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SEÇÃO V - GÊNESE, MORFOLOGIA E CLASSIFICAÇÃO DO SOLO

VARIABILITY OF APPARENTLY HOMOGENEOUS SOILSCAPES IN SÃO PAULO STATE, BRAZIL: I. SPATIAL ANALYSIS[(1)]

M. van den BERG[(2)] & J. B. OLIVEIRA[(3)]

SUMMARY

The spatial variability of strongly weathered soils under sugarcane and soybean/wheat rotation was quantitatively assessed on 33 fields in two regions in São Paulo State, Brazil: Araras (15 fields with sugarcane) and Assis (11 fields with sugarcane and seven fields with soybean/wheat rotation). Statistical methods used were: nested analysis of variance (for 11 fields), semivariance analysis and analysis of variance within and between fields. Spatial levels from 50 m to several km were analyzed. Results are discussed with reference to a previously published study carried out in the surroundings of Passo Fundo (RS). Similar variability patterns were found for clay content, organic C content and cation exchange capacity. The fields studied are quite homogeneous with respect to these relatively stable soil characteristics. Spatial variability of other characteristics (resin extractable P, pH, base- and Al-saturation and also soil colour), varies with region and, or land use management. Soil management for sugarcane seems to have induced modifications to greater depths than for soybean/wheat rotation. Surface layers of soils under soybean/wheat present relatively little variation, apparently as a result of very intensive soil management. The major part of within-field variation occurs at short distances (< 50 m) in all study areas. Hence, little extra information would be gained by increasing sampling density from, say, 1/km^2 to 1/50 m^2. For many purposes, the soils in the study regions can be mapped with the same observation density, but residual variance will not be the same in all areas. Bulk sampling may help to reveal spatial patterns between 50 and 1.000 m.

Index terms: soil variability, systematic sampling, Latosols, semivariance analysis.

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RESUMO: *VARIABILIDADE DE PEDO-PAISAGENS APARENTEMENTE HOMOGÊNEAS NO ESTADO DE SÃO PAULO, BRASIL: I. ANÁLISE ESPACIAL*

Abordou-se, quantitativamente, a variabilidade espacial de solos fortemente intemperizados sob cana-de-açúcar e rotação soja/trigo de 33 glebas em duas regiões do estado de São Paulo, Brasil: Araras (15 glebas com cana-de-açúcar) e Assis (11 glebas com cana-de-açúcar e sete glebas com rotação soja/trigo). Os métodos estatísticos empregados foram análise da variância por amostragem aninhada (para 11 glebas), análise de semivariância e análise de variância dentro das glebas e entre elas. Foram analisados níveis espaciais entre 50 m e vários km. Os resultados foram discutidos em relação a um estudo nas redondezas de Passo Fundo (RS) publicado anteriormente. Foram encontrados padrões de variação similares para teor de argila, teor de C-orgânico e capacidade de troca catiônica. As glebas estudadas mostram-se bastante homogêneas em relação a estas características relativamente estáveis. A variabilidade espacial de outras características (P-resina, pH, saturação por bases e por alumínio e também cor dos solos) variou entre regiões e, ou, uso/manejo das terras. O manejo dos solos com cana-de-açúcar provocou, aparentemente, modificações até camadas mais profundas em relação à rotação soja/trigo. Camadas superficiais dos solos sob soja/trigo apresentaram, aparentemente, pouca variação como resultado do manejo muito intensivo. Em todos os casos estudados, a maior parte da variação dentro das glebas ocorreu a pequenas distâncias (< 50 m). Esperava-se, portanto, obter pouca informação adicional pela intensificação da amostragem de 1/km^2 para 1/50 m^2. Para muitas finalidades, os solos estudados podem ser mapeados com a mesma densidade de observações, porém a variação não explicada pode não ser a mesma em todas as áreas. A coleta de amostras compostas possivelmente ajudaria revelar padrões espaciais entre 50 e 1.000 m.

Termos de indexação: amostragem sistemática, Latossolos, análise de semivariância.

INTRODUCTION

Unresolved spatial soil variability is one of the major factors that limit the quality of soil inventories, and evaluations based hereon. Therefore, spatial variation of soils should be quantified and the adequacy of soil maps for use in interpretative studies should be evaluated. The results of such studies can be used in combination with models to quantify the impact of errors/uncertainties, originating from unresolved spatial soil variability, on generated estimates of land-use system productivity, soil erodibility, fertiliser requirements and so on.

Quantification of the spatial variability of soils is an expensive and laborious job (Isaaks & Srivastava, 1989; Burrough, 1993). Berg & Klamt (1997a) hypothesised that the spatial variations of similar soils of different regions may be analogous. If spatial variability proves to be similar in landscapes dominated by soils of the same taxonomic groupings at a high level of generalisation, then optimised sampling strategies determined for a limited number of representative areas may be useful for optimising sampling in new areas. Additionally, quantified knowledge on spatial variability would contribute to a better understanding of relations between spatially variable soil (forming) processes and soil characteristics, giving further support to the development of improved survey methods.

The optimisation of field sampling would be of great importance in the case of strongly weathered soils (Ferralsols, Acrisols, Nitisols) in Brazil. These soils form a vast agricultural potential, much of which is under-explored. Most of the regions where they dominate have only been mapped at exploratory-reconnaissance scale (1:500.000 to 1:1.000.000), with a very low density of ground observations.

Statistical methods to quantify spatial variability of soils are usually referred to as geostatistics. Webster (1985) and Webster & Oliver (1990) have reviewed the most important ones: (a) nested analysis of variance and (b) semivariance analysis.

Nested analysis of variance describes the distribution of variance over exponentially increasing spatial scales. It is carried out on data collected in nested sampling schemes, i.e. samples distributed hierarchically in space. This technique is especially suited for a rough assessment of predominant scales of spatial variability (Nortcliff, 1978; Burrough & Kool, 1981, Corsten & Stein, 1991; Berg & Klamt, 1997a).

The semivariance, $\gamma(h)$, describes the variance of differences between sites as a function of their spatial separation *h* (called "lag") and is usually estimated from data collected from sampling grids or along transects over linearly increasing values of *h* (Burgess & Webster, 1980; Burrough, 1991). Semivariance analysis is best suited for refined assessment of spatial variability once rough estimates are available. Hence, nested analysis of variance and semivariance analysis are complementary techniques (Oliver & Webster, 1986, 1987).

Non-spatial statistics, often referred to as classical statistics (Reichardt et al., 1986; Bregt et al., 1987), can also be useful for examining spatial differences. For example, the analysis of variance within and between management units helps to assess whether soils within a management unit can be treated alike and to interpret yield records in terms of agricultural potential.

Oliveira (1972) observed that strongly weathered soils may present considerable variation over relatively short distances. His regular sampling (50 x 50 m grid) of an apparently homogeneous area of 16.5 ha, revealed a complex pattern comprising 2 soil orders, 4 great groups, 13 families and 17 series, as classified according to a preliminary version of the USDA Soil Taxonomy. Reichardt et al. (1986) and Berg & Klamt (1997a,b) presented brief reviews of other studies on spatial variability of strongly weathered soils in Brazil. Most of these studies used classical statistics and those that used geostatistics were at a detailed level (up to some tens of meters). Berg & Klamt (1997a,b) analyzed the spatial patterns of strongly weathered intensively cultivated (soybean/wheat) soils in the region of Passo Fundo (RS) at scales between 50 m and 30 km. The reviewed studies, together with the results of Berg & Klamt (1997a,b) suggest that, as a rule, chemical soil characteristics such as pH, extractable bases and base saturation, show large variability even at very short range (< 5 m). More permanent characteristics like soil texture and CEC show a much more stable spatial pattern, with major variation at large spatial scales (> 1 km). These different spatial levels of soil variability reflect differences in variation of soil forming factors at different scales. Berg & Klamt (1997a,b) suggest that soil management is mainly responsible for variations of chemical surface soil characteristics at very short distance and parent material for soil texture at long distance.

The objectives of this study are: (a) to determine the spatial variation of some properties of strongly weathered soils under sugarcane and soybean/wheat rotation in two regions in São Paulo State and compare results with those obtained by Berg & Klamt (1997a,b) for the Passo Fundo region; and (b) to assess the extent to which land-use (sugarcane vs. soybean/wheat) may influence the spatial variability of soil properties.

MATERIALS AND METHODS

The study regions

The study regions are situated near Assis and Araras (Figure 1). These regions are characterized by the abundance of strongly weathered soils, mapped as Latosols, Podzolics Tb, Quartzose Sands and Dusky Red Earths (Oliveira et al., 1981; Bognola et al., 1996). In both regions, many Latosols present some textural gradient and silt/clay ratio > 0.2, which would provide them with an argillic B horizon according to FAO/UNESCO (1990), and classify as Acrisols and Lixisols (Oliveira & Berg, 1996). The soils with no textural gradient are Ferralsols and ferralic Arenosols. Both regions have intensive agriculture. Major crops are sugarcane and citrus in Araras and sugarcane and soybean/wheat rotation in Assis. More information on soil types is given by Berg & Oliveira (2000), who discussed the relation between soil variability and the quality of existing soil maps in the regions.

Research strategy

The present study was conducted similarly to the study of Berg & Klamt (1997a,b). The following research strategy was adopted:

a) A total of 33 fields (on-farm management units) was selected in the two regions, based on the following criteria: (1) the fields should not have evident (previously mapped or visually observable) soil boundaries within them; (2) they should cover, together, most variability of strongly weathered soils in each region; (3) they must belong to well-managed enterprises; (4) in the Araras region all selected fields have sugarcane, whereas in the Assis region, fields have either sugarcane or soybean/wheat rotation. Information sources for selection were available soil maps (Oliveira et al., 1977; Oliveira et al., 1981; Prado et al., 1981; Souza Dias, 1985) and personal communication.

b) A nested auger sampling was done on part of the fields. The data collected in the field were used for a nested analysis of variance to get a rough idea of soil variability at different spatial scales.

c) An overall, more or less regular, auger sampling was used as a base for semivariance analysis and analysis of variance by field to get a more refined idea of spatial soil variability in the range from 300 to 1.000 m.

Nested sampling

For the nested sampling, seven fields were selected in Araras and four in Assis (Figure 1).

In the region of Araras, sampling was done at four levels, with the fields forming the highest level. Distances between the seven selected fields varied

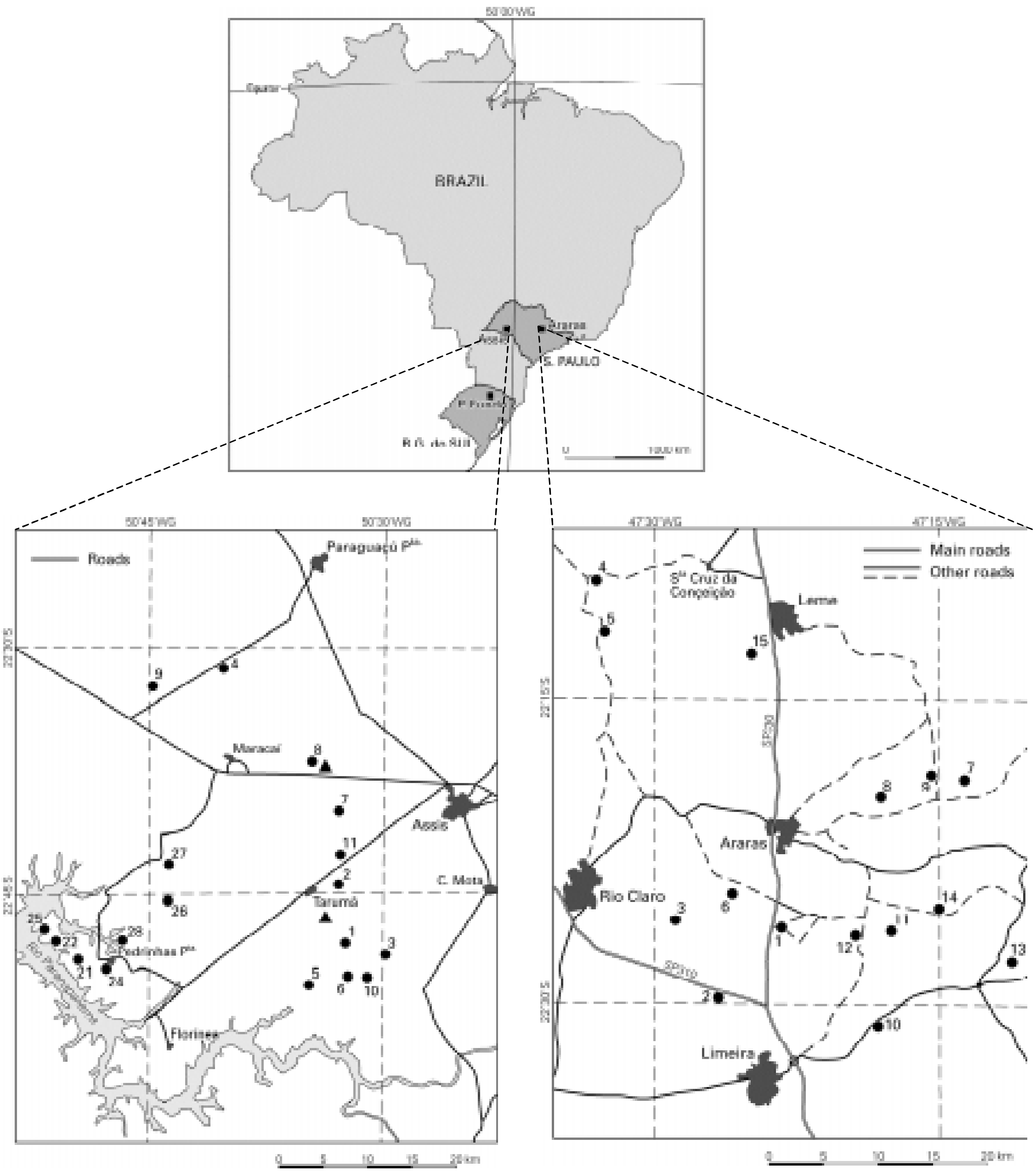

Figure 1. Location of the study regions Araras and Assis and compared study region Passo Fundo (RS) of Berg & Klamt (1997a,b). Study fields in Araras: nested sampling was done in fields 1-6 and 11; overall sampling in fields 1-15. Study fields in Assis: 1- 11: sugarcane fields; 21-28: soybean fields; nested sampling was done in fields 6, 7 and the fields indicated by triangles; overall sampling was done in fields 1-28.

between 3 and 30 km. For the second level, two points were arbitrarily chosen in each field, provided a minimum distance of 500 m between them was kept (the average distance between the points was approximately 600 m). From each point, two other sampling levels were derived with random direction and medium distances of 200 m (third level) and 50 m (fourth level), respectively, so that a total of 7 x 2 x 2 x 2 = 56 sampling points were analyzed. The hierarchy is illustrated in figure 2a, and an example of the layout of sampling sites in one field in figure 2b.

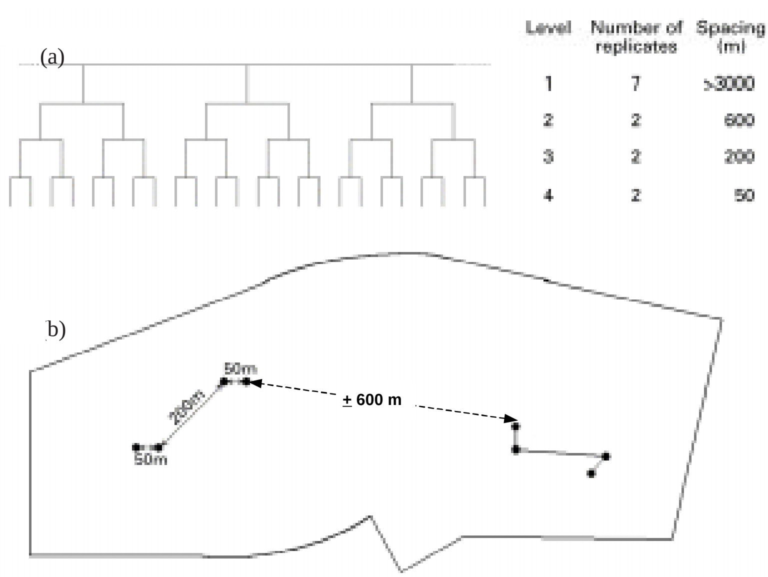

Figure 2. Layout of the nested sampling scheme in Araras and Passo Fundo. (a) Hierarchy of sampling levels; (b) Example of spatial distribution of sampling sites in one field.

A slightly different sampling scheme was used in the Assis region, with five spatial levels, having four fields at the highest level and 2, 2, 2 and three repetitions at distances of 750 m, 350 m, 125 m and 30 m, respectively, so that a total of 4 x 2 x 2 x 2 x 3 = 96 sites were sampled.

At each sampling site, penetrometer resistance was determined and soil samples were collected by auger. Samples from two depths, 0-20 cm and 60-80 cm, were analyzed for colour, clay content and pH.

Representative values for penetrometer resistance were obtained by taking the number of strokes on a penetrometer of impact to penetrate the layers of 0 to 30 cm and 30 to 65 cm in the Araras region, and the layer of 20-40 cm in the Assis region. At each site, six replicates were taken within a square of about 1.5 x 1.5 m. Penetrometer data were standardised to zero mean and unit variance within fields to "neutralise" the influence of rain showers during the field work. Cumulative variance at the 600 m level was considered as 100%. Hence, analysis of spatial variation of penetrometer data is not possible between fields.

Soil colour (Munsell, 1975) was determined on moist samples in the field. Colour hues were transformed to numerical values according to Lepsch et al. (1978): 7.5R = 10, 10R = 20, 2.5YR = 30, 5YR = 40 etc.

Clay contents were estimated in the field by "fingering" and comparison with reference samples. Soil pH (H_2O) values for the Araras region were determined with a pH meter in the laboratory; in the Assis region, the pH was determined in the field, with Bromocresol Green, Bromothymol Blue and Chlorophenol Red indicator fluids (Weast, 1974). The pH was determined without completely drying, crushing and sieving the soil, because a preliminary study had shown that the variance introduced by partly omitting pretreatment of the samples was negligible.

Overall sampling

Field methods

Soil samples were taken by auger, according to a previously designed scheme. Neighbouring sampling sites were 250-300 m apart. This resulted in 6 to 26 sampling sites per field. The distribution of sampling sites was as uniform as possible, but they were not arranged in a regular grid, because the fields were irregularly shaped. Sites in sugarcane fields had to be close to tracks (never closer than 25 m) because of difficult access and orientation in the high and dense sugarcane. In total, 395 sites were sampled by auger up to 100 cm depth and described in the field. Sampling sites were always taken between the plant rows, when present. Samples from two depths were analysed in the laboratory: 0-20 and 60-80 cm. The 60-80 cm layer was chosen to represent the subsurface soil, because it is important for crop growth but relatively little affected by soil management, and to facilitate comparison with the studies of Berg & Klamt (1997a,b), and also with the soil surveys of Oliveira et al. (1977), Oliveira et al. (1981) and Prado et al. (1981), as described by Berg & Oliveira (2000).

Geographical locations (UTM coordinates, m) and elevations above mean sea level (ALT, m) of the sampling sites in the Araras region were read from 1:10.000 topographic maps (Terrafoto, 1978/1980). Coordinates of sites in the Assis region were determined by using 1:50.000 maps (IBGE, 1973/1975), 1:35.000 air photographs (IGC, 1984) and 1:5000 and 1:10.000 maps, provided by the farms.

Slope angles (SL) were estimated in the field with a simple pocket device. This was not possible in fields with a dense stand of sugarcane, so they were estimated from the 1:10.000 and 1:5.000 topographical maps.

Colour hues were transformed into numerical values as described above for the nested sampling.

Laboratory methods

Resin extractable phosphorus was determined according to Raij & Quaggio (1983) by extraction using the "ion exchange resin". Laboratory methods for the following soil properties are described by Camargo et al. (1986): clay content (particle size fraction < 2 µm, g kg^{-1}) with the pipette method, and dispersion with sodium hexametaphosphate and NaOH; pH in soil:solution suspension 1:2.5 1 mol L^{-1} KCl; organic carbon by oxidation with potassium bichromate (slightly modified Walkley-Black); sum of exchangeable bases SB extracted with 1 mol_c L^{-1} NH_4OAc at pH 7. The cation exchange capacity (CEC) was calculated as the sum of SB and potential acidity (H + Al), extracted with 1 mol L^{-1} calcium acetate at pH 7 and titration with 0.1 mol L^{-1} NaOH. The aluminium saturation percentage (m) was calculated as 100% Al/(SB + Al), where Al is exchangeable acidity extracted with 1 mol L^{-1} KCl and titration with 0.1 mol L^{-1} NaOH. The base saturation percentage (V) was calculated as 100% SB/CEC.

Statistical analysis

The module NEST of the PC-GEOSTAT software package (Burrough & Keulen, 1987) was used to compute the nested analysis of variance. SYSTAT (Systat, 1985) was used to calculate averages, variances, skewnesses and kurtoses of the data of the overall sampling; and to execute one-way analysis of variance of soil characteristics within and between fields for the observations of the overall sampling. The percentage of total variance explained by division into fields was calculated as 100% $(1-s_{field}^2/s_{tot}^2)$, where s_{field}^2 is the estimated pooled within-field variance of the variable of interest and s_{tot}^2 refers to the estimated total variance of the same variable in all study fields of the region. The program SEMVAR, adapted from SEMIVA of the PC-GEOSTAT package (Burrough & Keulen, 1987), was used for semivariance analysis. This program determines semivariance (γ) as a function of I_{lag} from all data-pairs between $(I_{lag}-1)*d$ and $I_{lag}*d$ apart, where I_{lag} is an integer value ≥ 1 and d was set to 0.4 km.

RESULTS

Nested analysis of variance

Figures 3 and 4 summarize the results of the nested analysis of variance for the Araras and Assis regions, respectively. The average distances between sampling sites at each level are indicated on the abscissa; the accumulated variances are indicated on the ordinates.

Araras

With the exception of those for penetrometer resistance, the variograms for the Araras region are rather similar: variance increases slightly from the shortest sampling interval (50 m) to 600 m, followed by a considerable increase from the 600 m interval to that between field level. The main difference between the spatial behaviour of the different soil attributes is the variance at the lowest sampling level (nugget variance). The nugget variances are small in relation to total variance for clay content and colour hue, but relatively large for pH, chroma and value.

The variograms for penetrometer resistance of the 0-30 and 30-65 cm layers indicate that all spatial levels contribute to the overall variance. The short range variances are considerable: more than 30% of the within field variance is present within the 1.5 x 1.5 m^2 and more than 60% at the 50 m level.

Assis

Variance of pH in the Assis region (Figure 4) increases continuously with sampling level. Note the differences between results of the 0-20 cm layer and 60-80 cm layer.

Variograms of clay percentage are similar to those of the Araras region. Fields are uniform, but between-field variance is large. A considerable increase of variance is noted from the 350 m to the 750 m level. The highest clay contents were estimated (in the field) at 650 g kg^{-1} in both layers. The soil with least clay had approximately 100 g kg^{-1} clay in the 0-20 cm layer and 160 g kg^{-1} in the 60-80 cm layer.

The studied soils in the Assis region present much less variation in colour than the soils in the Araras region. Colours in Assis range from 10R 2/3 to 2.5YR 3/6 in the 0-20 cm layer and from 10R 3/3 to 2.5YR 4/6 in the 60-80 cm layer.

The variogram of penetrometer resistance shows very large variability at short distance. Fifty percent of the within-field variance is present within 1.5 x 1.5 m^2 and 80% within 30 m distance.

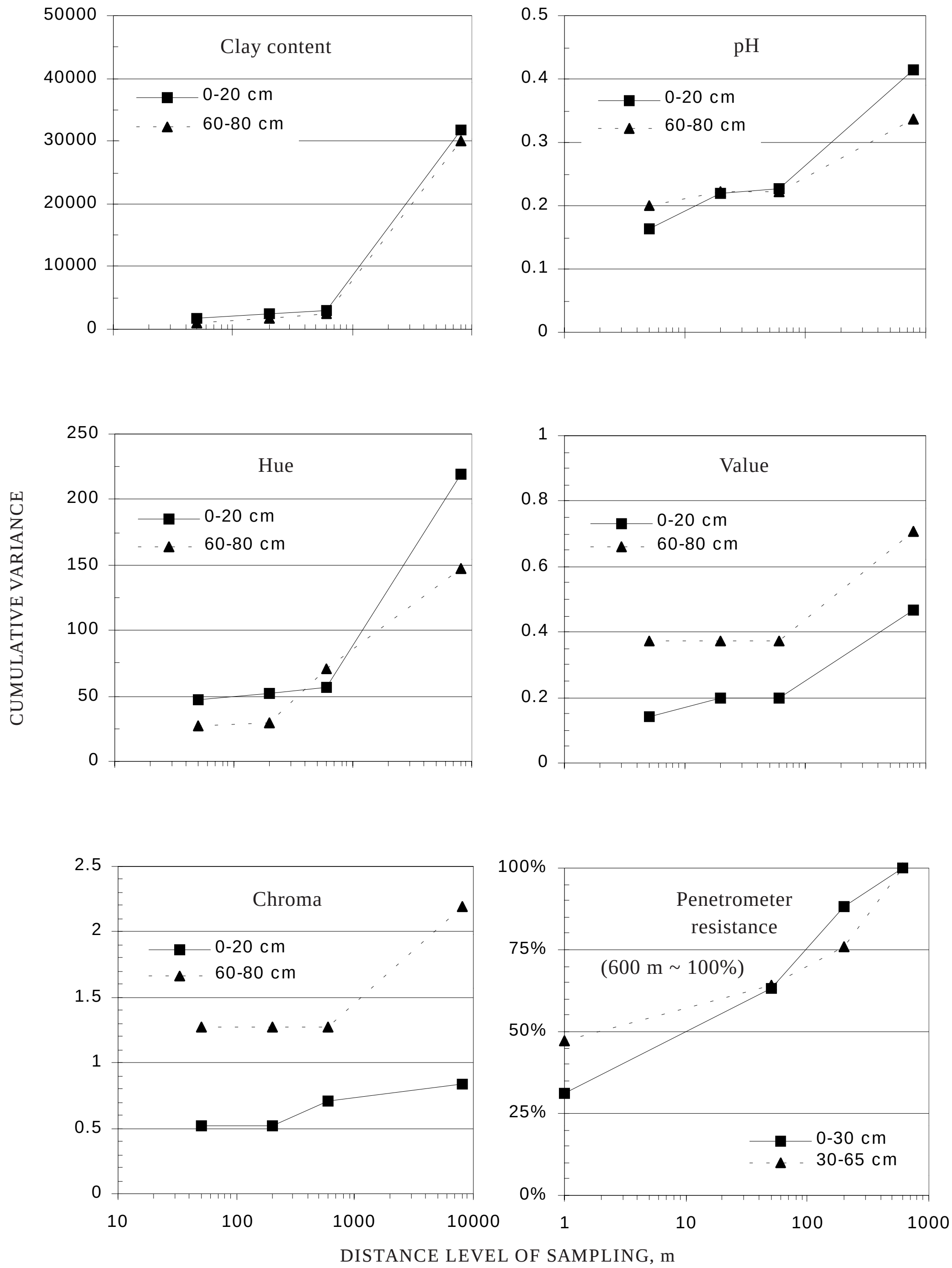

Figure 3. Nested variograms for the Araras region.

Analysis of overall sampling

Statistical analyses of the data of the overall sampling are given in table 1 for the Araras region; in table 2 for the sugarcane fields of the Assis region and in table 3 for the soybean fields of the Assis region.

Araras

General statistics (Table 1, part A). The average Al-saturation (*m%*) is considerably greater in the 60-80 cm layer than in the 0-20 cm layer, whereas V%, C, P, SB and CEC are greater in the upper 20 cm.

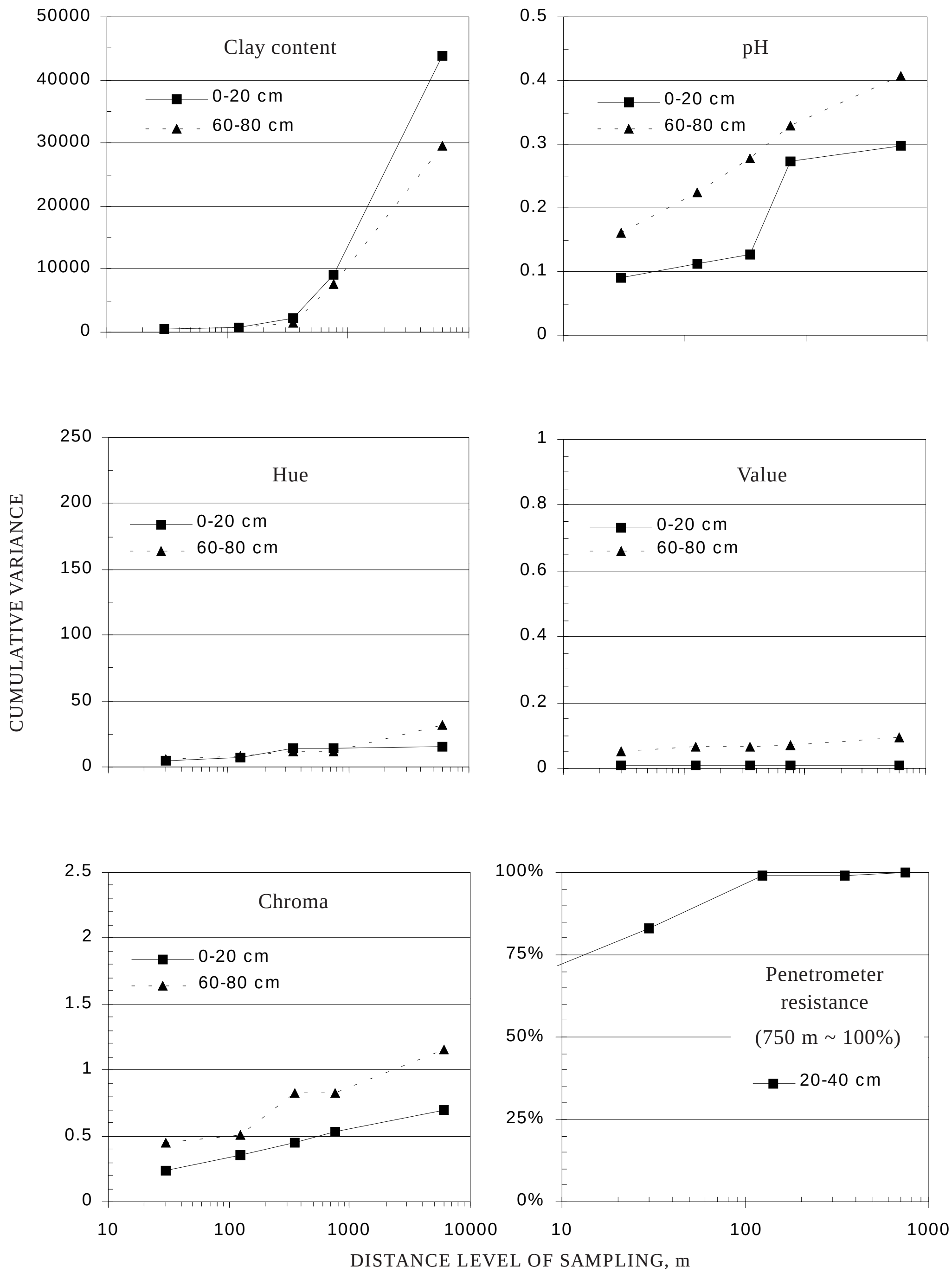

Figure 4. Nested variograms for the Assis region.

Semivariance analysis (Table 1, part B) shows that the bulk of the within-field variance is present within 300 m for all variables, except elevation above mean sea level (ALT) and P content. No spatial structure was detected (in the analyzed range) in most variables of the 60-80 cm layer and in several of the 0-20 cm layer.

Analysis of variance by field. Total variance exceeds within-field variance significantly for all variables, except P of the 60-80 cm layer (Table 1, part C). Division into fields resolved more than 90% of total variance in altitude (ALT) and clay content, and more than 50% of the variance in sum of bases (SB) and cation exchange capacity (CEC) at both

Table 1. Summary of statistical analysis of soil characteristics of the fields in the Araras region (15 fields, 166 sites)

Terrain	Altitude	SL	Colour		Clay	pH	SB	CEC	m	V	C	P
			Hue	Chr		KCl						
	m	cm m^{-1}			g kg^{-1}		— mmol$_c$ kg^{-1} —		—— % ——		g kg^{-1}	mg kg^{-1}
0-20 cm												
A) *General statistics*												
Minimum	607	0	30	1.0	20	3.7	4	9	0	11	2	1
Maximum	790	20	60	6.0	680	6.5	105	142	63	97	26	353
Algebraic mean	672	5	39	3.1	354	4.7	33	66	14	47	12	19
Geometric mean	671	4	39	3.0	283	4.7	25	59	5	42	11	11
B) *Semivariance analysis*												
γ (0.3)	62	7.4	22	0.5	2.3[1]	0.16	145	116	185	204	8	369
γ (0.6)	118	7.4	28	0.4	2.7[1]	0.19	177	145	222	246	10	995
γ (1.0)	206	8.4	37	0.4	3.9[1]	0.22	237	196	251	299	12	561
γ(1.4)	235	8.4	29	0.5	4.6[1]	0.24	299	329	336	284	16	2459
C) *Analysis of variance within and between fields*												
Total Var.	1868	14	50	0.73	38.0[1]	0.32	558	858	310	417	27	1131
field Var.	136	8	31	0.43	3.0[1]	0.20	188	161	226	256	10	919
% Var. explained	93	43	38	41	92	37	66	81	27	39	63	19
D) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	0.6	0.8	0.6	0.1	0.3	0.3	1.1	0.3	1.2	-0.2	0.3	6.0
Kurtosis	0.5	1.7	0.6	0.6	1.5	1.2	3.1	0.8	2.1	1.1	0.7	56.6
Log-transformed data:												
E) *Semivariance analysis*												
γ (0.3)	-	0.30	0.013	0.046	0.067	0.006	0.16	0.046	1.3	0.14	0.12	0.33
γ (0.6)	-	0.36	0.016	0.053	0.052	0.008	0.20	0.046	1.9	0.16	0.13	0.39
γ (1.0)	-	0.41	0.021	0.048	0.048	0.009	0.23	0.048	2.4	0.18	0.14	0.40
γ (1.4)	-	0.58	0.014	0.060	0.036	0.010	0.23	0.063	2.1	0.17	0.19	0.81
F) *Analysis of variance within and between fields*												
Total Var.	3.9'	0.82	0.030	0.088	0.575	0.014	0.59	0.266	3.1	0.25	0.31	0.86
Field Var.	0.29'	0.39	0.017	0.050	0.058	0.008	0.21	0.049	1.9	0.16	0.13	0.41
% Var. explained	93	51	43	43	90	43	64	81	39	36	58	52
G) Skewness, Kurtosis of residuals (measured values – field average)												
Skewness	0.2	-0.1	0.4	-0.8	-0.6	0.2	-0.3	-0.3	0.1	-0.9	-0.6	0.7
Kurtosis	0.3	0.3	0.4	1.9	9.0	0.7	0.7	2.7	0.3	1.8	3.4	2.3
60-80 cm												
A) *General statistics*												
Minimum	-	-	30	1.0	40	3.8	1	6	0	6	0	1
Maximum	-	-	60	8.0	780	6.1	81	137	91	83	22	34
Algebraic mean	-	-	39	4.9	396	4.6	18	47	32	33	6	2.5
Geometric mean	-	-	38	4.6	324	4.5	12	42	13	28	5	1.7
B) *Semivariance analysis*												
γ (0.3)	-	-	20	1.0	2.6[1]	0.10	79	112	227	128	4	10
γ (0.6)	-	-	27	1.4	3.2[1]	0.12	88	145	296	168	7	12
γ (1.0)	-	-	36	1.4	4.3[1]	0.11	78	133	259	177	7	17
γ (1.4)	-	-	36	1.9	4.3[1]	0.06	57	127	162	113	13	9
C) *Analysis of variance within and between fields*												
Total Var.	-	-	47	1.9	45.4[1]	0.24	283	525	699	340	11	15
Field Var.	-	-	30	1.3	3.4[1]	0.11	77	131	256	156	6	14
% Var. explained	-	-	37	32	93	54	73	75	63	54	45	7
D) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	-	0.7	0.2	0.6	1.1	0.8	0.5	-0.5	0.6	0.8	5.0
Kurtosis	-	-	0.9	0.4	2.3	2.7	2.6	1.6	1.4	1.3	2.5	32.0
Log-transformed data:												
E) *Semivariance analysis*												
γ (0.3)	-	-	0.011	0.061	0.056	0.004	0.22	0.065	1.0	0.13	0.20	0.39
γ (0.6)	-	-	0.015	0.066	0.050	0.005	0.25	0.063	1.3	0.17	0.26	0.42
γ (1.0)	-	-	0.020	0.065	0.053	0.005	0.24	0.060	1.3	0.16	0.26	0.39
γ (1.4)	-	-	0.016	0.105	0.032	0.002	0.12	0.043	0.8	0.12	0.39	0.42
F) *Analysis of variance within and between fields*												
Total Var.	-	-	0.027	0.098	0.505	0.011	0.80	0.248	3.3	0.33	0.40	0.51
Field Var.	-	-	0.016	0.068	0.055	0.005	0.23	0.064	1.2	0.16	0.25	0.42
% Var. explained	-	-	41	31	89	55	71	76	64	52	38	18
G) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	-	0.5	-0.7	-0.1	1.0	0.2	-0.5	-0.8	-0.1	-0.6	0.7
Kurtosis	-	-	0.3	2.2	5.6	2.6	1.4	4.1	2.8	0.7	2.8	3.8

(1) Multiply values by 10^3.

Table 2. Summary of statistical analysis of soil characteristics of sugar cane fields in the Assis region (11 fields, 167 sites)

Terrain	Altitude	SL	Colour		Clay	pH	SB	CEC	m	V	C	P
			Hue	Chr		KCl						
	m	cm m^{-1}			g kg^{-1}		— $mmol_c$ kg^{-1} —		—— % ——		g kg^{-1}	mg kg^{-1}
0-20 cm												
A) *General statistics*												
Minimum	370	0	22	2.0	50	4.0	4	16	0	10	3	1
Maximum	566	13	50	4.0	760	6.6	221	243	74	100	31	214
Algebraic mean	460	4	29	3.1	437	4.9	47	72	8	61	13	13
Geometric mean	-	3	29	3.0	334	4.9	34	59	3	58	11	8
B) *Semivariance analysis*												
γ (0.3)	104	3.2	7	0.10	2.9(1)	0.20	678	621	114	231	10	255
γ (0.6)	217	5.2	7	0.10	4.7(1)	0.23	781	662	147	272	11	212
γ (1.0)	327	6.9	8	0.11	6.7(1)	0.22	888	738	107	264	11	115
γ (1.4)	365	12.3	12	0.12	8.8(1)	0.19	1361	1147	103	241	12	91
C) *Analysis of variance within and between fields*												
Total Var.	2775	7.6	8	0.12	68.3(1)	0.26	1408	1878	146	322	42	409
field Var.	237	5.1	5	0.11	4.2(1)	0.23	669	573	118	257	11	308
% Var. explained	91	34	34	12	94	10	52	70	20	20	74	25
D) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-2.8	0.3	5.0	0.6	-2.2	0.7	2.0	2.3	2.4	-0.3	-0.3	-
kurtosis	20.9	1.3	47.1	2.6	17.6	0.8	9.5	12.3	9.2	0.2	4.2	-
Log-transformed data:												
E) *Semivariance analysis*												
γ (0.3)	-	0.32	0.007	0.012	0.031	0.008	0.26	0.069	1.2	0.10	0.059	0.40
γ (0.6)	-	0.51	0.007	0.012	0.046	0.009	0.32	0.082	1.5	0.12	0.070	0.35
γ (1.0)	-	0.61	0.007	0.012	0.064	0.009	0.33	0.104	1.4	0.11	0.078	0.51
γ (1.4)	-	0.78	0.011	0.012	0.076	0.007	0.31	0.099	1.1	0.10	0.062	0.42
F) *Analysis of variance within and between fields*												
Total Var.	-	0.63	0.009	0.014	0.658	0.010	0.71	0.427	1.8	0.129	0.342	0.85
field Var.	-	0.49	0.007	0.012	0.050	0.009	0.28	0.081	1.3	0.105	0.073	0.47
% Var. explained	-	23	19	14	92	9	60	81	29	19	79	45
G) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	-1.0	1.2	0.0	-1.2	0.4	-0.4	0.5	0.2	-1.4	-0.9	-
Kurtosis	-	1.2	12.4	3.4	8.9	0.4	1.9	1.9	-0.4	4.1	2.9	-
60-80 cm												
A) *General statistics*												
Minimum	-	-	26	3.0	100	3.9	0	0.9	0	1	1	0
Maximum	-	-	40	6.0	830	6.1	138	141	97	98	25	51
Algebraic mean	-	-	30	4.1	506	4.7	29	49	26	48	6	4
Geometric mean	-	-	30	4.1	420	4.7	16	42	8	38	6	3
B) *Semivariance analysis*												
γ (0.3)	-	-	2	0.15	1.1(1)	0.14	200	142	145	190	5.7	17
γ (0.6)	-	-	2	0.15	2.0(1)	0.16	257	195	191	259	7.6	15
γ (1.0)	-	-	3	0.12	3.3(1)	0.21	297	193	207	324	8.2	17
γ (1.4)	-	-	3	0.13	4.8(1)	0.19	425	300	99	275	5.6	8
C) *Analysis of variance within and between fields*												
Total Var.	-	-	2	0.20	67.6(1)	0.43	653	647	812	671	12.6	22
field Var.	-	-	2	0.15	2.3(1)	0.16	230	161	203	254	6.6	19
% Var. explained	-	-	18	29	97	62	65	75	75	62	48	11
D) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	-	4.6	1.4	0.2	0.2	1.0	1.0	0.2	0.1	2.6	-
kurtosis	-	-	38.5	8.2	4.4	0.3	3.3	2.8	1.5	-1.5	12.1	-
Log-transformed data:												
E) *Semivariance analysis*												
γ (0.3)	-	-	0.002	0.008	0.009	0.005	0.26	0.044	0.92	0.19	0.083	0.32
γ (0.6)	-	-	0.002	0.008	0.015	0.006	0.35	0.063	1.19	0.20	0.108	0.32
γ (1.0)	-	-	0.003	0.006	0.023	0.008	0.34	0.060	1.33	0.17	0.123	0.41
γ (1.4)	-	-	0.003	0.006	0.024	0.007	0.28	0.072	1.02	0.11	0.086	0.27
F) *Analysis of variance within and between fields*												
Total Var.	-	-	0.003	0.010	0.444	0.019	10.54	0.326	3.26	0.61	0.299	0.48
field Var.	-	-	0.002	0.007	0.018	0.007	0.33	0.053	1.14	0.20	0.104	0.35
% Var. explained	-	-	20	28	96	65	79	84	65	67	65	27
G) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	-	2.6	0.6	0.5	0.7	-0.4	0.1	-0.4	-1.0	-0.1	-
Kurtosis	-	-	19.0	6.1	1.6	4.1	0.4	0.4	1.0	2.7	2.6	-

(1) Multiply values by 10^3.

Table 3. Summary of statistical analysis of soil characteristics of soybean fields in the Assis region (seven fields, 62 sites)

Terrain	Altitude	SL	Colour		Clay	pH	SB	CEC	m	V	C	P
			Hue	Chr		KCl						
	m	cm m^{-1}			g kg^{-1}		— mmol$_c$ kg^{-1} —		—— % ——		g kg^{-1}	mg kg^{-1}
					0-20 cm							
A) *General statistics*												
Minimum	310	0	26	3.0	150	4.6	21	28	0	52	3	3
Maximum	415	8	50	4.0	730	6.9	110	134	9	100	24	93
Algebraic mean	359	3	32	3.4	439	5.6	55	69	1	81	11	34
Geometric mean	-	2	32	3.4	374	5.6	50	62	0	80	10	29
B) *Semivariance analysis*												
γ (0.3)	38	0.6	10	0.09	1.1[(1)]	0.08	93	77	3	43	3	183
γ (0.6)	154	2.2	4	0.07	1.7[(1)]	0.06	122	99	3	39	5	218
γ (1.0)	411	4.8	3	0.05	1.9[(1)]	0.07	200	165	3	41	4	215
C) *Analysis of variance within and between fields*												
Total Var.	1020	7	16	0.17	51.5[(1)]	0.15	542	946	4	124	27	405
field Var.	n.d	2	8	0.08	1.4[(1)]	0.07	111	94	4	42	4	209
% Var. explained	-	70	48	53	97	53	80	90	8	66	87	48
D) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	0.2	0.9	0.3	-1.0	0.4	0.6	1.0	1.6	-0.9	1.3	0.9
kurtosis	-	0.5	3.1	1.0	2.7	1.5	0.7	1.8	4.5	1.2	2.5	0.6
Log-transformed data:												
E) *Semivariance analysis*												
γ (0.3)	-	0.14	0.008	0.007	0.009	0.002	0.03	0.013	0.62	0.008	0.025	0.19
γ (0.6)	-	0.46	0.004	0.006	0.009	0.002	0.03	0.013	0.68	0.007	0.027	0.22
γ (1.0)	-	0.69	0.003	0.004	0.015	0.002	0.04	0.020	0.56	0.007	0.015	0.26
F) *Analysis of variance within and between fields*												
Total Var.	-	1.16	0.013	0.014	0.352	0.005	0.19	0.224	0.77	0.019	0.263	0.40
field Var.	-	0.41	0.007	0.007	0.011	0.002	0.03	0.014	0.68	0.007	0.027	0.22
% Var. explained	-	65	51	54	97	53	84	94	11	63	90	44
G) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	-0.1	0.5	0.2	-0.7	0.0	-0.1	0.5	0.4	-1.1	0.1	-0.6
Kurtosis	-	-1.4	2.0	-1.4	1.5	1.3	-0.3	-0.5	-0.5	1.6	0.1	1.5
					60-80 cm							
A) *General statistics*												
Minimum	-	-	26	3.0	200	3.9	4	13	0	12	2	1
Maximum	-	-	50	6.0	780	6.3	76	93	72	97	11	11
Algebraic mean	-	-	31	4.0	530	5.2	31	46	13	63	5	3
Geometric mean	-	-	31	3.9	489	5.1	25	43	13	58	4	3
B) *Semivariance analysis*												
γ (0.3)	-	-	12	0.26	1.1[(1)]	0.16	98	70	178	234	0.8	1
γ (0.6)	-	-	7	0.26	2.1[(1)]	0.31	177	108	262	418	1.7	2
γ (1.0)	-	-	2	0.16	1.8[(1)]	0.21	183	179	59	174	3.5	5
C) *Analysis of variance within and between fields*												
Total Var.	-	-	14	0.57	40.4[(1)]	0.51	291	242	493	487	3.7	3
field Var.	-	-	10	0.28	1.7[(1)]	0.24	134	95	224	324	1.5	2
% Var. explained	-	-	30	52	96	53	54	61	55	33	59	15
D) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	-	1.8	0.5	-0.8	-0.2	0.6	1.3	1.0	-0.4	1.3	2.4
kurtosis	-	-	6.3	0.3	1.7	0.5	0.9	3.0	2.8	0.0	2.4	8.3
Log-transformed data:												
E) *Semivariance analysis*												
γ (0.3)	-	-	0.010	0.014	0.006	0.006	0.14	0.035	0.9	0.12	0.047	0.12
γ (0.6)	-	-	0.007	0.015	0.011	0.012	0.23	0.038	1.4	0.17	0.058	0.15
γ (1.0)	-	-	0.002	0.010	0.010	0.008	0.10	0.043	0.8	0.05	0.107	0.40
F) *Analysis of variance within and between fields*												
Total Var.	-	-	0.013	0.039	0.180	0.021	0.55	0.13	3.2	0.23	0.184	0.22
field Var.	-	-	0.008	0.015	0.010	0.010	0.18	0.04	1.1	0.15	0.065	0.17
% Var. explained	-	-	34	62	94	55	67	71	66	37	65	21
G) *Skewness, Kurtosis of residuals (measured values – field average)*												
Skewness	-	-	1.0	0.5	-0.5	-0.3	-0.7	-0.1	0.5	-0.7	0.5	0.1
Kurtosis	-	-	3.8	0.1	0.5	0.6	0.6	1.8	0.4	0.9	0.0	-0.2

(1) multiply values by 10^3.

depths; and in organic C content of the 0-20 cm layer and in pH-KCl, base saturation (V%) and Al-saturation (*m%*) of the 60-80 cm layer.

Effect of log transformation. In a number of cases, skewness and kurtosis of the residuals from analysis of variance showed strong deviations from 0 (Table 1, part D). Parts E-G of table 1 show that variables with strongly skewed or kurtic distributions (notably P) obtain a much more normal distribution after log transformation. The variance accounted for by division into fields did not change much for most characteristics. An exception was P (0-20 cm), for which the relative within-field variance was strongly reduced, and the variance accounted for increased from 19 to 52%, probably because of the "smoothing" effect of transformation on outliers.

Assis

General statistics. Part A of tables 2 and 3 show that sugarcane and soybean/wheat fields have soils with similar average CEC and clay and organic C contents, in both analysed layers. Average P-content, pH, and base saturation of the 0-20 cm layer are much higher in the soybean/wheat fields than in the sugarcane fields.

Semivariance analysis. One can verify, from part B of tables 2 and 3, that semivariances of most soil characteristics of the 0-20 cm layer of the soybean/wheat fields are much less than those of the sugarcane fields. Semivariance of the 60-80 cm layer is generally similar for sugarcane and soybean/wheat fields (major exceptions are C-content and P). Results for large lag values show some irregular jumps or falls.

Analysis of variance by field. Part C of table 2 and 3 show that a very large proportion (> 90%) of the variance in clay content is accounted for by the division into fields. It accounts for more than 50% of the variance of slope, SB and CEC of both analysed layers, C content of the 0-20 cm layer and V%, *m%* and pH of the 60-80 cm layer. Note the large differences in variance in pH and V% of the 0-20 cm layer between soils with soybean/wheat rotation and soils with sugarcane.

Effect of log transformation. Several variables have strongly skewed or kurtic distributions (Table 2 and 3, part D). Differences between the 0-20 and 60-80 cm layers become less evident after log transformation (as in the Araras region) because it leads to comparison of relative rather than absolute values. The log transformation seemed appropriate for SB and CEC. For *m%*, V% and C, log transformation produced "more normal" distributions in some cases, but not all.

DISCUSSION

Comparison of nested analysis of variance with semivariance

For the Araras region, semivariance and analysis of variance by field agree well with the nested analysis of variance. This agreement was not as good for the Assis region: results of nested sampling yielded apparently too high estimates for within field variance of clay content and pH (60-80 cm) and for total variance of colour hue (Figure 4); and the semivariograms did not confirm the nested variance "jump", from the 350 to the 750 m level for pH (0-20 cm). Most of these discrepancies are probably due to the limited number of fields analysed by the nested sampling. Recall that only four fields were analysed in Assis and seven in Araras. The increase in variance detected for pH and clay content at the 750 m level in Assis is mainly the result of a single soil border that was detected across one of the fields.

Nevertheless, the general structure of the nested variograms agrees with the semivariograms that are based on a much more intensive sampling. The conclusion is that nested sampling can quickly provide a rough indication of spatial patterns, on which the density of an overall sampling can be based. Nested analysis cannot claim more than that, if only few samples are taken. If a denser sampling is feasible, linear or grid samplings are preferred, because these provide a more uniform cover of the survey area and sites are easier to locate. Corsten & Stein (1991) came to a similar conclusion when comparing results of interpolation in several spatial sampling designs.

Comparison of semivariance with analysis of variance by field

For most characteristics of the study regions, within field variances are very close to the semivariances at lags between 0.3 and 0.6 km. This does not necessarily mean that the range of spatial dependence is somewhere between 0.3 and 0.6 km, because the fields are of limited size. Semivariances for 1.4 km lag in sugarcane fields, and 1.0 km lag in soybean/wheat fields are not reliable. Although the number of data pairs at these lags seems sufficient (Assis: 98 in sugarcane fields, 48 in soybean-wheat fields), there are few truly independent observations (generally about 10), because the data pairs are located close to each other. This causes irregularities in the semivariograms for hue, and *m%* of the 0-20 cm layer (Araras), SB of the 0-20 cm layer (Assis, sugarcane) and pH, *m%*, V% and C of the 60-80 cm layer (Araras). The irregular semivariogram for P (Araras, 0-20 cm) is caused by a few disturbing outliers (note the large maximum value in table 1, part A).

In most cases, the bulk of within field variance was present within the 0.3 km lag. This suggests that, unless very dense sampling schemes are used, little is won by using interpolation methods that consider spatial dependence as proposed by Boucneau et al. (1998) and Rugowski & Wolf (1994). The fields in the present study can almost as well be described in classical terms of average and variance.

Effects of land use on soil properties and their variability

There is little doubt that many differences between the 0-20 and 60-80 cm layers are enhanced by liming and fertilisation that had greater effect on the 0-20 cm layer than on the 60-80 cm layer. Differences in variance between the 0-20 and 60-80 cm layers are also influenced by management: liming has decreased exchangeable Al and Al-saturation (*m*%) of the 0-20 cm layer of fields with acid soils. In this respect, fields have become less different from each other. In the case of pH and V%, variance within sugarcane fields is greater for the 0-20 cm layer than for the 60-80 cm layer, possibly because of uneven distribution of lime. Al saturation tends to decrease to nil, irrespectively of the amount of lime applied, above a threshold value at, say, pH 5.5 whereas pH continues to increase with liming. Hence, the effect of uneven lime application is a relatively large variance of pH and a relatively small variance of Al saturation in the surface layer. Likewise, the within-field variance of P is very large in the surface soil, probably induced by uneven application of fertilizers.

Berg & Klamt (1997b) suggest that short range variability seems to have been induced by soil management. However, variance levels of C-content, V% and CEC reported by Sparovek & Camargo (1997) for soils of a natural remnant forest in the west of São Paulo state are remarkably similar to those of the sugarcane fields in this study. Variance in P was considerably smaller in the forest soils. Sparovek & Camargo (1997) have attributed the large short-range variability of chemical surface soil characteristics in their study to short-range differences in vegetation. Present day soil management apparently imposes modifications on spatial patterns, but this does not necessarily imply that soils under natural vegetation are more homogeneous.

The soybean/wheat fields in this study and in the study of Berg & Klamt (1997a,b) generally have a better base status, higher pH, more P and less variability in the 0-20 cm layer than the sugarcane fields. These differences are probably caused by the more intensive management of soybean/wheat fields, which receive higher lime and P rates, and the smoothing by tillage, twice a year. Tillage of sugarcane fields occurs on average only once in six years. Lime and fertilized are placed in sugarcane fields, whereas they are broadcast in soybean/wheat fields. The relatively small P-contents of the 60-80 cm layer reflect the small natural P content and the immobility of P in the soil, which precludes enrichment from the fertilized topsoil. Large maximum values and semivariance for P at 60-80 cm depth in the sugarcane fields may have been caused by deep ploughing before planting. This may have occasionally contaminated the 60-80 cm layer of sugarcane fields with P-rich topsoil. Deep ploughing is not commonly practised in soybean management.

It must be noted that the comparison of sugarcane fields with soybean/wheat fields above is rather tricky. Study fields in the Assis region were not randomly distributed (Figure 1). Therefore, effects of management may easily be confounded with pedological differences.

Comparison of study regions

Published soil maps of the regions (Oliveira et al., 1977; Oliveira et al., 1981; Prado et al., 1981; Souza Dias, 1985; Bognola et al., 1996) suggest that soil variation is much larger in Araras than in Assis, mainly due to a more complex pattern of contrasting parent materials in the Araras region. Nevertheless, in many cases, the shapes of the nested variograms and semivariograms, and the results of the analysis of variance by field are remarkably similar, and even more so if the log transformed characteristics are compared. Results found in the Passo Fundo (RS) region by Berg & Klamt (1997a,b) also show some interesting similarities, notably with respect to more “permanent” soil characteristics, such as clay content, CEC and organic C content. This suggests that the spatial patterns found may be characteristic of strongly weathered soils of South and South East Brazil, even though the Passo Fundo region shows many differences with respect to climate, physiography, parent materials and soil types. More additional studies are necessary to confirm this hypothesis. Note that there are also some important differences between the regions. For example V%, *m*% and pH of the 60-80 cm layer show a relatively great amount of short distance variability for the soils in Araras and Assis and smaller variability for the Passo Fundo region, where all soils are acid, possibly as a result of its perhumid climate with more intensive leaching. Soil colour shows little variability in Assis and Passo Fundo and relatively large variability in the Araras region, with a considerable component at short distances, which seems to be related with the aforementioned complex pattern of contrasting often reworked parent materials in the Araras region.

Optimization of sampling

Two major spatial levels of soil variability appear to exist in the two regions of this study, and also in the Passo Fundo region studied by Berg & Klamt (1997a,b): (1) long range (> 1 km) spatial variability correlated with interacting climate, parent material, former vegetation and major land use is dominant for “stable” soil characteristics like clay content, C content and CEC; and (2) short range spatial variability which seems to be conditioned by soil management, especially in case of easily modified characteristics of the surface soil. Hence, for surveys at a regional level (say, scale 1:100.000), soils in the three regions can be mapped with the same sampling density, although the amount of unresolved variation may vary between regions. The large nugget variance for colour hue in Araras and pH in Araras and Assis indicate that drawing boundaries between Dark Red and Dusky Red Latosols, or eutrophic and dystrophic soils, entails considerable error. The results of Berg & Klamt (1997a,b) suggest that these groupings can be mapped with little error in Passo Fundo.

Further research is necessary on spatial variation at intermediate range. The results of this study suggest that this is of minor importance, but it may be masked by the large variability at short range. Bulked sampling could possibly be used to level out short-range variation in order to visualize the medium range patterns, which could then be mapped without too much additional cost (see figure 7.1 of Burrough, 1991). Such bulked samples could consist of samples collected within an area of, say, 10 x 10 m^2.

CONCLUSIONS

1. The soil properties clay content, CEC and C content show similar spatial variability structure in the study regions and the previously studied Passo Fundo region. Variability of these characteristics is small at distances up to 1 km or more and large between fields at more than 1 km distance.

2. The soil properties pH, V%, *m*% of the 0-20 cm layer and P of the 60-80 cm layer show a great amount of short distance variability for soils with sugarcane and smaller variability for soils with soybean/wheat rotation. These differences are apparently related to soil management.

3. The soil properties V%, *m*% and pH of the 60-80 cm layer show a relatively great amount of short distance variability for soils in Araras and Assis and smaller variability for the previously studied Passo Fundo region.

4. Soil colour shows relatively large variability in the Araras region, with a considerable component at short distances. The variability of soil colour is small in Assis and Passo Fundo.

5. Regardless of the soil characteristic(s) of interest, a sampling density of 1 per 0.25 km^2 or less (500-1000 m interval between nearest neighbours) is sufficient to resolve the major spatial patterns of strongly weathered soils in the studied areas. Variance of some soil characteristics within mapping units may still be considerable, depending on survey region and soil management. Increasing sampling density to 1 per 0.0025 km^2 (i.e. 50 m intervals) will result in little improvement of the quality of the soil survey.

6. The considerable variance of penetrometer resistance at very short distances (< 1 m) indicates that determinations of soil-water relations, or soil-rootability relations should be made on large soil volumes, or sufficient replicates should be taken to establish adequate average values.

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LITERATURE CITED

BERG, M. van den. Available water capacity in strongly weathered soils of southeast and southern Brazil. In: LATIN AMERICAN CONGRESS OF SOIL SCIENCE: SOLO-SUELO, 13., Águas de Lindóia, 1996. Extended Abstract. Águas de Lindóia, 1996. CD ROM.

BERG, M. van den. Retenção de água nos solos tropicais fortemente meteorizados do sul e sudeste do Brasil. In: SIMPÓSIO DE HIDRÁULICA E RECURSOS HÍDRICOS DOS PAÍSES DE LÍNGUA OFICIAL PORTUGUESA (SILUSBA), 3., Maputo, 1997. Anais. Maputo, 1997. v.2. t.2. p.1-10.

BERG, M. van den & KLAMT, E. Variabilidade espacial de características de solos na região do planalto médio, RS: I. Análise da variância por amostragem aninhada. R. Bras. Ci. Solo, 21:393-399, 1997a.

BERG, M. van den & KLAMT, E. Variabilidade espacial de características de solos na região do planalto médio, RS: II. Análise da semivariância e da variância. R. Bras. Ci. Solo, 21:401-408, 1997b.

BERG, M. van den & OLIVEIRA, J.B. Variability of apparently homogeneous soilscapes in São Paulo State, Brazil: II. Quality of soil maps. R. Bras. Ci. Solo, 24:393-407, 2000.

BOUCNEAU, G.; MEIRVENNE, M. van; THAS, O. & HOFMAN, G. Integrating properties of soil map delineations into ordinary kriging. European J. Soil Sci., 49:213-229, 1998.

BREGT, A.K.; BOUMA, J. & JELLINEK, M. Comparison of thematic maps derived from a soil map and from kriging of point data. Geoderma, 39:281-291, 1987.

BOGNOLA., I.A.; JOAQUIM, A.C.; PRADO, H.; LEPSCH, I.F.; MENK, J.R.F.; JAHEL, T.C.; SOARES, M.R.; MENEZES, F.D. & NOGUEIRA, S.M. Plano Cartográfico do Estado de São Paulo. Carta Pedológica Semidetalhada do Estado de São Paulo: Assis. Secretaria Agricultura e Abastecimento-Instituto Agronômico/Secretaria Economia e Planejamento-IGC, 1996. (Mapa escala 1:100.000)

BURGESS, T.M. & WEBSTER, R. Optimal interpolation and isorithmic mapping of soil properties. I. The semi-variogram and punctual kriging. J. Soil Sci., 31:315-331, 1980.

BURROUGH, P.A. Sampling designs for quantifying map unit composition. In: Spatial variabilities of soils and landforms. Madison, Soil Science Society of America, p.89-125. 1991. (Special publication, 28)

BURROUGH, P.A. Soil variability: A late 20th century view. Soils Fertil., 56:529-562, 1993.

BURROUGH, P.A. & KOOL, J.B. A comparison of statistical techniques for estimating the spatial variability of soil properties in trial fields. In: ISSS WORKING GROUP ON SOIL INFORMATION SYSTEMS, Paris, 1981. Proceedings. Paris, 1981. p.29-37.

BURROUGH, P.A. & KEULEN, J. van. PC-GEOSTAT - a set of programs for geostatistical analysis. Utrecht, University of Utrecht, Dept. of Physical Geography, 1987. 123p.

CAMARGO, O.A.; MONIZ, A.C.; JORGE, J.A. & VALADARES, J.M.A.S. Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas. Instituto Agronômico de Campinas, 1986. 94p. (Boletim técnico,106)

CORSTEN, L.C.A. & STEIN, A. Are nested designs recommendable for spatial semivariogram estimation? In: STEIN, A. Spatial Interpolation. Wageningen, Agricultural University, 1991. p.41-70. (Tese de Doutorado)

FAO/UNESCO. Soil map of the world, Revised Legend (reprinted with corrections). Rome, 1990. 119p. (World Soil Resources Report, 60)

HARRADINE, F.F. The variability of soil properties in relation to stage of profile development. Proc. Soil Sci. Soc. Am., 14:302-311, 1949.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE. Carta do Brasil, Escala 1:50.000. Secretaria de Planejamento da Presidência da Republica, IBGE-Superintendencia de cartografia; departamento de cartografia. Folhas: SF-22-Z-A-IV-2, SF-22-Z-A-IV-3, SF-22-Z-A-IV-4, SF0-22-Z-A-V-3, 1973/1975.

INSTITUTO GEOGRÁFICO E CARTOGRÁFICO - IGC. Levantamento areofotográfico, região Marília, Escala 1:35.000. SEP/CAR/IGC, 0.486, 09/84: FX15, fotos 14,20,22; FX 16, fotos 10,11, 1984.

ISAAKS, E.H. & SRIVASTAVA, R.M. An introduction to applied geostatistics. New York, Oxford University Press, 1989. 561p.

LEPSCH, I.F.; MENK, J.R.F.; OLIVEIRA, J.B.; SILVA, O.A.L.; MASSON, W. & BORDONI, O. Apoio Computacional em levantamento de solos. Campinas, Instituto Agronômico, 1978. 44p. (Boletim, 210)

MUNSELL. Munsell Soil Colour Charts. Baltimore, Munsell Color Company, 1975.

NORTCLIFF, S. Soil variability and reconaissance soil mapping: A statistical study in Norfolk. J. Soil Sci., 29:403-418, 1978.

OLIVEIRA, J.B. Variação de características morfológicas, físicas, químicas e mineralógicas em duas áreas de Oxissolo. Piracicaba, Escola Superior de Agricultura Luiz de Queiroz, 1972. 199 p. (Tese de Doutorado)

OLIVEIRA, J.B.; MENK, J.R.F. & ROTTA, C.L. Levantamento pedológico semidetalhado do estado de São Paulo: Quadrícula de Campinas. Rio de Janeiro, IBGE, 1977. mapa 1:100.000.

OLIVEIRA, J.B.; MENK, J.R.F.; BARBIERI, J.L.; ROTTA, C.L. & TREMOCOLDI, W.A. Levantamento pedológico semidetalhado do Estado de São Paulo: Quadrícula de Araras. Rio de Janeiro, Aerofoto Cruzeiro, 1981. mapa 1:100.000.

OLIVEIRA, J.B. & BERG, M. van den. Relation between the Soil Units of the FAO-UNESCO Soil map of the world Legend and the soil classes used in Brazilian surveys. Wageningen, International Soil Reference and Information Centre (ISRIC), 1996. 57p. (Technical Paper, 29)

OLIVER, M.A. & WEBSTER, R. Combining nested and linear sampling for determining the scale and form of spatial variation of regionalized variables. Geog. Anal., 18:227-242, 1986.

OLIVER, M.A. & WEBSTER, R. The elucidation of soil pattern in the Wyre forest of the West Midlands, England. II. Spatial distribution. J. Soil Sci., 38:279-307, 1987.

PRADO, H.; OLIVEIRA, J.B. & ALMEIDA, C.L.F. Levantamento pedológico semidetalhado do Estado de São Paulo: Quadrícula de São Carlos. Rio de Janeiro, Aerofoto Cruzeiro, 1981. mapa 1:100.000.

RAIJ, B. van & QUAGGIO, J.A. Métodos de análise de solo para fins de fertilidade. Campinas, Instituto Agronômico, 1983. 31p. (Boletim técnico, 81)

REICHARDT, K.; VIEIRA, S.R. & LIBARDI, P.L. Variabilidade espacial de solos e experimentação de campo. R. Bras. Ci. Solo, 10:1-6, 1986.

RUGOWSKI, A.S. & WOLF, J.K. Incorporating variability into soil map unit delineations. Soil Sci. Soc. Am. J., 58:163-174, 1994.

SOUZA DIAS, H. Mapeamento de solos da C.A.N.A. Assis, Cia. Agrícola Nova América, 1985. Mapa 1:50.000.

SPAROVEK, G. & CAMARGO, O.A. Sampling strategies for tropical forest nutrient cycling studies: A case study in São Paulo, Brazil. R. Bras. Ci. Solo, 21:635-642, 1997.

SYSTAT INC. Systat, the system for statistics. Version 2. Evanston, Systat Inc., 1985.

TERRAFOTO. Plano cartográfico do Estado de São Paulo. Secretaria de Economia e Planejamento, Coordenadoria de ação regional, divisão de Geografia. Execução Terrafoto S.A., atividades de aerolevantamento. Escala 1:10.000, 1978/1980.

WEAST, R.C., ed. Handbook of Chemistry and Physics, 55th edition. Cleveland, CRC Press, 1974. p.D115-116.

WEBSTER, R. Quantitative spatial analysis of soil in the field. Adv. Soil Sci., 3:1-70, 1985.

WEBSTER, R. & OLIVER, M.A. Statistical methods in soil and land resources survey. Oxford, Oxford University Press, 1990. 316p.