SPATIAL VARIABILITY OF SOME SOIL PHYSICAL PROPERTIES IN THREE SOILS OF SÃO PAULO, BRAZIL[1]

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ABSTRACT - Volumetric core samples and loose soil samples were collected at 1 m interval in 10 m long transects, on three major soil groups in São Paulo, Brazil. The soil cores were used for soil desorption curves and the bulk density, and the loose soil was used for particle size analysis. The parameters obtained from the soil water retention model, bulk density and particle size values were submitted to geostatistical analysis to study the spatial variability through the examination of semivariograms and cross-semivariogram. The results showed that the scale of variation changes from soil to soil, with maximum variation for the Podzolic Soil with clay surface texture, from the northeast part of the state. For this soil also, the spatial autocorrelation was the most expressive. The variability of the soil desorption parameters was related to the particle size parameters. The geostatistical analysis results allowed establishing sample spacing for the soils studied, to allow for estimation at any finer spacing, with no bias and minimum variance.

Index terms: soil water retention, soil hydraulic conductivity, soil water desorption, bulk density, particle size, soil.

VARIABILIDADE ESPACIAL DE ALGUMAS PROPRIEDADES FÍSICAS DE TRÊS SOLOS DE SÃO PAULO, BRASIL

RESUMO - Anéis volumétricos e amostras de solo solto foram coletadas num espaçamento de 1 m entre amostras, em transações de 10 m de comprimento, em três solos principais do estado de São Paulo. Os anéis volumétricos foram usados para determinações de curvas de retenção de água e densidade do solo, e as amostras de solo solto, para análise granulométrica. Os parâmetros obtidos do modelo que descreve a curva de retenção de água, a densidade do solo e os teores de argila, silte e areias foram submetidos a análise geoestatística para estudo de variabilidade de espaço, através do exame de semivariogramas e "cross"-semivariogramas. Os resultados mostraram que a escala de variação muda bastante de solo para solo, com máxima variação para o podzólico de textura argilosa na superfície, situado principalmente na parte nordeste do Estado. Para este solo também, a autocorrelação foi a de máxima expressão. A variabilidade dos parâmetros da curva de retenção seguiu proporcionalmente a distribuição de partículas do solo. A análise geoestatística permitiu estabelecer espaçamento entre amostras para os solos estudados, para permitir estimativas a espaços menores, sem tendência, e com variância mínima.

Termos para indexação: dessorção da água do solo, retenção de água no solo, tamanho das partículas do solo, densidade do solo, condutividade hidráulica do solo.

INTRODUCTION

Spatial variability of soil properties has been studied since the early 1900's (Montgomery 1913, Waynick 1918, Waynick & Sharp 1919, Harris 1920), with the use of a wide variety of sampling schemes and analysis, but with many difficulties of interpretation and generalization. Apparently, the major concern is that once a soil has been classified by soil survey, the units should be uniform and homogeneous (Pendleton 1919). This may be true but only with respect to those soil properties used in the soil classification and not

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necessarily for those properties more related to crop productivity, water movement in the soil profile and soil management, in general. Moreover, the improvement in methods of analysis and sampling (Robinson & Lloyd 1915) and the further development of the soil profile (Harradive 1949), many soil units have already been subdivided into two or more distinct units, and yet variation in soil properties has been reported both between and within soil units (Beckett & Webster 1971). Little is known about the variability of soil properties directly related to soil structure such as soil water retention and hydraulic conductivity. Nielsen et al. (1973) in a detailed study over a 150-hectare field concluded that a large number of samples is required to adequately represent the soil water retention curve of the soil, due to its great variability. It is also reported that the size of the sample affects directly the magnitude of the variability (McIntyre 1974). In general, the evaluation of the variability in these studies consisted in examining the coefficients of variation, which implies the existence of the variance and independence between neighboring samples. This assumption may not be true and is seldom tested (Vieira et al. 1981). Matheron (1963) introduced a new statistical theory called Geostatistics, which is based upon the existence of dependence between neighboring samples, measured through autocorrelation, and allows for the interpolation of values for the unmeasured locations with minimum variance and without bias.

Geostatistics has been used with success in soil survey data (Burgess & Webster 1980), soil water infiltration rate (Vieira et al. 1981), soil surface temperature (Vauclin et al. 1982, Vieira & Hatfield 1984), available water capacity (Vauclin et al. 1983), bulk density (Libardi et al. 1986) and agronomic data in general (Vieira et al. 1983, Reichardt et al. 1986).

The objective of this study was to evaluate the spatial variability of soil water retention, soil texture, and bulk density in three major soils of the São Paulo State in Brazil.

MATERIALS AND METHODS

The field sites for this study were located at the Instituto Agronômico Experimental Stations in Campinas, SP, Pindorama, SP and Mococa, SP, Brazil, respectively in soils Dusky-Red Latossol (LR), Sandy Red-Yellow Podzolic (PVA-S) and Clay Red-Yellow Podzolic (PVA-C) soils continuously planted with corn in the Summer and fallow in the Winter, with conventional tillage for the last 5 years. For each soil, 10 samples were collected with volumetric rings measuring 7.6 cm inside diameter and 10 cm height at the depth of 2 to 12 cm, in a straight line across the slope with 1 m spacing between each point. The water retention curves were determined using a method stablished by Vieira & Castro (1987). At the same locations and depths soils samples were collected for the particle size distribution analysis by the pipet method. There was a considerable loss of soil in ring number 2 for the PVA-C in the handling process, and for this reason this sample was not analysed, working, in this soil, with 9 samples.

The soil water retention data (θ, h) were submitted to the curve fitting and analysis described in Genuchten & Nielsen (1985) in which the soil water retetion curve (θ, h) is taken as

$$\theta = \theta r + \frac{\theta s + \theta r}{[1 + (\alpha h)^{n}]^{m}}, \qquad (1)$$

where θr is the residual water content (cm^3/cm^3), θs is the saturated water content (cm^3, cm^3), $\alpha = \frac{1}{h}$ and h_α is the soil air entry value (cm), and n and m are empirical parameters.

The particle size parameters, the bulk density and the parameters obtained from the water retention curve fitting equation (1) were used in the evaluation of the spatial variability through the semivariogram,

$$\gamma(h) = \frac{1}{2\,N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2, \qquad (2)$$

where N(h) is the number of neighbors of [Z (x_i) Z_i (x_i + h)] separated by a distance of h meters, and Z is any of the parameters. The presence of autocorrelation was detected through the existence of a range of the semivariogram any distance greater than 1 m, the sampling distance.

To evaluate the spatial correlation between pairs of variables the cross-semivariogram

$$\gamma_{12}(h) = \frac{1}{2\,N(h)} \sum_{i=1}^{N(h)} [Z_1(x_i) - Z_1(x_i + h)]\,[Z_2(x_i) - Z_2(x_i + h)], \quad (3)$$

was used. With this calculation it is hoped to find spatial autocorrelation between soil water retention parameters and other properties easier to measure such as clay, silt and sand content. This would allow for the sampling of the soil water retention at a greater interval and the use of particle size distribution to estimate values at any given location with no bias and mininum variance through a geostatistical method called Cokriging (Vauclin et al. 1983).

RESULTS AND DISCUSSION

The statistical moments for all the parameters for the three soils are shown in Table 1. Examination of the parameters on this table can be very useful as a general guide for the interpretation of the variability and of the correlation between variables. For instance, the coefficient of variation (C.V.) which expresses the relative variation within each soil group, regardless of the spatial distribution of the samples, is very low for bulk density for all the 3 soils, and it is maximum for Alpha (α). The large sample size of approximately 450 cm^3, in addition to the naturally low variability of bulk density within agricultural fields, may be the reason for this. The coefficient α has very small values, with means ranging between 0.08 and 0.5, and relatively large variances on the order of 10^{-1}, is very sensitive to small variations within the data set, which causes such high C.V. The coefficients of skewness and kurtosis identify the closeness to a normal distribution, as they approach 0 (zero) and 3, respectively. In general, the silt content and the bulk density tend to have kurtosis smaller than a normally distributed population because their range of variation is smaller than normal, since the values are all concentrated around the mean. The parameters α, n, and m increase as the amount of coarse particles increase, from LR, to PVA-C and PVA-C, and their respective C.V. decrease in the same direction. These are very normal results, if the soil is structureless. However, both LR - Campinas and PVA-C Mococa are well structured soils, in particular the PV-C which has a very well defined blocky structure. This in turn, is not entirely against the results of Table 1 since there are only two structural soils, and a wider range would, more likely, show its effect.

The correlation matrix between each pair of variables for the 3 soils is shown in Table 2. There is a very strong correlation between each pair of the parameters adjusted to soil desorption curve except for the water content at saturation which is only slightly correlated for the LR - Campinas. This agrees with the relationship between the mean values of α, n, and m and the amount of coarse materials found above, and further shows the low importance of the soil structure in these data, since α is related to the soil porosity, and correlated to n, and m, then it can be said that n and m are also related to the amount of coarse material in a structureless soil. Further, the highest correlation between α and n or m, are for the LR - Campinas and PVA-C - Mococa which are higher in finer materials and more likely to have structure effect on soil desorption. The PVA-C - Mococa shows some correlation between total coarse material and bulk density, and between fine sand and bulk density, which should be expected, since the contribution of fine sand to the bulk density is usually very significant. The only correlation shown between α and any particle size parameter was found for the LR - Campinas with clay or coarse sand, but it is very small and may not be significant. There is also some negative correlation between corase sand content and θ s form the PVA-C - Mococa, as the sand directly affects the porosity of the soil.

Next, we will discuss the semivariogram and cross-semivariograms only for those parameters which showed some significant autocorrelation. None for the soil desorption curve parameters showed spatial autocorrelation.

On Figures 1 a and b are the semivariograms for clay + silt and silt, respectively for the LR. The one for clay + silt shows a linear relationship with distance, without bounds to a maximun value. This virtually means that on the length of the transect, the variability did notyet reach its full scale and the calculated variance may not have any significance in this situation, since the semivariograms do not level off to their values. The semivariogram for silt alone (Fig. 1b) shows an exponential model with a sill much higher than the calculated variance. However, it appears that a siet value was being reached by the semivario-

TABLE 1. Statistical moments for all the three soils.

Name	Unit	Num.	Mean	Variance	C.V.	Minimun	Maximun	Skewness	Kurtosis
				LR - Campinas					
Clay	%	10	57.60	1.0400	1.77	56.00	59.00	-0.3003	3.359
Silt	%	10	9.70	0.4100	6.60	9.00	11.00	0.3657	2.293
Fine	%	10	67.30	1.6090	1.88	65.00	70.00	0.3176	1.208
Csand	%	10	14.70	0.4100	4.34	14.00	16.00	0.3658	2.290
Fsand	%	10	18.00	1.6000	7.03	16.00	21.00	0.8894	3.906
Coarse	%	10	32.70	1.6100	3.88	30.00	35.00	-0.3046	3.183
B.D.	g/cc	10	1.36	0.0184	3.15	1.28	1.43	-0.5497	2.361
Thets	%vol	10	0.46	0.0086	4.14	0.42	0.48	-0.8222	3.816
Alpha	1/cm	10	0.53	0.6330	149.80	0.03	2.79	2.2130	6.642
N-Coe	dml	10	1.09	0.0042	1.89	1.06	1.12	0.2687	0.794
M-Coe	dml	10	0.08	0.0030	20.69	0.06	0.11	0.1943	1.568
				PVA-C - Mococa					
Clay	%	10	35.60	9.2400	8.54	32.00	43.00	1.3230	3.937
Silt	%	10	9.70	0.8100	9.28	8.00	11.00	-0.1975	2.258
Fine	%	10	45.30	7.8100	6.17	42.00	52.00	1.1750	3.691
Csand	%	10	30.70	6.0100	7.99	26.00	34.00	-0.4657	2.040
Fsand	%	10	24.00	1.2000	4.56	22.00	26.00	0.0000	2.500
Coarse	%	10	54.70	7.8100	5.11	48.00	58.00	-1.1750	3.677
B.D.	g/cc	10	1.45	0.0014	2.63	1.38	1.50	-0.1867	1.438
Thets	%vol	10	0.46	0.0016	8.67	0.41	0.54	0.7731	2.329
Alpha	% vol	10	0.46	0.0161	63.57	0.05	0.41	0.4720	1.694
N-Coe	dml	10	1.12	0.0006	2.13	1.09	1.18	0.7932	6.092
M-Coe	dml	10	0.11	0.0003	16.92	0.08	0.15	0.7145	3.363
				PVA-S - Pindorama					
Clay	%	9	6.77	0.1728	6.13	6.00	7.00	-1.3370	2.786
Silt	%	9	1.55	0.4691	44.03	1.00	3.00	0.8367	2.497
Fine	%	9	8.33	0.2222	5.66	8.00	9.00	0.7060	1.506
Csand	%	9	28.56	5.5800	8.27	23.00	31.00	-1.1820	3.705
Fsand	%	9	63.33	5.3340	3.65	60.00	68.00	0.5089	2.572
Coarse	%	9	91.89	0.7660	9.52	91.00	94.00	1.1230	9.032
B.D.	g/cc	9	1.49	0.0037	4.05	1.39	1.58	-0.3865	1.695
Thets	%vol	9	0.37	0.0004	5.38	0.34	0.40	0.0006	1.702
Alpha	1/cm	9	0.08	0.0094	119.50	0.03	0.36	2.3880	6.875
N-Coe	dml	9	1.46	0.0139	8.12	1.23	1.62	-0.5925	2.309
M-Coe	dml	9	0.31	0.0035	19.26	1.19	0.38	-0.8165	2.512

gram, approximately to the value of the variance (0.41). If this is true, then the range of 2 m would mean that samples collected at this or any larger distances, would be independent of each other. In order to find out whether the apparent sill is true or not, jackkniffing procedures should be applied (Vieira et al. 1983). However, with this low number of samples, in one single transect, the usefullness of jackkniffing is quite limited, and it is best to

TABLE 2. Correlation matrices between each pair of variables.

LR - Campinas

Name	Clay	Silt	Fine	Csand	Fsand	Coarse	B.D.	Thets	Alpha	N-Coe	M-Coe
Clay	1.000	0.123	0.866	-0.337	-0.698	-0.866	-0.457	0.557	0.455	-0.506	-0.502
Silt	1.123	1.000	0.603	0.024	-0.617	-0.603	-0.055	-0.319	-0.459	0.340	0.345
Fine	0.866	0.603	1.000	-0.259	-0.873	-0.999	-0.395	0.287	0.134	-0.235	-0.229
Csand	-0.337	0.024	-0.259	1.000	-0.247	0.259	0.382	-0.555	-0.464	0.469	0.470
Fsand	-0.698	-0.617	-0.873	-0.247	1.000	0.872	0.203	-0.007	0.100	-0.002	-0.008
Coarse	-0.866	-0.603	-0.999	0.259	0.872	1.000	0.395	-0.287	-0.134	0.235	0.229
B.D.	-0.457	-0.055	-0.395	0.382	0.203	0.395	1.000	-0.541	-0.583	0.658	0.660
Thets	0.557	-0.319	0.287	-0.555	-0.007	-0.287	-0.541	1.000	0.660	-0.685	-0.686
Alpha	0.455	-0.459	0.134	-0.464	0.100	-0.134	-0.583	0.660	1.000	-0.691	-0.698
N-Coe	-0.506	0.340	-0.235	0.469	-0.002	0.235	0.658	-0.685	-0.691	1.000	1.000
M-Coe	-0.502	0.345	-0.229	0.470	-0.008	-0.229	0.660	-0.686	-0.698	1.000	1.000

PVA-C - Mococa

Name	Clay	Silt	Fine	Csand	Fsand	Coarse	B.D.	Thets	Alpha	N-Coe	M-Coe
Clay	1.000	-0.409	0.956	-0.915	-0.390	-0.956	-0.628	0.496	-0.463	0.285	0.032
Silt	-0.409	1.000	-0.123	0.231	-0.203	0.123	0.228	-0.339	-0.140	0.030	0.033
Fine	0.956	-0.123	1.000	-0.921	-0.490	-0.999	-1.220	0.430	-0.548	0.041	0.046
Csand	-0.915	0.231	-0.921	1.000	0.112	0.921	0.417	-0.606	0.518	0.175	0.172
Fsand	-0.390	-0.203	-0.490	0.112	1.000	0.490	0.625	0.260	0.241	-0.495	-0.502
Coarse	-0.956	0.123	-0.999	0.921	0.490	1.000	0.610	-0.430	0.548	-0.041	-0.046
B.D.	-0.628	0.228	-0.610	0.417	0.625	0.610	1.000	-0.010	-0.139	-1.668	-0.177
Thets	0.496	-0.339	0.430	-0.606	0.260	-0.430	-0.010	1.000	-0.376	-0.687	-0.695
Alpha	-0.463	-0.140	-0.548	0.518	0.241	0.548	-0.139	-0.376	1.000	-0.102	-0.094
N-Coe	0.029	0.030	0.041	0.175	-0.495	-0.041	-0.167	-0.687	-0.102	1.000	1.000
M-Coe	0.032	0.033	0.046	0.172	-0.502	-0.046	-0.177	-0.695	-0.094	1.000	1.000

PVA-S - Pindorama

Name	Clay	Silt	Fine	Csand	Fsand	Coarse	B.D.	Thets	Alpha	N-Coe	M-Coe
Clay	1.000	-0.737	-0.189	0.465	-0.386	0.238	0.157	-0.217	0.186	-0.120	-0.131
Silt	-0.737	1.000	0.803	-0.534	0.304	-0.638	0.217	-0.148	-0.338	0.352	0.366
Fine	-0.189	0.803	1.000	-0.366	-0.102	0.718	0.453	-0.406	-0.326	0.406	0.416
Csand	0.465	-0.534	-0.366	1.000	-0.930	0.245	-0.301	0.157	-0.222	0.045	0.075
Fsand	-0.386	0.304	0.102	-0.930	1.000	0.128	0.330	-0.227	0.250	-0.093	-0.121
Coarse	0.238	-0.638	-0.717	0.245	0.128	1.000	0.058	-0.174	0.060	-0.123	-0.117
B.D.	0.157	0.217	0.453	-0.301	0.330	0.058	1.000	-0.354	0.055	-0.141	-0.137
Thets	-0.217	-0.148	-0.406	0.157	-0.227	-0.174	-0.354	1.000	0.149	-0.316	-0.339
Alpha	0.186	-0.338	-0.326	-0.222	0.250	0.060	0.055	0.149	1.000	-0.731	-0.771
N-Coe	-0.120	0.352	0.406	0.045	-0.093	-0.123	-0.141	-0.316	-0.731	1.000	0.997
M-Coe	-0.131	0.366	0.416	0.746	-0.121	-0.117	-0.137	-0.339	-0.771	0.997	1.000

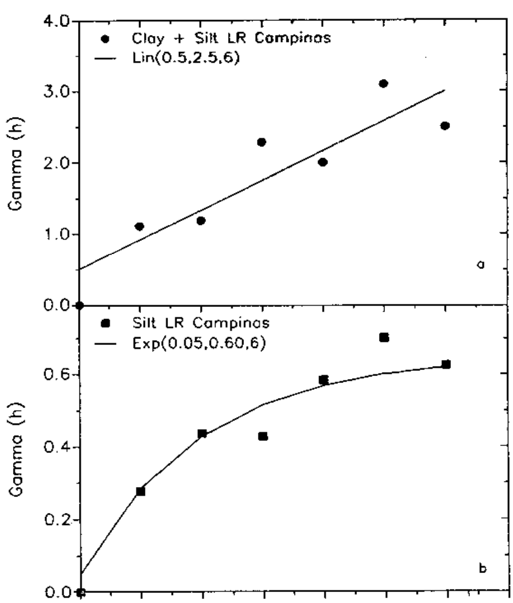

FIG. 1. Semivariogram a) Fine particles LR b) Silt LR.

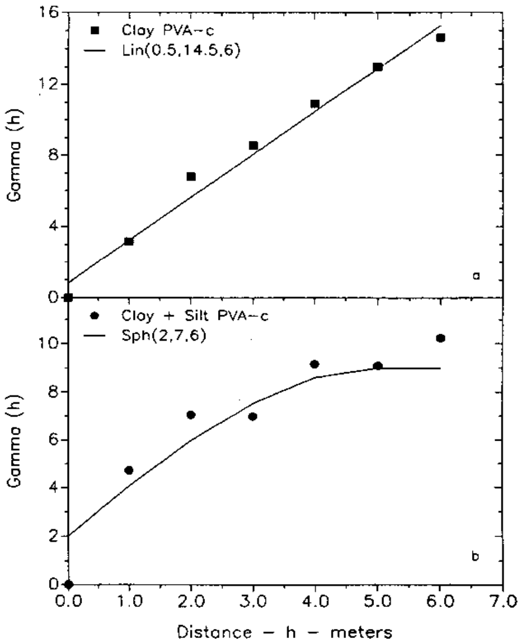

FIG. 2. Semivariogram a) Clay PVA-C. b) Fine particles PVA-C.

accept the linear and exponential models as being real.

The semivariograms for the textural components clay and clay + silt of the PVA-C and are shown in Fig. 2. The spatial autocorrelation for clay PVA-C in Fig. 2a shows a very well defined linear relationship with distance without bounds to any sill value. Again, the semivariogram for fine particles shown in Fig. 2b, reminded quite closely the one for silt content on the LR - Campinas in Fig. 1b, in as much as they also have reached and apparent sill at 2 m. Again, with this few number of samples in one single transect, it is safer to assume that their shapes are the ones shown. The silt content on the PVA-C has also a sill higher than the variance, but 4 m spacing, otherwise, a linear relationship as shown in Fig. 2a. The semivariogram for fine sand content for PVA-C (Fig. 3a) has a sill value very close to the value of the variance, and therefore is likely to thave stationarity. A range of 3 m could be assumed, for this variable. The semivariogram for coarse sand PVA-C

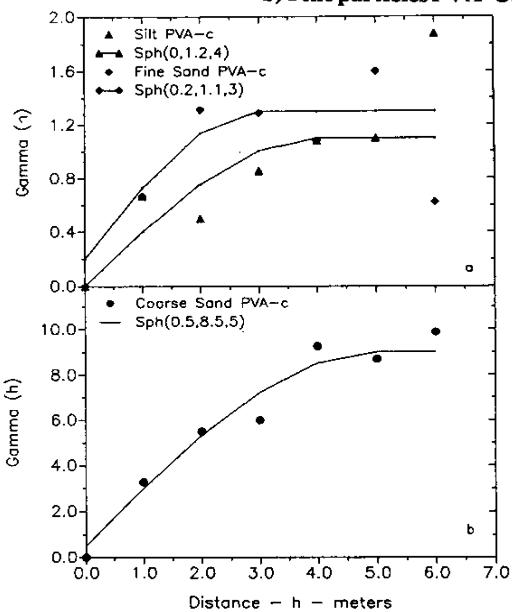

FIG. 3. Semivariogram a) Silt PVA-C and Fine Sand PVA-C b) Coarse Sand PVA-C.

(Fig. 3b), although very well behaved, has a sill much higher than the sample variance, with a spherical model and a range of 5 m describing it very well.

The only variable for PVA-C - Pindorama which showed spatial autocorrelation was the bulk density, shown in Fig. 4, through which a gaussian model with no nugget effect and a range of 7 m could be quite easily adjusted.

Is should be noted that, because the particle size variables sum to 100, the semivariograms of the fine particles content (clay and silt) is identical to the coarse particles content (coarse sand and fine sand).

Based on the correlation coefficients between pairs of variables, shown in Table 2, the cross-semivariogram between the ones more expressive are shown in Fig. 5. The fine and coarse particles for the LR show a negative cross-semivariogram on Fig. 5a, as a reflect of their naturally inverse relationship. The usefullnees of this information lies on the possibility of measuring fine particles at larger spacing than the coarse particles, and using their autocorrelation to estimate values at any finer spacing using Cokriging techniques with no bias and minimum variance (Vauclin et al. 1983). Basically the same can be said for the PVA-C on Fig. 5b, except that this one is clearer than the one for LR. The apparent sill reached at 5 m however is much smaller than the sample covariance. Fig. 5c shows the cross-semivariogram between coarse particles and the parameter Alpha for the PVA-C with a poorly defined correlation. Although it does not help very much to estimate only alpha when n and m still need to be determined, but it is always helpful to know that for this soil, the coefficient alpha is correlated with the amount of coarse material, as this will affect future sampling schemes.

The parameters of the semivariograms and cross-semivariograms models are shown in Table 3. It should be understood these parameters simply represent the first rough approximation to the models, and, ideally, jackkniffing should be done to verify them. Besides the fact that jackkniffing is not of much help in small values such as these, their purpose here is simply to roughly describe the semivariograms for comparisons and overall comments. More details of these and other models can be found elsewhere (Vieira et al.

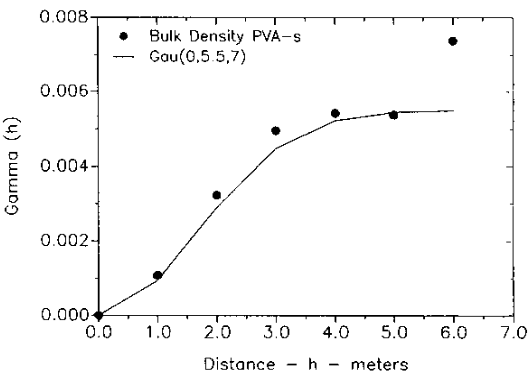

FIG. 4. Semivariogram bulk density PVA-S.

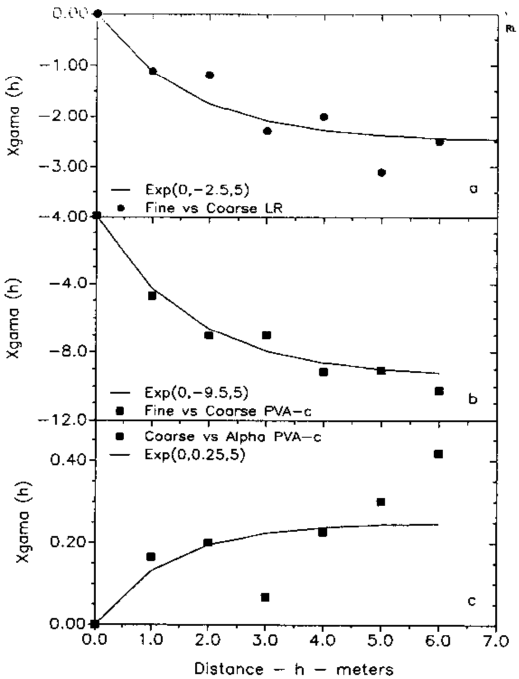

FIG. 5. Cross-semivariograms:
a) Fine vs. Coarse LR
b) Fine vs. Coarse PVA-C.
c) Coarse vs. Alpha PVA-C.

TABLE 3. Parameters of semivariograms and cross-semivariogram.

Variable	Nugget effect	Range	Sill	Model
Fine LR	0.5	6.0+	2.5+	Linear
Silt LR	0.05	6.0+	0.6+	Exponential
Clay PVA-C	0.5	6.0+	15.0	Linear
Fine PVA-C	2.0	6.0+	9.0+	Spherical
Silt PVA-C	0.0	4.0	1.2	Spherical
Silt PVA-C	0.5	5.0	9.0	Spherical
Coarse sand PVA-C	0.2	3.0	1.3	Spherical
Fine sand PVA-C	0.0	7.0	0.0	Gaussian
Bulk Density PVA-C	0.0	5.0	-2.5	Exponential
Fine vs. Coarse PVA-C	0.0	5.0	-9.5	Exponential
Coarse vs. Alpha PVA-C	0.0	5.0	0.2	Exponential

1983). The low values for nugget effects relative to the silt value, mean here that the variability below the sampling distance of 1 m is small, and high confidence estimation should be expected. Many of the variables reached a silt value higher than the sample variance. The smallest correlation distance found was for the fine sand PVA-C, of 3 m. However, the total sand particles for PVA-C whose semivariogram is identical to the one for clay + silt (Fig. 3b) did not reach a range until 6 m, and is more commonly measured than fine sand. The models indentified as linear without silt could, as well, be substituted by an exponential, which approaches the silt asymptotically, since the slope between consecutive points decreases with distance. In other words, it is expected that, if we had some more samples in the same transect, or more transect tending to a total square grid, the siltw ould be reached.

CONCLUSIONS

1. Soil water desorption curves are very expensive and time consuming determinations, and yet, very important for soil and water management decisions. In this sense, and based upon the fact that no correlation was found for the soil desorption curve parameters, sampling for this property should be based upon the physical processes needed to quantify, regardless of distance concept.

2. For the particle size variables the spatial autocorrelation found indicates that sampling at 4 m interval would still provide enough information to do geostatistical estimation of values at finer spacings, without bias and with minimum variance. This is particularly true for the PVA-C, which showed the most number of variables spatially autocorrelated.

3. More research is needed in this subject, in particular to find out whether this spacing would still hold in a regular square grid.

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