

Effect of tillage on the spatial variability of soil water properties

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Diiwu, J.Y., Rudra, R.P., Dickinson, W.T. and Wall, G.J. 1998. **Effect of tillage on the spatial variability of soil water properties.** *Can. Agric. Eng.* 40:001-008. Soil samples, taken from the A and B horizons of no tillage and conventional tillage treatment sites were analyzed for texture, organic carbon content, bulk density, effective porosity, and saturated hydraulic conductivity. The statistical parameters of mean, variance, coefficient of variation, and coefficient of skewness, as well as scaling factors, were determined for each of the variables. Autocorrelation structures were also investigated. The lognormal distribution gave the best-fit for the scaling factors. The spatial variability of physical and hydraulic properties in each horizon was quite high. The variability of the properties in the A horizon of the no tillage treatment was higher than that in the A horizon of the conventional tillage treatment. Differences in variability of the properties in the B horizon were not as large as in the A horizon, although all differences were considerable. Saturated hydraulic conductivity was the most spatially variable soil property and its variability was affected most by tillage. The spatial variability of soil texture was not affected by tillage. **Keywords:** hydraulic properties, spatial variability, tillage, scaling factors, fractile diagram.

Des analyses de texture, de teneur en carbone organique, de densité apparente, de porosité et de conductivité hydraulique saturée ont été faites sur des échantillons de sol prélevés des horizons A et B de sites expérimentaux non labourés ou labourés de manière conventionnelle. La moyenne, la variance, le coefficient de variation et le coefficient d'asymétrie, ainsi que des coefficients d'échelle, ont été déterminés pour chacune des variables. Les structures d'autocorrélation ont également été examinées. Les coefficients d'échelle avaient une distribution log normale. La variabilité spatiale des propriétés physiques et hydrauliques de chaque horizon était très grande. La variabilité spatiale des propriétés de l'horizon A du site non labouré était plus grande que celle de l'horizon A labouré conventionnellement. Les différences dans les propriétés de l'horizon B n'étaient pas aussi grandes que celles de l'horizon A, bien que toutes les différences étaient considérables. La conductivité hydraulique saturée était la propriété qui présentait le plus de variabilité spatiale, et cette variabilité était surtout influencée par le type de labour. La variabilité spatiale de la texture n'a pas été influencée par le type de labour. **Mots-clés:** propriétés hydrauliques, variabilité spatiale, labour, coefficients d'échelle.

INTRODUCTION

The spatial variability of soil physical and hydraulic properties has been widely recognized and investigated for many years. The recognition of the need for optimum sampling to fairly represent the field-scale properties, as well as the need to make the best use of land and water resources, has led to a surge of interest in field-scale variability. Over the years, studies have been directed at the nature and extent of variability, factors contributing to spatial variability (such as the presence of

particles of various dimensions, aggregates, peds, and biopores), and consequences of variability for water and solute transport (Babalola 1978; Biggar and Nielsen 1976; Jury et al. 1987a; Nielsen et al. 1973; Peck et al. 1977; Warrick and Nielsen 1980; Warrick et al. 1977). Spatial variability of soil properties directly or indirectly influences components of the hydrologic cycle, as well as other processes which affect erosion and water quality.

Various attempts have been made to incorporate spatial variability in field-scale transport studies. These include stochastic transport models, in which the soil is considered as a realization of a random field (Bresler and Dagan 1979; Russo 1989; Simmons 1982) and stochastic stream tube modelling, in which the entire field is considered to consist of parallel non-interacting columns in each of which soil properties are assumed uniform along the depth of the column (Bresler and Dagan 1979). It has also been proposed that field-scale variability be quantified in terms of the first and second statistical moments (Bresler et al. 1984). A scaling approach, based on the concept of similar media, also has been used (Miller and Miller 1956; Peck 1983). The strength of the scaling approach is that it represents the spatial variability by a single physically-based parameter.

In a detailed study of spatial variability of hydraulic conductivity and soil water characteristics in a 150-ha field, Nielsen et al. (1973) found that these soil properties varied widely in the field and the lognormal distribution gave the best-fit probability distribution for hydraulic conductivity. For other soil properties, the normal distribution gave the best-fit. Russo and Bresler (1982) analyzed one-dimensional piston flow as well as transient flow and compared the solutions by using a multivariate distribution of soil hydraulic properties with those of stochastic-conceptual flow problems based on the scaling approach. While the two approaches gave the same results for piston flow, those for transient flow did not agree as well.

Some studies have been undertaken on the effect of structural irregularities such as aggregates, peds, and macropores, as well as the effect of chemicals on the spatial variability of hydraulic properties of soil (Ahuja et al. 1984; Bresler et al. 1984). Efforts also have been made to study the effect of spatial variability on the overall water budget modelling at a watershed scale (Peck et al. 1977). A simulation model, based on a scaling approach, was used to explore the effect of spatial variability of hydraulic properties on the water budget modelling of a forested watershed. Sharma et al. (1980) carried out a similar study on a grassland watershed to

investigate the effect of variability on field-measured infiltration. Luxmoore and Sharma (1980) used a computer model to simulate and compare drainage, evaporation, and runoff processes in six watersheds by taking into account the effects of spatial variability of soil properties. Results from these and other studies reported in the literature have been mixed. This paper explores the application of a time series approach and scaling theory to investigate the effect of tillage on the spatial variability of some soil water properties.

THEORY

The soil properties considered in this study were bulk density, effective porosity, percent sand, silt, clay, and organic matter, and saturated hydraulic conductivity. These soil properties were measured at a finite number of points in a test field; therefore, their values at other points in the field are subject to uncertainty. Due to this uncertainty, each soil property was considered to be a random variable for which the measured values were realizations. Each random variable was assumed to be stationary in space, so that its value at every point in the field was governed by the same probability law (Haan 1977). Each random variable was therefore a regional variable, characterized by a probability distribution which was identified by the parameters of mean, standard deviation, skewness, and coefficient of variation (Jury et al. 1991).

Salas et al. (1980) suggested that the lag-k autocorrelation function (r_k) can be used as a dimensionless measure of linear dependence in a time series (x_i) where $i = 1, 2, 3, \dots$ and $k = 1, 2, 3, \dots$. The r_k were defined by using the expression:

$$r_k = \frac{\sum (x_i - \mu)(x_{i+k} - \mu)}{\sum (x_i - \mu)^2} \quad (1)$$

where μ denotes the mean of the time series. They suggested that the tendency for r_k to gradually, or in some consistent manner, approach zero for increasing lag-k indicates linear dependence, while a fluctuating r_k indicates independence in the series.

Using the close analogy between time and one-dimensional space, r_k was adopted in this study as a measure of variability in the spatial series. A trend in r_k would therefore indicate the existence or non-existence of a spatial dependence structure, which in turn would be an indication of non-variability or variability in the spatial series.

The theory of microscopic geometric similitude, as proposed by Miller and Miller (1956), is the basis for the scaling approach. Here the concept of similar media is invoked to define scaling factors for the hydraulic properties being analyzed. Ahuja et al. (1984) derived an expression for scaling factors (α_i) for hydraulic conductivity using the equation:

$$\alpha_i = \frac{N(K_{si})^{1/2}}{\sum (K_{si})^{1/2}} \quad (2)$$

where:

- i = sampling location,
- N = total number of sampling locations, and
- K_{si} = saturated hydraulic conductivity measured at location i .

A similar expression for scaling factors for effective porosity also was derived by Ahuja et al. (1984) using the expression:

$$\alpha_{ei} = \frac{N(\phi_{ei})^{n/2}}{\sum (\phi_{ei})^{n/2}} \quad (3)$$

where;

- ϕ_{ei} = effective porosity at location i , and
- n = an empirical parameter.

Ahuja et al. (1984) suggested values of 4 or 5 for n . They showed that α_i and α_{ei} were statistically the same; so that once the distribution of either set of scaling factors had been derived, it could be used to calculate the distribution of soil hydraulic properties. This possibility also has been demonstrated by Jury et al. (1987b) in a scaling analysis that included spatial correlation structure in the field. Saturated hydraulic conductivity and effective porosity at any location i were expressed as:

$$K_{si} = \alpha_i^2 K_s^* \quad (4)$$

$$\phi_{ei} = (\alpha_{ei})^{2/n} \phi_e^* \quad (5)$$

where K_s^* and ϕ_e^* are average values of saturated hydraulic conductivity and effective porosity, respectively, over the entire field and may be computed using:

$$K_s^* = \frac{1}{N^2} \left[\sum (K_{si})^{1/2} \right]^2 \quad (6)$$

$$\phi_e^* = \frac{1}{N^{2/n}} \left[\sum (\phi_{ei})^{n/2} \right]^{2/n} \quad (7)$$

These are reference-state values of saturated hydraulic conductivity and effective porosity.

METHODOLOGY

Soil samples were collected from a field located on a farm in the Kettle Creek Watershed in Southwestern Ontario. The soils in the watershed are of the Huron series (Hagerty and Hilborn 1986). In 1989 the field was divided into two parts, one of which had been under no tillage treatment and the other under conventional tillage treatment for management purposes. The part under conventional tillage treatment had been subjected to disk harrow in the spring and mouldboard plough in the fall, while the one under no tillage treatment had been left untilled. Cropping over the study period included rotating wheat (*Triticum aestivum* L), soybeans (*Glycine max* L), and corn (*Zea mays* L). The thickness of the A horizon varies between 250 and 300 mm and the portion of the B horizon considered for this study varies between 250 and 300 mm in thickness. The textural classification of soil in the field is essentially silt loam (Diiwu et al. 1994).

Table I: Basic statistics of soil properties in the A and B horizons of the field.

Horizon	Zero Tillage		Conventional Tillage	
	A	B	A	B
Sand (%)	24.3 - 31.3 (27.92) [0.072] {-0.2}	12.8 - 30.2 (24.54) [0.329] {-0.5}	30.1 - 36.5 (32.26) [0.075] {0.98}	27.5 - 34.3 (30.23) [0.083] {0.61}
Silt (%)	51.8 - 55.5 (54.05) [0.023] {-0.1}	42.3 - 59.4 (52.54) [0.092] {-0.7}	49.9 - 55.6 (53.92) [0.042] {-1.0}	53.9 - 59.8 (57.45) [0.037] {-0.6}
Clay (%)	15.5 - 22.1 (18.05) [0.117] {0.88}	10.4 - 37.1 (22.92) [0.425] {0.51}	13.4 - 14.9 (13.85) [0.040] {1.34}	10.0 - 15.1 (12.32) [0.152] {0.37}
Organic Matter (%)	3.5 - 4.3 (3.66) [0.082] {0.78}	0.7 - 1.2 (0.94) [0.191] {-0.2}	2.3 - 3.5 (2.98) [0.140] {0.17}	0.9 - 1.4 (1.1) [0.208] {0.43}
Bulk Density (Mg/m ³)	1.25 - 1.45 (1.39) [0.057] {-0.1}	1.45 - 1.65 (1.60) [0.011] {-0.7}	1.25 - 1.45 (1.37) [0.070] {-0.6}	1.28 - 1.63 (1.61) [0.041]
Effective Porosity (m ³ /m ³)	0.163 - 0.327 (0.32) [0.063] {-0.2}	0.133 - 0.291 (0.28) [0.062] {-0.1}	0.141 - 0.274 (0.26) [0.075] {0.21}	0.162 - 0.298 (0.28) [0.017] {-0.4}
Ksat (mm/h)	9.29 - 508 (97.45) [1.403] {2.34}	12.1 - 370 (91.34) [1.198] {1.67}	10.1 - 65.3 (33.41) [0.684] {0.92}	7.31 - 142 (58.39) [0.850] {1.71}

* - * : Range of Values

(): Mean Value

[] : Coefficient of Variation

{ } : Coefficient of Skewness

Ksat: Saturated hydraulic conductivity

Three sets of soil cores and one set of freehand samples were collected from several locations in each of the A and B horizons at the sites under no tillage and conventional tillage treatments. In the A horizon, soil samples were collected at the soil surface and in the B horizon they were collected at a depth of about 400 mm from the soil surface. For the A horizon, two sets of core samples were obtained by carefully driving a steel cylinder, 48 mm in diameter and 25 mm in depth, into the soil at each of the four sides of each of 12 rainfall simulation plots. For each tillage treatment, there were two rows with three rainfall simulation plots in each row and any two adjacent plots were about 50 m apart. Each rainfall simulation plot measured 1 m x 1 m at the soil surface. The core sample, still in the steel

cylinder, was immediately placed in a previously weighed plastic bag which was then tightly fastened to prevent loss of moisture from the bag. The third set of core samples was obtained by a similar procedure using steel cylinders 56 mm in depth and 48 mm diameter. The set of freehand samples also was collected from each of the four sides of each of the 12 rainfall simulation plots. Three sets of core samples were similarly obtained from the B horizon after removing the A horizon. A set of free-hand samples also was collected from the four sides of each of the 12 rainfall simulation plots after the excavation, approximately from the same locations where the core samples were collected. The free-hand samples were taken by simply grabbing about 100 g of soil and quickly placing it in a sampling bag which was then securely fastened. For each of the three sets of core samples and the freehand samples, 24 samples were collected in each of the A and B horizons in each of the tilled and no-tilled areas of the field.

One set of the core samples was used to determine bulk density at each sampling location using the gravimetric method (Blake 1965). Another set was used to determine saturated hydraulic conductivity by the constant head permeameter method (Klute 1965). The third set of core samples was used to determine soil water characteristics at specific matric potentials by the pressure plate method (Hillel 1980). The effective porosity, defined as that portion of porosity that mainly contributes to the flow of water when the soil is saturated with water, was determined by subtracting soil water content at field capacity (at a matric potential of 3330 mm) from the soil water content at saturation (Ahuja et al. 1984; Brooks and Corey 1964). The freehand samples were used to determine percent sand, silt, clay, and organic matter at each sampling location by means of sieving and sedimentation (Day 1965).

The statistical parameters of mean, standard deviation, skewness, and coefficient of variation were computed for each of the soil properties, each being considered to be a random variable (Wilkinson et al. 1992). The ranges and coefficients of variation were used as preliminary indications of spatial variability for each random variable. The Spearman correlation coefficients between saturated hydraulic conductivity and each of bulk density, effective porosity, and percent sand, silt, clay, and organic matter were obtained separately for the A and B horizons for no tillage and conventional tillage treatments.

The expression for autocorrelation suggested by Salas et al. (1980) and given in Eq. 1 was adopted for the analysis of the spatial variability of each random variable in the A and B horizons for no tillage and conventional tillage treatments. The shapes of the resulting correlograms were used to explain trends in spatial variability. Probability plots were used to determine the best-fit theoretical distributions for the data. The normal, lognormal, and gamma distributions, most commonly used for

Table II: Correlation coefficients of saturated hydraulic conductivity with bulk density, effective porosity, percent sand, silt, clay, and organic matter.

Horizon	Zero Tillage		Conventional	
	A	B	A	B
Bulk Density	-0.120	-0.132	-0.443	-0.44
Sand (%)	0.552	0.029	0.319	0.486
Silt (%)	0.500	-0.406	-0.015	-0.143
Clay (%)	-0.971	0.145	0.339	-0.371
OrgM (%)*	0.493	-0.224	-0.235	0.029
Effective Porosity	0.252	0.347	0.05	0.347

*OrgM: Organic Matter Content

soil water properties, were considered (Biggar and Nielsen 1976; Nielsen et al. 1973; Sharma et al. 1980). In most cases, the lognormal distribution gave the best-fit. This was confirmed by means of the chi-square and Kolmogorov-Smirnov tests of goodness-of-fit at the 90 and 95% confidence levels.

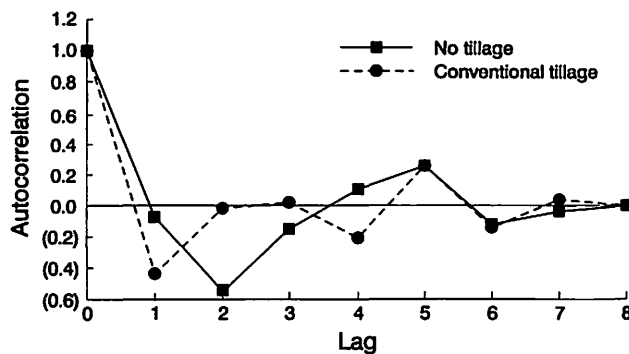


Fig. 1. Correlogram of bulk density in A horizon.

Following the approach suggested by Ahuja et al. (1984), the scaling factors for saturated hydraulic conductivity and effective porosity were computed using Eqs. 2 and 3. For Eq. 3, values of 4 and 5 were used for n and the distributions of the corresponding scaling factors were compared by means of their fractile diagrams. The fractile diagrams for $n=4$ and $n=5$ matched quite well for both the A and B horizons, except at the extremes. From these results, it appeared that the choice of $n=4$ or $n=5$ did not greatly affect the probability distribution of scaling factors of effective porosity for the test field. The results for the value $n=4$ were used for subsequent analyses.

Fractile diagrams of the scaling factors for saturated hydraulic conductivity and effective porosity were drawn and compared. For each horizon, the fractile diagram for no tillage treatment was compared with that for the conventional tillage

treatment. Although Ahuja et al. (1984) showed that the scaling factors computed from saturated hydraulic conductivity and those computed from effective porosity were statistically the same, both sets of scaling factors were used in this study.

RESULTS and DISCUSSION

Statistical parameters of soil properties

The statistical parameters of mean, range, skewness, and coefficient of variation computed for each of the soil properties are shown in Table I. These data reveal the central tendency and variability of soil properties in the study field by horizon and by tillage treatment. The mean sand, silt, and clay contents in both the A and B horizons for both tillage treatments indicate that soil in the study field can be classified as silt loam, according to the USDA soil classification system. The relative magnitudes of the ranges and coefficients of variation seem to indicate that the variability in particle size distribution was greater for the zero tillage treatment than for the conventional tillage treatment. However, an unpaired t-test showed that the differences in coefficients of variation were significant at the 5% significance level, while the differences in means were not. Hence, for particle size distribution, any noticeable differences from one location to another can be attributed to random variability in the field.

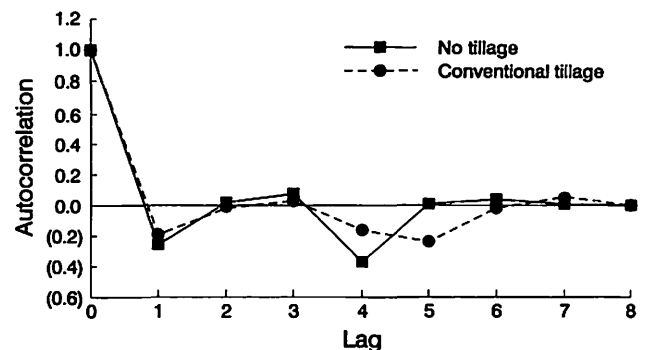


Fig. 2. Correlogram of bulk density in B horizon.

The results presented in Table I reveal that bulk density varied in the study field from 1250 to 1650 kg/m³. From these results, it would appear that the mean bulk density values differ from horizon to horizon, being higher for the B horizon but essentially the same from the no tillage treatment to the conventional tillage treatment. The variability in values, as indicated by the coefficients of variation, differed between horizons and tillage treatments, being greater in the A horizon than in the B horizon and being greater for the conventional tillage treatment than for the no tillage treatment. An unpaired t-test at the 5% significance level confirmed that the means were significantly different between horizons but not between tillage treatments. The timing of sampling may be one possible reason for similar mean bulk densities between tillage treatments. Sampling of soil in October gave sufficient time for the tilled soil to settle.

The organic matter content in the samples ranged between 0.7 and 4.3% and also varied between horizons and tillage

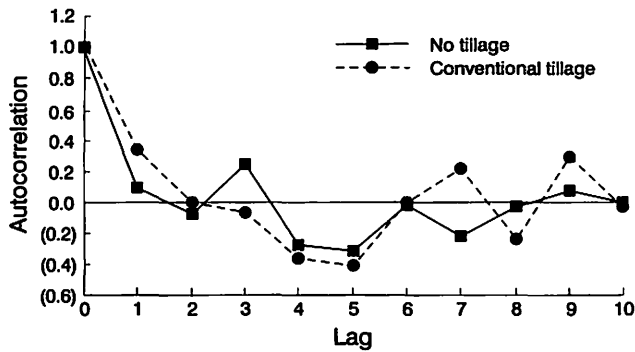


Fig. 3. Correlogram of percent organic matter in A horizon.

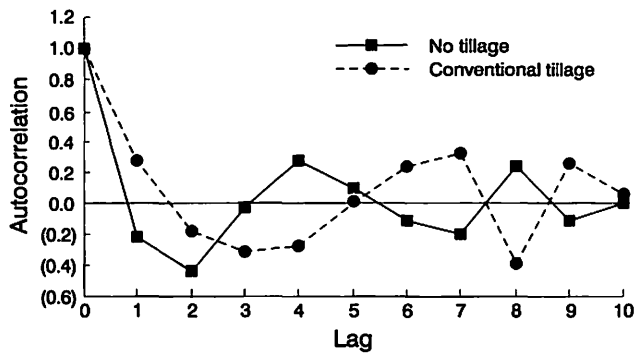


Fig. 4. Correlogram of percent organic matter in B horizon.

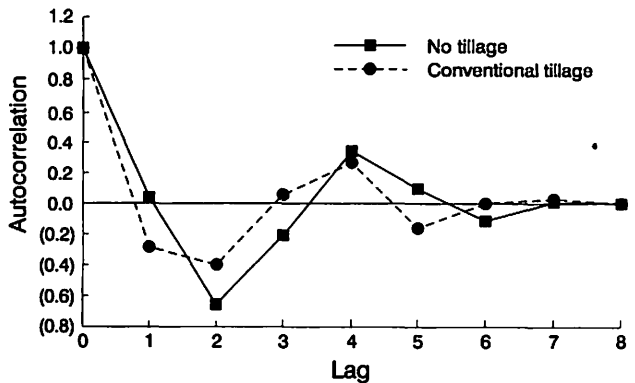


Fig. 5. Correlogram of effective porosity in A horizon.

treatments. The spatial variability of organic matter content was more for the conventional tillage treatment than for the no tillage treatment. Also, organic matter content was greater in the A horizon than in the B horizon. Statistical analyses revealed that the means and coefficients of variation for organic matter were significantly different at the 5% significance level between no tillage and conventional tillage treatments in the A horizon but not in the B horizon.

Effective porosity in the samples ranged from 0.133 to 0.327 m³/m³ and seems to be a function of horizon but not of

tillage treatment. An unpaired t-test indicated that the mean effective porosities in the A and B horizons for each tillage treatment are significantly different at the 5% significance level but not so between tillage treatments in each horizon. The variability in effective porosity is the same in the two horizons for the no tillage treatment but slightly different for the conventional tillage treatment where it was higher in the A horizon than in the B horizon.

The mean saturated hydraulic conductivity in the A and B horizons for the conventional tillage treatment were significantly different at the 5% significance level, but not for the no tillage treatment. The variability of saturated hydraulic conductivity related to tillage as well as being greater for the no tillage treatment than for the conventional tillage treatment. The relative ranges in variability of saturated hydraulic conductivity were much greater than those of the other soil properties. The results also showed that the coefficients of variation of saturated hydraulic conductivity were between 70 and 140% as compared to 1 to 40% for all other properties. This reveals that saturated hydraulic conductivity is the most variable of all the soil properties studied. The non-zero correlation coefficients between saturated hydraulic conductivity and soil physical properties, presented in Table II, indicate that each of these properties influences soil hydraulic conductivity. The extreme variability of saturated hydraulic conductivity may therefore be attributed to the cumulative effect of the variability of all the soil physical properties. However, further studies would be needed to be able to explain the possible causes of this result.

Autocorrelation of soil properties

Figures 1 to 8 present the correlograms of bulk density, organic matter content, effective porosity, and saturated hydraulic conductivity. The autocorrelation for small values of lag is expected to be positive in the absence of spatial variability. Thus, any negative values in that range may be attributed to variability. Moreover, extreme fluctuations in the entire range of lag are also attributable to spatial variability (Salas et al. 1980). Therefore, from Figs. 1 to 8, it would appear that all soil properties analyzed exhibit some degree of spatial variability but to different extents in the A and B horizons for both the no tillage and conventional tillage treatments. In the case of bulk density, tillage seems to increase variability in the A horizon as depicted by more fluctuations in the correlograms for the conventional tillage treatment than in those for the no tillage treatment (Figs. 1 and 2). The variability of organic matter content in both the A and B horizons seems to increase with tillage, being greater in the A horizon than in the B horizon, as revealed by the fluctuations in the correlograms in Figs. 3 and 4. The variability of effective porosity in the A horizon is not greatly affected by tillage, as indicated by identical fluctuations in the correlograms for the no tillage and the conventional tillage treatments (Fig. 5). In the B horizon the variability of effective porosity increased with tillage, as indicated by more fluctuations in the correlograms for conventional tillage treatment than those for no tillage treatment (Fig. 6).

Extremely high fluctuations in the correlograms in Figs. 7 and 8 compared to the fluctuations in the correlograms in Figs. 1 to 6 indicate that saturated hydraulic conductivity exhibits more spatial variability than the other soil properties. This result also was indicated by very high values of the coefficient of variation of saturated hydraulic conductivity as compared with the coefficients of variation of the other soil properties. Also,

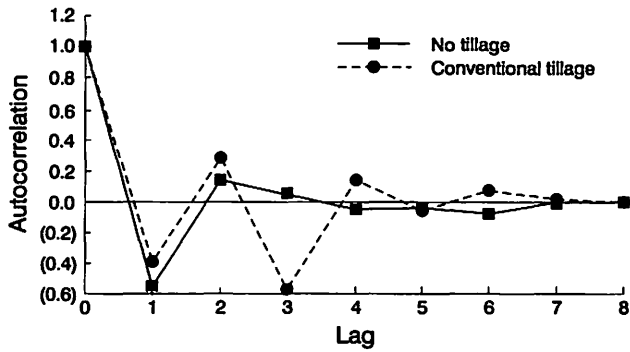


Fig. 6. Correlogram of effective porosity in B horizon.

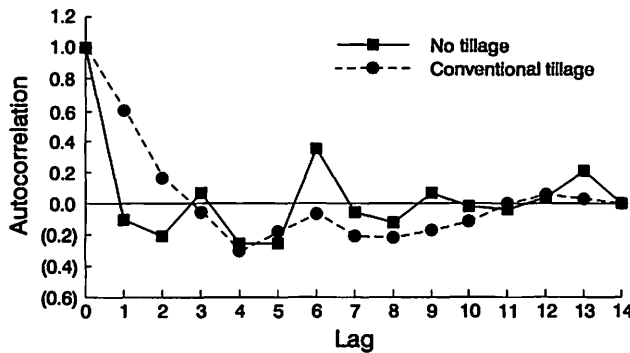


Fig. 7. Correlogram of saturated hydraulic conductivity in A horizon.

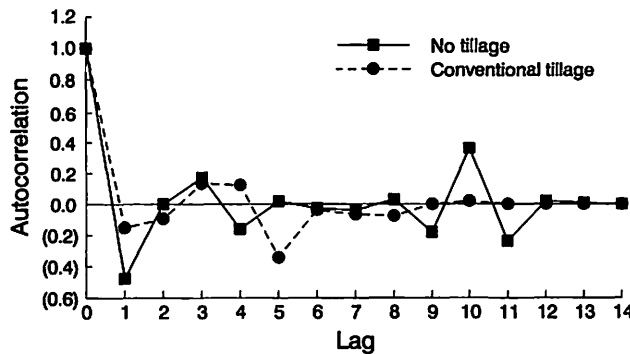


Fig. 8. Correlogram of saturated hydraulic conductivity in B horizon.

saturated hydraulic conductivity was more variable under no tillage treatment than under conventional tillage treatment, as indicated by more fluctuations in the correlograms for the no tillage treatment than those for the conventional tillage treatment.

Frequency distributions

The coefficients of skewness presented in Table I were used to set a basis for choosing the best fit frequency distributions for the soil properties. It is clear from these data that all the soil properties have skewed frequency distributions, although the

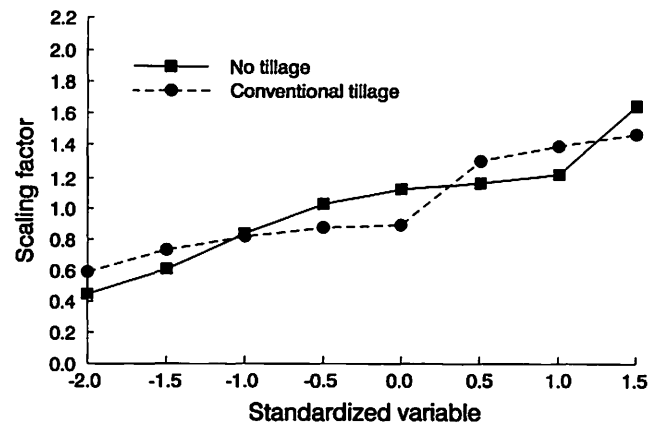


Fig. 9. Fractile diagram of scaling factors of effective porosity in A horizon.

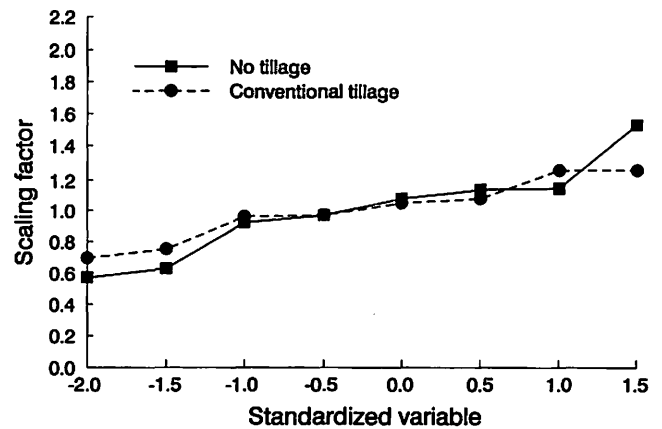


Fig. 10. Fractile diagram of scaling factors of effective porosity in B horizon.

skewness is only slight in some cases such as for bulk density in the B horizon. This probably indicates that compaction during ploughing likely resulted in a fairly normal frequency distribution of bulk density. The results also reveal that the frequency distributions associated with saturated hydraulic conductivity are the most skewed of all the soil properties analyzed.

For the scaling factors of effective porosity and saturated hydraulic conductivity, the lognormal distribution gave the best fit for both the A and B horizons for both the no tillage and conventional tillage treatments, using the chi-square and Kolmogorov-Smirnov tests of goodness-of-fit at the 90 and 95% confidence levels. The lognormal distribution also gave the best fit probability distribution for all the other soil properties, except bulk density for which the normal distribution gave the best fit. The fractile diagrams of scaling factors presented in Figs. 9 to 12 show that the frequency distributions of effective porosity and saturated hydraulic conductivity are not markedly affected by tillage. Only noticeable deviation occurs at the extremes, probably because tillage has a greater effect on large and small pores than on pores of intermediate size.

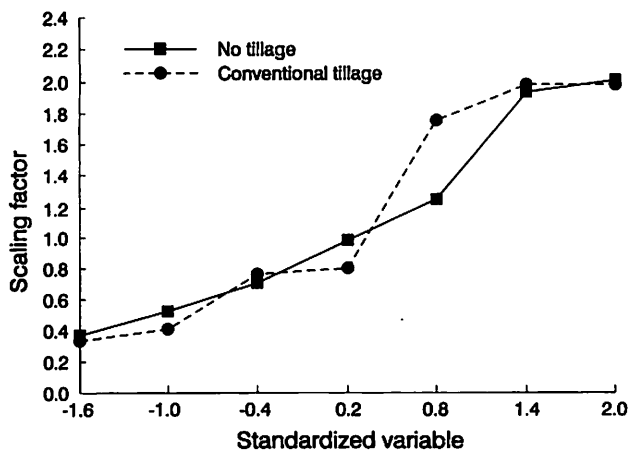


Fig. 11. Fractile diagram of scaling factors of saturated hydraulic conductivity in A horizon.

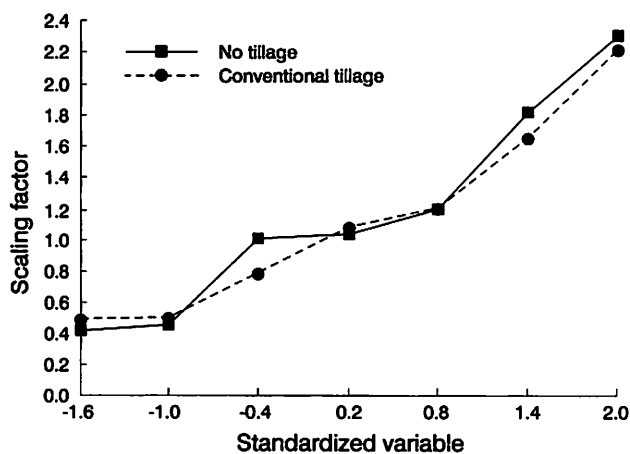


Fig. 12. Fractile diagram of scaling factors of saturated hydraulic conductivity in B horizon.

CONCLUSIONS

The analyses of the statistical parameters, autocorrelograms, and frequency distributions have shown that bulk density, organic matter content, effective porosity, and saturated hydraulic conductivity can vary significantly between A and B horizons and between no tillage and conventional tillage treatments over a silt loam field in Southern Ontario. Spatial variability in bulk density and effective porosity may be due to non-uniform distribution of organic matter and non-uniform compaction during tillage. The spatial distribution of macropores as well as aggregates offer other possible causes for the variability of the soil water properties. The variability of soil hydraulic properties in the field seem to be affected more by tillage than by the variability of physical properties of field soil. The spatial variability of soil hydraulic properties tends to be reduced with tillage. Therefore, the spatial variability of the transport of water and contaminants in field soil could be reduced by tillage.

The results of tests of significance of differences in means and coefficients of variation and the analyses of the

autocorrelograms indicate the same trends of spatial variability of soil water properties. Moreover, the autocorrelograms also present graphical information of these trends, making the time series technique a competitive approach to the analysis of spatial variability of soil water properties.

ACKNOWLEDGMENTS

The financial support of each of the following organizations to this work is greatly appreciated: Natural Science and Engineering Research Council (NSERC) of Canada, the Canadian Commonwealth Fellowship Programme, and the Water Resources Research Institute of CSIR of Ghana.

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