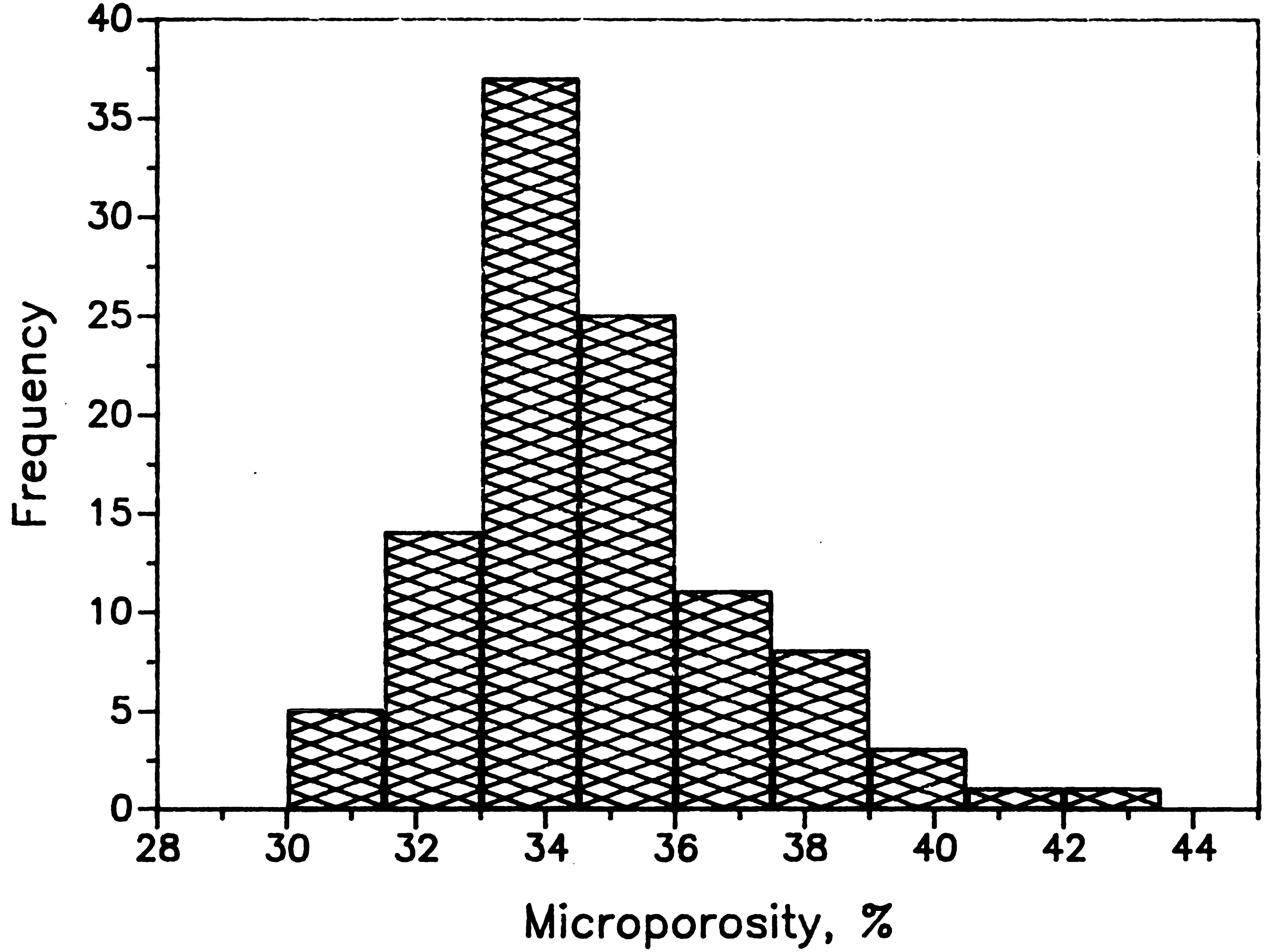

Figure 1.5. Frequency of microporosity values including all points sampled in the experimental area.

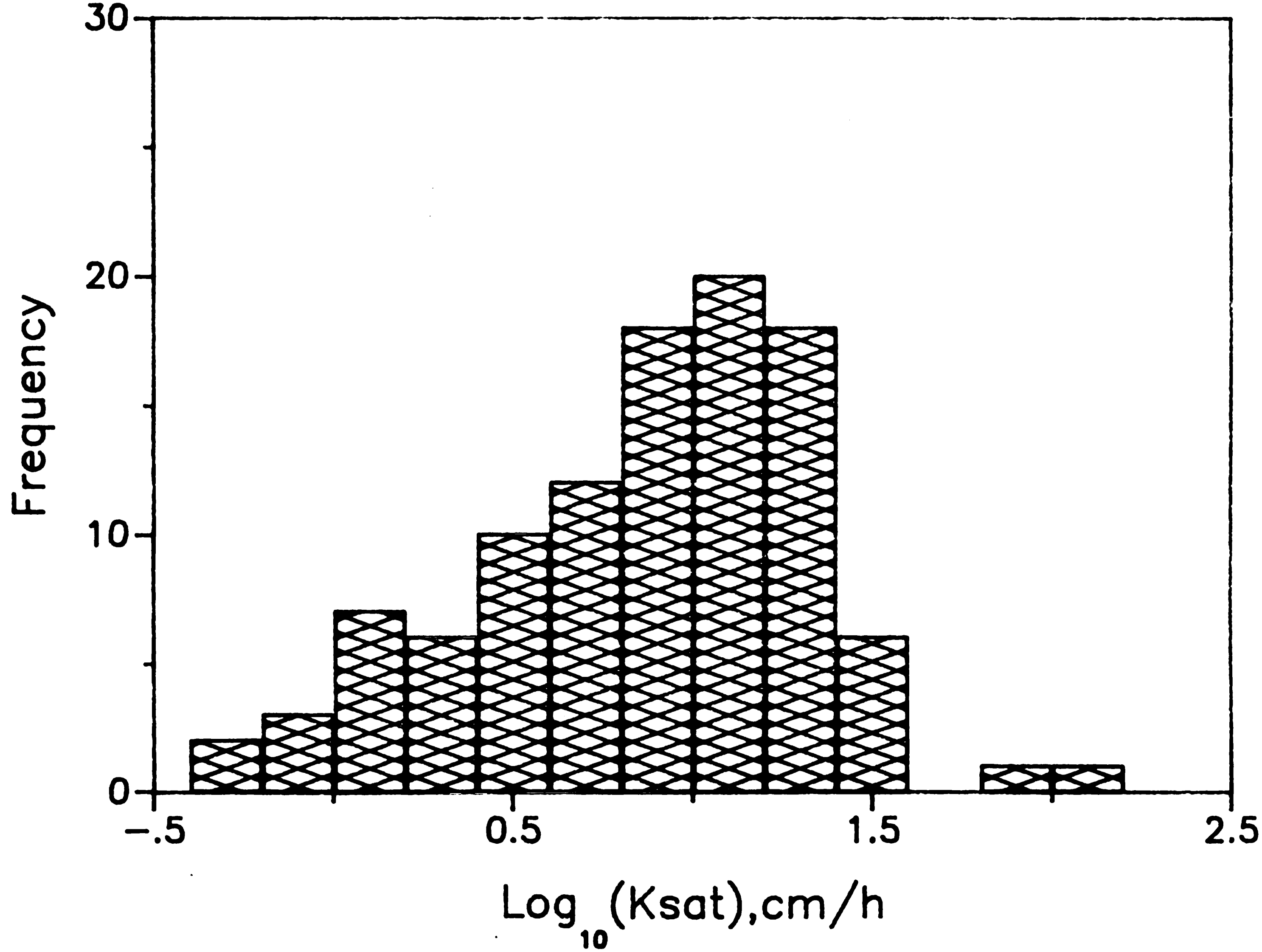

Figure 1.6. Frequency of saturated hydraulic conductivity values including all points sampled in the experimental area.

Table 1.1. Mean, number of observation, variance, coefficient of variation, nugget variance, sill, range and coefficient of determination of selected soil physical properties of a Typic Hapludalf at Kellogg Biological Station

Variate	Mean	N	Variance	CV	Nugget	Sill	Range	r^2
					Bulk Density, Mg m^{-3}			
TR1	1.43	19	.0052	5	0.0018	0.0055	18.1	0.32
TR2	1.47	17	.0132	7	0.0000	0.0193	31.7	0.83
TR3	1.42	21	.0072	6	0.0006	0.0093	27.2	0.82
N-S	1.44	79	.0077	6	0.0016	0.0087	43.2	0.88
45*	1.44	79	.0077	6	0.0015	0.0077	32.7	0.78
90*	1.44	79	.0077	6	0.0007	0.0102	38.6	0.94
					Total Porosity, %			
TR1	47.74	19	9.18	6	0.00	10.55	28.4	0.91
TR2	45.83	17	16.32	9	0.00	16.38	29.0	0.74
TR3	44.42	21	9.61	7	0.00	10.83	15.5	0.66
N-S*	44.30	79	9.98	7	5.27	10.01	36.4	0.87
45*	44.30	79	9.98	7	0.04	11.25	34.8	0.74
90*	44.30	79	9.98	7	0.00	9.60	17.4	0.85
					Macroporosity, %			
TR1	12.08	19	7.56	23				
TR2	10.03	17	7.78	27	0.30	11.98	37.5	0.74
TR3	10.70	21	19.80	41	0.00	22.22	13.4	0.70
N-S*	10.10	79	11.90	34	0.00	13.05	17.0	0.97
45*	10.10	79	11.90	34	0.00	13.37	15.1	0.72
90*	10.10	79	11.90	34				
					Microporosity, %			
TR1	35.65	19	4.62	6	1.67	5.29	25.9	0.81
TR2	35.79	17	6.10	7				
TR3	33.71	21	3.45	5	0.64	3.79	16.8	0.81
N-S*	34.24	79	3.65	5	1.84	3.68	28.0	0.97
45*	34.24	79	3.65	5	1.84	3.68	28.0	0.97
90*	34.24	79	3.65	5	0.44	3.12	14.2	0.84
					Saturated Hyd. Conductivity, cm/h			
TR1	17.92	19	75.5	48				
TR2	12.38	17	81.7	73				
TR3	6.20	21	8.5	47				
N-S*	7.69	78	39.9	82	0.00	0.092	13.55	0.96
45*	7.69	78	39.9	82	0.00	0.083	10.22	0.84
90*	7.69	78	39.9	82	0.00	0.094	13.86	0.84

TR-transect, used for isotropical analysis;
Spherical model was fit for all properties and data sets
*-direction from north used for anisotropical analysis.
Range is given in meters
Blank spaces indicate no model fit well for respective data set

The spherical model proved to be the best fit of the four models tested and has been shown to fit many semi-variograms of many soil properties (Webster, 1985). For certain transects, the macroporosity and saturated hydraulic conductivity, none of the models fit, indicating totally random behavior and no spatial dependence in the data. Each soil parameter will be discussed separately. Since the semi-variogram and block kriging interpolation can be generated from the nugget, sill, and range, only selected data will be presented graphically to illustrate trends in these results.

Bulk Density

The bulk density values along the three West-East transects showed apparent periodicity indicating spatial dependence(Figure 1.7 to 1.9). There was a small difference in the mean and variance of each transect but the coefficient of variation (CV) are low (Table 1.1). The surface bulk density for all three transects had a significant degree of spatial dependence, with the range for the three transects varying from 18 to 32 m (Figure 1.10 to 1.12, Table 1.1). Random variation as measured by the nugget variance was zero for transect 2 and as high as 33% of the variance for transect 1 where the model fit accounted for only 32% of total variance. The semi- variograms for the three directions were similar indicating a high degree of spatial dependence (range varied from 33 to 43m) and only a slight anisotropy in bulk density (Figure 1.13). This might expected since the area has been tilled in a similar fashion over a long history of cultivation and these data are for the 0 to 7.6 cm depth only. Gajem et al. (1981) found significant spatial variability of bulk density with range values around 25m.

Since bulk density is spatially dependent and its variance is isotropic, a block kriging of bulk density using the semi-variogram for the N-S transect was used to interpolate bulk density values for the experimental area. The

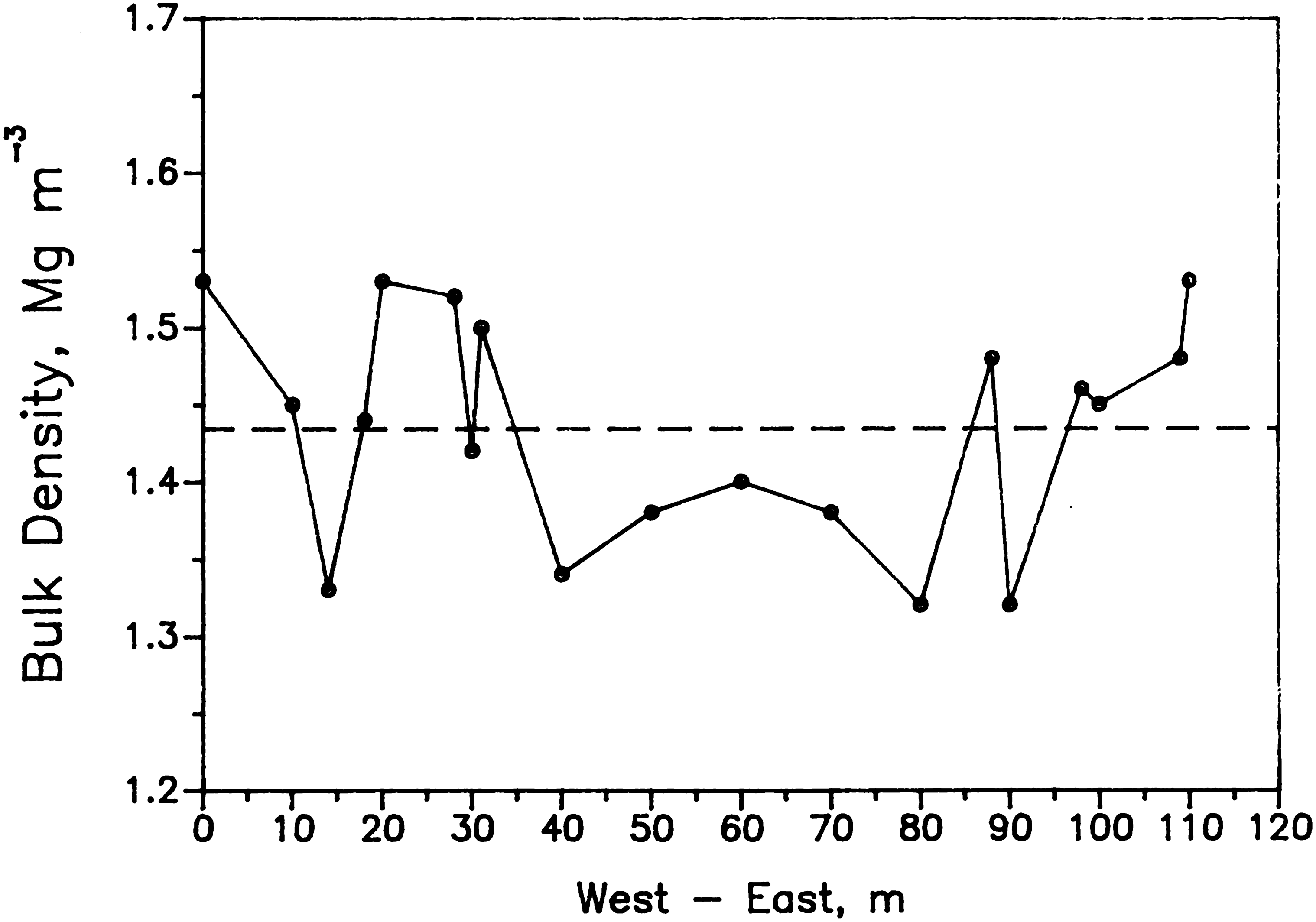

Figure 1.7 Bulk density values along of transect 1 of a Typic Hapludalf at 0 to 7.6 cm depth. Dashed line represents data set mean.

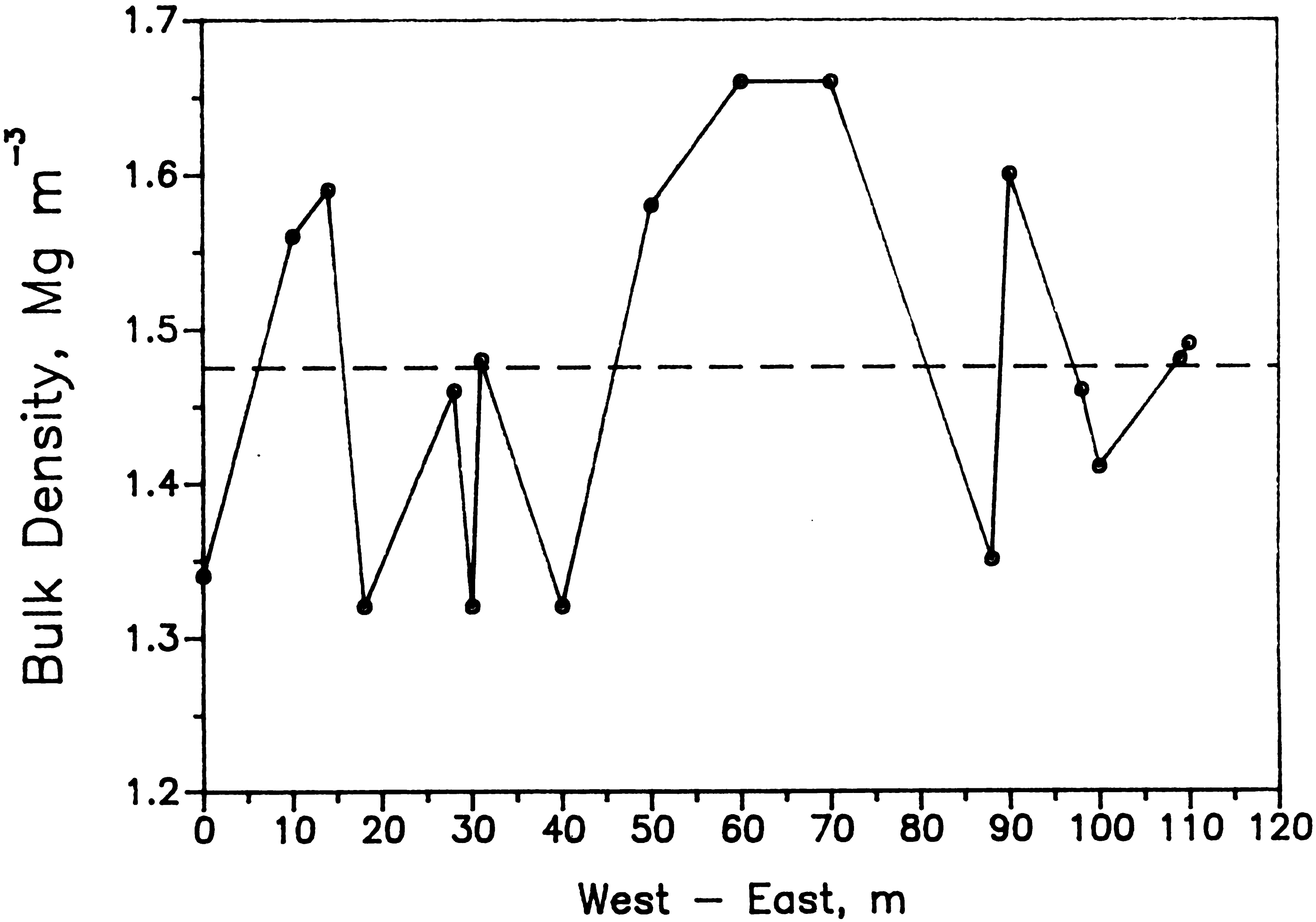

Figure 1.8 Bulk density values along of transect 2 of a Typic Hapludalf at 0 to 7.6 cm depth. Dashed line represents data set mean.

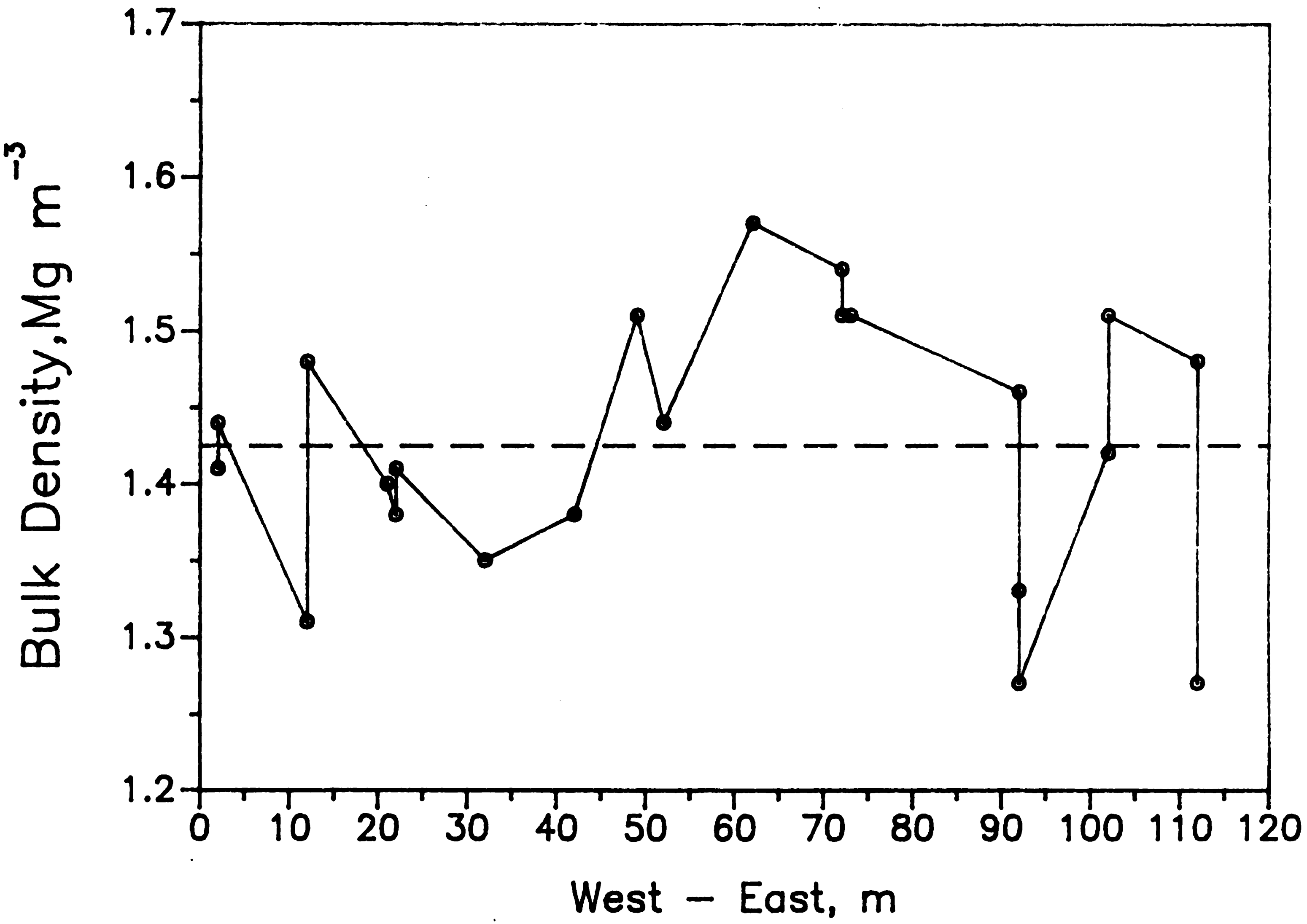

Figure 1.9 Bulk density values along of transect 3 of a Typic Hapludalf at 0 to 7.6 cm depth. Dashed line represents data set mean.

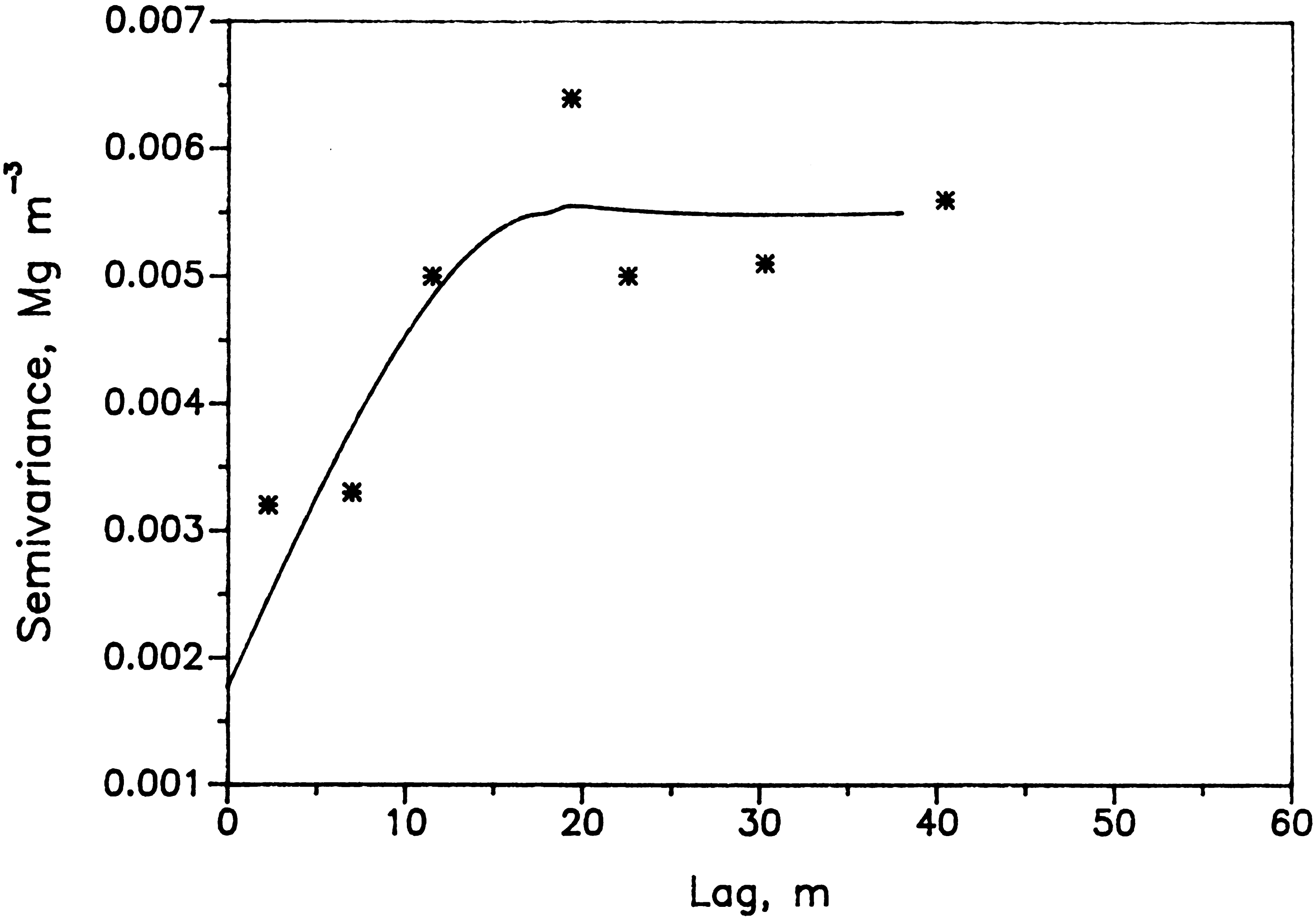

Figure 1.10 Semivariogram of bulk density for transect 1 of a Typic Hapludalf at 0 to 7.6 cm depth.

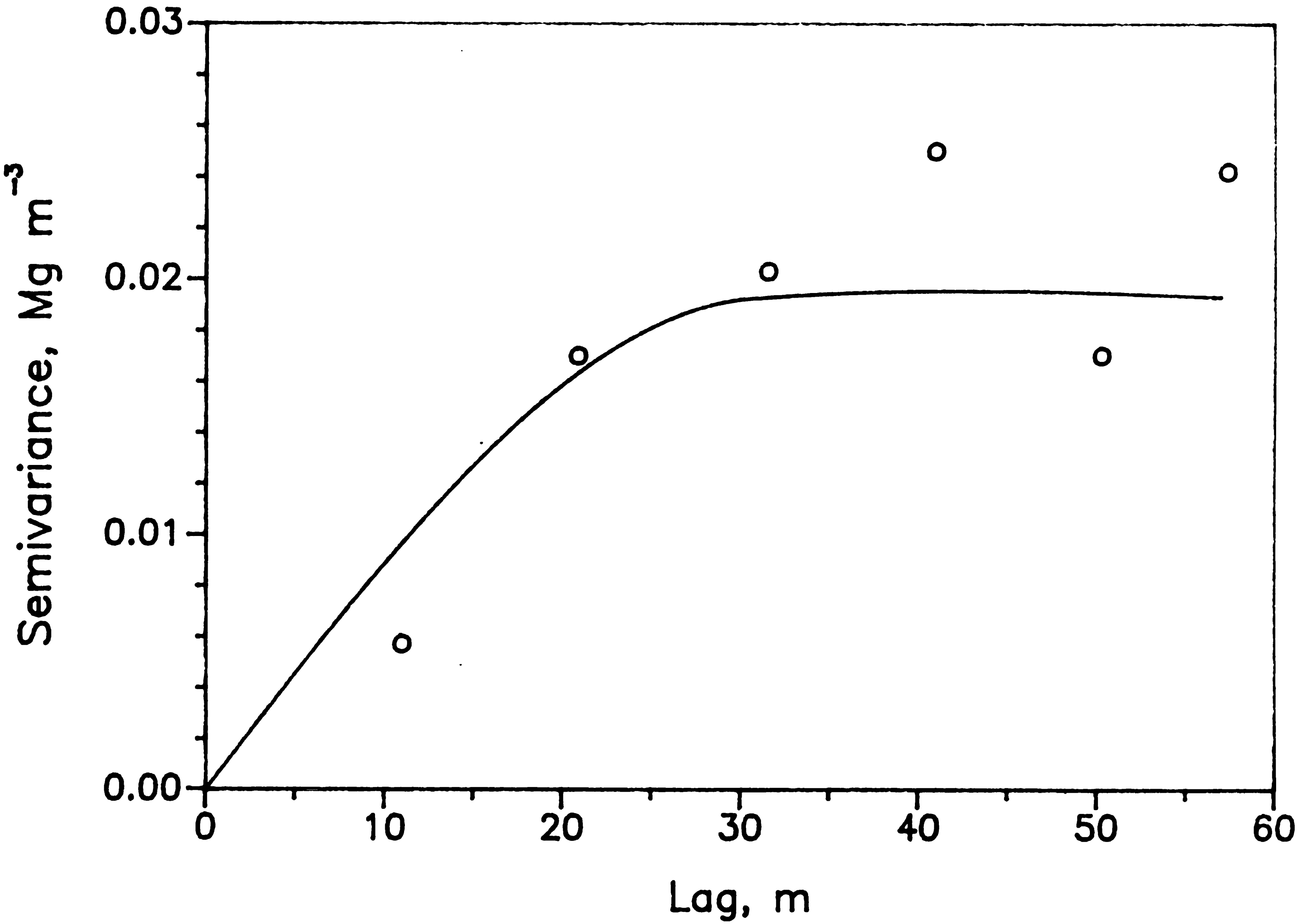

Figure 1.11 Semivariogram of bulk density for transect 2 of a Typic Hapludalf at 0 to 7.6 cm depth.

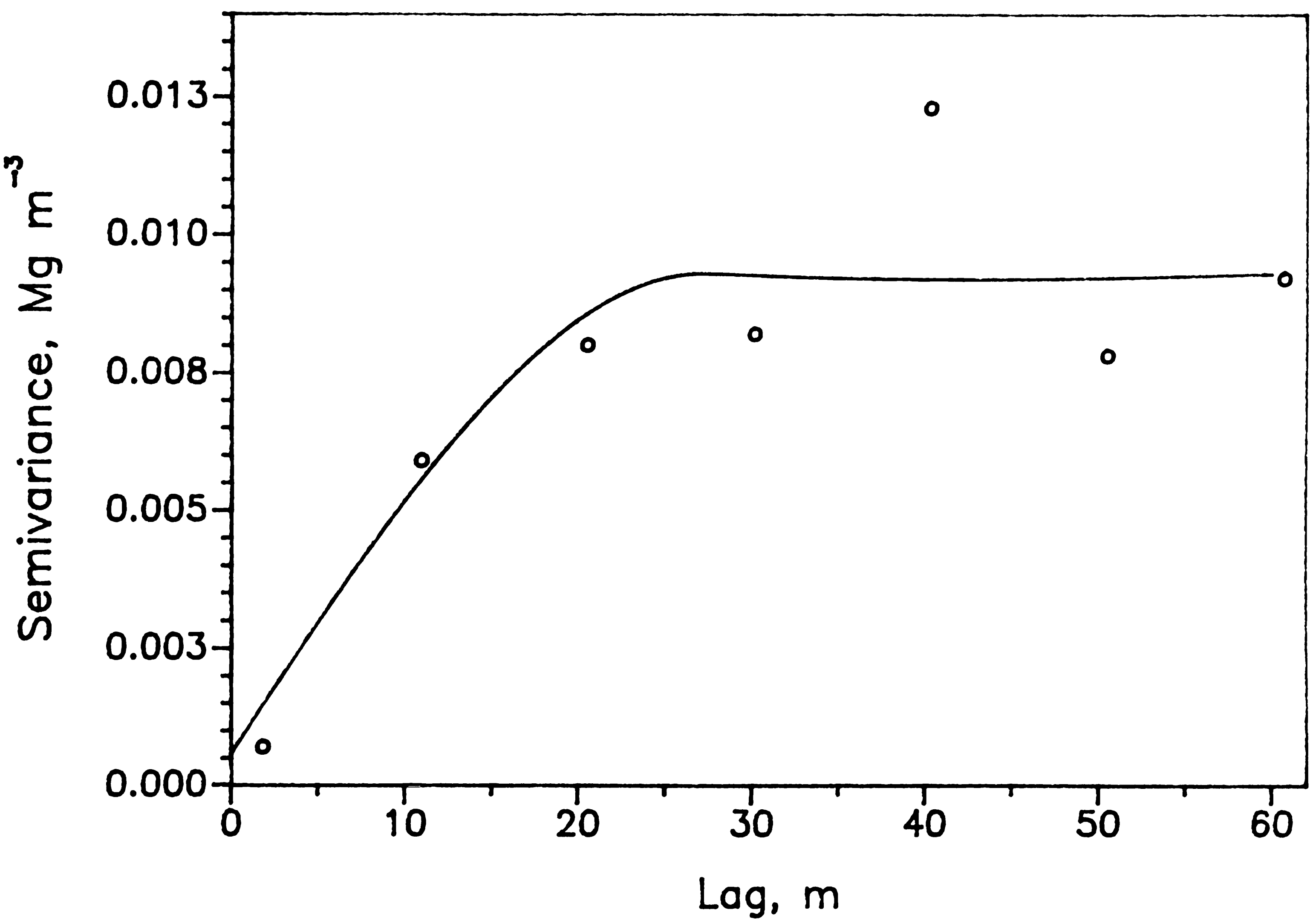

Figure 1.12 Semivariogram of bulk density for transect 3 of a Typic Hapludalf at 0 to 7.6 cm depth.

perspective and topographic representation of the block kriging interpolation of bulk density are given in Figure 1.14 and 1.15.

Porosity

Total porosity for the three West-East transects showed a high degree of spatial dependence as indicated by nugget variance of zero (Table 1.1). The spatial dependence (range) varied from 16 to 29 m. For the N-S semi-variogram, the nugget variance was 53% of the sill, indicating a large random component in the south-north direction. However, in the 45 and 90 degree directions, the semi-variograms were very similar to the West East transect. The mean total porosity in transect 1 is higher than the other transects.

Macroporosity in transect 1 showed a random distribution (Figure 1.16) and did not fit any of the models tested (Table 1.1) The mean macroporosity of transect 1 was higher (12 versus 10%) than other transects. This is consistent with that observed for total porosity. For all other transects, macroporosity was spatially dependent with very low nugget variances. The range was high in transect 2 (37.5m) and varied from about 12 to 13.4 for transect 3 and the three directions. The CV for macroporosity was much higher than for bulk density or other porosity measurements, ranging from 23 to 41%.

Microporosity in transect 2 showed a random distribution and did not fit any of the models tested (Table 1.1). The variance in microporosity was lower than for total porosity or macroporosity. Microporosity was spatially dependent with the range varying from 14 to 26m. However, the nugget variance ranged from about 14 to 50 % of the variance depending on the transect and direction of the semi-variogram.

Russo and Bresler (1981) measured spatial variability of soil hydraulic properties using autocorrelation. They reported spatial dependence equal to

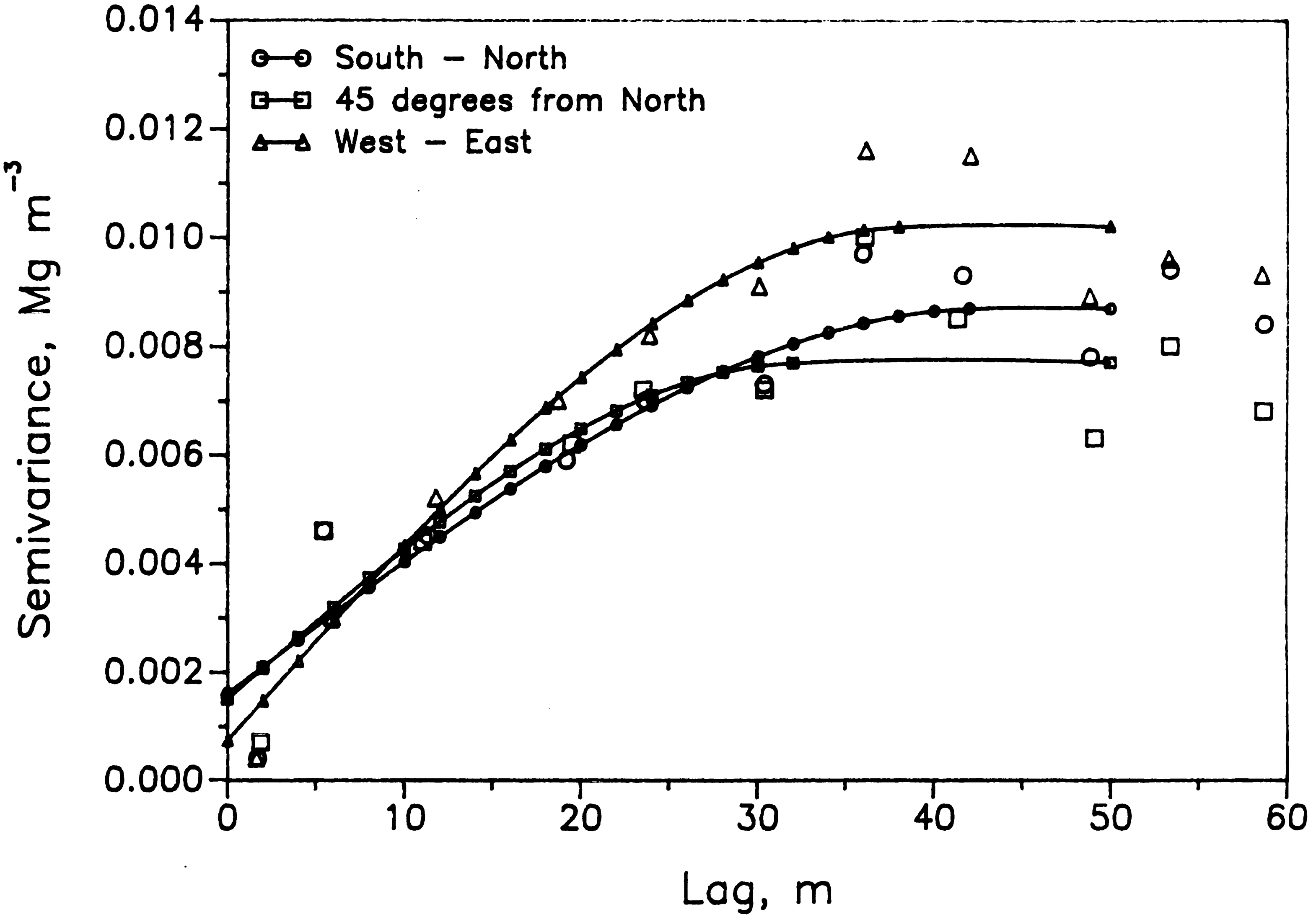

Figure 1.13. Semivariogram of bulk density for whole area of a Typic Hapludalf at 0 to 7.6 cm depth.

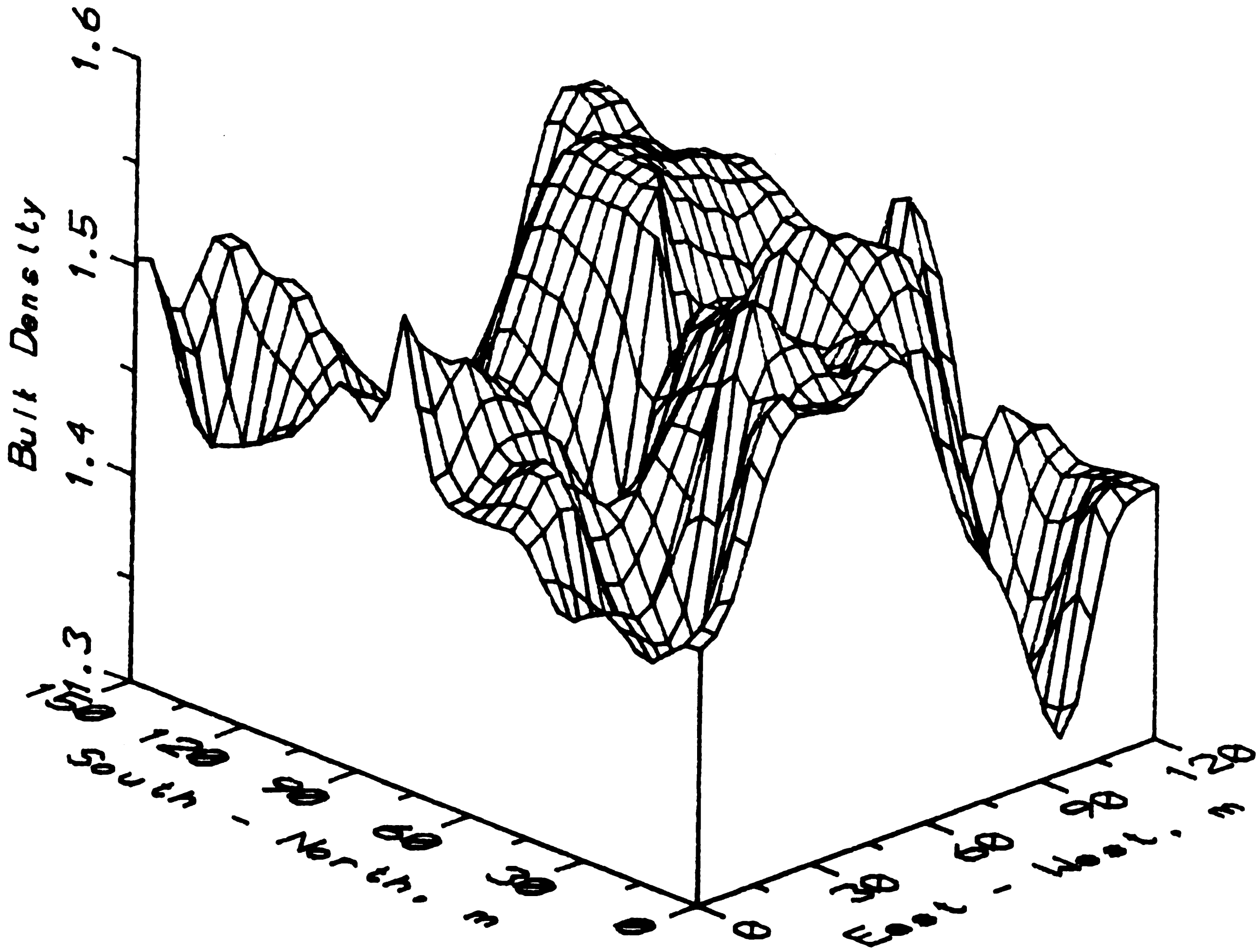

Figure 1.14. View in perspective of block Kriging interpolation of bulk density of a Typic Hapludalf at 0 to 7.6 cm depth.

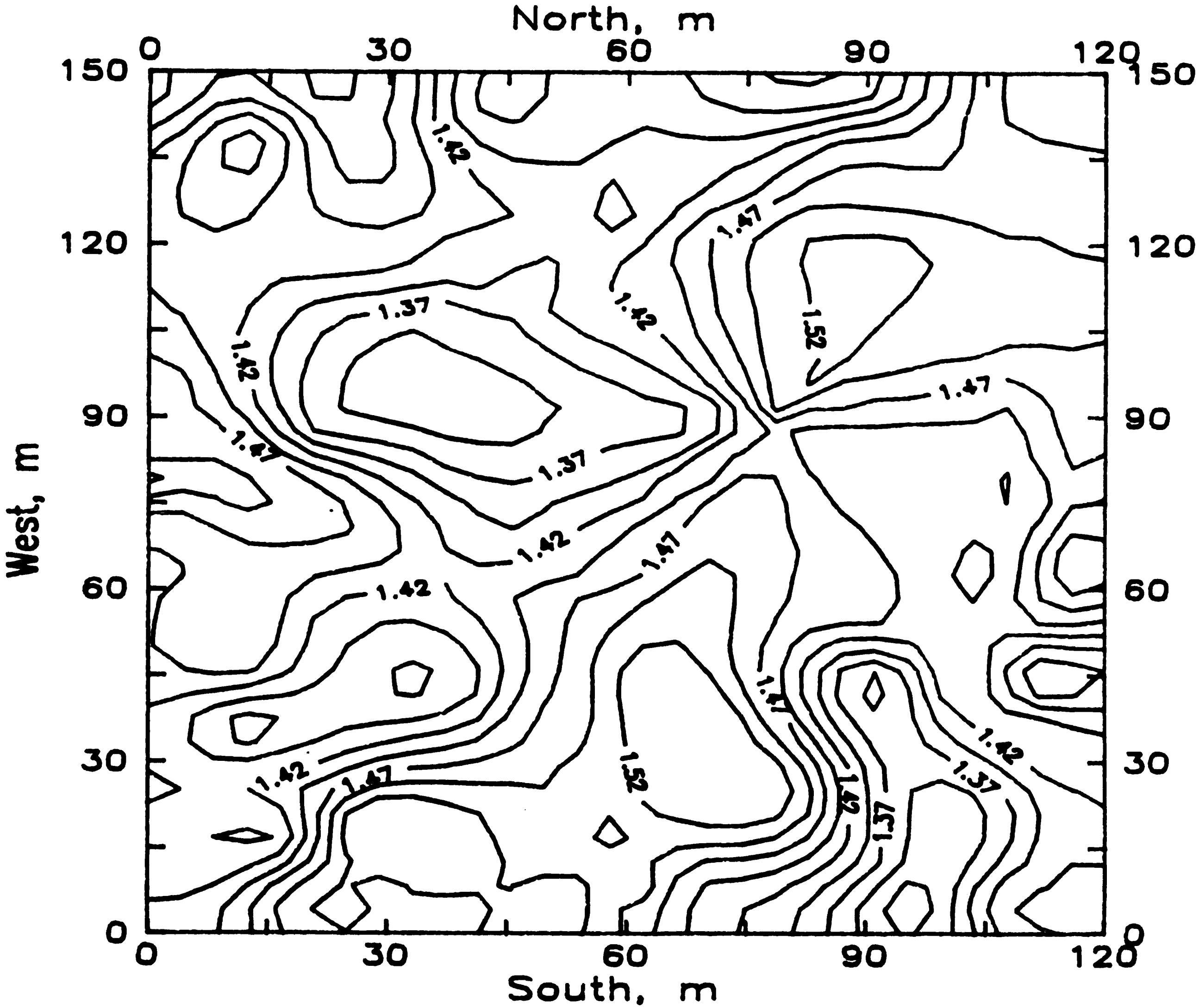

Figure 1.15. Topographic view of block Kriging interpolation of bulk density of a Typic Hapludalf at 0 to 7.6 cm depth.

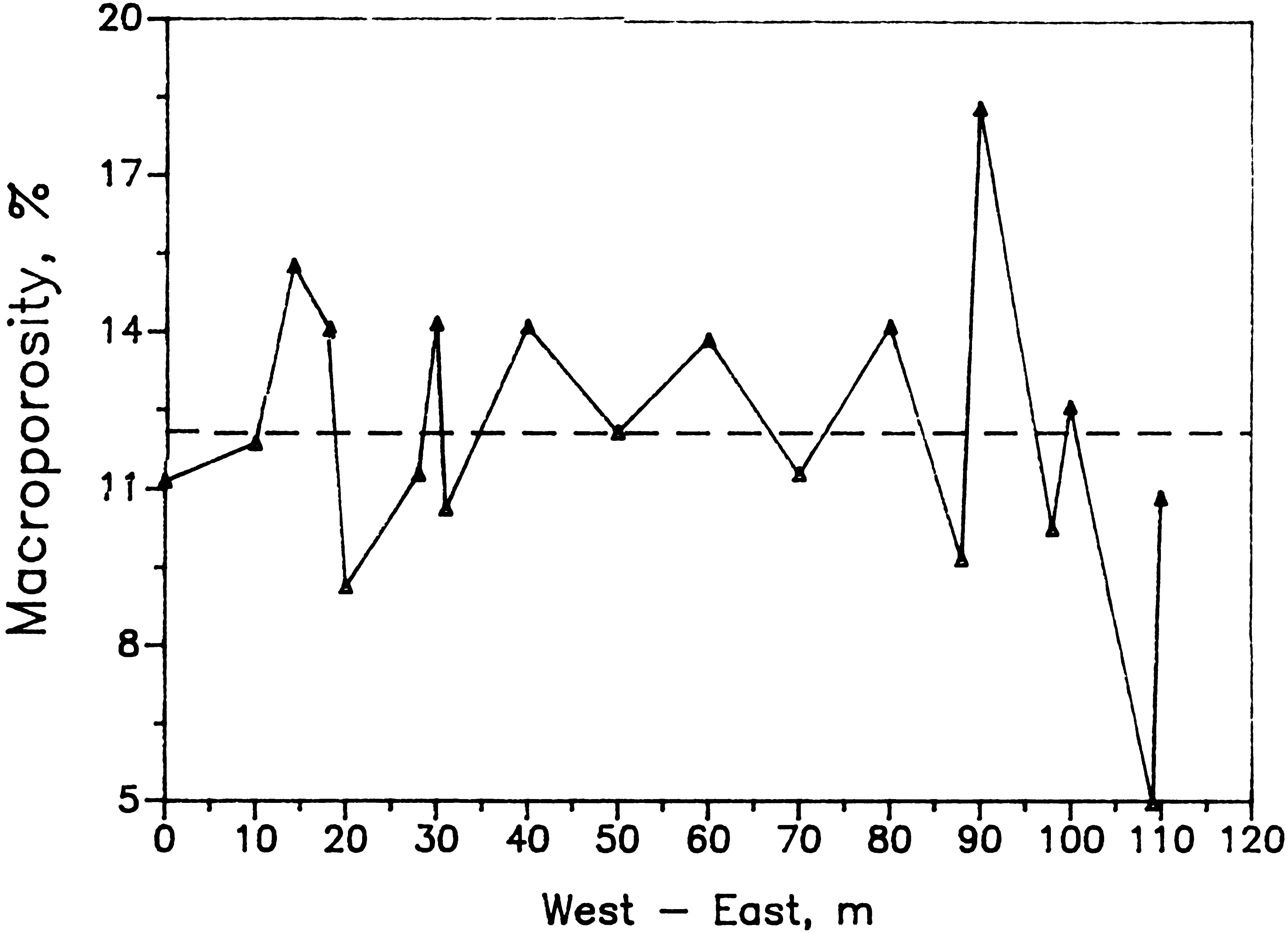

Figure 1.16 Macroporosity values along of transect 1 of a Typic Hapludalf at 0 to 7.6 cm depth. Dashed line represents data set mean.

35m for pore size index calculated from pore size distribution data.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity was highly variable, had high CV's and was different for each of the west- east transects. The data showed a random distribution for each transect and may have resulted from high variability. For the combined data, however, the spherical model fit the data and showed a high degree of spatial dependence with zero nugget variance and a range between 10 and 14m. The semi- variograms were similar in all directions indicating saturated hydraulic conductivity for the 0 to 7.6 cm depth is isotropic.

SUMMARY AND CONCLUSIONS

The bulk density, total porosity, macroporosity, microporosity, and saturated hydraulic conductivity of a loam surface soil were shown to be spatially dependent. In general, total porosity, macroporosity and saturated hydraulic had no random component (zero nugget variances) while bulk density and microporosity had nugget variances ranging from 7 to 50% depending on the transect and direction of the semi-variogram.

Spatial dependence for the whole area ranged from 10.2 m for saturated hydraulic conductivity to 43.2 m for bulk density, with the various porosity measurements intermediate. Certain of the East-west transects for macroporosity and microporosity and none of the west- east transects for saturated hydraulic conductivity showed spatial dependence.

The significant structure of spatial dependence indicates the importance of considering spatial variability of soils in agricultural studies and give us a way to better predict soil properties across landscapes that are important for crop production.

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CHAPTER 2

TEMPORAL VARIATION OF SOIL PHYSICAL PROPERTIES INDUCED BY TILLAGE

ABSTRACT

Tillage induced effects on soil structure are temporally variable but comparisons of tillage effects are frequently made using measurements obtained one or two times during a year. This study was conducted to characterize the temporal variation of selected soil physical properties of a soil managed under no-tillage (NT) and conventional tillage (CvT) compared to a never tilled (NeT) soil. Management effects on soil structure were investigated using undisturbed soil cores sampled 19 times over a three year period from non-trafficked interrows to measure bulk density, pore geometry (size and distribution), and saturated hydraulic conductivity (K_{sat}) at Hickory Corners, MI, on a Kalamazoo loam (Fine-loamy, mixed, mesic Typic Hapludalfs) cropped to continuous corn (Zea mays L.). Total porosity, macroporosity (pores > 48 um diameter), and saturated hydraulic conductivity over three years were consistently lower and bulk density consistently higher under NT compared to CvT management. However, as a consequence of temporal variation, statistical significance of differences between tillage systems were time dependent. Seasonal variation in all measured soil properties was cyclic for all treatments and both soil depths, being more pronounced in porosity and K_{sat} than in bulk density. Since the NT and NeT soils varied little in time, differences were

largely controlled by the considerable temporal variation in CvT. The temporal variation in porosity and bulk density in NT and CvT was largely associated with variation in macroporosity and both macro- and microporosity (pores < 48 um diameter) in the NeT soil. Macroporosity was highly correlated to both bulk density and K_{sat} with a different relationship observed for NT and CvT than for NeT soils. In addition to the cyclic patterns of variation, long-term trends for each measured parameter were observed and varied by soil management. The long-term trends did not indicate that measured parameters had reached equilibrium over the three year duration of this study. Freezing and thawing did not appear to have ameliorating effects on soil physical properties. The temporal variation in soil physical properties induced by tillage was cyclic and appeared to be controlled by the variation in macroporosity for the NT and CvT soils and both macro- and microporosity in the NeT soils.

INTRODUCTION

Soils managed under no-tillage have been shown to acquire physical characteristics quite different from those found under conventional tillage (Bauder et al., 1981; Campbell et al., 1974; Cassel, 1985; Erickson, 1985; Gantzer and Blake, 1978; Griffith et al., 1986; Pidgeon and Soane, 1977). No-tillage of soils has been reported to alter many aspects of soil structure including bulk density, porosity, pore geometry (size and continuity), and aggregate size and stability. Changes in soil structure alter the mechanical, water and gas transport and retention, and thermal properties of soils, properties of considerable importance to root growth and development as well as machine-soil interactions. Research on tillage has either focused directly on changes in soil structure induced by tillage (Douglas and Goss, 1987; Gantzer and Blake, 1978; Voorhees and Lindstrom, 1984) or on how changes in soil structure have affected such things as water retention (Blevins et al., 1971; Hill et al., 1985), infiltration (Lindstrom et al., 1984), soil strength (Bauder et al., 1981; Cassel et al., 1978), evapotranspiration (Phillips, 1980), soil temperature (Burrows and Larson, 1962) and root growth (Barber, 1971).

Comparisons of tillage effects on soil structure have often been static in that measurements have been made at a single time or at a specific time of the year. Only recently has consideration been given to the spatial and temporal variation in soil structure imposed by tillage. Temporal variation in soil structure and related properties have been reported for bulk density, porosity, and water retention (Gantzer and Blake, 1978; Cassel, 1983; Onofiok, 1988), mechanical resistance (Cassel et al., 1978), sorptivity, hydraulic conductivity, and water retention (Mapa et al., 1986), soil erodibility indices (Coote et al., 1988), and macroporosity and saturated hydraulic conductivity (Carter, 1988). Soil structure is dynamic even in untilled systems where factors such as freezing and thawing, root growth and exudates, wetting and drying cycles, carbon turnover, biological activity, fertilization, and soil management may strongly affect the dynamics of soil structure (Low, 1972). In cultivated systems, seasonal changes in structure can be pronounced by an effect of tillage, planting, and associated wheel traffic. Voorhees and Lindstrom (1984) reported that 3 to 4 yr were required to observe measurable improvement in soil porosity in conservation tillage. Cassel (1985) points out the need for extreme caution when generalizing structural differences between systems samples at only 1 or 2 time points per year. Such differences can be more pronounced in one portion of the growing season than in other seasons, and the temporal variation more pronounced for one tillage system than another. The seasonal dynamics of structural changes may have significant impacts on important processes in soils. Soil porosities in the fall and early spring, for example, may strongly influence the stratification of nutrients mineralized from recent litter by affecting aeration and leaching potentials while those in late spring and early summer may determine root branching morphologies and affect C use efficiency in growing crops.

This study was conducted to characterize the temporal variation of soil bulk density, pore geometry (size and distribution), and saturated hydraulic conductivity of a Kalamazoo loam soil managed under no-tillage and conventional tillage compared to a never tilled site over a four year period. This study is a component of an ecosystem study designed to develop a better understanding of how belowground processes interact to regulate nutrient availability in agricultural ecosystems (Pierce and Robertson, 1990).

MATERIALS AND METHODS

The research was conducted at the Kellogg Biological Station in south-central Michigan. The soil is a Kalamazoo loam (fine loamy, mixed, mesic, Typic Hapludalf), formed in glacial outwash parent materials. The experiment was initiated in the spring of 1986 , and a full description of the soils, their management and cropping history over the 1986-1989 period are given in Pierce and Robertson (1990). The experiment consisted of two tillage treatments - no-tillage (NT) and conventional tillage (CvT) and two N fertilizer treatments -none and 124 kg N ha^{-1} yr^{-1} - established in a randomized complete block design with four replications on the main site area. Directly adjacent to the main site is an area that has never been tilled (NeT) where two treatments - corn slot planted and natural vegetation - were established in a randomized complete block design with four replications. Neither treatment in the never tilled area received any commercial fertilizers. Conventional tillage consisted of spring moldboard plowing followed by one or two passes of a disk and/or field cultivator. The NT areas had not received tillage since the spring of 1985. All wheel traffic was controlled throughout the course of the study. Corn (Zea mays L.) was grown in 1986-1988 and soybeans (Glycine max (Merr.) L.) were grown in 1989. Corn was irrigated with solid set irrigation in 1986-1988 as needed. Each plot measured 40 meters by 30 meters.

Undisturbed soil cores (7.6 cm in diameter and 7.6 cm high) were sampled using a double-cylinder sampler for measuring bulk density, total porosity, pore-size distribution, and saturated hydraulic conductivity. Three cores were obtained for each sampling date from soil depths of 0 to 7.6 cm and 7.6 to 15.2 cm from each replication of the N fertilized treatments of the NT and CvT treatments and the NeT treatment planted to corn. Cores were obtained from the non-trafficked rows 15 cm from the corn row. Soil cores were sampled 19 times between June of 1986 and April of 1989. From early spring to late fall of 1987 samples were taken on almost a monthly based. Sampling was intensified for a four week period in spring of 1988 to measure short-term variation in the early spring. Successive samplings were made adjacent to previous samplings in order to decrease spatial variability.

Cores were saturated from the bottom and then weighed so that total porosity could be measured at saturation. Saturated hydraulic conductivity was measured by the constant head method (Klute, 1965). Cores were then equilibrated on a tension table or pressure-plate apparatus at matric potentials of -1, -2, -3, -4, -6, -10, -33.3, and -100 kPa. These were converted to equivalent pore size diameter-EPSD of 288, 144, 96, 72, 48, 28, 8, and 3.0 micrometers (Childs, 1940; Leamer and Shaw, 1941; Richards, 1965). Cores were then oven dried. Bulk density, total porosity, and pore size distribution were calculated from the above measurements.

Soil physical properties data were analyzed by depth. Analyses of variance and LSDs were performed for each sampling date.

RESULTS AND DISCUSSION

Temporal Variation of Bulk Density

Bulk density was consistently highest for NT soil for both the 0 to 7.6 and 7.6 to 15.2 cm depths over the period of measurement (Figures 2.1). Increased bulk density in no-tilled soils has been reported for several soils and climatic conditions (Carter,1988; Gantzer and Blake,1978; Hill and Cruse,1985; Shear and Moschler,1969; Triplett et al.,1968; Voorhees,1983). Bulk density in NeT soil was consistently lowest in the surface 7.6 cm and CvT soil was intermediate. Tillage and cropping of soil over long periods has been reported to increase bulk density over undisturbed soil and is associated with decreased soil organic matter and concomitant decline in soil aggregation (Elliot, 1986; Low, 1972; Weill et al., 1989). In the 7.6 to 15.2 cm depth, CvT soil has lower bulk densities than NeT soil in the early period of the study but generally lower bulk densities as time progressed.

There was a slight trend for bulk density to increase in NT over the period of measurement (Table 2.1). This trend can be explained by the action of natural consolidation forces, such as rainfall energy, and an increasing effective

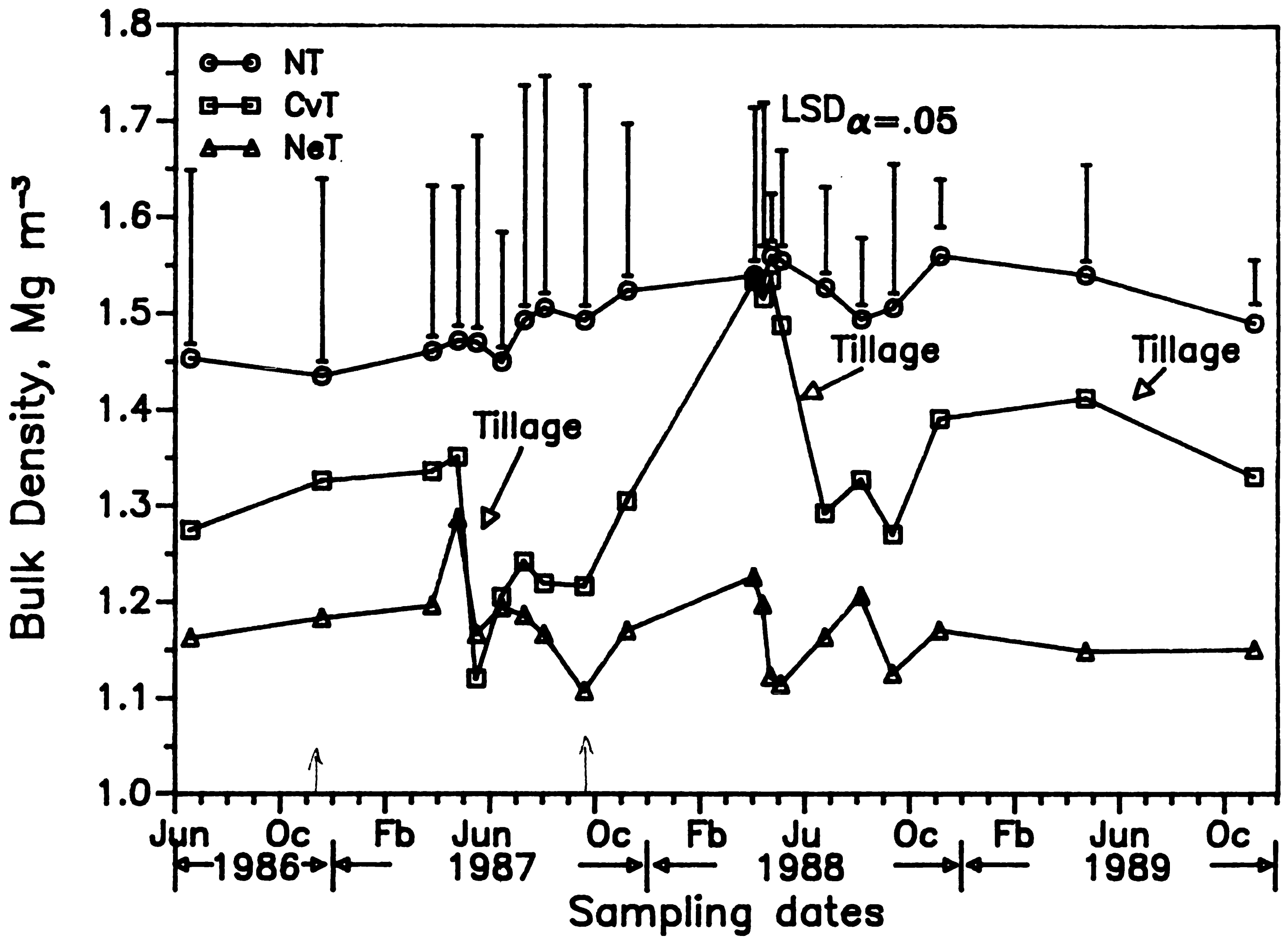

Figure 2.1.1: Temporal variation of bulk density of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NeT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 0 to 7.6 cm .

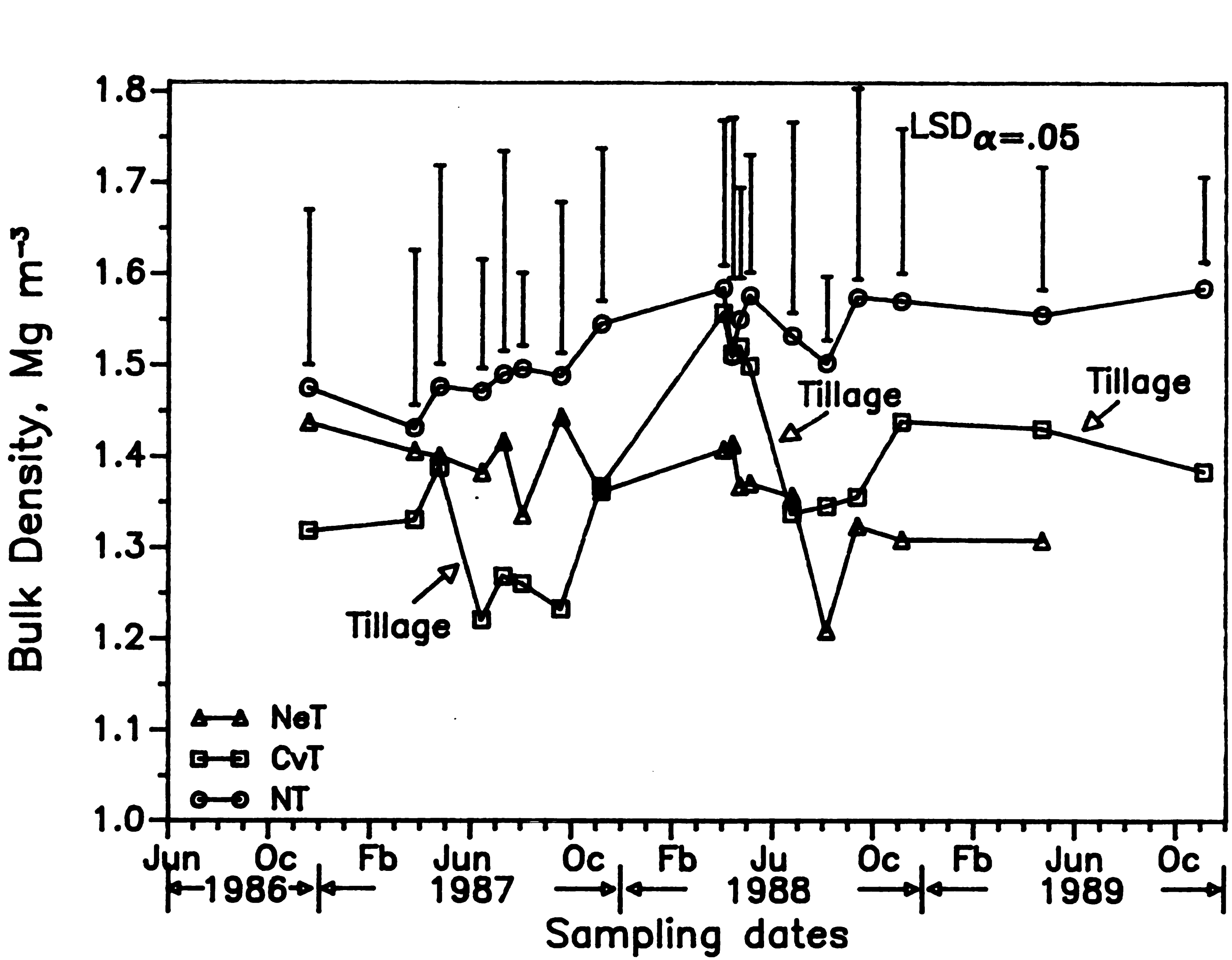

Figure 2.1.2: Temporal variation of bulk density of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NeT over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 7.6 to 15.2 cm .

Table 2.1. Coefficients of linear regression between measured soil properties and time in days from first sampling date of a Kalamazoo loam under conve|tional tillage (CvT), no-tillage (NT) and never tilled (NeT) management.

Tillage System	0 - 7.6 cm Int	0 - 7.6 cm Sl(10^{-3})	0 - 7.6 cm r^2	7.6 - 15.2 cm Int	7.6 - 15.2 cm Sl(10^{-3})	7.6 - 15.2 cm r^2
			Bulk Density, Mg m^{-3}			
NT	1.45	0.08	0.42**	1.44	0.13	0.62**
CvT	1.25	0.15	0.15	1.28	0.16	0.19
NeT	1.19	- 0.04	0.09	1.46	-0.16	0/.43**
			Total Porosity, %			
NT	43.6	-4.2	0.49**	43.9	-4.96	0.51**
CvT	52.1	-/7.1	0.22*	51.1	-7.50	0.25*
NeT	55.6	-2.5	0.15	44.2	2.69	0.09
			Macroporosity, %			
NT	9.9	-0.58	0.01	11.8	-2.90	0.25*
CvT	19.9	-5.2	0.09	20.2	-7.3	0.17
NeT	12.9	1.8	0.07	10.1	1.4	0.03
			Microporosity, %			
NT	33.3	-3.4	0.36**	32.4	-2.5	0.33*
CvT	31.2	-0.84	0.02	30.9	-0.15	0.01
NeT	42.5	-4.3	0.26*	34.1	-1.3	0.06
			Saturated Hydraulic Conductivity, cm h^{-1}			
NT	4.2	-1.1	0.03	7.5	-4.7	0.16
CvT	14.7	-7.7	0.15	21.4	-17.9	0.51**
NeT	14.1	5.0	0.13	2.3	10.1	0.32*

Int: Y-intersept; Sl: slope of linear regression.
*, ** significant at the 0.05 and 0.01 probability levels, respectively.

stress occurring during the drying of successive wetting and drying cycles. Under natural consolidation forces, a constant value of bulk density is expected to be reached. At such value, the intrinsic soil resistance will overcome natural consolidation forces. Pidgeon and Soane (1977) reported that 3 years were required for soils under no-tillage to reach an equilibrium bulk density when direct drilling in a long term barley mono-culture system. Carter (1988) reported a small temporal variation in bulk density with no-tillage with no clear trend of increasing values. It is unclear as to whether an equilibrium level has been reached in the NT soil in this study. Bulk densities in the CvT soil were quite variable for both depths with a slight trend to increase with time (Table 2.1). Bulk densities in the NeT soil varied less than the CvT soil and more than the NT soil and showed no trend in the surface 7.6 cm but tended to decline over the measurement period in the 7.6 to 15.2 cm depth (Table 2.1). The NeT soil has approximately 10 cm of A horizon overlying an E horizon approximately 20 cm thick. Corn was grown without tillage in the NeT treatment sampled and corn root growth may have had an ameliorating effect on the structure of this horizon resulting in a decline in bulk density as indicated in Figure 2.1.2.

Seasonal variation in bulk density was cyclic for all treatments and both depths. This is best illustrated by the NeT soil for the 0 to 7.6 cm depth in Figure 2.1.1. Beginning in the fall of 1986, there was an increase in bulk density over winter, followed by a slight decline during spring, an increase during the summer months, a decline in the fall, and an increase over winter. This cycle is repeated for the next period of measurement. The cycle is more dramatic in the CvT soil because of the tillage disturbance. While less dramatic, there is considerable similarity between the cycle in the NT and the NeT soils. This might be expected if no-tillage, in the long-term, mimics a natural ecosystem.

The cyclic phenomena observed in this study appears to be associated with soil temperature and moisture conditions favorable for biological activity, which is consistent with observations of earthworm activity in the experimental area.

As a consequence of the temporal variation in bulk density, differences between tillage treatments are time dependent in that differences are significantly different for certain sampling times only (note LSD's in Figure 2.1). Since the NT and NeT vary little relative to CvT, the differences between tillage systems were largely controlled by the temporal variation in CvT. These results emphasize the importance of consideration of temporal variation in the interpretation of soil measurements in tillage experiments. Large temporal variation of bulk density after tillage operations in soil under conventional tillage has been reported by several authors(Gantzer and Blake,1978; Cassel,1983; Voorhees,1983; Carter,1988; Onofiok, 1988).

The consolidation difference between no-tillage and conventional tillage seems to be associated with low values of bulk density induced by tillage operations. Tillage operations such as in conventional tillage create loose soil with low resistance between soil aggregates(clods) with easy consolidation after rainfall events. Natural factors that help to alleviate compacted soil such as the shrinking and swelling associated with drying and wetting of clay soils(Larson and Allmaras,1971) seems had the opposite effect on fresh plowed soil. Cassel (1983) reported on increase of 0.24 Mg m^{-3} in bulk density associated with 26 mm of rainfall in 17 days interval. He observed an apparent threshold of bulk density values for the 0-15 cm depth which seemed to be more closely associated with quantity than intensity of rainfall. In Michigan, during the 1987 and 1988 crop seasons, rainfall sufficient to cause soil saturation occurred after July, which may explain the increase in bulk density late in the crop season. Freezing and thawing appeared to have little effect on bulk density as values showed slight increases overwinter. The alleviating effects of freezing on soil compaction may have been masked by consolidation effect of effective stress increase during drying period in early spring. Kay et al. (1985) reported that soils under both conventional and no-tillage management reconsolidated upon thawing and returned to near prefreezing bulk densities prior to spring planting. Voorhees (1983) reported little effect of natural forces alone on reducing wheel track bulk density on either the moldboard plow or reduced tillage in Minnesota However, Carter(1988) reported lower bulk density and higher macroporosity on conventional tillage, 16-24cm soil depth, after the winter season(cool boreal soil-temperature regime) in Canada.

Temporal Variation in Porosity

Pore size distribution under no-tillage and conventional tillage in the 0 to 7.6cm depth for four 1987 sampling dates are presented on Figure 2.2. The cumulative percent for all pore size classes were higher for CvT than for NT, with the NeT soil intermediate (data not shown). Difference between pore size distributions for each date were small in NT and were somewhat cyclic they decreased and increased throughout the 1987 season. Differences between pore size distributions in CvT soils were considerable and consistent, indicating a clear decrease in cumulative percent of pores in CvT soil as natural consolidation proceeded. The curves in CvT for pores < 48 um EPSD are nearly parallel indicating the relative change in these pores as the soil consolidates is nearly the same over this range of pore sizes. However, the pores > 48 um EPSD are transient over time as indicated by the non-parallel curves.

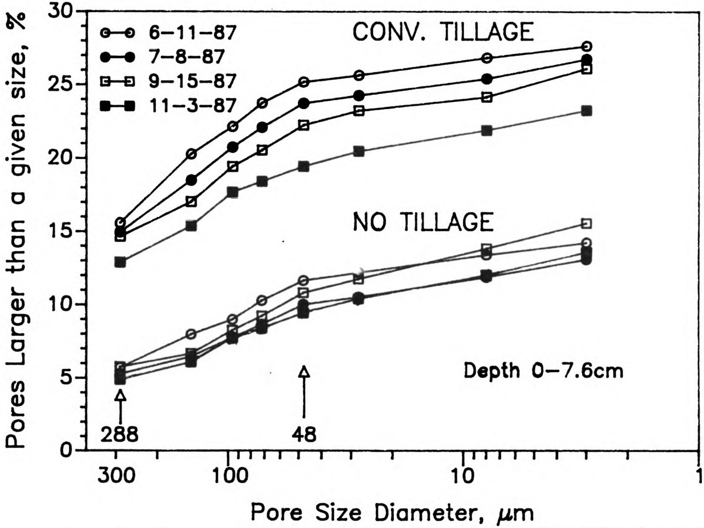

Figure 2.2: Pore size distribution of a Kalamazoo loam under no-tillage(NT) and conventional tillage (CvT) in 0 to 7.6 cm depth for four 1987 sampling dates.

Total porosity measured at saturation followed similar trends to bulk density for the 0-7.6 cm and 7.6-15.2 cm depths (Figure 2.3). No-tillage had the lowest total porosities, the least variation, and a slightly downward trend in total porosity over the duration of the study. The NeT soil had the highest total porosity and CvT was intermediate in the 0 to 7.6 cm depth with a reversal in pattern similar to that for bulk density in the 7.6 to 15.2 cm depth. The trend in CvT and NT was toward a slight decline in total porosity with time. The trend in the NeT soil was for total porosity to slightly decline in the 0 to 7.6 cm depth and slightly increase in the 7.6 to 15.2 cm depth. The cyclic pattern of temporal variation total porosity was more pronounced than that for bulk density.

The inflection point in the curves in Figure 2.2 occurs at an EPSD of approximately 48 μm. Pores larger than 48 μm EPSD were more easily drained than pores smaller than 48 μm EPSD. We chose 48 μm EPSD as the lower limit of macroporosity. Therefore, pores greater than 48 μm EPSD are herein considered macropores and those smaller than 48 μm EPSD are considered micropores.

Macroporosity was considerably higher and more temporally variable in the CvT soil than the NT soil for both soil depths (Figure 2.4). The NeT soil had higher macroporosity than the NT in the 0 to 7.6 cm depth but little differences were observed between NeT and NT at the 7.6 to 15.2 cm depth. The cyclic pattern of temporal variation is also present for macroporosity in these soils with quite similar patterns for the NeT and NT soils. Microporosity was highest in the NeT soil and not different between the NT or CvT soils for either soil depth (Figure 2.5). The cyclic pattern of temporal variation in microporosity is evident for the NeT soil but only weakly expressed in the other treatments. Both macro- and micro-porosity were lowest after winter for all treatments and both soil

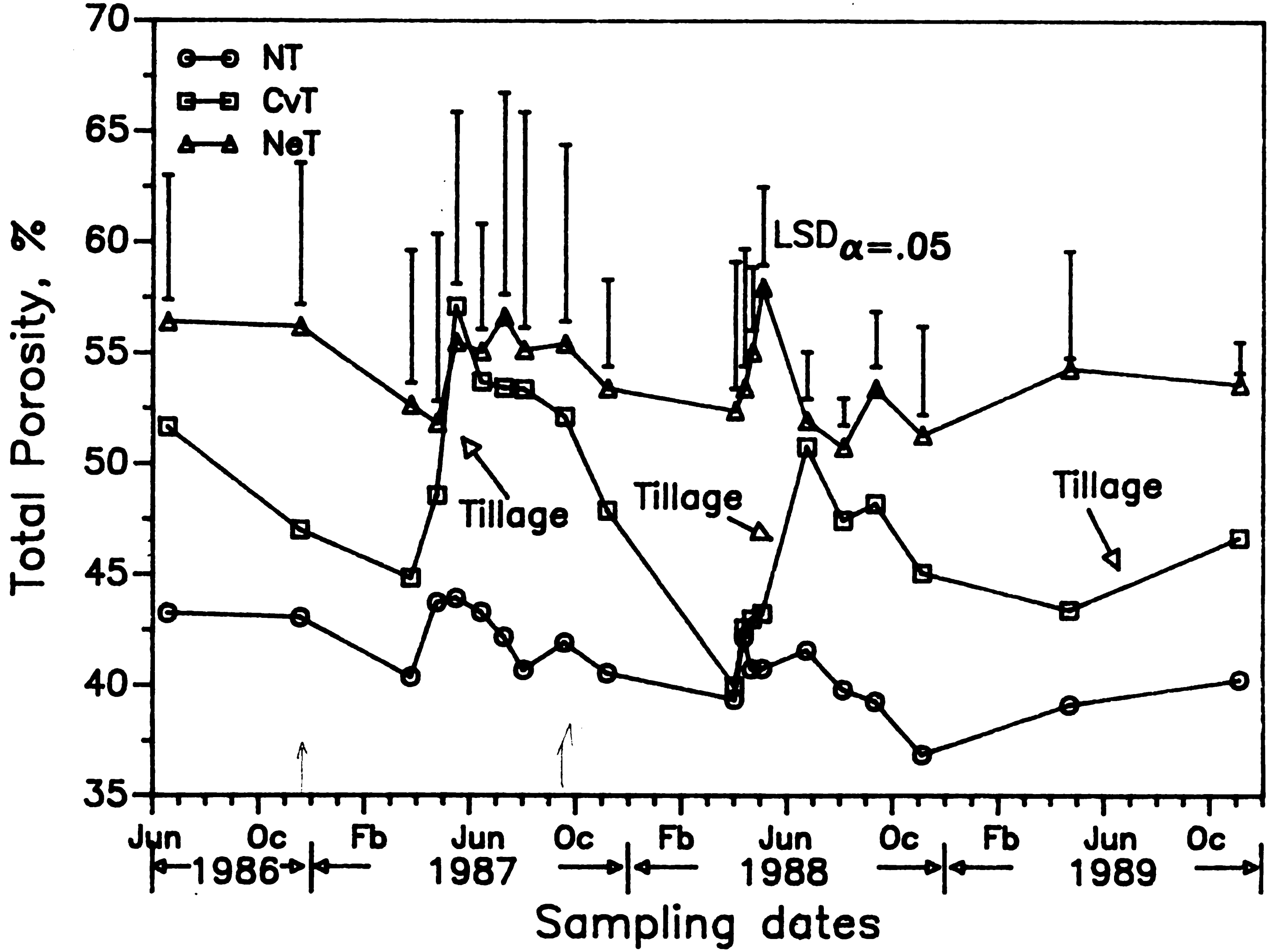

Figure 2.3.1: Temporal variation of total porosity of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NvT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 0 to 7.6 cm (graph A).

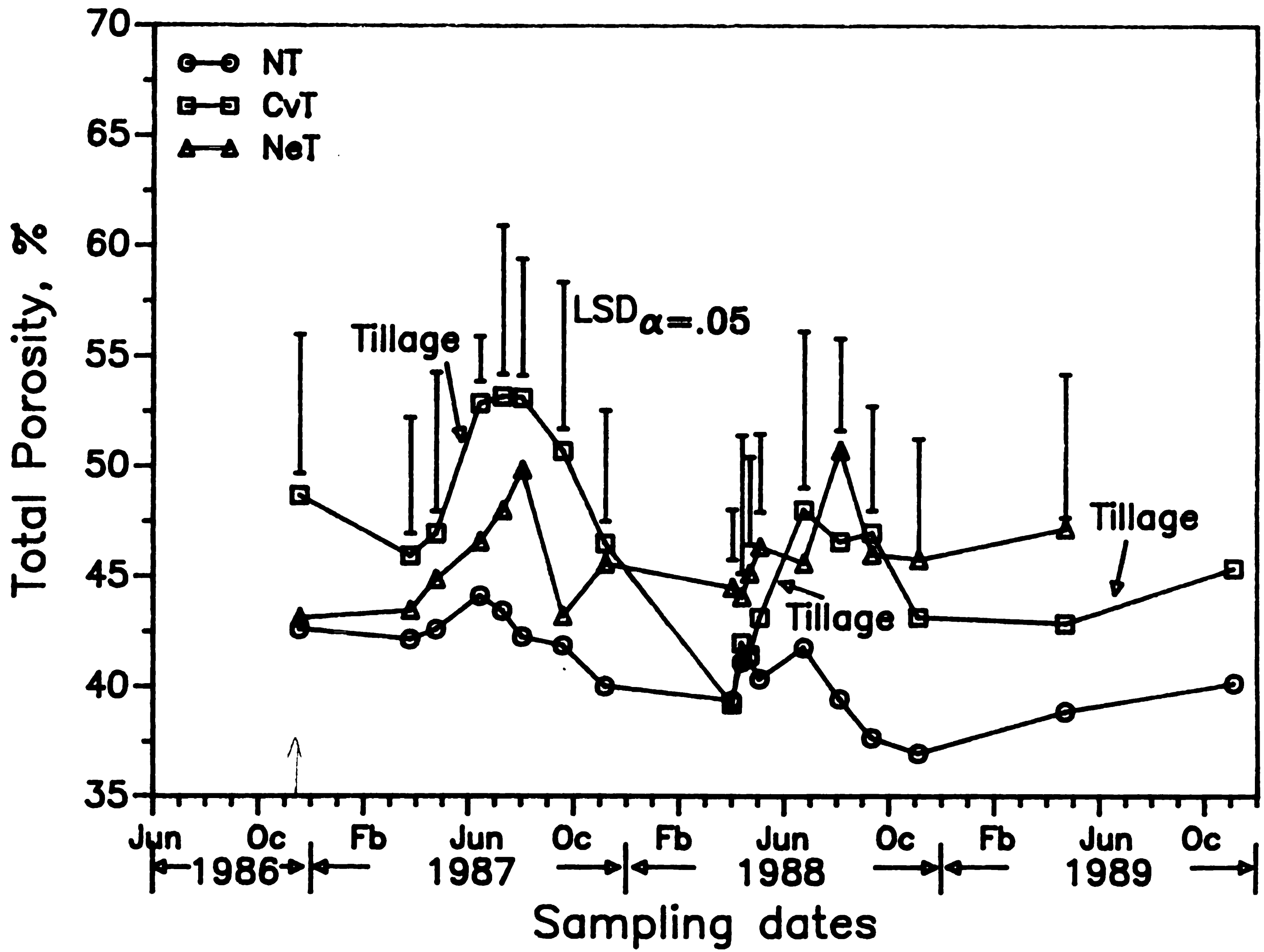

Figure 2.3.2: Temporal variation of total porosity of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NvT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 7.6 to 15.2 cm.

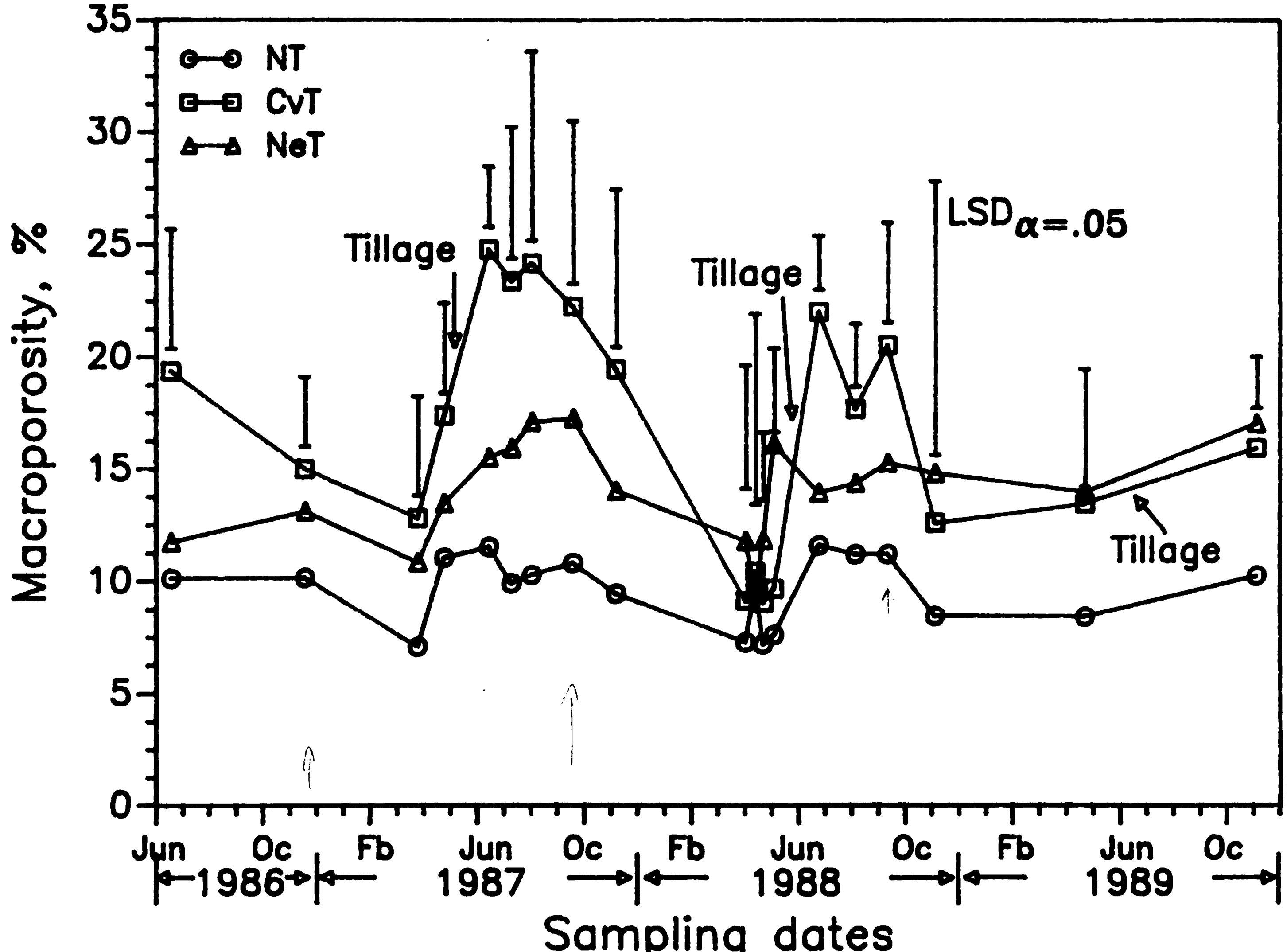

Figure 2.4.1: Temporal variation of macroporosity of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NeT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 0 to 7.6 cm.

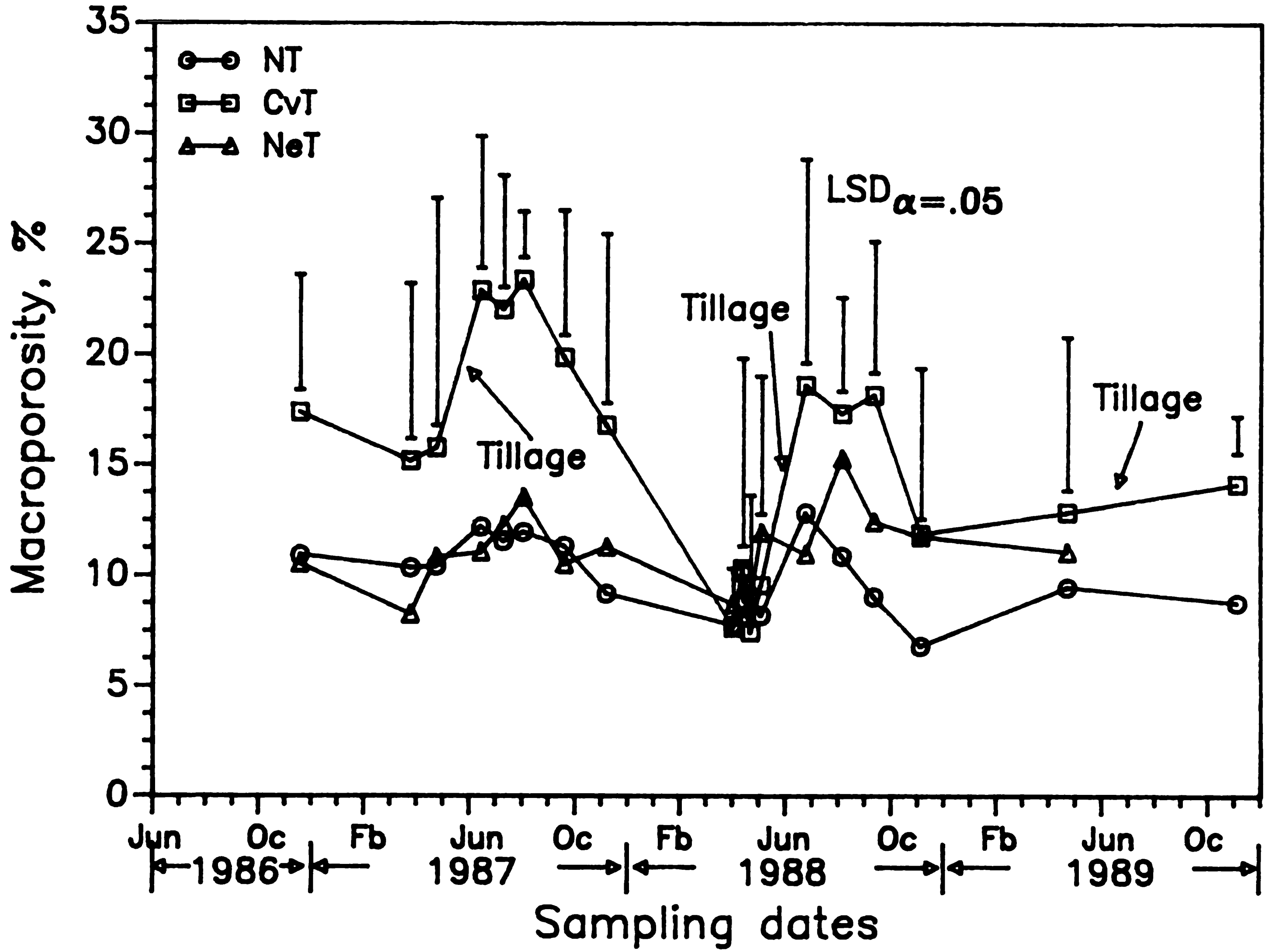

Figure 2.4.2: Temporal variation of macroporosity of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NeT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 7.6 to 15.2 cm.

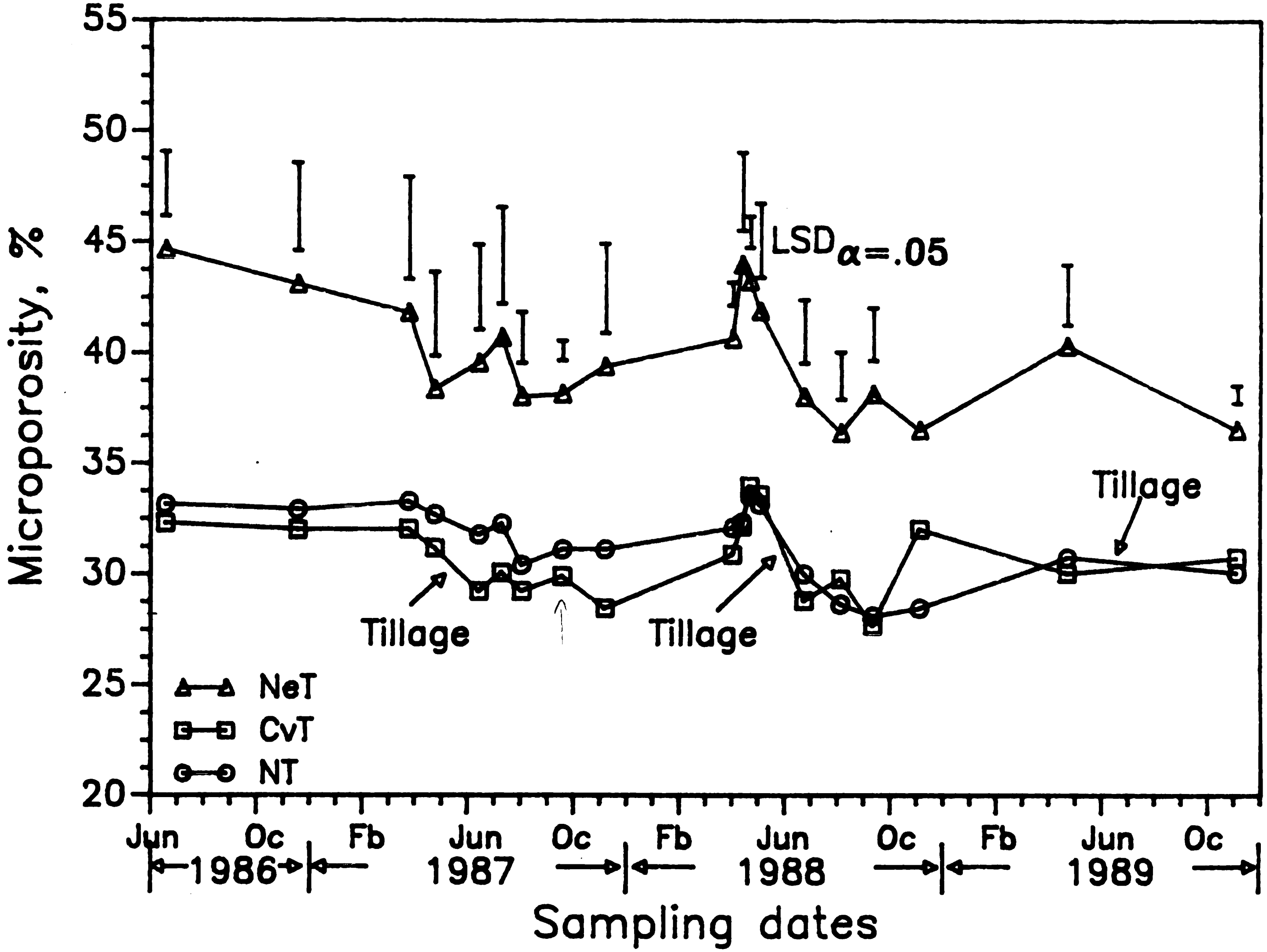

Figure 2.5.1: Temporal variation of microporosity of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NeT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 0 to 7.6 cm.

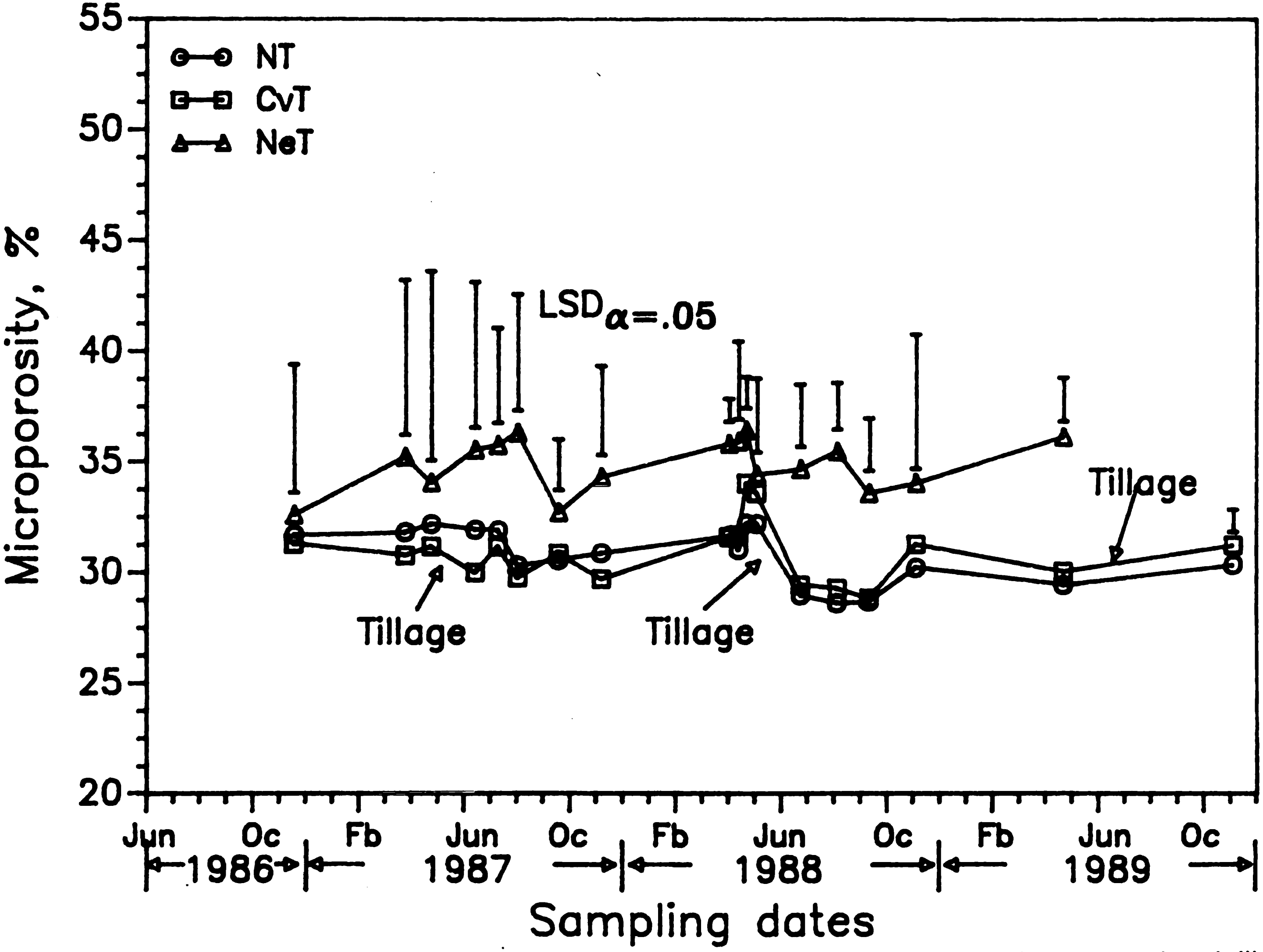

Figure 2.5.2: Temporal variation of microporosity of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NeT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 7.6 to 15.2 cm.

depths. Carter (1988), Douglas and Goss (1987), Gantzer and Blake (1978), and Hill et al.(1985) reported higher total porosity and macroporosity in soil under conventional tillage compared to no-tillage. The large temporal variation of soil macroporosity under conventional tillage is associated with tillage operations creating more than 15%(absolute value) of tillage induced macroporosity and the relatively low stability of large pores in soil. In general, larger values were observed after tillage operations, and lower were observed by late fall and early spring. There was only a weak trend for macroporosity to decline slightly in the 7.6 to 15.2 cm soil depth in the NT and CvT soils and no trend for change in the 0 to 7.6 cm depth (Table 2.1). In the NT for both soil depths and the NeT 0 to 7.6 cm soil depth, there was a slight trend for microporosity to decline with time (Table 2.1).

These data indicate the temporal variation in porosity and bulk density is due to variation in macroporosity alone in the NT and CvT soils and a combination of macro- and micro-porosity in the NeT soil, although the major effect in NeT is primarily due to variation in macroporosity. The strong influence of macropores on the dynamics of soil porosity is clear from the strong relationship between bulk density and macroporosity given in Figure 2.6. The regression of 1008 data points is nearly identical to that obtained by Carter (1988) for 62 samples from a loamy sand in western Canada.

Temporal Variation in Saturated Hydraulic Conductivity

Saturated hydraulic conductivity was consistently higher and more variable in CvT than NT (Figure 2.7). The K_{sat} of the NeT soil in the 0 to 7.6 cm depth was equal to or higher than that in the CvT soil but lower than or equal to the CvT soil in the 7.6 to 15.2 cm depth. The cyclic pattern of temporal

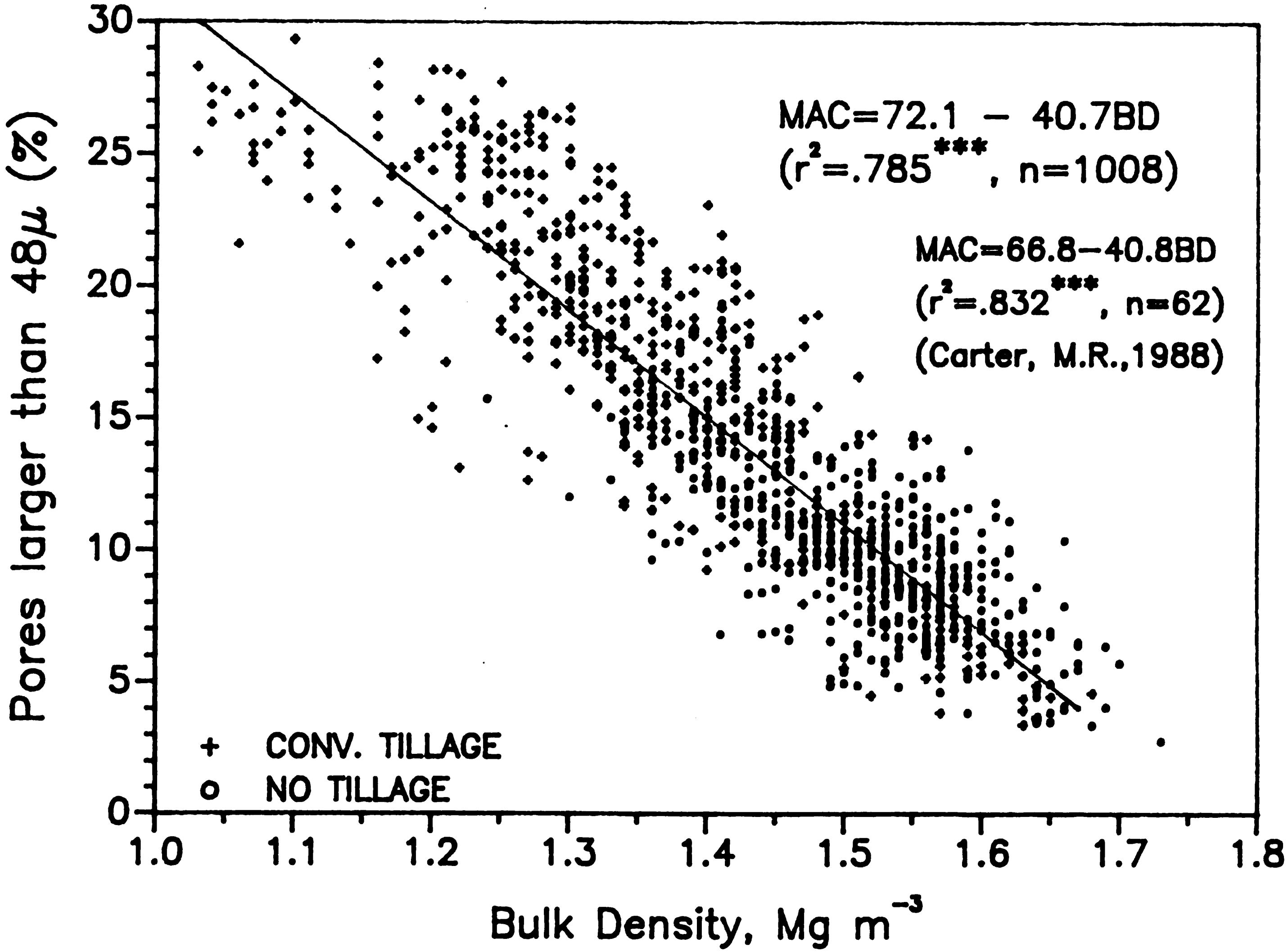

Figure 2.6: Relationship between bulk density and macroporosity of a Kalamazoo loam textured soil under conventional tillage and no-tillage for 0 to 15.2 cm depth.

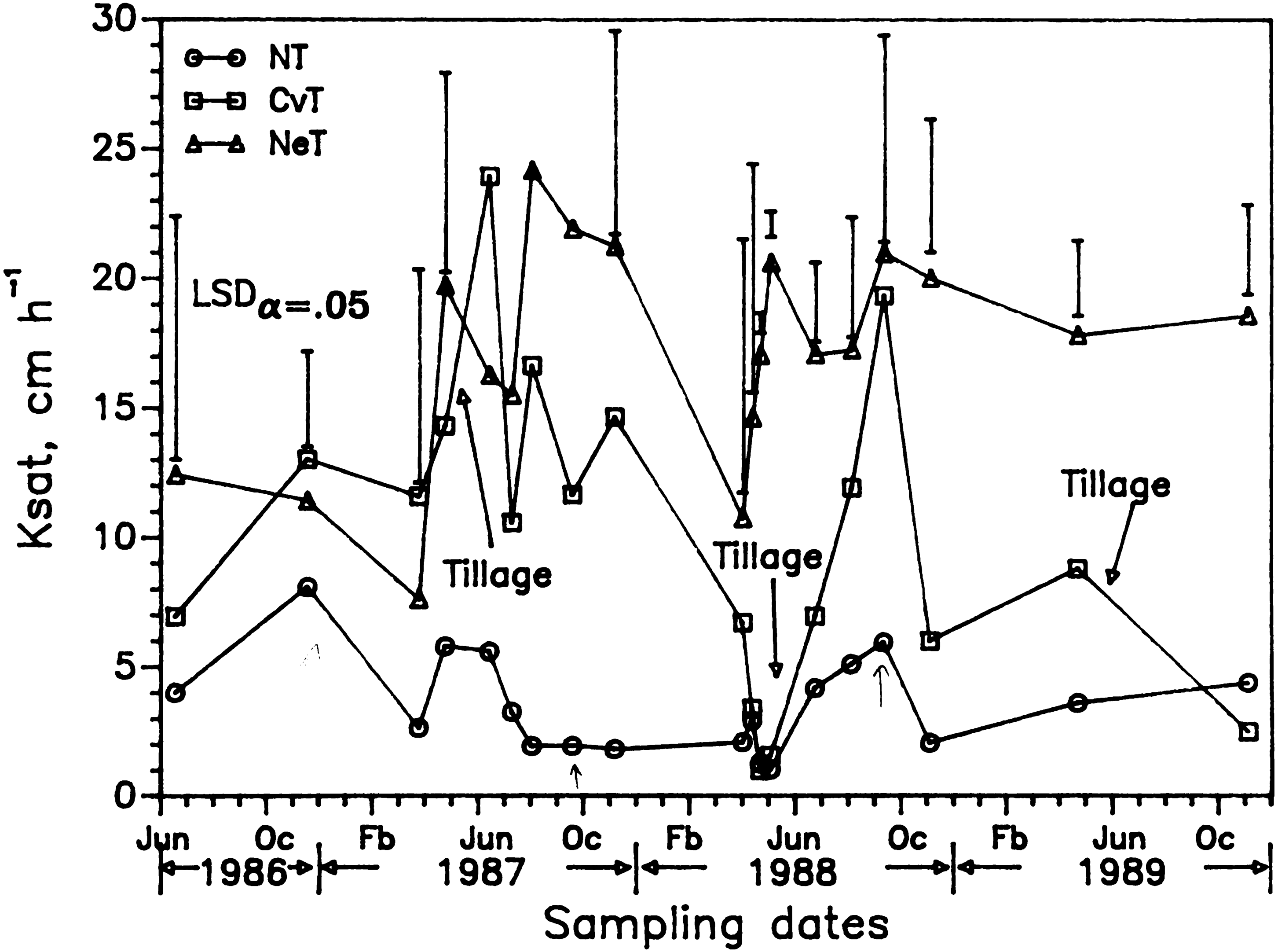

Figure 2.7.1: Temporal variation of saturated hydraulic conductivity of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NeT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 0 to 7.6 cm.

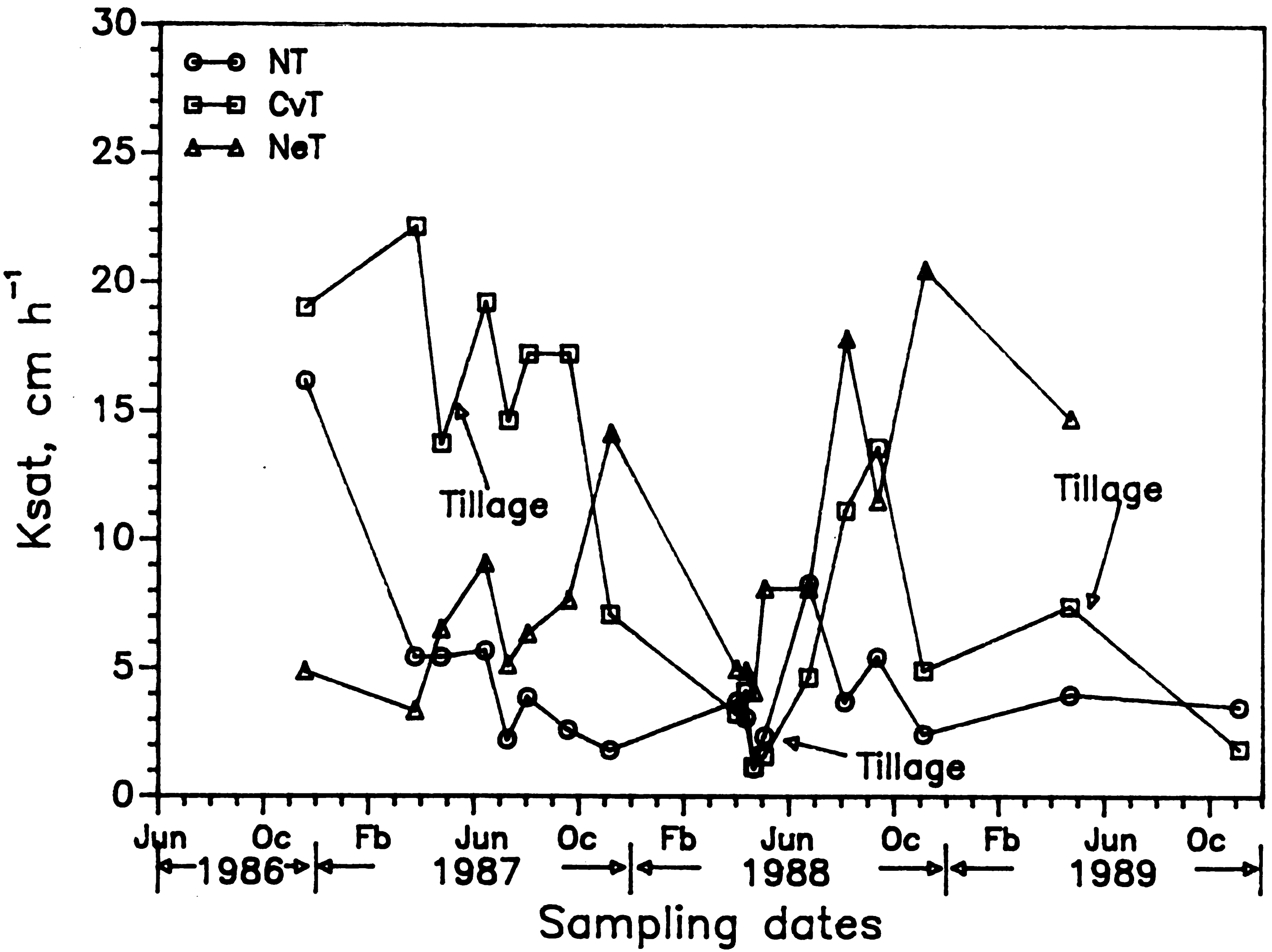

Figure 2.7.2: Temporal variation of saturated hydraulic conductivity of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT) and never tilled (NeT) over a four year period. The LSD's compare means of conventional and no-tillage at each sampling date for 7.6 to 15.2 cm.

variation is evident in the K_{sat} data, with minimal values occurring in the spring soon after winter and largest values occurring in late spring and fall. Temporal variation was often highest in the NeT soil even though macroporosity was highest in the CvT soil. This indicates better pore continuity in the NeT soil than the CvT or NT soils. Higher variation of K_{sat} on early spring was detected in never tilled soil, illustrating the seasonal dynamics of the biological community. There was a trend for K_{sat} in the 7.6 to 15.2 cm soil depth to decline in the CvT soil and increase in the NeT soil (Table 2.1). There was a strong correlation between macroporosity and K_{sat} for data from the CvT and NT soils as illustrated in Figure 2.8. The relationship between K_{sat} and macroporosity was different and weaker for the NeT soil.

The higher K_{sat} of Ap horizon under conventional tillage, compared to no-tillage, was observed by Douglas and Goss (1987), and Carter (1988). However, Douglas and Goss (1987), using large sample size, measured higher K_{sat} in soil under no-tillage than conventional tillage. The authors suggest that annual ploughing destroyed the continuity of channels between topsoil and subsoil with direct reflection on Ksat. Mapa et al.(1986) measured significant change of hydraulic properties over time. Hydraulic conductivity near saturation was the most sensitive measure of temporal changes of hydraulic properties decreasing 100-fold with wetting and drying after tillage.

CONCLUSIONS

The temporal variation in soil physical properties induced by tillage was cyclic and appeared to be controlled by the variation in macroporosity for plowed and no-tillage soils and both macro- and microporosity in the never

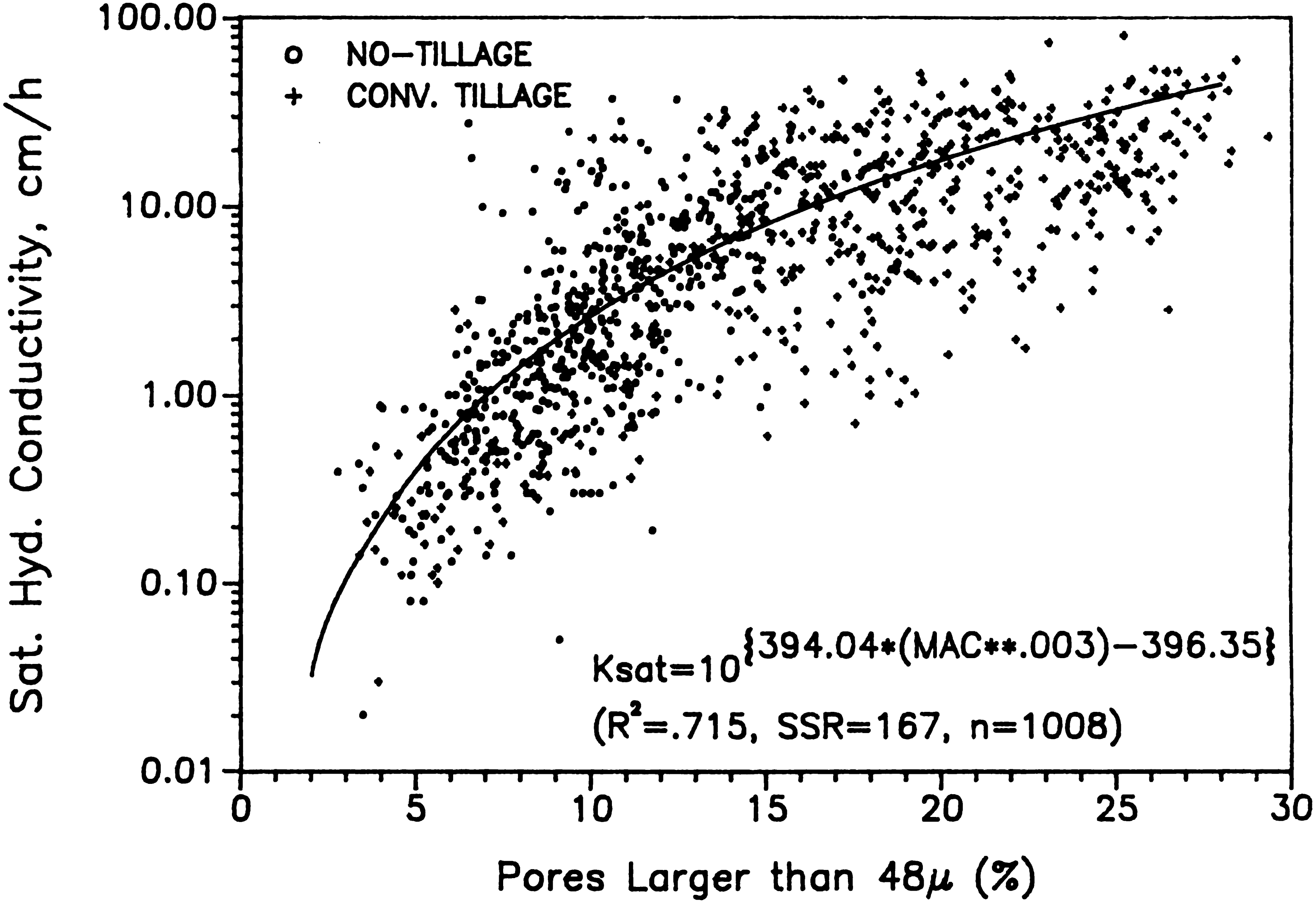

Figure 2.8: Relationship between macroporosity and saturated hydraulic conductivity (Ksat) of a Kalamazoo loam textured soil under conventional tillage and no-tillage for 0 to 15.2 cm depth.

tilled soil. As a consequence of temporal variation, statistical significance of differences between tillage systems were time dependent, an important consideration in the interpretation of soil measurements in tillage experiments. The long-term trends did not indicate that measured parameters had reached equilibrium over the three year duration of this study. These data indicate that freezing and thawing did not appear to have ameliorating effects on soil physical properties.

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CHAPTER 3

TEMPORAL VARIATION IN STRUCTURAL STABILITY INDUCED BY TILLAGE

ABSTRACT

Changes in cropping and soil management practices can alter soil structure dramatically and the nature of these changes can be cyclic. This study was conducted to characterize the temporal pattern of variability of aggregate stability induced by tillage. Water-stable aggregate size distribution (WSASD) was measured 13 times over a two year period in 1988 and 1989 at Hickory Corners, MI, on the surface layer of a Kalamazoo loam (Fine-loamy, mixed, mesic Typic Hapludalfs) managed under conventional (plowed) tillage (CvT), no-tillage (NT), and never tilled (NeT) cropped to corn (Zea mays L.) and soybeans (Glycine max (Merr.) L.). The aggregate stability was 2 to 4 times higher and organic carbon content more than 4 times greater in NeT than CvT or NT soils. The temporal patterns of aggregate stability were cyclic in the CvT and NT soils but not in the NeT soil. The magnitude and temporal pattern of variation varied with aggregate-size class in the CvT and NT but not the NeT soil. Temporal variation was highest in the 4 to 6.3 mm aggregate size class, which varied from 4 to 63 % of the aggregates by weight depending on the date of sampling. The magnitude and occurrence of differences in aggregate stability between CvT and NT varied with time, with the NT soil having larger aggregates than CvT soil at many sampling dates. Differences in temporal

pattern was associated with soil water contents and attributable to differences in rainfall patterns in the two years. Cultivation of soil greatly reduces aggregate stability in the long-term and greatly increases its seasonal variability while no-tillage increased aggregate stability only slightly.

INTRODUCTION

Tillage affects soil structure in significant ways. Comparisons of virgin to cultivated soils have shown that cultivation profoundly reduces the stability of soil structure (Dormaar, 1983; Elliot, 1986; Ketcheson, 1980; Olmstead, 1946) and that such deterioration can be rapid, occurring after only a few years of plowing (see Low, 1972, for discussion). Changes in cropping and soil management practices can alter soil structure dramatically (Tisdale and Oades, 1980; Weill et al., 1988). No-tillage or direct drilling has been reported to increase aggregate stability over plowing (Douglas and Goss, 1982; Hamblin, 1980; Mannering et al., 1975). Structural form (pore size, distribution, and continuity), the pore space within and between structural units (aggregates or peds), is also significantly altered by tillage. Total porosity and pore continuity decrease under long-term cultivation (Blevins et al., 1983; Douglas and Goss, 1987) and are significantly affected by degree and amount of tillage (Gantzer and Blake, 1978; Hill, 1990).

The deterioration of soil structural stability is a major factor contributing to increased rates of soil degradation by processes such as erosion (Coote et al., 1988; Wall et al., 1988) and compaction (Raghavan et al., 1990), with consequent effects on productivity and the environment. In addition, aggregate stability dictates the ability of structural form to resist degradative forces in soils

(Kay, 1990). Therefore, there is considerable interest managing soils, particularly by using conservation tillage systems, to improve soil aggregation (Elliott, 1986; Gupta and Germida, 1988; Perfect et al.,1990a; Tisdall and Oades, 1980).

Studies on soil structural stability have mainly focused on effects of soil, plant, and climatic factors on aggregate stability (Elliott, 1986; Gupta and Germida, 1988; Krishna Murti and Rengasamy, 1977; Perfect et al.,1990a; Tisdall and Oades, 1982) and often deal with long term effects of soil management (Low, 1972; Baldock and Kay, 1987). Changes in soil structure are dynamic in the short term, however, and seasonal effects have been reported (Bullock et al.,1988; Douglas and Goss, 1982; Perfect et al., 1990b). Reinert and Pierce (1990a) reported that temporal variation in bulk density, total porosity, and saturated hydraulic conductivity was cyclic for a plowed, no-tilled, and never tilled loam soil and that variation in macroporosity (defined as pores with equivalent pore diameter > 48 um) was primarily responsible for the magnitude of the variation. Seasonal variation of structural stability has been reported to be associated with organic matter content and type (Douglas and Goss, 1982; Webber, 1965;Weill et al., 1989), clay content and type (Kemper et al., 1987;Krishna Murti and Rengasamy, 1977), roots and fungal hyphae (Gupta and Germida, 1988; Stone and Buttery, 1989; Tisdall et al., 1978), cropping systems (Baldock and Kay, 1987; Perfect et al., 1990a,b; Reid et al., 1982), freezing and thawing (Kemper et al., 1989; Harris et al., 1966; Bullock et al., 1988), and with wetting and drying cycles (Shiell et al., 1988; Utomo and Dexter, 1982).

The cyclic nature of aggregate stability (Greenland et al., 1962; Rennie et al., 1954; Webber, 1965) and of structural form (Cassel et al., 1978; Mapa et al., 1986; Reinert and Pierce, 1990) have been established. However, studies on soil structure have generally addressed long-term effects without consideration of short-term variation or have a limited measurement frequency. It is for this reason that studies on soil structure often are not conclusive or yield conflicting results to similar studies. Therefore, quantification of the temporal variation of structural stability as affected by tillage and cropping history over a several year period is needed to more completely assess management impacts on soil structure.

The objective of this study was to characterize the effect and temporal pattern of variability of conventional tillage, no-tillage, and never tilled management on aggregate size distribution and aggregate stability.This study is a component of a ecosystem study designed to develop a better understanding of how belowground processes interact to regulate nutrient availability in agricultural ecosystems (Pierce and Robertson, 1990).

MATERIAL AND METHODS

The research was conducted at the Kellogg Biological Station in south-central Michigan. The soil is a Kalamazoo loam formed in glacial outwash parent material. Selected soil physical properties of this soil is given by Reinert and Pierce (1990b). The experiment was initiated in the spring of 1986, and consisted of two tillage treatments - no-tillage (NT) and conventional tillage (CvT) and two N fertilizer treatments -none and 175 kg N ha^{-1} yr^{-1}, established in a randomized complete block design with four replication on main site area (Pierce and Robertson, 1990). Conventional tillage consisted of spring moldboard plowing followed by one or two passes of a disk and/or field cultivator. The NT areas had no tillage since the spring of 1985. Directly adjacent to the main site is an area that has never been tilled (NeT) where two treatments - corn slot planted and natural vegetation - were established in a randomized complete block design with four replication. Neither treatments in the never tilled area received any commercial fertilizers. All wheel traffic was controlled throughout the course of the study. Corn was grown in 1986-1988 and soybeans were grown in 1989. Corn was irrigated with solid set irrigation in 1986-1988 as needed. Each plot measured 40 meters by 27 meters.

Undisturbed soil samples were collected from fertilized plots of NT and CvT, and from NeT plots. Samples were obtained from 0-5 cm depth of the non-trafficked rows at 13 times between April of 1988 and November of 1989. Successive sampling were made adjacent to previous sampling in order to decrease spatial variability and at days were soil moisture were around field capacity. With field moisture soils were carefully broken to obtain a sufficient amount of aggregates for analyses and after the aggregates were let to air dry at room temperature. In the breaking process deformation and smearing were avoided by gently breaking larger aggregates or soil clods at the surface of weakness. The air-dry soil was then passed through an 6.3 mm sieve and captured partially by an 4.4 mm sieve. On 9-8-1988 and 11-2-1988 aggregates between 2 and 1 mm were also separated. Samples were then stored at 4 C until analyzed.

Soil structural stability was assessed using the water-stable aggregate-size distribution (WSASD) measurement method of Kemper and Chepil (1965) for all sampling dates. The nest of six sieves used were 4.0, 2.0, 1.0, .5, .25, and .1 mm. A 25 g sample of separated aggregates (6.3-4.4 mm) were placed on 4.0 mm sieve and wetted by a fine sprayer trying to minimize disruption caused by air trapping. For two sampling dates (9-8-1988 and 11-2-1988), wet aggregate stability (WAS) was determined using the single sieve method of Kemper and Rosenau (1986) using a 4 g sample of separated aggregates with diameters between 1.0 and 2.0 mm. For both methods, the time for wetting and sieving, stroke length and cycles frequency of wet sieving apparatus, sand correction, and calculations were as described in the cited methods.

Organic carbon was measured in all samples taken in 1989 using the wet combustion method (Nelson and Sommers, 1982). Only samples from NT plots were analyzed in 1988. Soil water contents were measured volumetrically at the time of sampling bulk soil using intact soil cores for the 1988 and early 1989 sampling. For the period June 21st to November 1989, volumetric soil water contents were measured using time domain reflectometry (TDR).

Analysis of variance and least significance difference analysis were performed to compare means of conventional tillage and no-tillage for each sampling dates.

RESULTS AND DISCUSSION

Long-term cultivation has resulted in a substantial reduction in aggregate stability of the surface layer of the Kalamazoo loam soil. For soil sampled on April 21, 1987, approximately 89.8 % of the water stable aggregates in the NeT soil had diameters greater than 4.0 mm compared to 23.6 % for the CvT soil (Table 3.1). The geometric mean diameter (GMD) for the NeT soil was 4.37 and for the plowed soil 0.60 (Table 3.1). The higher aggregate stability on non-cultivated or permanent grass soils is expected and has been attributed to higher organic matter and minimized exposure to its

Table 3.1. Water stable aggregates size distribution, geometric mean diameter (GMD), and mean weight diameter (MWD) of a Kalamazoo loam textured under no-tillage (NT), conventional tillage (CvT), and never tilled (NeT) management at 0 to 5 cm depth in April 21, 1987.

Size class (mm)/ AS index	NT	CvT	NeT
6.3-4.0	14.6	23.6	89.8
4.0-2.0	6.0	6.1	4.3
2.0-1.0	5.3	5.1	3.0
1.0-0.5	11.9	9.5	0.9
0.5-0.25	25.1	21.6	0.6
0.25-0.1	23.5	22.8	0.3
< 0.1	13.5	11.3	1.6
GMD, mm	0.46	0.6	4.37
MWD, mm	1.24	1.67	4.80

AS: aggregate stability

decomposition, absence of tillage disruption, and effective influence of roots (Douglas and Goss, 1982; Low, 1972; Tisdall and Oades, 1982). Organic C in the NeT soil is approximately 3.9 % compared to approximately 0.7 % for the cultivated soil. Tisdall and Oades (1982) pointed out that persistent organic binding is responsible for higher aggregate stabilization. No-tillage of this soil did not improve aggregation in the 0 to 5 cm layer. However, only two years had elapsed since tillage had ceased in the spring of 1985. The GMD for the NT soil (0.46) was slightly lower than the CvT soil. Similar trends were apparent for mean weight diameter (MWD) of these soils (Table 3.1).

The temporal patterns of GMD for the period April, 1988 to November, 1989 are cyclic for the NT and CvT soils and relatively stable for the NeT soil (Figure 3.1.1). The GMD for the NeT soil was always substantially higher than the NT and CvT soils but did decline over the period of measurement. A decline in soil structure in the NeT soil may result from the vegetation change from grass to continuous cropping. Lamb et al (1985) reported a small reduction in total nitrogen after twelve years of no-tillage cropping of a native sod in Nebraska. The seasonal variation in the CvT and NT was considerably more in 1988 than in 1989. Minimum values occurred in the spring and fall of 1988 and the spring of 1989. Maximum values of GMD occurred in August of 1988 but the August sampling was unfortunately missed in 1989. There were no significant differences in GMD between NT and CvT in 1988. However, GMD for NT was significantly higher than CvT for all sampling in 1989. The amplitude of the temporal variation in the MWD was higher than for GWD for the NT and CvT soils but the trends were the same (Figure 3.1.2). However, in the NeT soil, there was less temporal variation in MWD than GWD. This is associated with the different ways size classes are weighted in the two calculations.

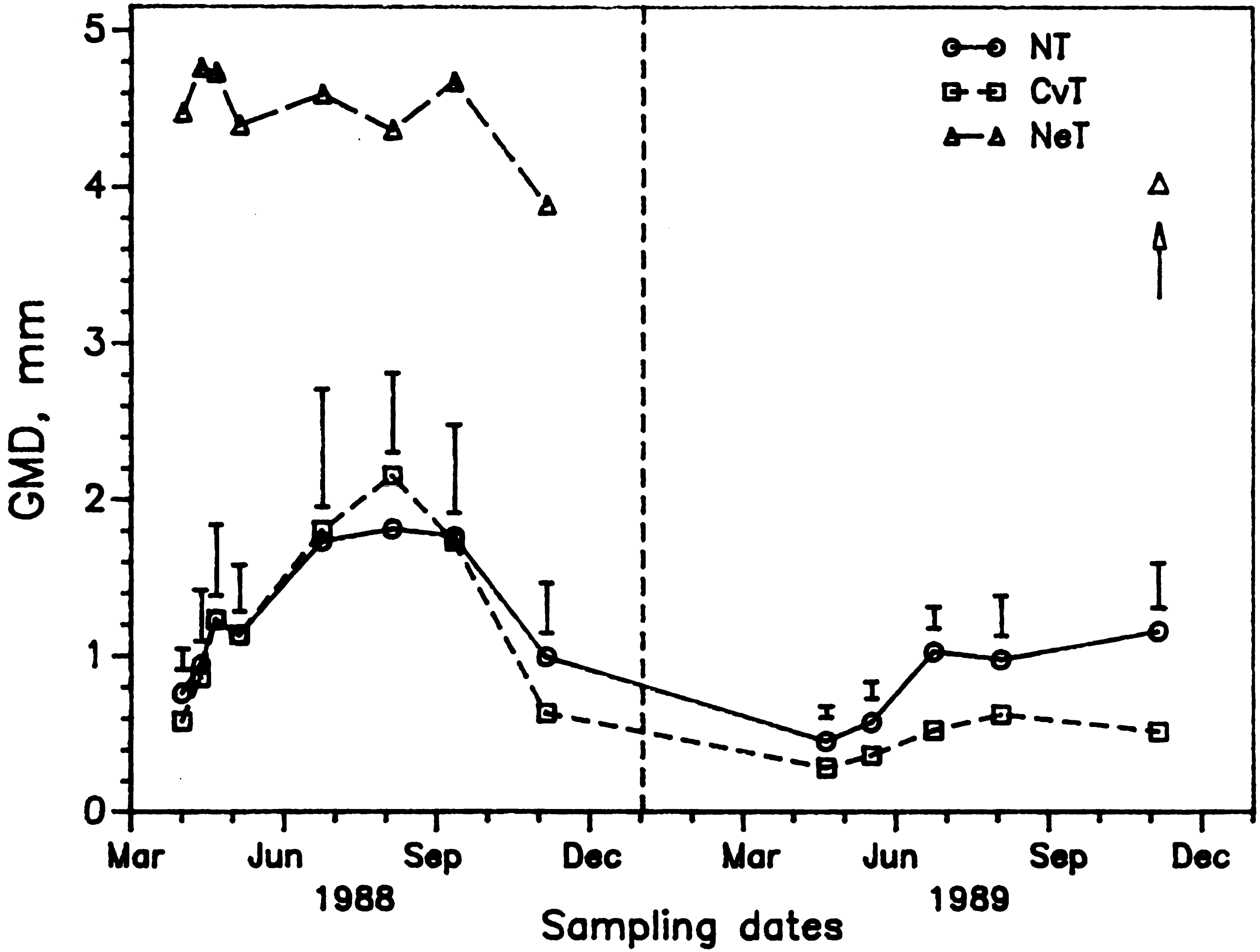

Figure 3.1.1: Temporal variation of geometric mean diameter-GMD of aggregates. The LSD's compare means of conventional and no-tillage at each sampling date for 0 to 5 cm depth.

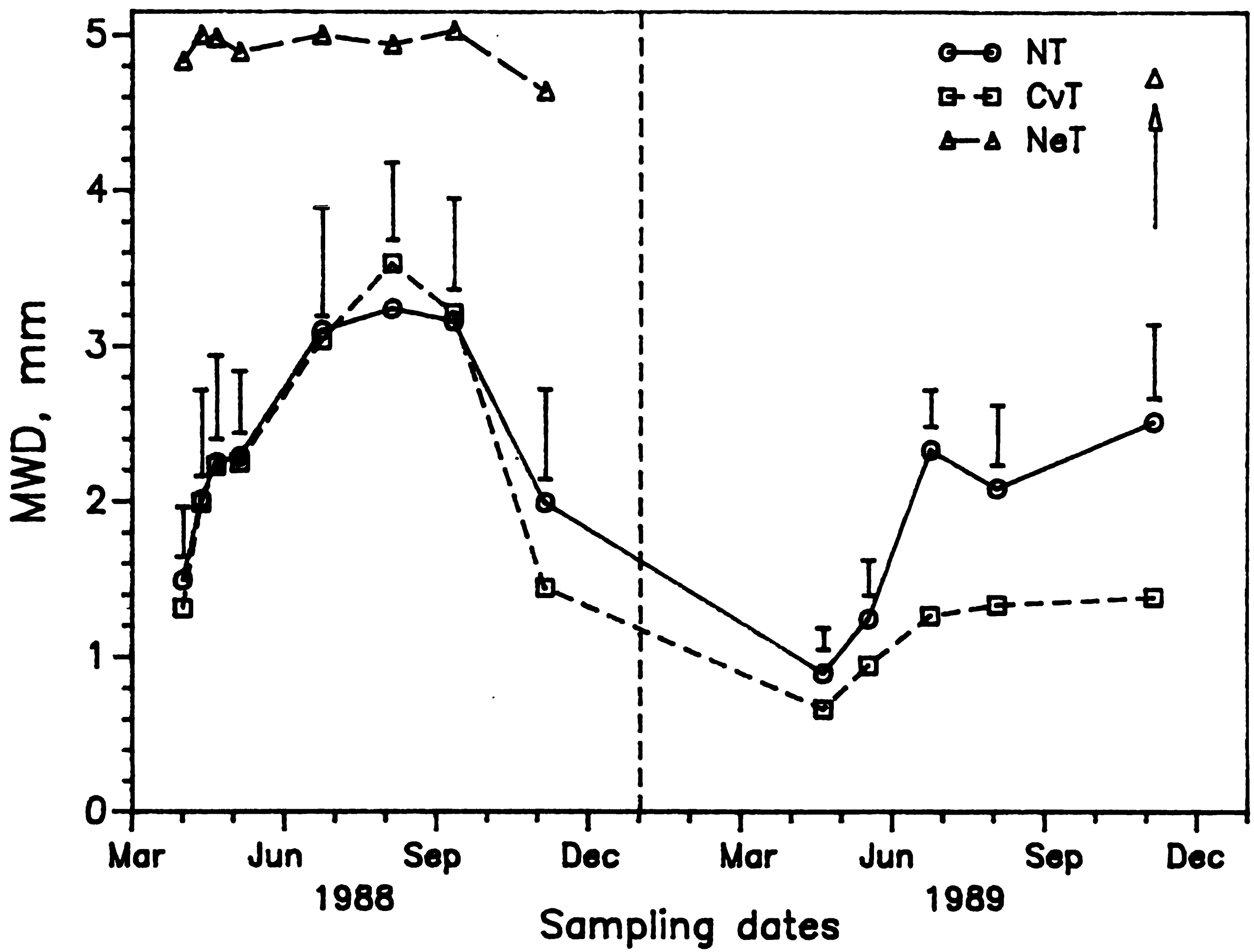

Figure 3.1.2: Temporal variation of mean weigth diameter-MWD of aggregates. The LSD's compare means of conventional and no-tillage at each sampling date for 0 to 5 cm depth.

Organic C in the NT soil varied over the measurement period from 0.55 to 1.08 % (Figure 3.2). The temporal variation in organic C was similar in pattern to GMD and MWD within a season (compare Figures 3.1.1 and 3.1.2 with 3.2). However, there was no general relationship between organic C and GWD or MWD ($r = 0$) since the relative magnitudes shifted from 1988 to 1989. The changes in organic C for NT and CvT were not significantly different during 1989 (Figure 3.2). It would appear, therefore, that both organic C and aggregate stability are cyclic and have similar patterns within a season but are not involved in a cause-effect relationship. Volumetric water contents measured at the time of sampling (Figure 3.3) show strikingly similar temporal patterns to GWD and MWD. The relationship between aggregate stability and wetting and drying is long recognized (Perfect et al., 1990a,b; Utomo and Dexter, 1982). The difference in temporal patterns in 1988 and 1989 is related to the differences in rainfall patterns in these years (Figure 3.4). In 1988, a significant drought extended well into July and was followed by a reasonable wetting cycle in August and September. In 1989, heavy rains in June were followed by short wetting and drying cycles and an additional heavy rain in August followed by an extended dry period. The aggregation in both CvT and NT soils responded similarly to the drying and wetting cycle during the May to September period in 1988 but responded differently to the wet conditions in 1989. The pattern of structural stability in 1988 mimics the pattern of minimum temperatures (Figure 3.5). This was not the case in 1989 when rainfall was higher, although the temperature patterns in 1988 and 1989 were similar. Bullock et al. (1988) reported significant relationships between minimum temperatures and aggregate stability over a single year cycle.

The magnitude and pattern of temporal variation varied with aggregate

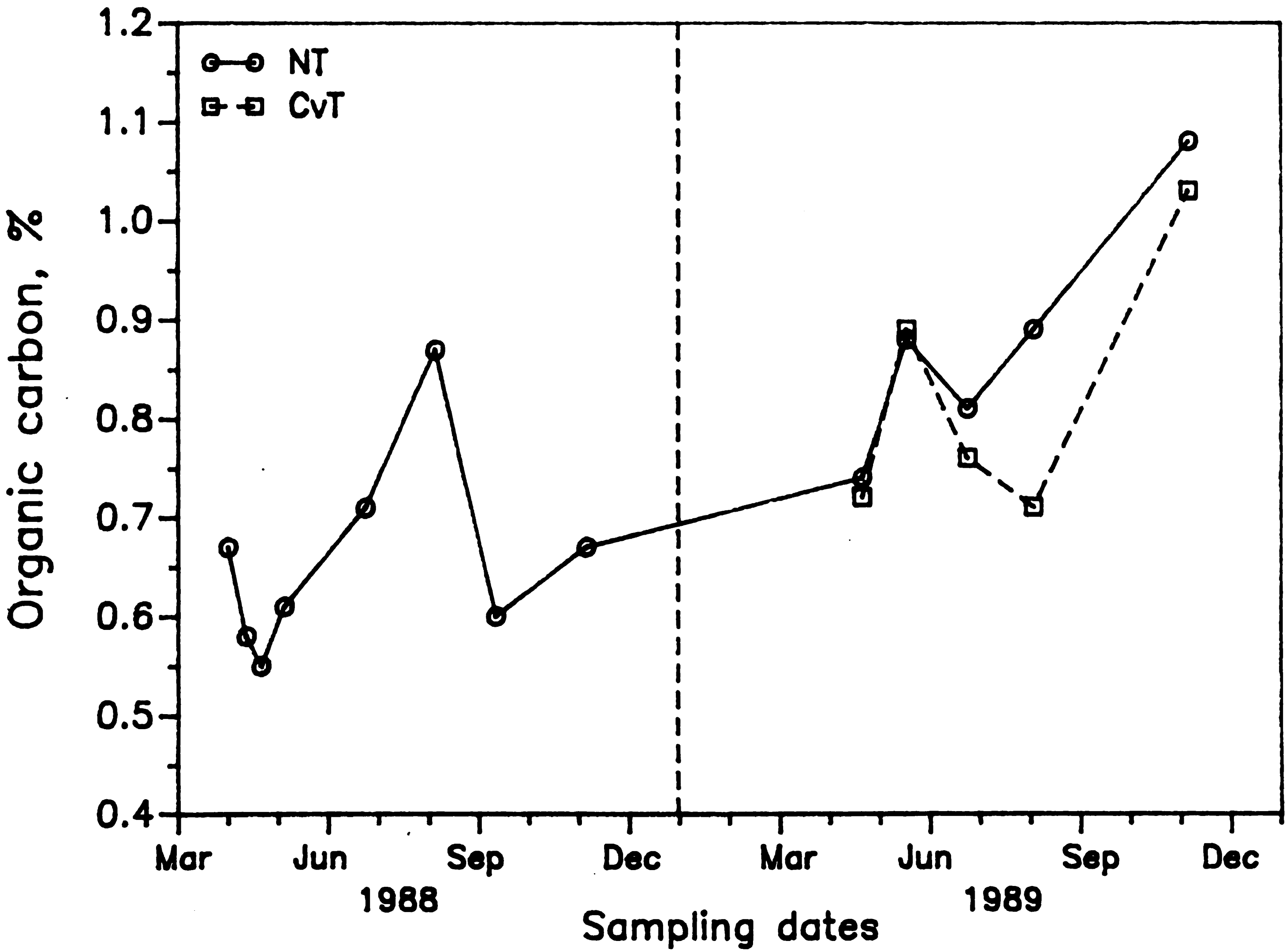

Figure 3.2: Temporal variation of organic carbon of a Kalamazoo loam soil under no-tillage (NT)and conventional tilllage (CvT) management.

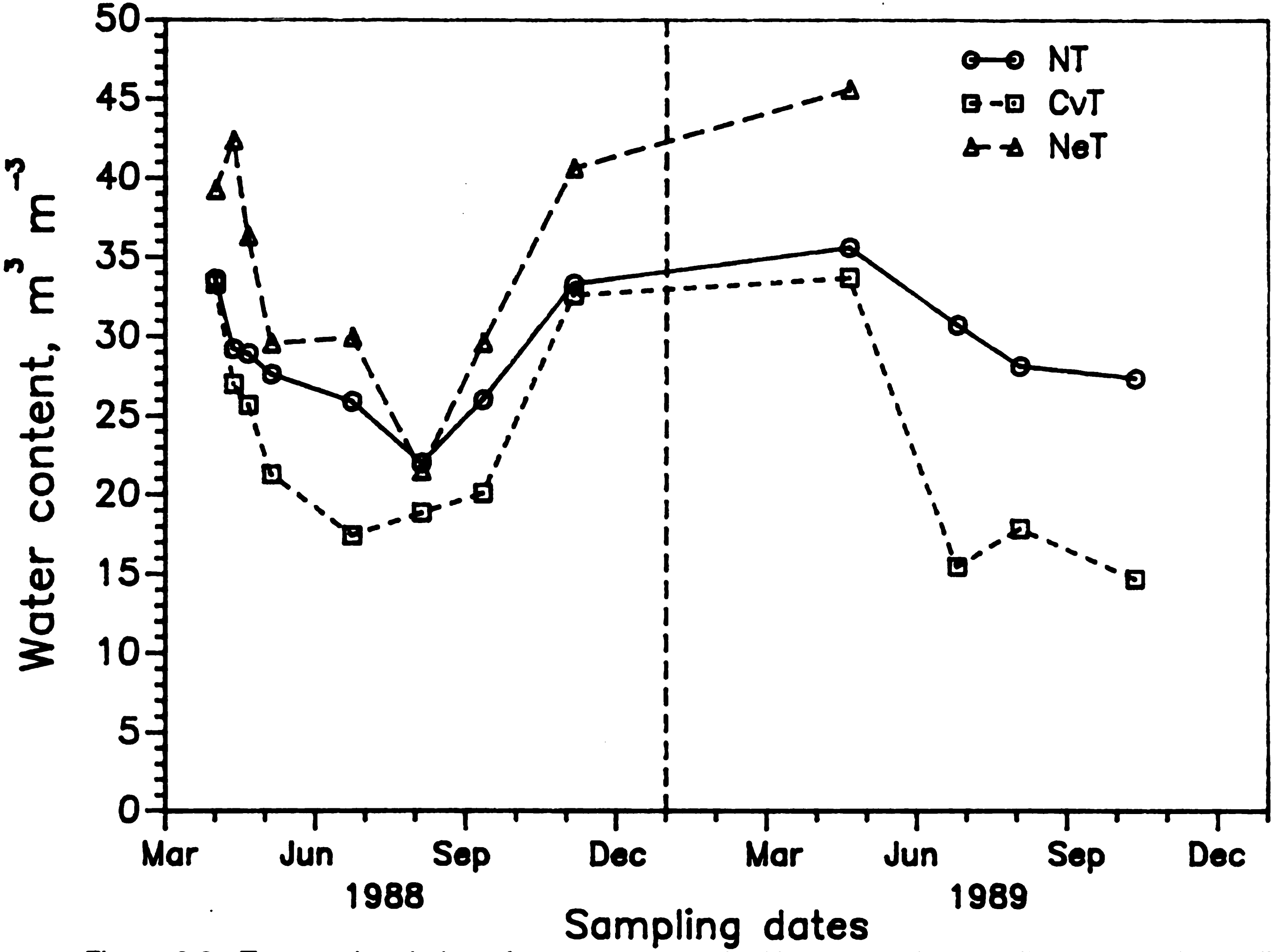

Figure 3.3: Temporal variation of water content of a Kalamazoo loam soil under no-tillage (NT), conventional tillage (CvT), and never tilled (NeT) management for 0 to 7.6 cm depth. The water content for June, July, and October of 1989 sampling were measured for 0 to 15 cm depth.

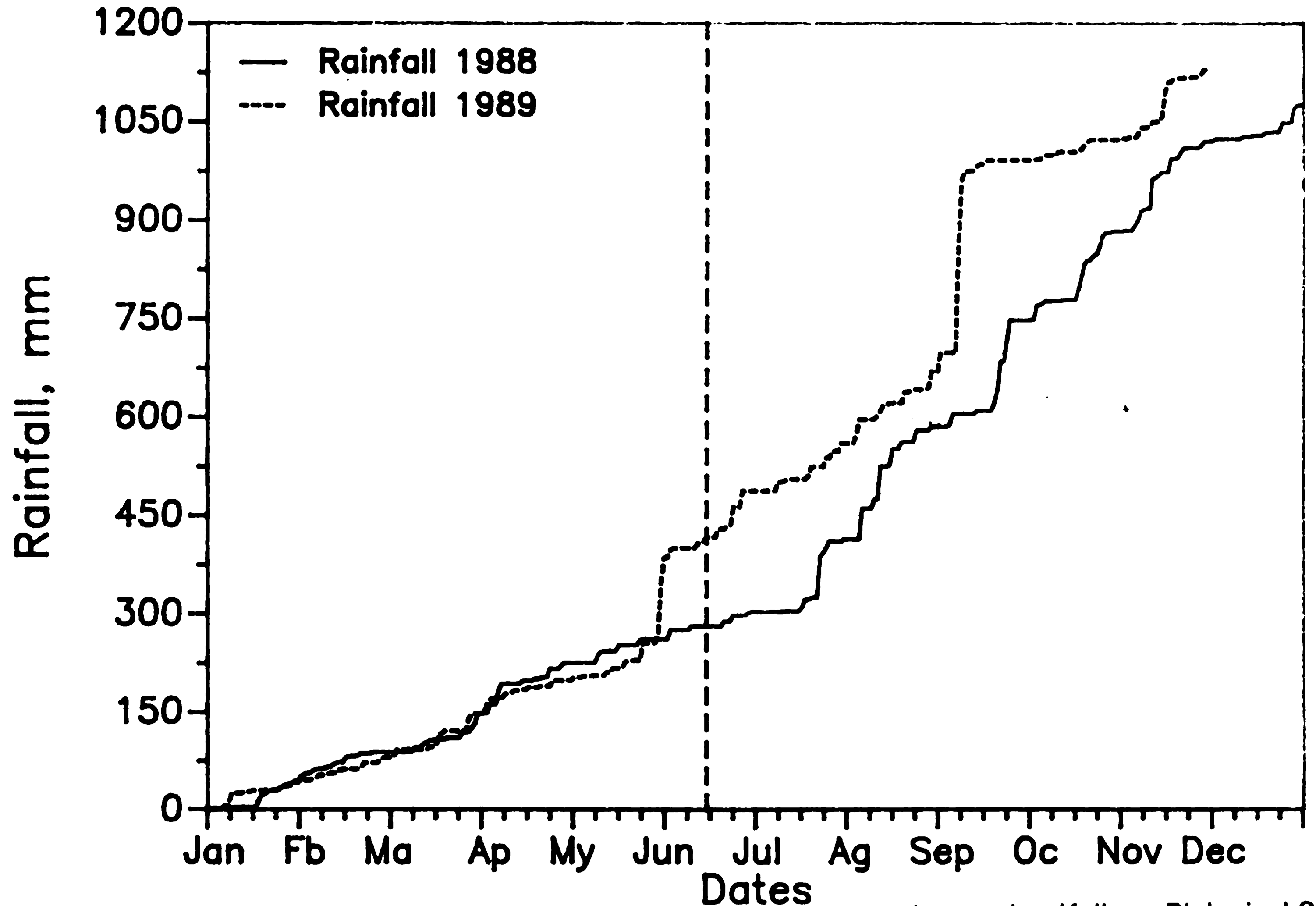

Figure 3.4: Cumulative amount of rainfall plus melted snow observed at Kellogg Biological Station weather service for 1988-1989 period.

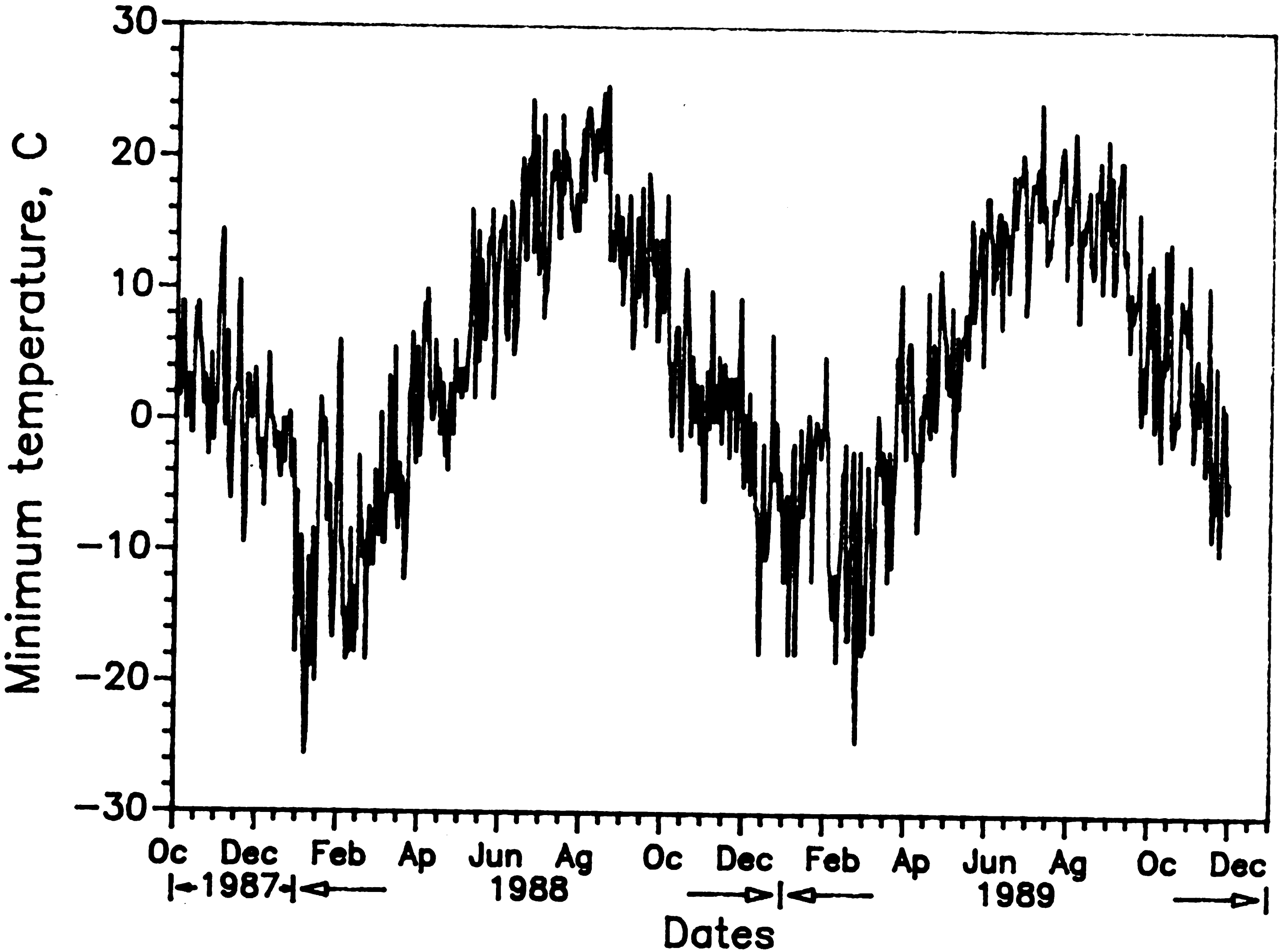

Figure 3.5: Minimum daily air temperature observed at Kellogg Biological Station weather service for 1987-1989 period.

size class for the NT and CvT soils but not for the NeT soil (Table 3.2 and Figure 3.6). Temporal variation was highest for the > 4 mm diameter size class which accounted for 63 % of the aggregates (by weight) in August 2, 1988 and only 4 % of the aggregates in April 20, 1989 in the CvT soil, with corresponding numbers for the NT soil of 56 % and 6 %. The 0.5 to 1.0 and 0.25 to 0.5 mm size classes were most variable of the other size classes and changed inversely in response to increases and decreases in the > 4.0 mm size class. Differences between NT and CvT for the different aggregate size classes varied with time (Table 3.2). NT soil had significantly higher aggregates in the larger size classes and CvT soil higher aggregates in the lower size classes in early spring of 1988 and all of 1989. Therefore, the magnitude and occurrence of differences in aggregate stability between tillage systems is temporally dependent. Temporal dependence of the structural form properties (pore geometry and bulk density) of this soil was reported by Reinert and Pierce (1990).

The state of aggregation at any time of year is a function of aggregate formation and degradation (Harris et al., 1966). A dynamic seasonal processes that affect aggregate stability is discussed by Bullock et al. (1988). In general there is a integrated action of factors toward structural stability degradation from fall to early spring and a restoration action from early spring to end of summer. Such factors act on internal resistance of aggregates and mainly on interchanging aggregate size. Freezing and thawing has been reported to decrease aggregate size (Harris et al., 1966; Kemper et al., 1989), and at field condition wetting and drying (Ramsay et al., 1986) and increasing root density and microbial biomass associated with soil warming has increased water-stable macroaggregates (Perfect et al., 1990; Stone and Buttery, 1989). The latter

Table 3.2. Temporal variation of water stable aggregate size distribution of a Kalamazoo loam under no-tillage (NT) and conventional tillage (CvT) at 0 to 5 cm depth for 1988-1989 period.

	1988								1989				
Tillage	4-1	4-12	4-21	5-3	6-21	8-2	9-8	11-2	4-20	5-15	6-21	7-31	11-2
								6.3 - 4.0 mm					
NT	13.2a	27.7a	34.0a	34.6a	53.3a	56.4a	55.1a	26.8a	6.0a	10.3a	34.5a	28.1a	39.5a
CvT	14.0a	30.4a	33.5a	34.8a	52.0a	63.2a	56.2a	17.8a	3.7a	8.2a	13.1a	14.0a	16.7b
LSD	7.0	12.3	11.5	8.4	15.8	11.4	13.5	11.3	1.7	3.3	4.8	7.8	9.4
								4.0 - 2.0 mm					
NT	11.2a	7.7a	6.2a	6.3a	4.6a	4.7a	4.4a	7.4a	4.4a	9.1a	8.7a	9.9a	8.7a
CvT	7.1b	4.5b	6.4a	5.9a	4.3a	3.7a	4.1a	7.1a	3.9a	6.2b	7.1a	6.5b	6.3b
LSD	3.1	1.3	1.2	1.5	1.8	1.3	1.4	3.0	1.6	2.8	2.1	2.5	2.2
								2.0 - 1.0 mm					
NT	13.5a	8.8a	7.0a	8.3a	6.1a	4.4a	4.4a	10.7a	9.4a	12.1a	7.9a	9.8a	5.2b
CvT	8.4b	6.1b	7.1a	6.3b	5.3a	4.1a	4.7a	8.9a	7.3a	7.3b	9.2a	10.2a	7.9a
LSD	3.4	1.3	1.1	1.4	2.1	1.5	2.0	2.0	2.5	2.2	1.9	1.6	1.7
								1.0 - 0.5 mm					
NT	22.2a	16.3a	15.0a	14.9a	10.5a	8.4a	8.4a	17.9a	22.3a	19.0a	12.1b	14.7b	8.6b
CvT	17.0b	12.1b	15.1a	12.7b	9.5a	7.6a	8.3a	14.5a	13.6b	13.6b	16.1a	20.1a	13.5a
LSD	2.9	2.9	3.7	2.1	3.7	3.0	3.5	3.5	2.4	2.4	2.1	2.0	1.7
								0.5 - 0.25 mm					
NT	21.4b	21.2a	19.7a	18.4a	13.4a	12.8a	12.8a	18.9a	29.0a	22.4a	15.8b	17.2b	12.7b
CvT	25.8a	21.3a	18.7a	18.9a	13.2a	9.9a	11.6a	19.8a	24.4b	22.6a	21.5a	22.2a	20.5a
LSD	3.8	5.2	4.9	3.8	5.1	3.8	4.5	4.4	2.3	2.2	2.3	3.5	2.4
								0.25 - 0.10 mm					
NT	10.3a	8.4a	9.1a	11.4a	7.0a	7.1a	7.3a	9.2b	15.9b	13.3b	9.4b	9.7b	9.5b
CvT	15.4b	11.7a	8.7a	9.2a	6.8a	5.6a	7.5a	13.9a	20.9a	18.3a	14.0a	13.0a	16.2a
LSD	2.5	2.6	2.9	3.1	2.6	1.8	2.5	2.4	3.0	3.0	3.7	2.5	2.2
								< 0.1 mm					
NT	8.1b	9.9b	8.8a	8.3a	6.9a	6.0a	7.6a	9.0b	12.9b	13.7b	11.4b	11.2b	15.6a
CvT	12.3a	14.0a	10.3a	10.0a	7.1a	5.9a	7.6a	17.6a	26.2a	23.8a	19.0a	13.9a	18.9a
LSD	1.7	2.3	2.2	2.1	2.0	1.6	1.7	3.7	5.5	3.5	5.9	2.6	7.8

LSD: compare means at 0.05 probability

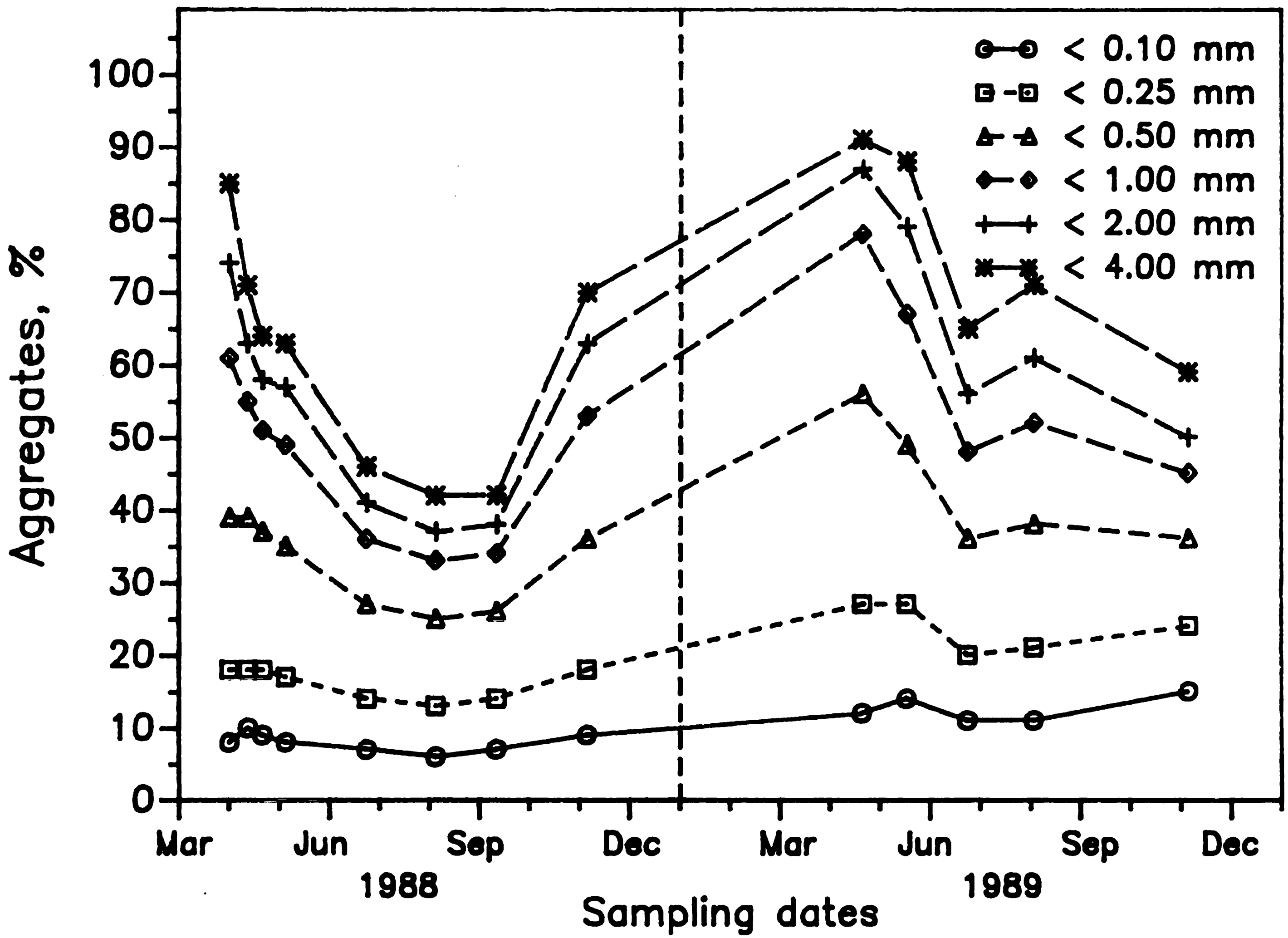

Figure 3.6.1: Temporal variation of cumulative percentage of aggregates smaller than a given diameter of a Kalamazoo loam under no-tillage management.

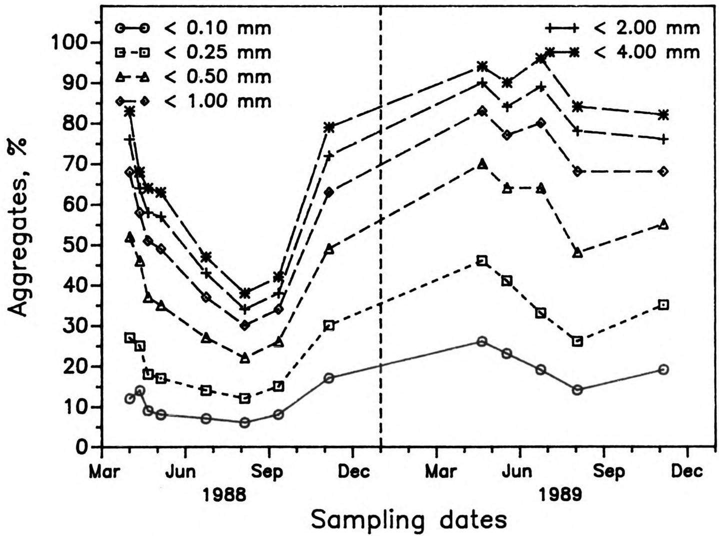

Figure 3.6.2: Temporal variation of cumulative percentage of aggregates smaller than a given diameter of a Kalamazoo loam under conventional tillage management .

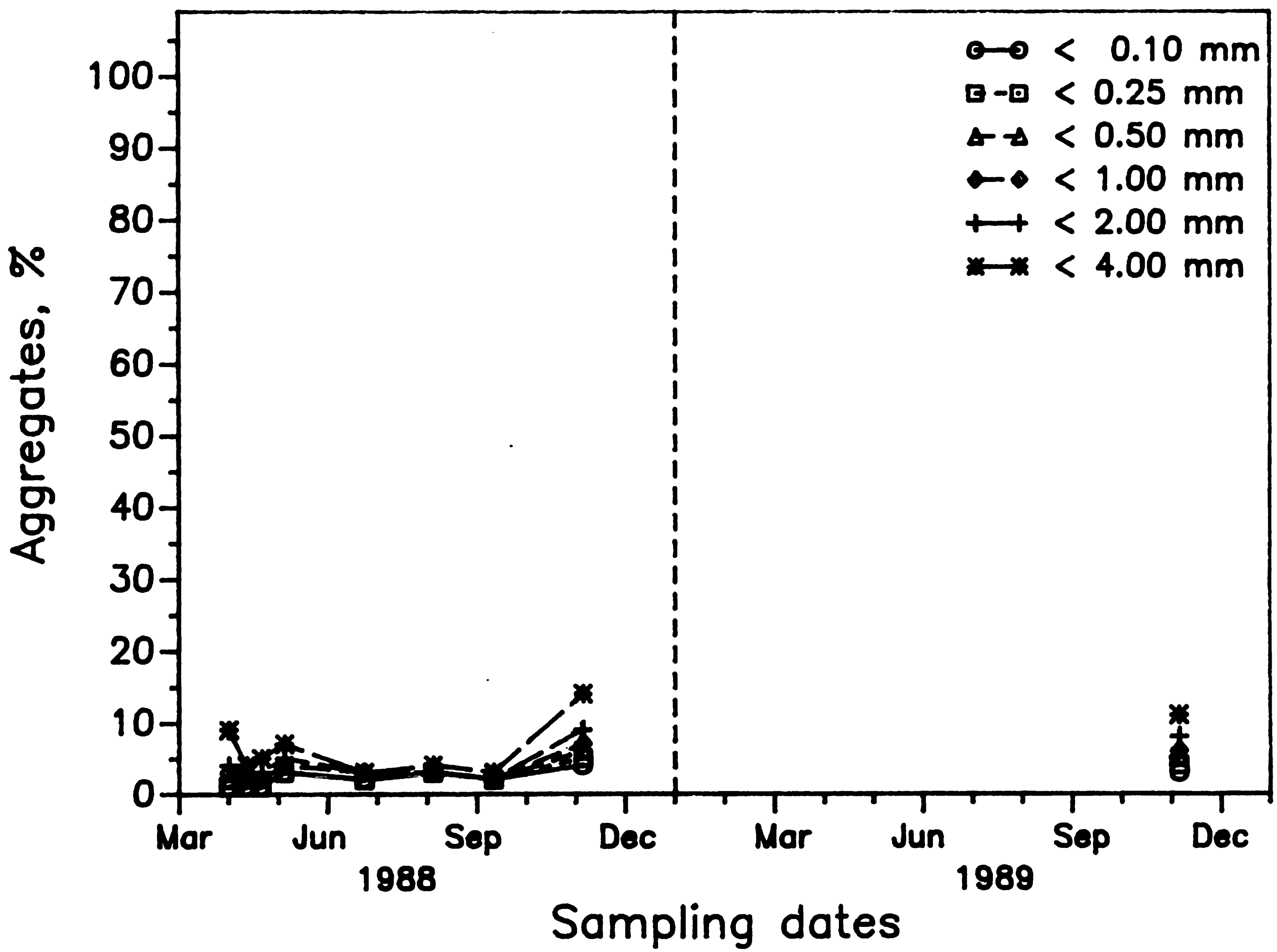

Figure 3.6.3: Temporal variation of cumulative percentage of aggregates smaller than a given diameter of a Kalamazoo loam under never tilled (NeT) management .

show the importance of use methods of measurement which considers size distribution of aggregates from samples which experiences seasonal effects in the field.

Mannering et al. (1975) reported that after 5 years of no-tillage in continuous corn, the aggregation index (obtained using a single wet sieve method) in the 0 to 5 cm layer was 0.768 for no-tillage and 0.347 for moldboard plow. The single wet sieve method (WAS), recommended as a single measure of aggregate stability (Kemper and Rosenau, 1985), was used to measure wet aggregate stability on two sampling dates in the fall of 1988 (Table 3.3). The aggregation index showed similar trends in aggregate stability to those observed with aggregate size distribution. The WAS method was highly correlated to GMD and MWD but underpredicted GMD and overpredicted MWD for the CvT and NT soils (Figure 3.7). Therefore, the temporal patterns in aggregation index measured by WAS should be comparable to aggregate size reported here.

CONCLUSIONS

The structural stability of a never tilled soil was considerably higher than a soil under long-term cultivation. No-tillage increased aggregate stability over conventional tillage but the differences were temporally variable and related to rainfall patterns and associated soil water contents. The never-tilled soil showed slight temporal variability over the period of measurement. However, aggregate stability in the never-tilled soil decreased with time under no-tillage cropping of corn. The temporal variation in the NT and CvT was cyclic and depended on size class, with the 4.0 to 6.3 mm diameter size class most

Table 3.3. Wet aggregate stability (WAS) of a Kalamazoo loam under conventional tillage (CvT), no-tillage (NT), and never tilled (NeT) management for two dates in 1988.

Soil Management	9-8-88	11-2-88
Conventional tillage	48.8A	25.2A
No-tillage	55.6A	38.8A
Never tilled	95.4	84.8

WAS - is expressed as % of oven dry aggregate corrected for sand. Measured using Kemper (1965) method.
Capital letters compare means of CvT with NT using LSDs at $p=0.05$

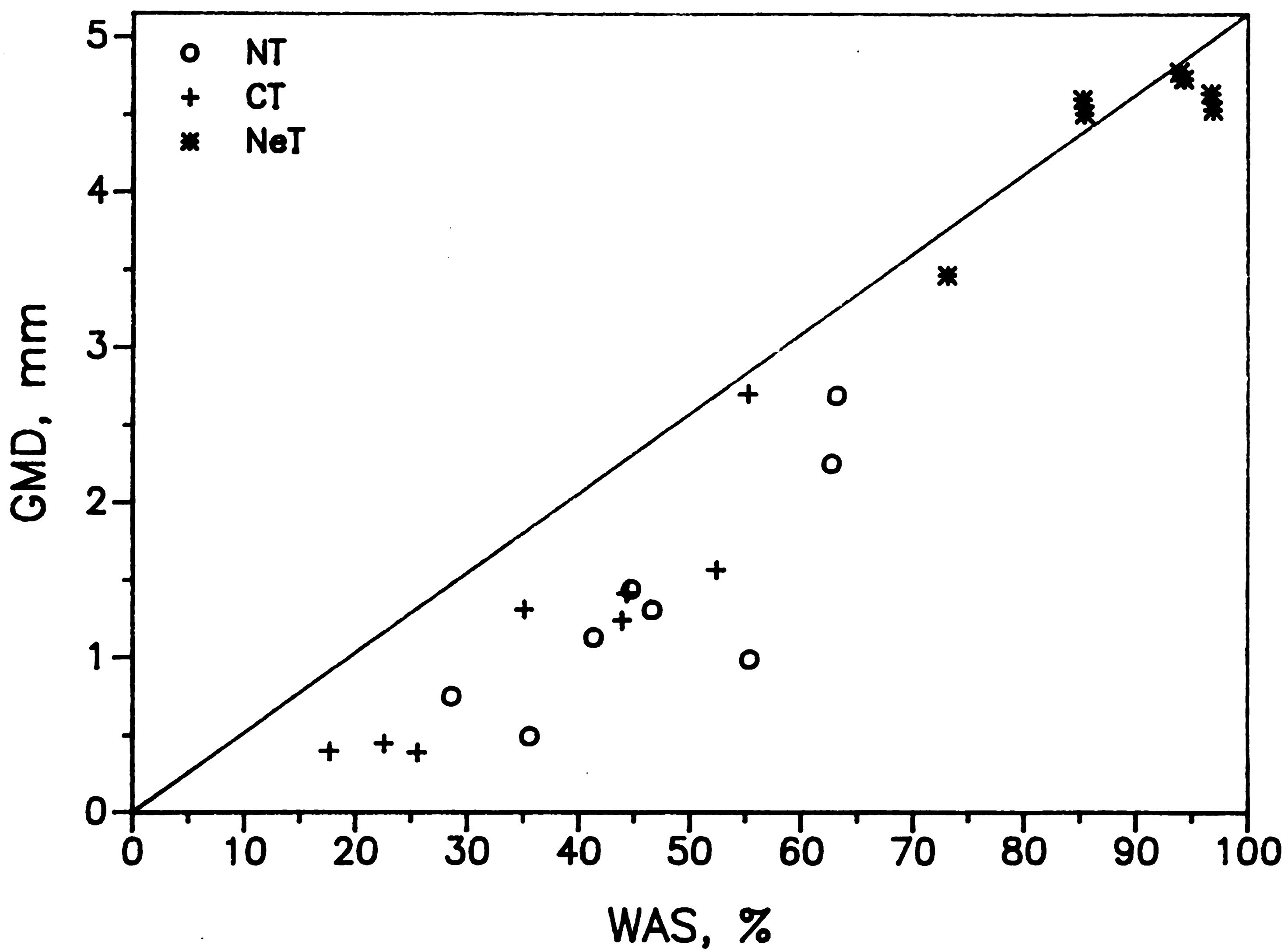

Figure 3.7.1: Relationship between geometric mean diameter (GMD) and wet aggregate stability (WAS) of a Kalamazoo loam soil under no-tillage (NT) and conventional tillage (CvT) management at two dates in 1988.

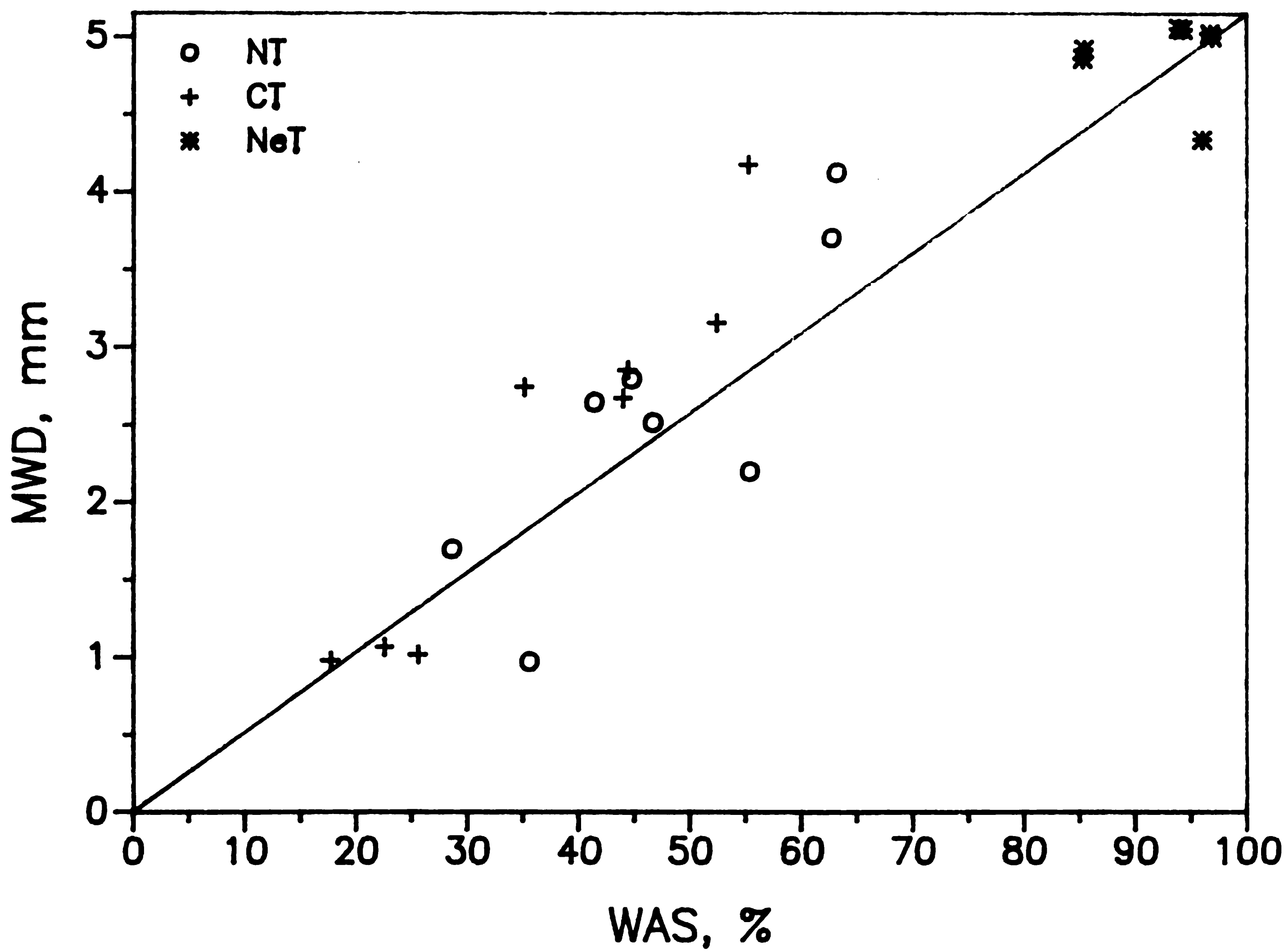

Figure 3.7.2: Relationship between .mean weight diameter (MWD) and wet aggregate stability (WAS) of a Kalamazoo loam soil under no-tillage (NT) and conventional tillage (CvT) management at two dates in 1988.

variable. These data show that natural, undisturbed soil systems have very stable soil structure that is relatively unaffected by cyclic patterns imposed by weather fluctuations whereas soils under long-term cultivation have unstable structure. It would be expected that if no-tillage management of soils is to mimic the natural ecosystem in the long-term,the stability of soil structure should increase and its temporal variation decrease relative to a plowed soil.

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CHAPTER 4

COMPRESSION OF A TYPIC HAPLUDALF OVER A RANGE OF BULK DENSITY IMPOSED BY TILLAGE AND NO-TILLAGE

ABSTRACT

Although the compressibility of unsaturated soil is strongly affected by stress history, the extent to which cessation of tillage for extended periods affects the compressive behavior of soil is not well known. The objectives of this study were to determine the compression behavior of a loam textured soil over a range of initial bulk densities imposed by tillage and no-tillage for several initial water saturations, and to quantify the previous stress history effects on the compressibility of this unsaturated soil. Compression tests were conducted with consolidometers using undisturbed soil samples from no-tillage (NT) and conventional tillage (CvT) experimental plots. The initial values of bulk density ranged from 1.18 to 1.65 Mg m^{-3} and the initial water saturation ranged from 10 to 85 %. The compressibility of an unsaturated loam-textured soil showed little difference for tilled or untilled management at similar initial bulk densities, but was strongly affected by the initial state of compaction and water saturation which are affected by tillage. Initial water saturation had a greater impact on soil compression at higher initial water contents and bulk density a greater impact on compression at lower initial water saturations. The compression index varied with bulk density and initial water saturation. These data illustrate a strong effect of stress history on the compressibility of this unsaturated soil

undergoing virgin compression. These data also suggest the major effect of no-tillage on the compressive behavior of this soil four years after the cessation of tillage is predominantly in its effect of increasing bulk density.

INTRODUCTION

The gradual densification of soils by compaction is becoming a significant soil degradative process worldwide (Lal, 1990). Compaction degrades soils by reducing or eliminating structural pores (Lal and Stewart, 1990) which influence the important processes that regulate productivity in soils. Compaction of agricultural soils has been primarily associated with increased mechanization in the form of heavier farm machinery and increased cultivation (Larson et al., 1980; Raghavan et al., 1990). Cultural practices, such as no-tillage, adds to the complexity of the compaction problem since elimination of tillage may enhance the potential for compaction (Culley and Larson, 1987). However, the extent to which cessation of tillage contributes to the mechanical behavior of soil apart from that associated with differences in stress history is unclear.

The susceptibility of soils to compression and its prediction have been the major focus of studies on the compaction of agricultural soils (Culley and Larson, 1987; Dexter and Tanner, 1973 and 1974; Gupta and Allmaras, 1987; Horn, 1988; Johnson et al. 1983; Larson et al. 1980; Stone and Larson, 1980). Despite qualitative attempts to describe soil compaction susceptibility (McCormack, 1987; Voorhees, 1987; Barber et al.,1989), studies attempting to model agricultural compaction from an applied stress have received greater attention (Blackwell and Soane, 1981; Burger et al. 1988; Gupta and Allmaras, 1987; Gupta et al. 1989; Smith, 1985). Difficulties of developing a mathematical model to describe stress-strain relationships have led to the development of empirical equations relating applied load with compaction states (Harris, 1971; Vanden Berg,1961). This relationship has been shown to be either exponential or logarithmic (Culley and Larson, 1987; Dexter and Tanner, 1973; Hovanesian, 1958; Hovanesian and Buchele, 1959; Johnson et al.,1983; Larson et al., 1980; Leeson and Campbell, 1983; Smith, 1985). However, these equations do not account for some important factors that affect the stress-strain relationship of a soil (Horn, 1988).

Soil physical properties and the technique used to apply force greatly influences compression properties of soils. Larson et al. (1980) showed the compression index (slope of linear portion of compression curve) of soils from eight soil orders increased with increase in clay content up to 33%, and then remained constant as clay further increased. For these soils, the compression curves with initial pore water potential ranging from -5 kPa to -100 kPa were approximately parallel. These studies were carried out on sieved soils at low initial bulk densities and represented conditions found in a fresh plowed soil after several secondary tillage operations. Compressibility of a soil also increases with increasing moisture content (Dexter and Tanner, 1973, 1974; Horn, 1988; Hovanesian, 1958; Leeson and Campbell, 1983). Dexter and Tanner (1973) pointed out that changes in soil compressibility which accompany changes in moisture content are far greater than any changes in other mechanical properties.

The stress history or state of compaction and soil structure are important factors influencing soil compressibility (Harris, 1971). Dexter and Tanner (1974) and Horn (1988) showed distinct differences in mechanical behavior when soils are disturbed as compared to when undisturbed. These differences are attributed to a different soil matrix arrangement or more likely to differences in initial bulk density. Harris (1971) and Horn (1988) pointed out that for a given soil subjected to a set of external forces, the lower initial bulk density exhibited the greater compression. Culley and Larson (1987) used undisturbed soil cores to show the compressibility of unsaturated clay loam-textured soil was strongly affected by stress history or by initial bulk weight volume (m^3Mg^{-1}). In their study, the initial bulk densities for no-tillage soils were significantly higher than for conventional tillage.

Mechanical manipulation of soil and load applied with machinery traffic associated to tillage operations deeply affect the state of compaction. Triplett et al. (1968), Culley et al. (1987), Douglas and Goss (1987), Reinert and Pierce (1990), Carter (1988), and Hill (1990) have all reported significantly higher bulk density in soils under no-tillage than tilled soils. To what extent this indicates higher bearing capacity in soils under no-tillage is unclear.

The objectives of this study were to determine the compression behavior of a loam-textured soil over a range of initial bulk densities imposed by tillage and no-tillage for several initial water saturations, and to quantify the previous stress history affects on the compressibility of this unsaturated soil.

MATERIAL AND METHODS

In 1986, an experiment was initiated on a Typic Hapludalf (Kalamazoo loam) at the Kellogg Biological Station, Hickory Corners, MI to compare no-tillage (NT) with conventional tillage (CvT) (spring moldboard plowing plus cultivation) with traditional and limited chemical inputs (Pierce and Robertson, 1990). The soil in the NT plots was last plowed in the spring of 1985. The CvT plots were plowed in the spring of each year of the study to a depth of 20 cm and received one pass each of a disk and a field cultivator prior to planting.

Corn (Zea mays L.) was grown in 1986, 1987, and 1988 and soybeans (Glycine max (L.) Merr.) in 1989. Each plot measured 30 by 40 meters and farm size equipment was used for all tillage and planting operations. Wheel traffic was controlled in the plots. Selected soil properties are given in Table 4. 1 for soil sampled in the spring of 1986 prior to initiation of the experimental treatments and again in the spring of 1989 (prior to spring plowing) after three years of the tillage experiment.

Large square Intact soil cores (10 cm by 10 cm by 14 cm) were sampled from the non-tracked interrows from each replication of the NT and CvT tillage treatments twice in 1989; once in the spring prior to tillage and again in the fall after harvest. The cores were carefully pressed into the surface soil layer when the soil moisture content was near field capacity. The cores were stored at 4 degrees C until needed for the consolidation test.

Prior to the consolidation tests, stainless steel cores (beveled consolidation rings, 3.0 mm thick, 62.5 mm i.d and 19.5 mm in height) were carefully pushed into the surface of the previously sampled undisturbed cores. A range in initial bulk density for each tillage treatment was possible due to spatial variation within the field. To achieve a range in soil moisture contents, soil in the consolidation rings were allowed to dry slowly by enclosing them in perforated containers for a period of time to attain a desired moisture content and allowed to equilibrate at each moisture content for 2 days. The process was repeated several times. The range in initial conditions for each tillage system is presented in Table 4.2.

Uniaxial compression tests were conducted with a typical fixed-ring consolidometer and a consolidation ring diameter to height ratio of 3.2. The strain measuring device used a dial gage reading with 0.0025 mm/div. The loads were applied in a geometric progression with respective measuring of

Table 4.1. Selected characteristics of the surface horizon of a Kalamazoo soil (fine-loamy, mixed, mesicTypic Hapludalf).

Soil Characteristic	Spring[(1)] 1986	Spring 1989[(2)] CT	NT	ConRing CT	NT
	---------- 0-7.5 cm--------			------2-4 cm-----	
Bulk density, Mg m^{-3}	1.44	1.41	1.54	1.34	1.44
Total Porosity, %	44.3	43.4	39.1	47.1	43.2
K saturated, cm h^{-1}	7.7	5.8	1.6		
Water content (%vol)					
at - 1 kPa	39.1	36.9	35.5	37.6	36.1
- 3 kPa	36.7	32.5	33.0		
- 6 kPa	34.5	30.0	30.7		
- 10 kPa	33.3	29.9	30.5	28.0	27.8
- 33 kPa	30.6	27.3	28.4		
-100 kPa	28.7	25.5	26.6	21.7	21.8
Water Saturation, %					
at - 1 kPa	88.3	85.0	90.8	79.8	83.6
- 10 kPa	75.2	68.9	78.0	59.4	64.3
-100 kPa	64.7	58.7	68.0	46.1	50.5
Clay content, %	14.1				
Silt content, %	46.8				
Sand content, %	39.1				
pH (surface)	6.72				
Organic carbon, %	0.79	0.72	0.86		
Plastic Limit	17				
Liquid limit	30				
Plastic index	13				

(1)- number of replicates equal 98
(2)- number of replicates equal 12
ConRing- using consolidation ring
NT - no-tillage; CT - conventional tillage

Table 4.2. Statistical values for the initial soil conditions of compression tests.

Soil Property	n	minimum	maximum	Range	Mean	Std Dev
No-tillage						
IWC (m^3 m^{-3})	48	0.05	0.38	0.33	0.21	0.08
IWSat, %	48	10.7	85.4	74.7	47.0	18.7
IBD (Mg m^{-3})	48	1.26	1.65	0.39	1.44**	0.07
Conventional tillage						
IWC (m^3 m^{-3})	46	0.06	0.39	0.32	0.21	0.09
IWSat (%)	46	11.6	83.9	72.3	43.4	19.8
IBD (Mg m^{-3})	46	1.18	1.54	0.36	1.34**	0.08

** - Significant difference between tillages at $p=0.01$
IWC - Initial water content
IWSat - Initial water saturation
IBD - Initial bulk density

strain. The load sequence used was: 17, 52, 103, 206, 413, and 620 kPa. The weight and dimensions of each consolidation ring and water content were obtained at the beginning of each test to calculate initial water saturation and initial bulk density. The consolidation rings were placed between two porous stones for the test. A set of compression tests were performed for a range of water saturations and initial bulk densities as indicated in Table 4.2. Preliminary consolidation tests indicated that for a wide range of moisture contents and initial bulk densities, a load application of 10 minutes was sufficient to realize 99% of the strain for a given load (Figure 4.1).

A computer algorithm was developed to calculate precompression pressure and the compression index for the measured compression curves (void ratio versus applied load) using the Casagrande method (as cited by Holtz and Kovacs, 1981). In the analysis of variance to compare tillage systems, initial bulk density and initial water saturation were used as covariates. For the analysis of the single effects of initial water saturation or initial bulk density, initial bulk density and initial water saturation were used as covariates in the respective analyses.

RESULTS AND DISCUSSION

The average bulk density of the core rings prior to the consolidation test was significantly higher for the NT (1.44 Mg m^{-3}) than the CvT (1.34 Mg m^{-3}) treatment (4.2). The range in bulk densities for the NT and CvT treatments (0.389 and 0.355 Mg m^{-3}, respectively) was broad enough and the overlap of the ranges sufficient to evaluate both the effects of initial bulk density and tillage system on the consolidation behavior of this soil.

Compression curves for four initial bulk densities measured at low initial

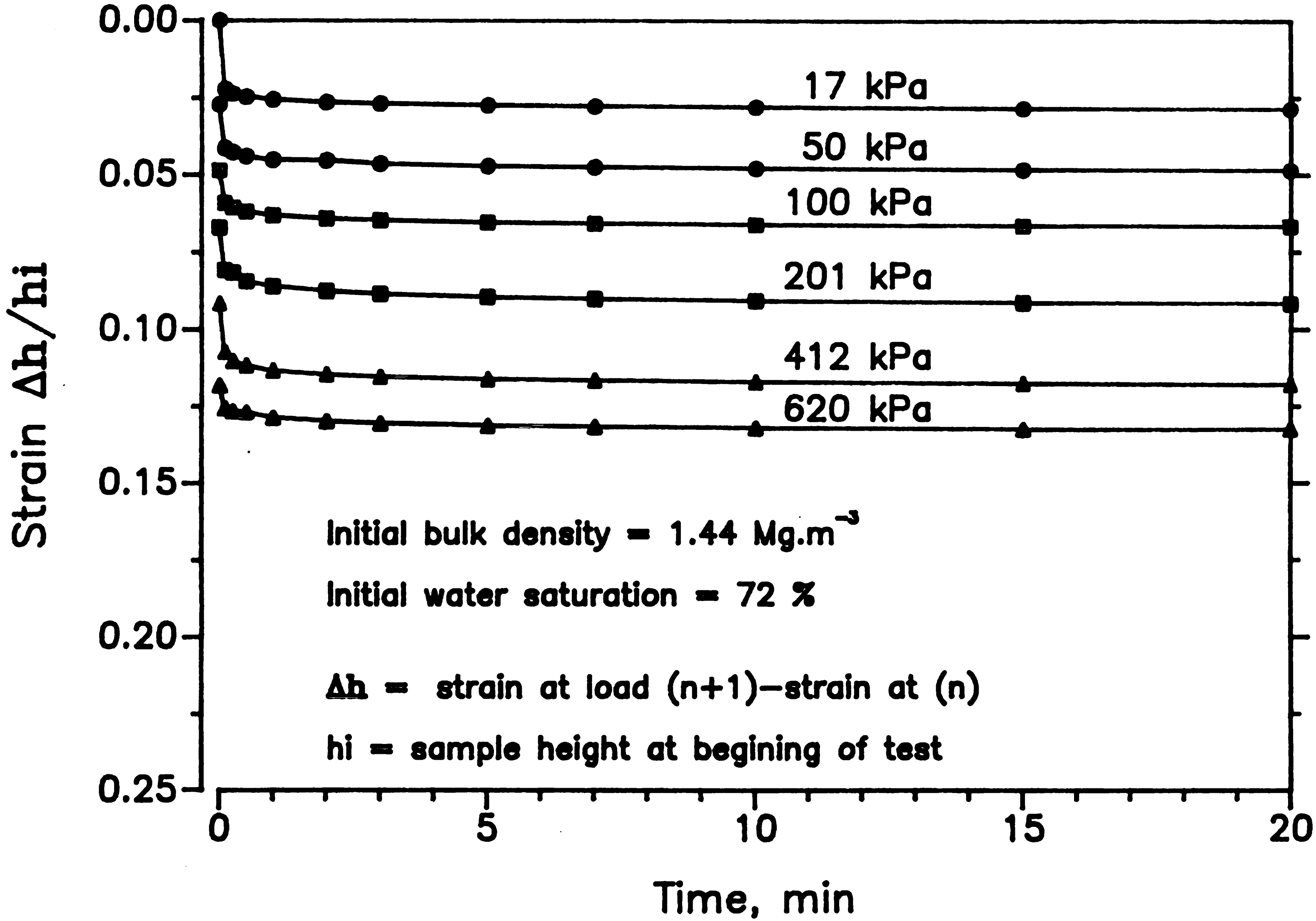

Figure 4.1: Soil strain as function of time for different applied loads for intact soil cores of the Kalamazoo loam .

water saturations (20-24%) illustrate the significant effect of initial condition on the consolidation behavior of this soil (Figure 4.2). As the initial bulk density increased, the linear portion of the virgin compression curves begin at higher applied loads and the slopes (compression indices) decrease (Table 4.3). The compression curves for NT and CvT soils at similar initial bulk densities were not significantly different. This is illustrated in Figure 4.2 by comparing the NT and CvT curves for initial bulk densities of 1.36 and 1.38 Mg m^{-3}, respectively. The small differences between these compression curves are attributed to slight differences in initial bulk densities and water saturations. This was true for other comparisons of tillage at similar bulk densities at all levels of water saturation within the range of overlap in bulk densities between the two tillage treatments. The analysis of variance comparing tillage treatments using initial bulk density and initial water saturation as covariates indicated no difference between compression properties of the tillage systems. No-tillage had an average value of precompression pressure of 56.2 and a compression index of 0.247 as compared to 55.9 and 0.276, respectively, for CvT treatment. When compression data are not normalized for bulk density, the difference in compression properties between tillage type at the same water saturation is accounted for by the difference in the state of compaction or its initial bulk density. Therefore, the major effect of tillage on the consolidation behavior of this soil is accounted for by changes in bulk density. Differences in other soil physical and chemical properties induced by tillage over four years on this soil (Reinert and Pierce, 1990), such as changes in aggregate stability or soil organic matter, appear to have negligible effects on the compression curves. The strong relationship between the compressive behavior of soils to the previous stress history was also reported by Culley and Larson (1987) for a clay loam-textured surface soil. They reported a negative correlation between initial

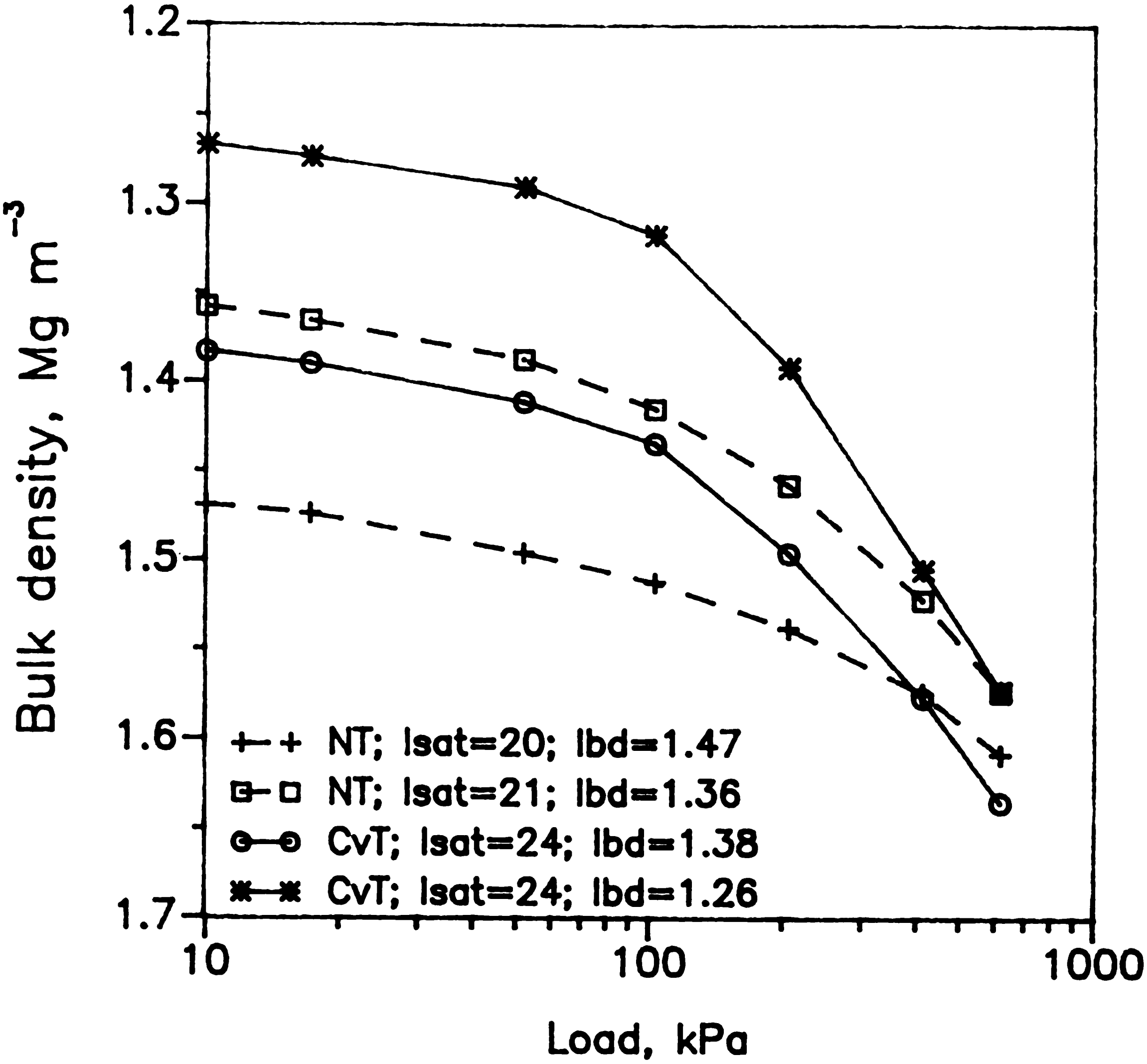

Figure 4.2: Compression curves of intact soil cores of a Kalamazoo loam under no-tillage and conventional tillage at different initial bulk densities for similar initial water saturations.

Table 4.3. Precompression pressure and compression index for different classes of initial water saturation and initial bulk density.

Class of	Precompression pressure (kPa)					Compression index				
IWS	<1.3	1.3-1.4	1.4-1.5	>1.5(1)	LSD	<1.3	1.3-1.4	1.4-1.5	>1.5	LSD
< 20	103Ab	174Aa	155Aa	----	45	0.42a	0.29Bb	0.15Ac	---	0.09
20-30	67ABb	134Ba	155Aa	----	26	0.39b	0.28Bab	0.17ABa	---	0.13
30-40	21Cb	61Cb	124ABa	151Aa	57	0.35c	0.32Bbc	0.26Cb	0.19AB	0.07
40-50	23BCab	22Db	94BCa	72Bab	71	0.32a	0.30Baa	0.27Ca	0.28B	0.10
50-60	14Ca	17Da	48CDa	----	55	0.31a	0.25Ba	0.26Ca	----	0.09
60-70	----	----	20Db	70Ba	23	---	---	0.20Ba	0.19AB	0.04
> 70	----	10Db	22Da	26Ca	11	---	0.18Ab	0.17ABab	0.16A	0.03
LSD	48	21	46	43		0.15	0.07	0.04	0.10	

(1) classes of initial bulk density, Mg m^{-3}
IWS - Initial water saturation, %
Capital letters compare means within a column and lower case letters compare means within a row according to LSDs at $p = 0.05$.

bulk density and the compression index averaged over their range of initial conditions of matric potential. The Minnesota soil has about 35 % clay and is highly aggregated while the Michigan soil has about 14 % clay and is not highly aggregated (Reinert and Pierce, 1990). Thus, lack of tillage might be expected to change more in the Minnesota soil.

Since tillage treatments had no significant effect on compression properties at the same initial bulk densities, the data for tillage are combined for the remainder of this discussion.

The effects of initial bulk density and initial water saturation on strain for different load applications are presented in Figure 4.3. For each load application, soil strain decreased as the bulk density increased for all water saturations. At low water saturations (less than 50 %), the relationship between strain and initial bulk density is curvilinear (statistically significant, although nearly linear for values > 40 % saturation) while at higher water saturations (greater than 50%), the relationship is linear. For the same load application for a given bulk density, the strain increased to a maximum and decreased as the water saturation increased (Figure 4.4), although for IBD of 1.29 Mg m^{-3}, the single observation at initial water saturation of 73% greatly influenced the shape of the curve. Soehne (1958) reported similar results indicating an optimum moisture content at which maximum density occurs for a given energy applied. For bulk densities around 1.3 Mg m^{-3}, the initial water saturation for maximum strain was approximately 40-50% as opposed to 60 % when bulk density was around 1.4 Mg m^{-3}, indicating greater initial water saturation for maximum strain as the bulk density increases (Figure 4.4). However, at initial water saturations greater than 60 % the effect of soil bulk density on strain diminishes and approaches zero at initial water saturations greater than 75% (Figure 4.3). The results in Figures 4.3 and 4.4 illustrate the interaction of

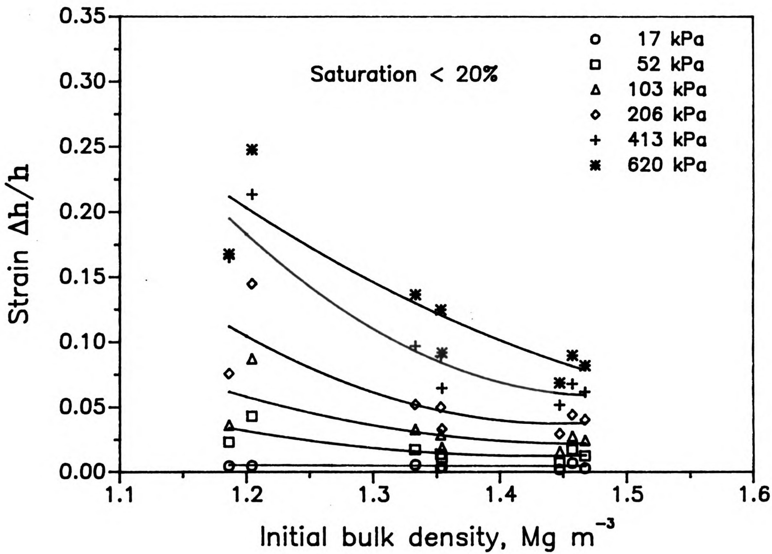

Figure 4.3.1: Soil strain as function of initial bulk density for intact soil cores of a Kalamazoo loam under different loads for initial water saturation <20%.

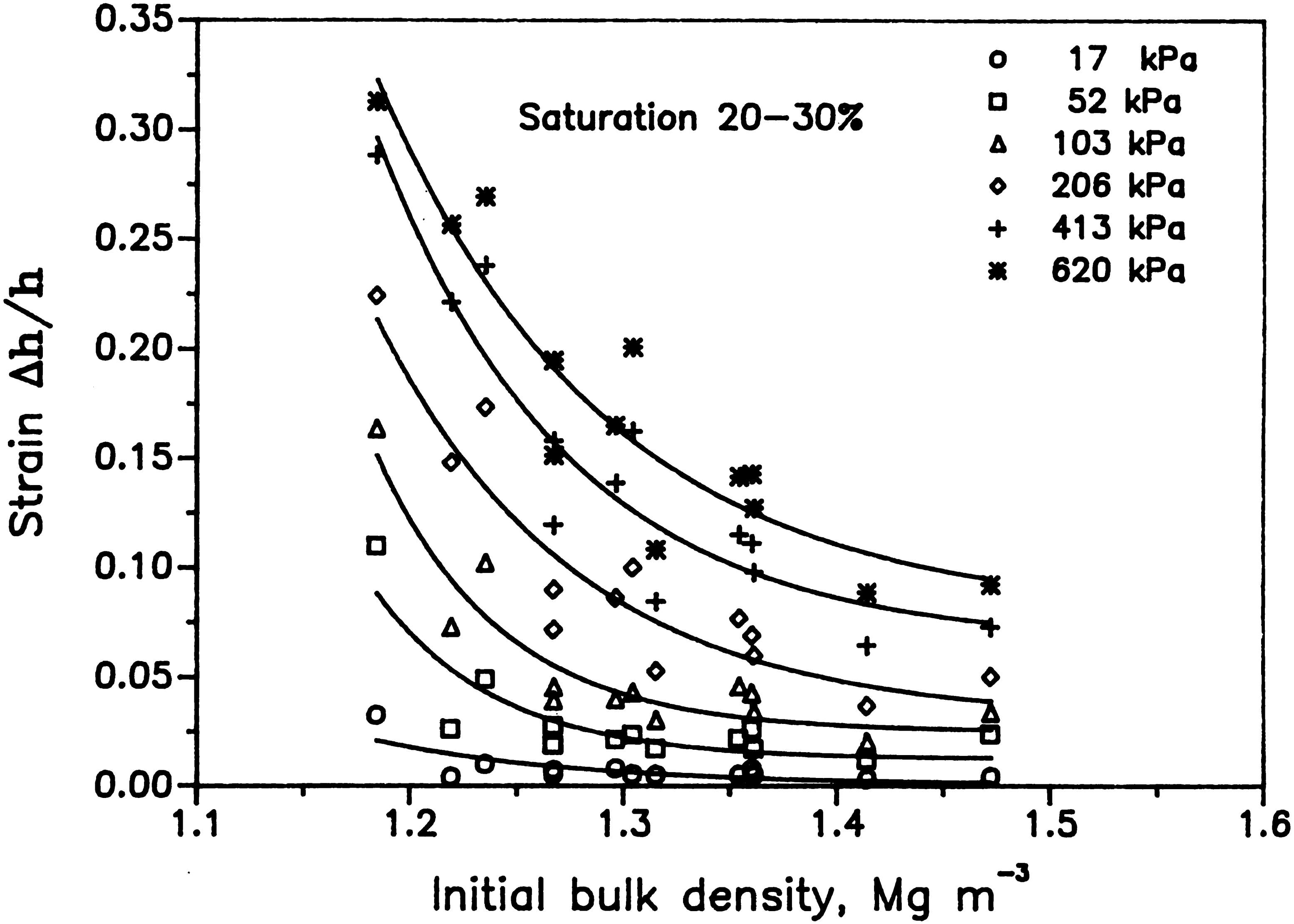

Figure 4.3.2: Soil strain as function of initial bulk density for intact soil cores of a Kalamazoo loam under different loads for initial water saturation 20-30 %.

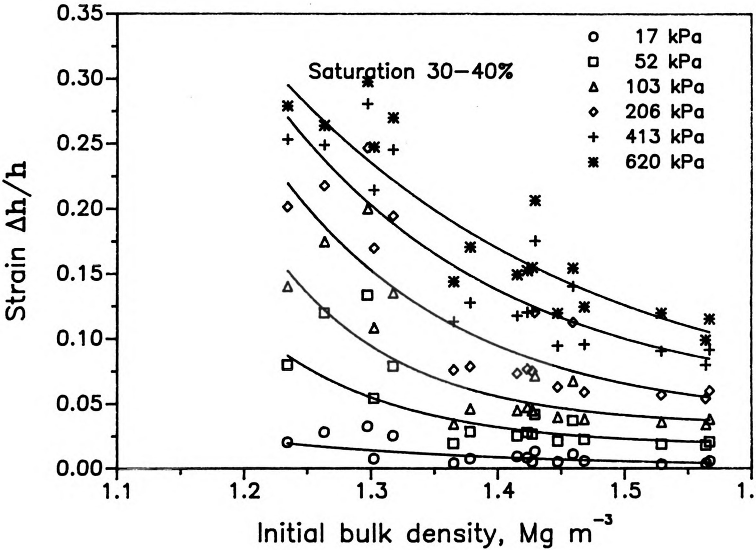

Figure 4.3.3: Soil strain as function of initial bulk density for intact soil cores of a Kalamazoo loam under different loads for initial water saturation 30-40 %.

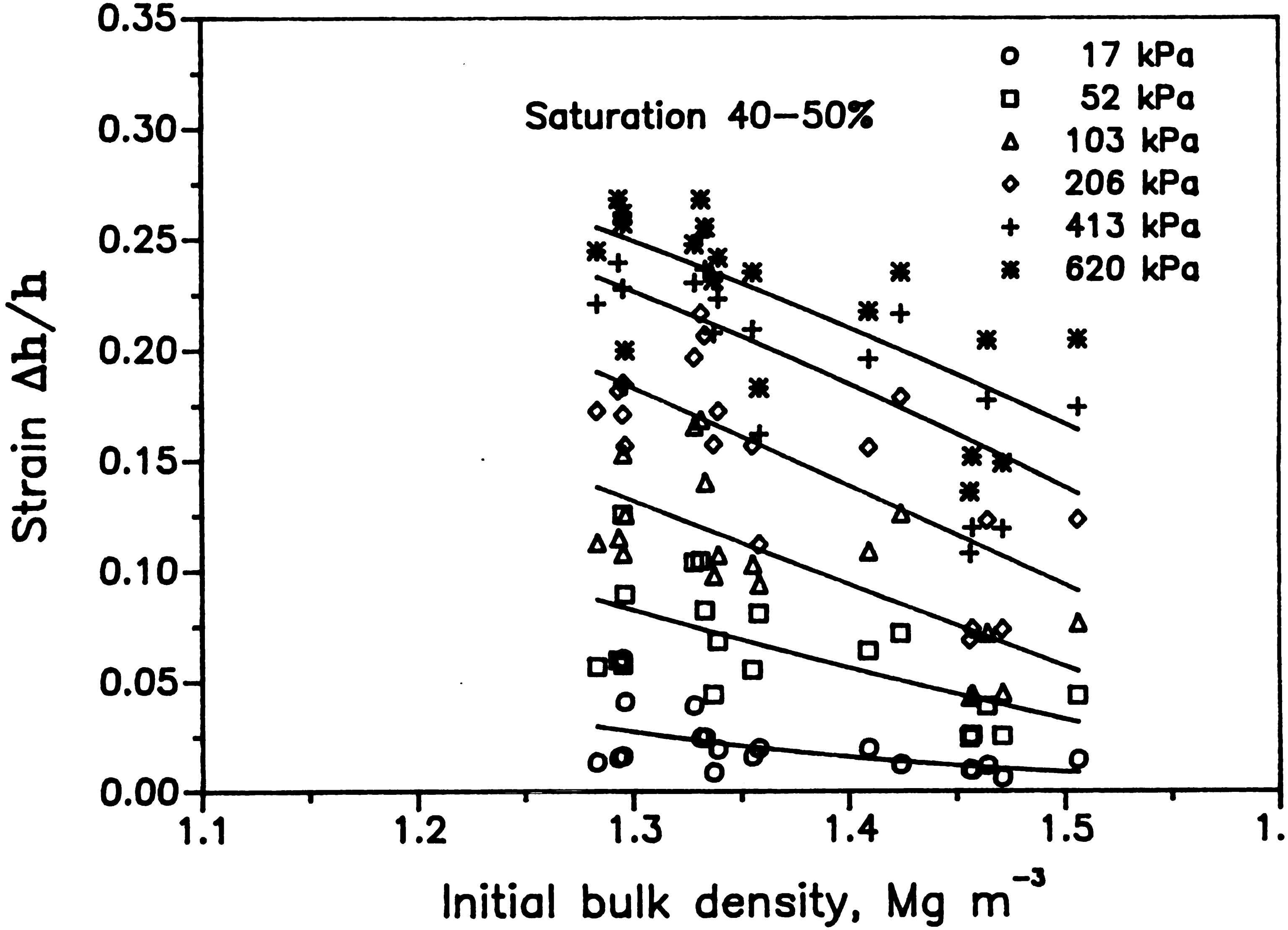

Figure 4.3.4: Soil strain as function of initial bulk density for intact soil cores of a Kalamazoo loam under different loads for initial water saturation 40-50 %.

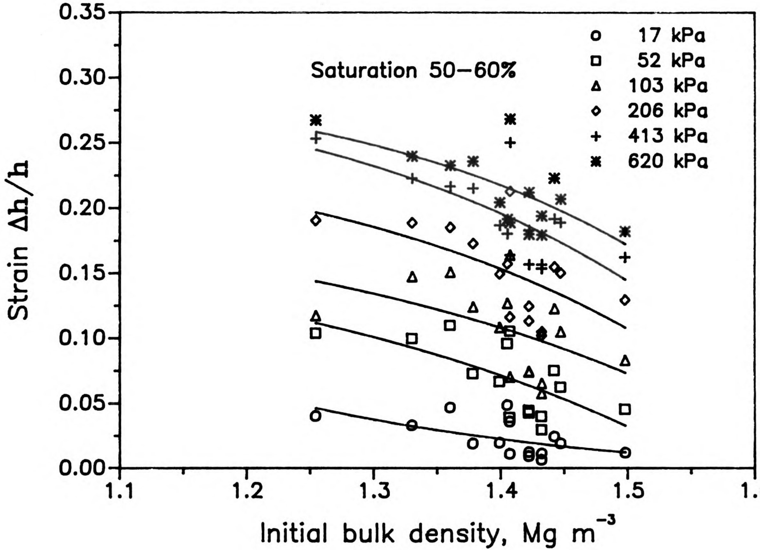

Figure 4.3.5: Soil strain as function of initial bulk density for intact soil cores of a Kalamazoo loam under different loads for initial water saturation 50-60 %.

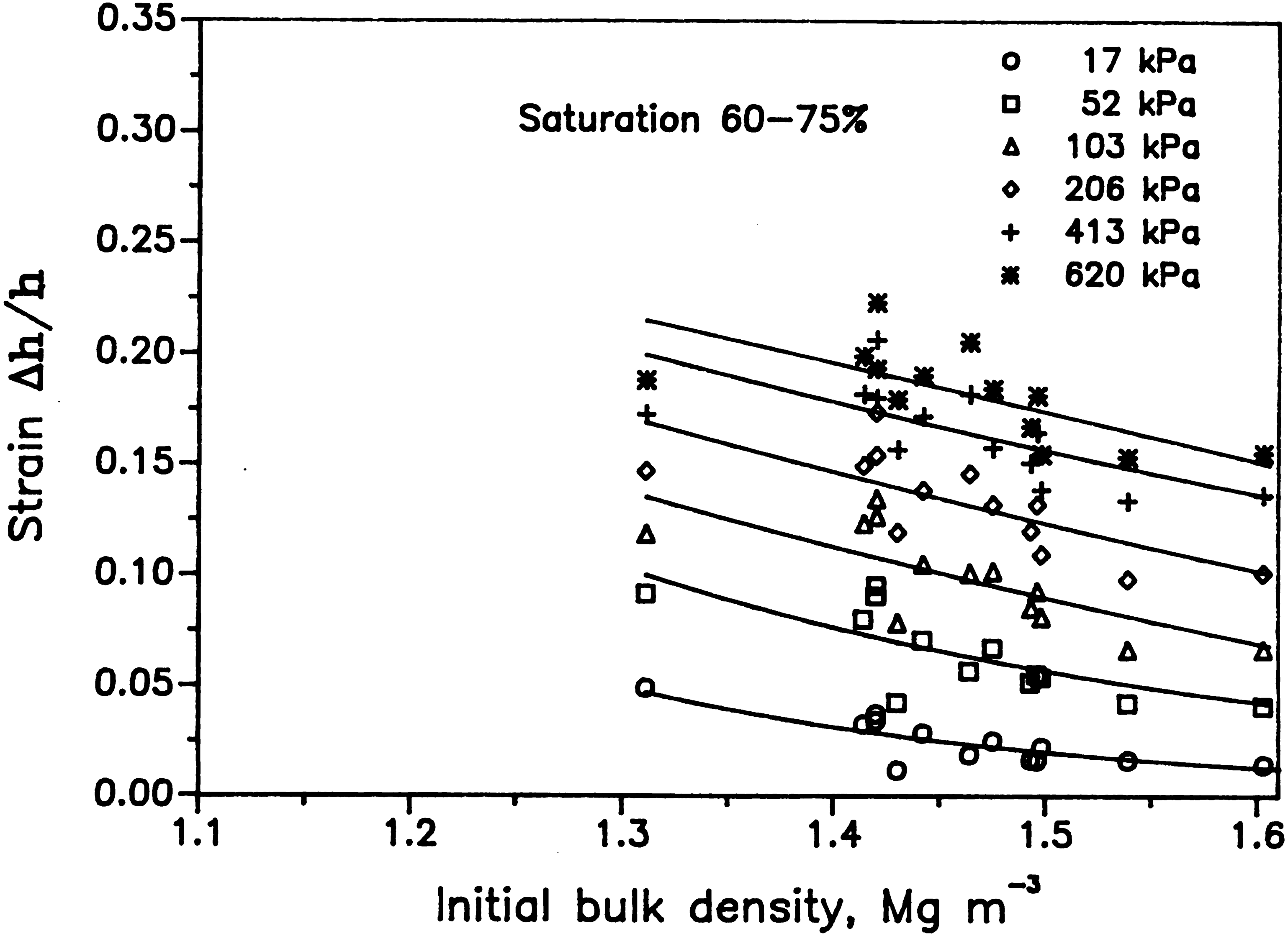

Figure 4.3.6: Soil strain as function of initial bulk density for intact soil cores of a Kalamazoo loam under different loads for initial water saturation 60-75 %.

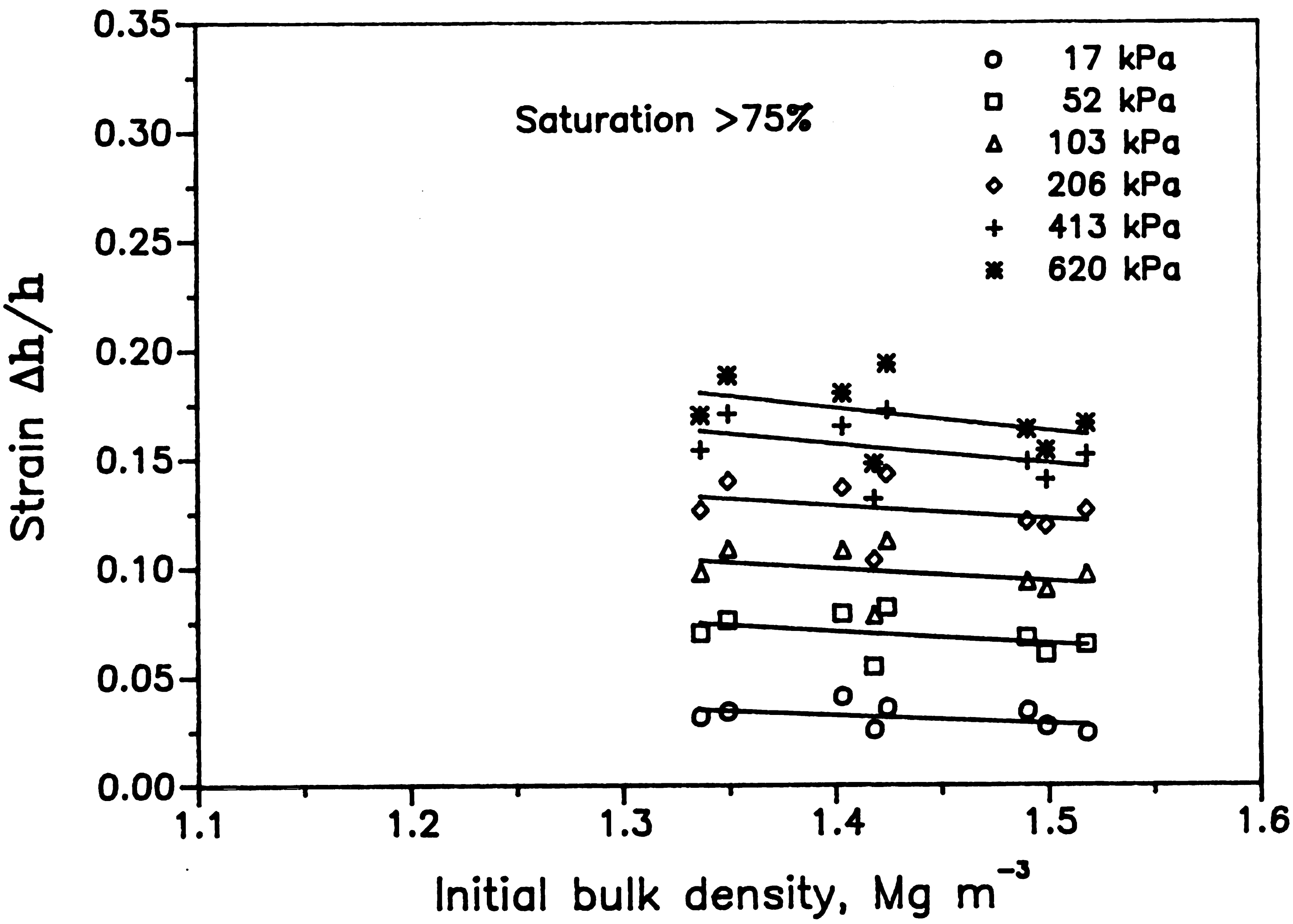

Figure 4.3.7: Soil strain as function of initial bulk density for intact soil cores of a Kalamazoo loam under different loads for initial water saturation > 75 %.

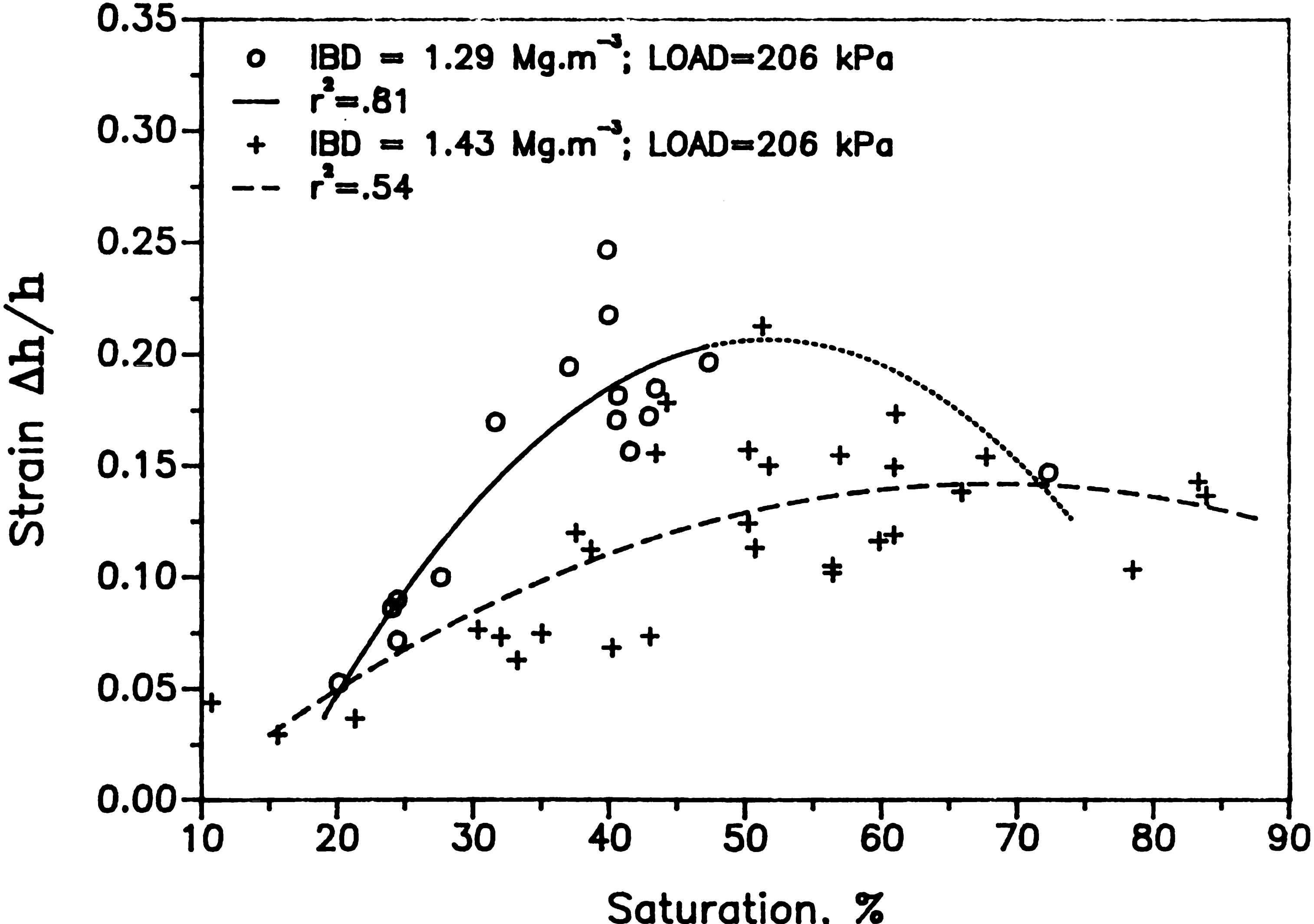

Figure 4.4: Soil strain as function of initial water saturation for intact soil cores of a Kalamazoo loam for a load of 206 kPa at initial bulk densities of 1.29 and 1.43 Mg m^{-3}

effects of initial conditions when considering compressibility of unsaturated agricultural soils. These results also explain the greater resistance to compression, at the same water saturation, of soils under no-tillage since the bulk density is generally higher than tilled soil.

The relationship between initial water saturation and applied load for a narrow range of initial bulk densities (1.35-1.38 Mg m^{-3}) is illustrated in Figure 4.5. As water saturation increases, the compression curves are displaced to the left. The curves are nearly parallel for initial water saturations < 60 % but change slope for the > 60% initial water saturation. However, the slope of the virgin compression portion of the curve (compression index) varies by bulk density and initial water saturation (Table 4.3).

The effect of water saturation on precompression pressure was greater than the effect of bulk density (Table 4.3). The data indicate a linear relationship between precompression pressures with both bulk density and water saturation, respectively. An exception was observed for the relationship between precompression pressure and bulk density for initial water saturations lower than 20%. This may be related to our inability to measure high precompression pressures associated with a dry soil with high bulk density. Equations relating precompression pressure, void ratio at precompression, and recompression slope with initial conditions of bulk density and water saturation are presented in Table 4.4. The maximum initial water saturation, MAXIWS, to predict precompression using the equation in Table 4 was found to be a function of initial bulk density according to Equation [1]:

$$\text{MAXIWS} = -98 + 120 * \text{IBD} \qquad [1]$$

For initial water saturations greater than MAXIWS, the precompression pressure is predicted to be about 10 kPa. A similar relationship between both the matric potential and the state of compaction and precompression pressure was

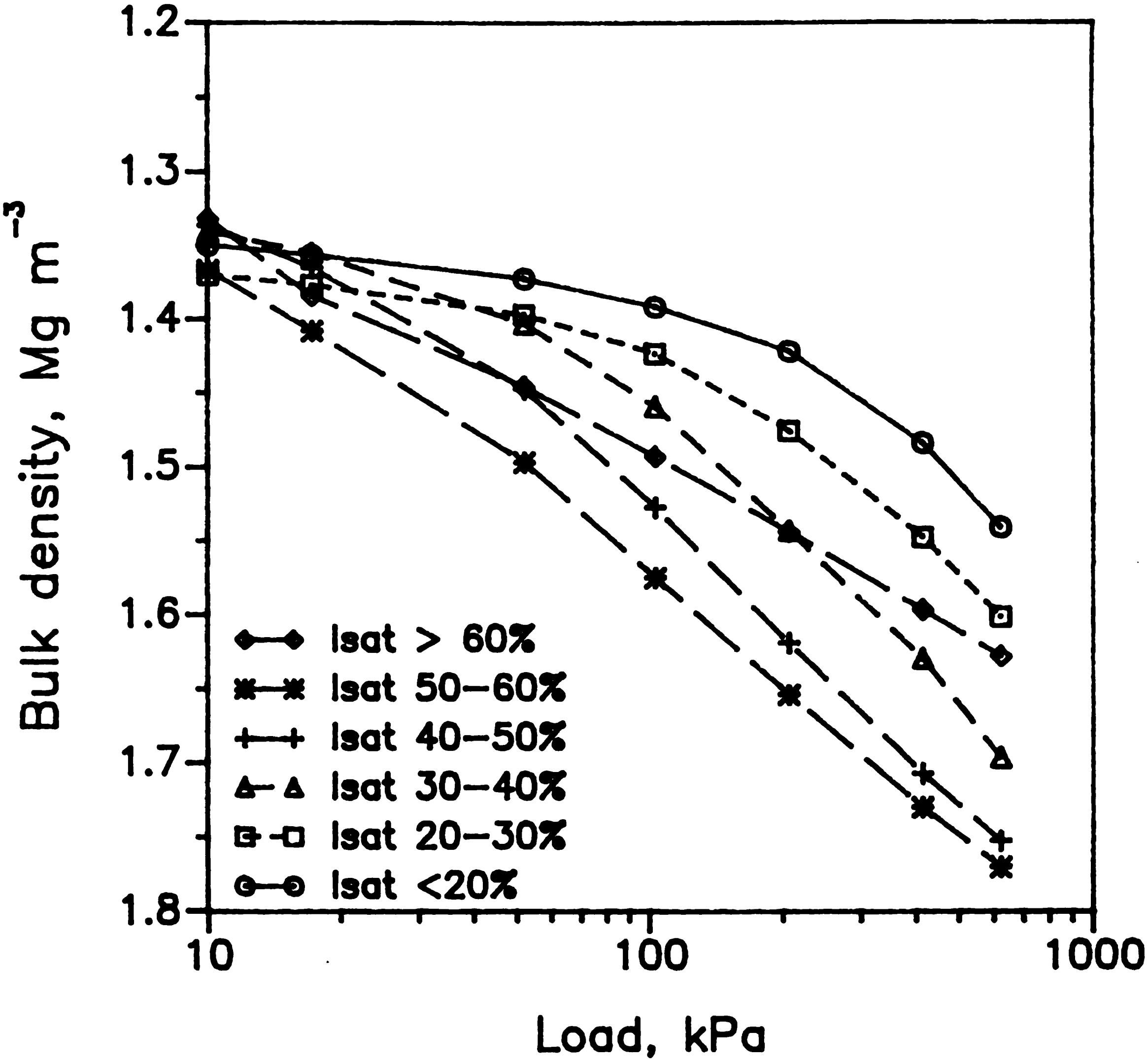

Figure 4.5: Compression curves of intact soil cores of a Kalamazoo loam for six initial water saturations for a narrow range of initial bulk densities (1.34-1.37 Mg m^{-3}).

Table 4.4. Precompression pressure, void ratio at precompression (VRP), and recompression slope (RS) as a function of initial bulk density (IBD) and initial water saturation (IWS).

Parameter	Multiple Linear Regression Equation	R^2	N
Precompression	-263 - 2.66 * IWS + 322 * IBD	0.68	94
VRP	2.68 + 0.0007 * IWS - 1.36 * IBD	0.90	94
RS	-0.19 - 0.0004 * IWS + 0.110 * IBD	0.30	94

IBD is in units of Mg m^{-3} and IWS as %.

observed by Culley and Larson (1987).

The compression indices indicate a significant effect of initial conditions on compression tests (Table 4.3). Compression indices for this soil were more strongly related to initial bulk densities when water saturations were lower than 45 % (Figure 4.6a), and more strongly related to initial water saturation when greater than 45% (Figure 4.6b).. This implies that at lower water saturations, soil compression is limited because particle movement is restricted by the lack of water which lubricates the particles allowing them to easily compact. At greater water saturations, compression is limited by the amount of air filled pore space which is compressible until complete water saturation. Harris (1971) pointed out that, in general, for partially saturated conditions, the higher the moisture content of soil, the more it is compacted by a given applied stress. After reaching the saturation point, changes in compaction wound result only by squeezing water out of the soil. Soils with bulk density lower than 1.4 Mg m^{-3} had much smaller differences in compression indices for all water saturation classes (4.3). Larson et al. (1980) showed that water content did not affect the compression indices for disturbed soils with initial bulk densities smaller than 1.3 Mg m^{-3}.

CONCLUSIONS

The compressibility of unsaturated loam-textured soil showed little difference for tilled or untilled management , but was strongly affected by initial state of compaction and water saturation which are affected by tillage. Initial water saturation had a greater impact on soil compression at higher initial water contents and bulk density a greater impact on compression at lower initial water saturations. The slope of the linear portion of the compression curves were not

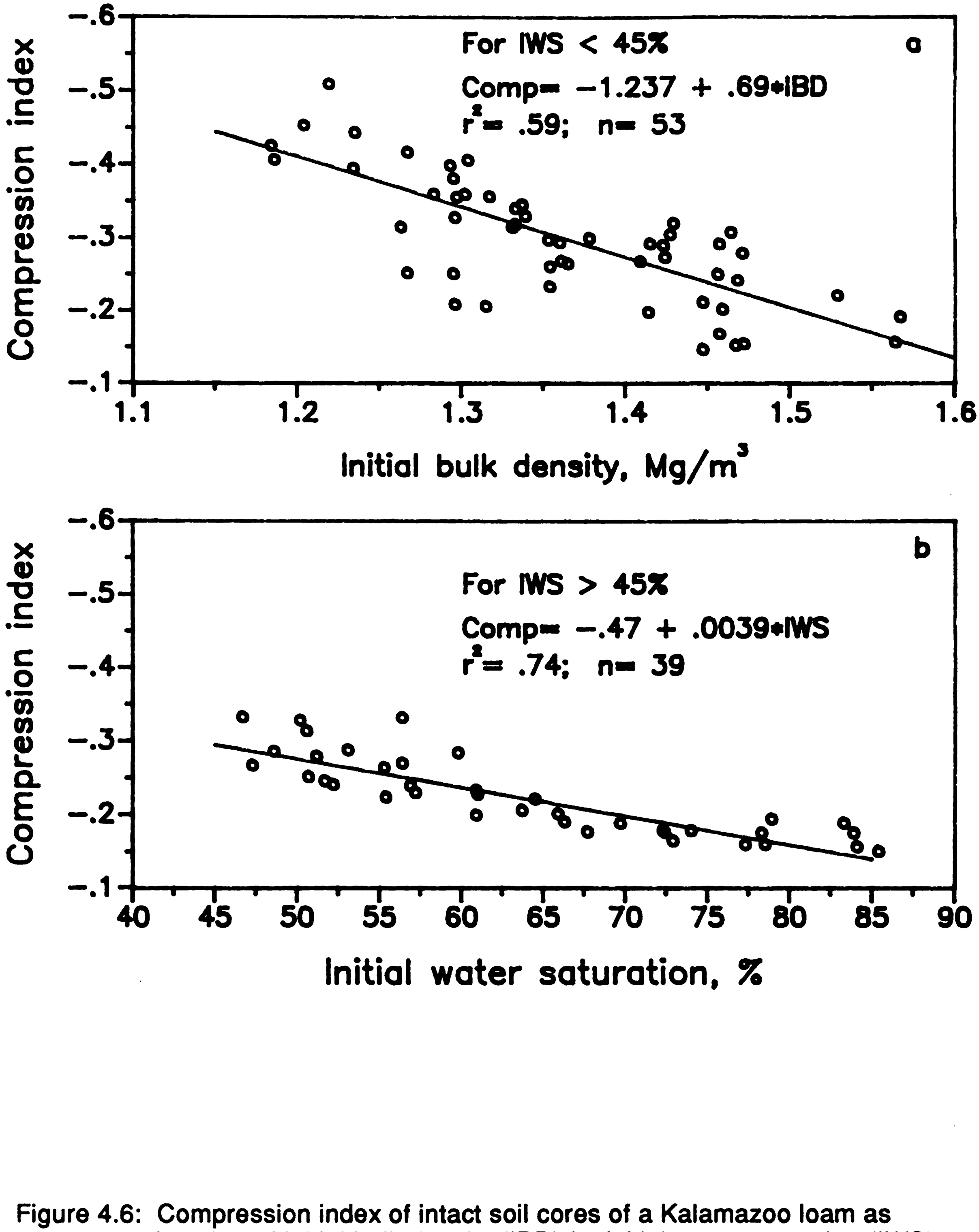

Figure 4.6: Compression index of intact soil cores of a Kalamazoo loam as function of initial bulk density (IBD) for initial water saturation (IWS) < 45 % (a) and as a function of IWS for IWS > 45 % (b).

parallel for different initial soil moisture conditions nor were they parallel for different initial bulk densities at similar moisture conditions. These data illustrate the strong effect of stress history on the compressibility of unsaturated soil undergoing virgin compression. These data also suggest the major effect of no-tillage on the compressive behavior of this soil four years after the cessation of tillage is predominantly in its effect of increasing bulk density even in untracked zones. This may account for observations that no-tillage soils are often more easily trafficked following rainy periods than tilled soils.

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GENERAL CONCLUSIONS

Soil physical properties demonstrated a well defined spatial dependence over the experimental site. It is suggested that agricultural experiments installed to investigate any property or variable affected by bulk density, porosity, and/or hydraulic conductivity consider spatial distance.

The cyclic pattern in temporal variation observed in soil physical properties related to the form and stability of soil structure for conventional tillage, no-tillage, and never tilled management were well defined. The structural stability cycle were strongly related with wetting and drying cycle in a yearly scale.

Statistical significance of differences between tillages were time dependent, an important consideration in the interpretation of soil measurements in tillage experiments. The long trend did not indicate that measured parameters had reached equilibrium over the four year duration of this study.

The strong effect of stress history on the compressibility of unsaturated soil undergoing virgin compression suggests that effect of no-tillage on the compressive behavior of soils in the first few years after cessation of tillage is predominantly due to the effect of increasing bulk density.

APPENDIX A.

Definition of terms

Compression of soil: change of soil volume caused when soils are stressed. Similar to soil compaction.

Compressibility of soil: susceptibility to compression.

Consolidation curve: relationship between log of applied load and void ratio for saturated soil (W. A. Larson personal communication).

Compression curve: relationship between log of applied load and void ratio for unsaturated soil (W. A. Larson personal communication).