SEÇÃO I - FÍSICA DO SOLO

SPATIAL VARIABILITY OF PHYSICAL ATTRIBUTES OF AN ALFISOL UNDER DIFFERENT HILLSLOPE CURVATURES[1]

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SUMMARY

The influence of relief forms has been studied by several authors and explains the variability in the soil attributes of a landscape. Soil physical attributes depend on relief forms, and their assessment is important in mechanized agricultural systems, such as of sugarcane. This study aimed to characterize the spatial variability in the physical soil attributes and their relationship to the hillslope curvatures in an Alfisol developed from sandstone and growing sugarcane. Grids of 100 x 100 m were delimited in a convex and a concave area. The grids had a regular spacing of 10 x 10 m, and the crossing points of this spacing determined a total of 121 georeferenced sampling points. Samples were collected to determine the physical attributes related to soil aggregates, porosity, bulk density, resistance to penetration and moisture within the 0–0.2 and 0.2–0.4 m depth. Statistical analyses, geostatistics and Student's t-tests were performed with the means of the areas. All attributes, except aggregates > 2 mm in the 0–0.2 m depth and macroporosity at both depths, showed significant differences between the hillslope curvatures. The convex area showed the highest values of the mean weighted diameter, mean geometric diameter, aggregates > 2 mm, 1–2 mm aggregates, total porosity and moisture and lower values of bulk density and resistance to penetration in both depth compared to the concave area. The number of soil attributes with greater spatial variability was higher in the concave area.

Index terms: soil-landscape relationship, geostatistics, semivariogram.

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RESUMO: *VARIABILIDADE ESPACIAL DE ATRIBUTOS FÍSICOS DE UM ARGISSOLO SOB DIFERENTES CURVATURAS DO RELEVO*

A influência das formas do relevo tem sido estudada por diversos autores e explica a variabilidade dos atributos do solo na paisagem. Os atributos físicos do solo são dependentes das formas do relevo, e a avaliação desses atributos é importante em sistemas mecanizados como o da cultura de cana-de-açúcar. O presente estudo teve como objetivo caracterizar a variabilidade espacial dos atributos físicos de Argissolos desenvolvidos de arenito e cultivados com cana-de-açúcar bem como a relação desses com as curvaturas do relevo. Uma malha de dimensão de 100 x 100 m foi delimitada em uma área caracterizada pela forma convexa e outra em uma área caracterizada pela forma côncava. As malhas tinham espaçamento regular de 10 x 10 m, e os pontos de cruzamento desse espaçamento determinaram os pontos de coleta das amostras, num total de 121 pontos amostrais georreferenciados. Amostras foram coletadas para determinação dos atributos físicos: agregados, porosidade, densidade do solo, resistência à penetração e umidade nas profundidades 0,00–0,20 e 0,20–0,40 m. Foram realizadas análises estatísticas e geoestatísticas. Todos os atributos, com exceção dos agregados > 2 mm na profundidade de 0,00–0,20 m e dos macroporos nas duas profundidades, apresentaram diferença significativa entre as curvaturas. A área convexa apresentou os maiores valores de diâmetro médio ponderado, diâmetro médio geométrico, agregados > 2 mm, agregados de 2–1 mm, volume total de poros e umidade e os menores valores de densidade do solo e resistência à penetração nas duas profundidades estudadas, em relação à área côncava. A área côncava apresentou maior número de atributos do solo com maior variabilidade espacial.

Termos de indexação: relação solo-paisagem, agregados, densidade do solo, porosidade, geoestatística, semivariograma.

INTRODUCTION

Several studies have reported the influence of the landscape on the variability of soil physical attributes and its relationship with plant growth (Pennock et al., 2001; Rezaei & Gilkes, 2005; Terra et al., 2006). The relief is an independent and major soil formation factor (Jenny, 1941) that determines the soil distribution in the landscape (Bockheim et al., 2005). Therefore, its participation in soil formation can be studied apart. Landscape attributes such as curvatures and slopes, among others, influence the hydrological conditions, resulting in different moisture and water flow patterns. In studies by Seibert et al. (2007), the influence of topography on the formation of different soil types mediated by hydrological processes was characterized, and this influence can possibly be understood and predicted through the use of soil physical attributes (Mello et al., 2007).

The adoption of highly mechanized cultivation and harvesting techniques in sugarcane plantations has provoked alterations in the behavior of soil physical attributes and in the sugarcane yields (Souza et al., 2004a,b). The main effect of mechanization is soil compaction, and further studies to evaluate this process are necessary to optimize crop production. The evaluation of soil physical attributes is important to diagnose the degree of compaction and guide the physical soil management.

In studies to diagnose the soil physical state of a landscape, some authors have found that the spatial variability in soil physical attributes is related to the landscape forms (Souza et al., 2004a; Brito et al., 2006; Camargo et al., 2008). The potential of soil degradation by a management varies according to the location of the landscape and the spatial distribution of landscape attributes (Cambardella et al., 2004; Pennock, 2003). Soares et al. (2005) affirmed that, to understand the temporal variation in the soil physical attributes, it is necessary to consider vertical and lateral variations (along the toposequence). Juhász et al. (2006) concluded that the physical-hydric behavior of the studied soil is influenced by landscape conditions.

Campos et al. (2006) emphasized the importance of landscape models to understand the soil-geomorphology relationships. The same authors reported on the model established by Troeh (1965), which is based on relief profiles and hillslope curvatures in which the pedoforms vary from linear over convex to concave. Nizeyimana & Bicki (1992), Pennock et al. (2001), De Alba et al. (2004), Montanari et al. (2005), Van Oost et al. (2005), and Brito et al. (2006) studied the relationships between the spatial variability in soil attributes and terrain curvature.

The dependence and spatial variability of soil attributes can be characterized by geostatistical analyses. These analyses involve mainly the semivariogram, which is the estimation and modeling of the spatial variance structure, and kriging, which is the prediction of regionalized variable values of unsampled points or regions (Vieira, 2000).

The spatial variability of aggregate stability and organic matter in an Oxisol was explained by Souza et al. (2004a) by small variations in the slope gradient and in relief forms. The spatial dependence of stable aggregates was observed in an Oxisol studied by Camargo et al. (2008) and was spatially correlated to the clay fraction mineralogy. Zanette et al. (2007) evaluated the spatial moisture variability of a Hapludox and found values for this attribute ranging from 5.20 to 10.67 m. The authors reported that no spatial dependence was observed in the studied attribute in deeper depths.

Geoestatistical analyses also make the determination possible of intensity and form of attribute sampling because the semivariogram range values indicate the ideal sampling distance (Vieira et al., 1992). In this case, attributes with larger range values require a smaller sample quantity than attributes with lower range values. However, in the absence of spatial dependence, classical statistics are applied (Silva et al., 1989).

The objective of this study was to characterize the spatial variability of physical attributes of a sugarcane-cultivated Alfisol developed from sandstone and the relationship between these attributes and hillslope curvatures.

MATERIAL AND METHODS

The study area is located in Catanduva, state of São Paulo (latitude 21°05’57.11"S and longitude 49 ° 01 ’ 02.08 ” W). The regional climate, according to Köppen’s classification, is tropical hot humid, type Aw, with dry winters. The average precipitation is 1,350 mm, and the average annual temperature 23 °C. The temperature in the hottest month is > 22 °C and in the coldest month < 18 °C. The principal vegetation types in the Catanduva region are seasonal rainforest and cerrado (savanna-like), and the current predominant land use in the region for over 20 years was sugarcane cultivation, in a harvest system that includes burning.

The soils, classified as a Typic Hapludalf (Soil Survey Staff, 1999) with medium texture, are derived from weathering sedimentary sandy rocks from the Bauru Group, Adamantina Formation (IPT, 1981). The studied area was characterized with aerial pictures of the elevation profile of the region at a scale of 1:35,000, and the fields were classified by geomorphological and pedological classifications.

To identify the relief forms according to Troeh (1965), a 200 ha area was mapped using the Global Positioning System (GPS) equipment. Coordinates and altimetry were used to construct a digital elevation model (DEM) using the Surfer program (1999) (Figure 1). The field and DEM observations allowed the identification of two areas of interest, one a convex and the other a concave hillslope area. In the DEM area (Figure 1), arrows indicate the intensity and surface water flow, illustrating the slope modeling and, consequently, the water flow distribution pattern. In the concave area, the water flow is heterogeneous and has a disorganized distribution pattern, whereas in the convex area, this distribution pattern is homogeneous and organized. The granulometric and chemical characterizations of the hillslope curvatures are presented in Table 1.

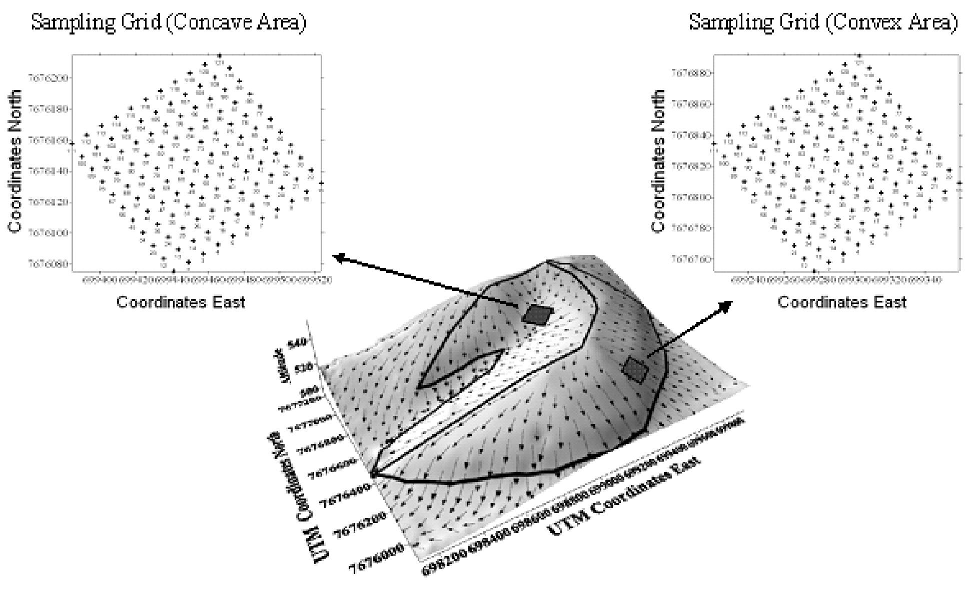

Figure 1. Digital Elevation Model (DEM) of the study area. Arrows indicate land modeling and water flow.

Table 1. Granulometric, chemical and A+E thickness horizon attributes of the convex and concave hillslope curvatures (an average 121 points in each area)

Depth	Clay	Silt	Sand	OM	pH $CaCl_2$	SB	CEC	V	Total Fe	A+E thickness horizon
m	g kg^{-1}			g dm^{-3}		mmol$_c$ dm^{-3}		%	g kg^{-1}	m
					Convex Area					
0.0 to 0.2	190	43	784	15	5.1	28	53	52	0.4	0.30
0.2 to 0.4	218	50	732	11	4.5	32	61	54	---	
					Concave area					
0.0 to 0.2	171	35	796	13	4.8	29	52	56	0.2	0.39
0.2 to 0.4	187	73	740	10	4.2	36	63	57	---	

OM: organic matter; SB: sum of bases; V: base saturation; CEC cation exchange capacity; Fe total: Fe extracted with sulfuric acid. Adapted from Guisardi (2003), Barbieri (2007) and Sanchez (2007).

Two grids (100 x 100 m) were installed at locations representing each of the areas. The grids had a regular spacing of 10 x 10 m, and the intersections of this spacing determined the sampling points, amounting to a total of 121 georeferenced sampling points. Trenches (0.3 x 0.3 m, 0.5 m deep) were opened for the collection of undisturbed soil samples in volumetric rings and disturbed soil samples. The samples were collected at depths of 0–0.2 and 0.2–0.4 m.

The collected samples were crumbled and left to dry in the shade. One part of the soil was sieved in a 9.51 mm diameter grid sieve for aggregate analysis, and the other part was sieved in a 2.0 mm sieve. Aggregate size and stability were determined using the method described by Kemper & Chepil (1965). The aggregates retained in the 4.76 mm sieve were subjected to slow pre-moistening by atomizing with distilled water and afterwards shaken for 15 min in a set of sieves with 2.0, 1.0, 0.5, 0.25, 0.125 and 0.105 mm mesh in a water-filled container. The material retained in each sieve was heated to 105 ^{o}C in an oven. Based on the obtained results, the mean geometric diameter (MGD) and the mean weighted diameter (MWD) were calculated.

In order to determine soil porosity (total porosity, macropores and micropores), the undisturbed samples were saturated for 48 h in a tray with water filling two-thirds the height of the soil ring. After the saturation period, the samples were drained at a pressure of -0.006 MPa using a tension table (Embrapa, 1997). In the same samples, bulk density was determined with the volumetric ring method according to Embrapa (1997), as well as moisture. The soil resistance to penetration was field-determined at each grid point using an model IAA/Planalsucar impact penetrometer, and the values were calculated according to Stolf (1991).

The laboratory analysis results were subjected to descriptive statistical analyses. For the evaluation of the difference between mean values of the attributes between the areas, the Student's t-test was applied. All results were obtained using the MINITAB 14 statistical package (Minitab, 2000).

For the spatial dependence analysis geostatistical techniques were used (Vieira et al., 2000). The semivariograms were estimated under the hypothesis of intrinsic stationarity, and a mathematical model was adjusted for those that showed spatial dependence. The semivariogram is a graph that characterizes the spatial dependence structure of a variable (or of variables) under study. The semivariogram can be defined as a function that connects the semivariance with the distance vector, and can be analytically and/or graphically represented. It is estimated by the following equation:

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

where N (h) is the number of experimental data pairs separated by vector h, and Z represents the measured values for soil or crop attributes. The semivariogram is normally represented by the graph of γ (h) versus h. The program GS+ was used for spatial dependence evaluation (Gamma Design Software, 1998).

RESULTS AND DISCUSSION

The value distribution of most of the studied attributes was symmetric, with skewness and kurtosis values of approximately zero; the mean and median values were very close to each other (Tables 2 and 3). Exceptions were aggregates between 1–2 mm (at both depths), MWD, aggregates > 2 mm from the convex area and attributes of aggregates in the concave area at both depths other than aggregates between 1–2 mm in the 0–0.2 m depth.

Table 2. Descriptive statistics of attributes of the convex area: mean weighted diameter (MWD), mean geometric diameter (MGD), aggregates > 2 mm (> 2 mm), aggregates 1–2 mm (1–2 mm) and aggregates < 1 mm (< 1 mm), micropores (micro), macropores (macro), total pore volume (TPV), bulk density (Bd), resistance to penetration (RP) and moisture (MO) in the 0–0.2 and 0.2–0.4 m depth

	Mean	Median	Var.	Max.	Min.	Asymmetry	Kurtosis	SD [(1)]	CV [(2)]	*p* [(3)]
					0.00-0.20 m					
MWD (mm)	0.71	0.63	0.08	1.46	0.25	1.09	0.79	0.27	39.0	0.00
MGD (mm)	0.65	0.64	0.01	0.87	0.48	0.31	-0.43	0.09	13.5	0.15
> 2 mm (%)	14.20	10.75	88.10	43.58	1.34	1.09	0.52	9.39	66.1	0.00
1-2 mm (%)	7.35	6.16	20.45	24.61	0.91	1.43	2.27	4.52	61.5	0.00
< 1 mm (%)	78.45	80.64	117.9	95.20	51.4	-0.64	-0.41	10.86	13.8	0.00
Micro (%)	22.75	22.85	12.26	31.59	15.4	0.07	-0.49	3.502	15.4	0.51
Macro (%)	14.31	13.87	20.62	24.96	3.94	0.19	-0.34	4.541	31.7	0.05
TPV (%)	37.04	36.95	9.77	44.41	31.0	0.13	-0.63	3.12	8.44	0.51
Bd (g cm^{-3})	1.46	1.46	0.008	1.65	1.28	0.01	-0.71	0.09	6.18	0.42
RP (MPa)	1.77	1.73	0.36	3.20	0.70	0.34	-0.70	0.60	34.1	0.04
MO (%)	15.07	15.01	1.90	18.67	12.0	0.36	0.10	1.38	9.16	0.28
					0.20-0.40 m					
MDW (mm)	0.62	0.56	0.05	1.52	0.24	1.53	3.20	0.23	36.5	0.00
MGD (mm)	0.63	0.64	0.01	0.85	0.47	0.40	-0.11	0.08	11.9	0.18
> 2 mm (%)	10.78	8.92	64.43	44.00	0.40	1.48	2.48	803	74.5	0.00
1-2 mm (%)	7.95	6.76	23.92	25.79	0.74	1.19	1.76	4.89	61.5	0.00
< 1 mm (%)	81.27	83.50	107.7	97.58	51.2	-0.78	0.01	10.38	12.8	0.00
Micro (%)	23.01	22.49	17.84	32.82	14.4	0.46	-0.30	4.224	18.3	0.01
Macro (%)	13.64	14.05	19.53	23.33	3.00	-0.38	0.23	4.419	32.4	0.08
TPV (%)	36.63	36.12	9.20	45.89	30.7	0.81	0.77	3.03	8.3	0.00
Bd (g cm^{-3})	1.49	1.48	0.008	1.81	1.25	0.61	1.78	0.09	6.1	0.00
RP (MPa)	3.67	3.69	0.99	6.31	1.60	0.15	-0.25	0.99	27.1	0.09
MO (%)	15.25	15.18	2.27	19.25	11.8	0.24	0.19	1.51	9.89	0.43

[(1)] Standard deviation. [(2)] Coefficient of Variation (%). [(3)] Anderson-Darling normality test ($p > 0.05$ normal data distribution). Var.: variance, Min.: minimum, Max.: maximum.

Data normality is not a requirement for the application of geostatistical techniques; however, it is recommended that the distribution tails should not be overly long. The coefficient-of-variation values (CV) (Tables 2 and 3) of attributes varied between low (< 12 %), average (12–24 %) and high (> 24 %), according to the classification proposed by Warrick & Nielsen (1980). The high values of this estimate reveal the need for an evaluation that allows a better understanding of the data variation. The CV estimate is a helpful technique in the evaluation of attribute variability used to determine the minimum sampling number (Cline 1944; Montanari et al., 2005). However, it does not permit the evaluation of the spatial dependence of attributes that are verified, among others, by geostatistical techniques.

It was observed that the mean attributes values that determine aggregate stability, i.e., the mean weighted diameter (MWD) and mean geometric diameter (MGD), were highest in the 0–0.2 m depth (Tables 2 and 3).

The TPV and macropore values were greater in the surface depth. In this study the macropore values, in both areas and depths, were between 13.29 and 14.31 % higher than the 10 % considered the minimum for plant growth (Drewry & Paton, 2005; Drewry et al., 2006; Reynolds et al., 2008).

The Bd values were close to the values found by Araújo et al. (2004) in a recently cleared and burned area. In Ultisol with 45 % clay, Falleiro et al. (2003) found mean Bd values between 1.14 to 1.37 g cm^{-3} and reported that the lowest values observed for to conventional tillage were a consequence of soil turning, aimed mainly at an increase in porosity.

In the convex area, where the relative Bd values were lowest, the resistance-to-penetration values (RP) were also lowest and moisture highest (in both depths). These results agree with those reported by Lampurlanés & Cantero-Martinez (2003). Lima et al. (2006) stated that, according to the significant correlation found between moisture, resistance to penetration and pre-consolidation pressure, the Ultisol load capacity can be estimated by its resistance to penetration, confirming the importance of this attribute in the evaluation of the physical soil qualities. The mean RP values, in the 0–0.2 m depth in both areas, were above the critical value for root growth (3 MPa), according to Lipiec & Håkansson (2000).

The mean values of the studied attributes were compared to the values reported in the literature, and it was observed that they were not different from values found in Brazilian Alfisol and Ultisol. However, a range of maximum and minimum values

Table 3. Descriptive statistics of attributes in the concave area: mean weighted diameter (MWD), mean geometric diameter (MGD), aggregates > 2 mm (> 2 mm), aggregates 1–2 mm (1–2 mm) and aggregates < 1 mm (< 1 mm), micropores (micro), macropores (macro), total pore volume (TPV), bulk density (Bd), resistance to penetration (RP) and moisture (MO) in the 0–0.2 and 0.2–0.4 m depths

	Mean	Median	Var.	Max.	Min.	Asymmetry	Kurtosis	SD [(1)]	CV [(2)]	*p* [(3)]
					0.00-0.20 m					
MWD (mm)	0.58	0.48	0.11	2.60	0.22	3.16	14.24	0.33	57.2	0.005
MGD (mm)	0.56	0.54	0.01	1.23	0.45	3.59	19.98	0.10	17.5	0.005
> 2 mm (%)	12.56	9.48	91.99	64.90	2.16	2.48	9.12	9.59	76.4	0.005
1-2 mm (%)	2.84	2.60	2.13	6.98	0.29	0.67	-0.03	1.46	51.5	0.005
< 1 mm (%)	84.60	86.94	102.3	97.16	30.2	-2.25	7.97	10.12	12	0.005
Micro (%)	21.52	21.43	17.47	33.13	10.1	-0.17	0.50	4.18	19.4	0.063
Macro (%)	13.45	12.33	19.39	27.40	7.52	0.98	0.54	4.40	32.7	0.005
TPV (%)	35.03	34.30	15.28	45.06	25.4	0.52	-0.03	3.90	11.2	0.007
Bd (g cm^{-3})	1.52	1.52	0.014	1.88	1.28	0.68	0.97	0.12	7.9	0.006
RP (MPa)	2.54	2.51	0.65	4.93	0.55	0.31	0.02	0.80	31.7	0.410
MO (%)	13.16	12.94	3.07	17.87	9.28	0.69	0.54	1.75	13.3	0.005
					0.20-0.40 m					
MDW (mm)	0.45	0.40	0.05	1.42	0.18	1.99	5.51	0.22	48.2	0.005
MGD (mm)	0.53	0.52	0.01	0.85	0.43	1.49	3.61	0.07	13.3	0.005
> 2 mm (%)	8.17	6.38	48.01	39.46	0.62	2.24	6.32	6.93	84.8	0.005
1-2 mm (%)	3.03	2.35	5.469	12.22	0.20	1.65	3.11	2.33	77.1	0.005
< 1 mm (%)	88.53	90.84	80.45	98.97	37.5	-2.40	9.06	8.97	10.3	0.005
Micro (%)	19.27	19.20	9.561	28.66	11.1	-0.05	0.61	3.09	16.0	0.071
Macro (%)	13.29	12.56	16.59	24.57	6.30	0.62	-0.49	4.07	30.6	0.005
TPV (%)	32.53	32.37	9.14	40.98	26.9	0.48	0.14	3.02	9.30	0.195
Bd (g cm^{-3})	1.53	1.53	0.01	1.76	1.34	0.13	0.20	0.07	5.13	0.508
RP (MPa)	4.80	5.06	5.08	10.13	0.55	-0.25	-0.18	2.25	46.9	0.005
MO (%)	13.35	13.12	2.60	17.48	9.79	0.35	-0.19	1.612	12.1	0.110

[(1)] Standard deviation. [(2)] Coefficient of Variation (%). [(3)] Anderson-Darling normality test ($p > 0.05$ normal distribution of data). Var.: variance, Min.: minimum, Max.: maximum.

were observed (Tables 2 and 3) which, for some attributes, were not within the interval cited by national and international authors. This fact, together with the high attribute variation (CV), suggests the need for a spatial variability analysis.

It is emphasized that the evaluation of soil attributes revealed aspects such as mobility of water and air in the soil, which affects root growth and makes soil susceptible to compaction. The existence of a range of values for these attributes indicates that the average values do not represent the spatial activity in the area. This aspect is important for the planning of local soil management and indicates that an analysis of the spatial variability of attributes is required.

The Student's t-test results (Table 4) revealed a significant difference (5 %) in the attributes means between the convex and concave areas at the two studied depths, with the exception of the percentage of aggregates > 2 mm in the 0–0.2 m depth and macropores at both studied depths.

It was observed that, in the convex area, there were greater values for the MWD, MGD and percentages of aggregates > 2 mm and between 1–2 mm, TPV and moisture and lowest Bd and RP values in both depths. Therefore, it can be stated that the physical quality of the soils in the convex area was better (Reynolds et al., 2002) than of soils in the concave area, which reflects the clear influence of relief forms on the attributes since the applied management in the two areas was the same. Cambardella et al. (2004) verified the effect of landscape on soil quality by finding positive relationships between the best quality indices, also obtained with physical attributes, and the higher positions in the landscape. In the study of Soares et al. (2005), the relief influenced the changes in density and macropores of an Oxisol under sugarcane, confirming the results of Souza (2004).

These results can be explained by the higher clay, organic matter and total iron contents in convex than in concave area soils (Table 1). These attributes are fundamental for soil aggregation (Arca & Weed, 1966; Tisdall & Oades, 1982; Azevedo & Bonumá, 2004). The difference between them is related to a reduced thickness of the A+E horizon of the soils in the convex area (0.30 m) than in the concave area (0.39 m) (Table 1). Therefore, in the convex area, there is a greater influence of the more clayey horizon which is characteristic of Alfisols. Thus, the influence of relief on soil thickness and on the fundamental soil aggregation attributes due to water flow characteristic for each curvature indicates the role of the relief as integration of factors that determine the soil physical attributes.

Table 4. Means in the convex and concave areas: mean weighted diameter (MWD), mean geometric diameter (MGD), aggregates > 2 mm (> 2 mm), aggregates 1–2 mm (1–2 mm), aggregates < 1 mm (< 1 mm), micropores (micro), macropores (macro), total pore volume (TPV), bulk density (Bd), resistance to penetration (RP) and moisture in the 0–0.2 and 0.2–0.4 m depths, at the 121 points

	Hillslope curvature	Mean	Student's t-test	Hillslope curvature	Mean	Student's t-test
		0.00-0.20 m			0.20-0.40 m	
MWD (mm)	Convex	0.71	-3.17*	Convex	0.62	-5.89*
	Concave	0.58		Concave	0.45	
MGD (mm)	Convex	0.65	-7.96*	Convex	0.6 3	-11.44*
	Concave	0.56		Concave	0.53	
> 2mm (%)	Convex	14.20	-1.35 ns	Convex	10.78	-2.70*
	Concave	12.56		Concave	8.17	
1-2 mm (%)	Convex	7.35	-10.43*	Convex	7.95	-9.97*
	Concave	2.84		Concave	3.30	
< 1 mm (%)	Convex	78.45	4.56*	Convex	81.27	5.82*
	Concave	84.60		Concave	88.53	
Micro (%)	Convex	22.75	-2.48*	Convex	23.01	-7.85*
	Concave	21.52		Concave	19.27	
Macro (%)	Convex	14.31	-1.49 ns	Convex	13.64	-0.64ns
	Concave	13.45		Concave	13.29	
TPV (%)	Convex	37.04	-4.41*	Convex	36.63	-10.52*
	Concave	35.03		Concave	32.53	
Bd (g cm^{-3})	Convex	1.46	4.68*	Convex	1.49	4.23*
	Concave	1.52		Concave	1.53	
RP (Mpa)	Convex	1.77	8.41*	Convex	3.67	5.03*
	Concave	2.54		Concave	4.80	
Moisture (%)	Convex	15.07	-9.42*	Convex	15.25	-9.48*
	Concave	13.16		Concave	13.35	

*: significant at 5% and ns: not significant by the Student's t-test.

To evaluate spatial dependence, semivariograms (Figures 2, 3, 4 and 5) were constructed. The following models were adjusted to the attribute data: (a) exponential for MWD, aggregates > 2 mm, macropores, RP and moisture in the convex area in the 0–0.2 m depth, Bd in the convex area in the 0.2–0.4 m depth and RP in the concave area at both depths; (b) spherical for aggregates > 1 mm, micropores, TPV, Bd in the convex area in the 0–0.2 m depth, MWD, aggregates > 2 mm, micropores, TPV, RP and moisture of convex area in the 0.2–0.4 m depth, micropores, TPV and Bd of the concave area in the 0.2–0.4 m depth.

Of all the attributes for which exponential and spherical models were adjusted to semivariograms, the degree of spatial dependence was only high [Co/(Co+C1) < 25 %] for macropores in the convex area in the 0–0.2 m depth and moderate for the other attributes [Co/ (Co+C1) between 25 % and 75 %] according to the classification of Cambardella et al. (1994).

The preliminary semivariograms for macropore attributes in the 0–0.2 m depth, macropores, micropores, TPV and moisture in the 0.2–0.4 m depth in the concave area showed an increased variance without stabilization. This demands the removal of the trend or a non-stationarity that can be performed by adjusting the data to a surface trend (Davis, 1973). In this study, the use of a linear surface was chosen for the removal of the attribute trends that showed these phenomena according to the methodology described by Vieira et al. (1992) and Vieira (2000). The semivariograms resulting from the removal of the trend revealed an absence of spatial dependence of these attributes, presenting a pure nugget effect instead (Figures 4 and 5).

The called pure nugget effect (PNE) of data was also observed in the following attributes: MGD, aggregates between 1–2 mm in the 0–0.2 m depth, MGD, aggregates between 1–2 mm, aggregates > 1 mm, macropores in the 0.2–0.2 m attributes for the convex area and MWD, MGD, aggregates > 2 mm, aggregates between 1–2 mm and aggregates > 1 mm in the 0–0.2 m depth, MWD, MGD, aggregates > 2 mm, aggregates between 1–2 mm, aggregates < 1 mm and Bd in the 0.2–0.4 m depth for the concave area. A random spatial distribution was identified for these attributes, and in this case, classical statistical analyses are recommended (Silva et al., 1989), and the mean estimate values are representative of the area.

Figures 2, 3, 4 and 5 show that the spatial dependence of attributes in the convex is stronger than in the concave area, where the number of attributes with pure nugget effects is higher.

The range values of the attributes of the convex were greater than those of the concave area, except for microspore attributes, with a lower range in the convex than in the concave area. Souza et al. (2004a)

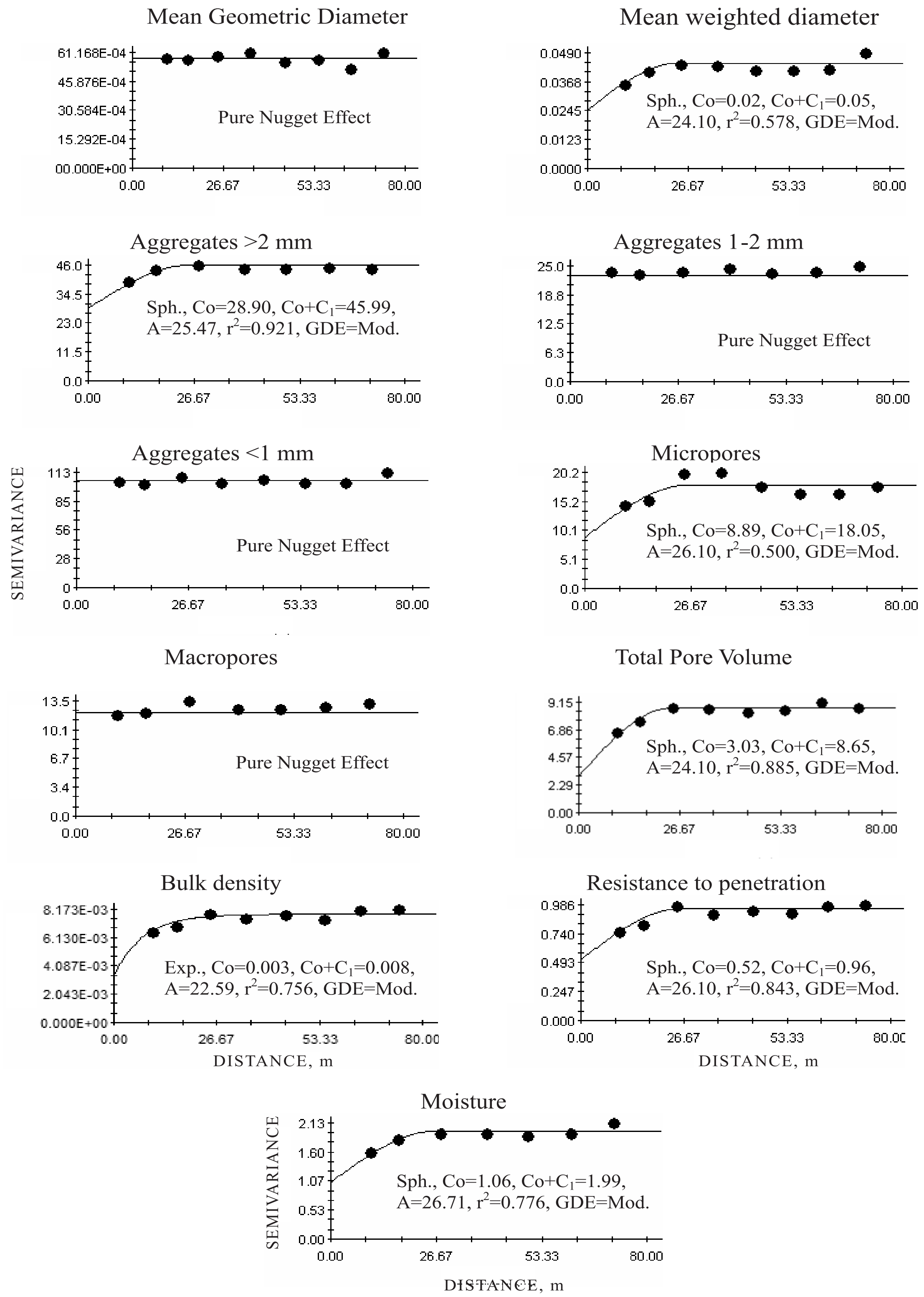

Figure 2. Semivariograms of the studied attributes of the convex area (0–0.2 m). Exp.: exponential; Sph.: spherical; Co: nugget effect; C_1: sill; a: range (m); r^2 = coefficient of determination.

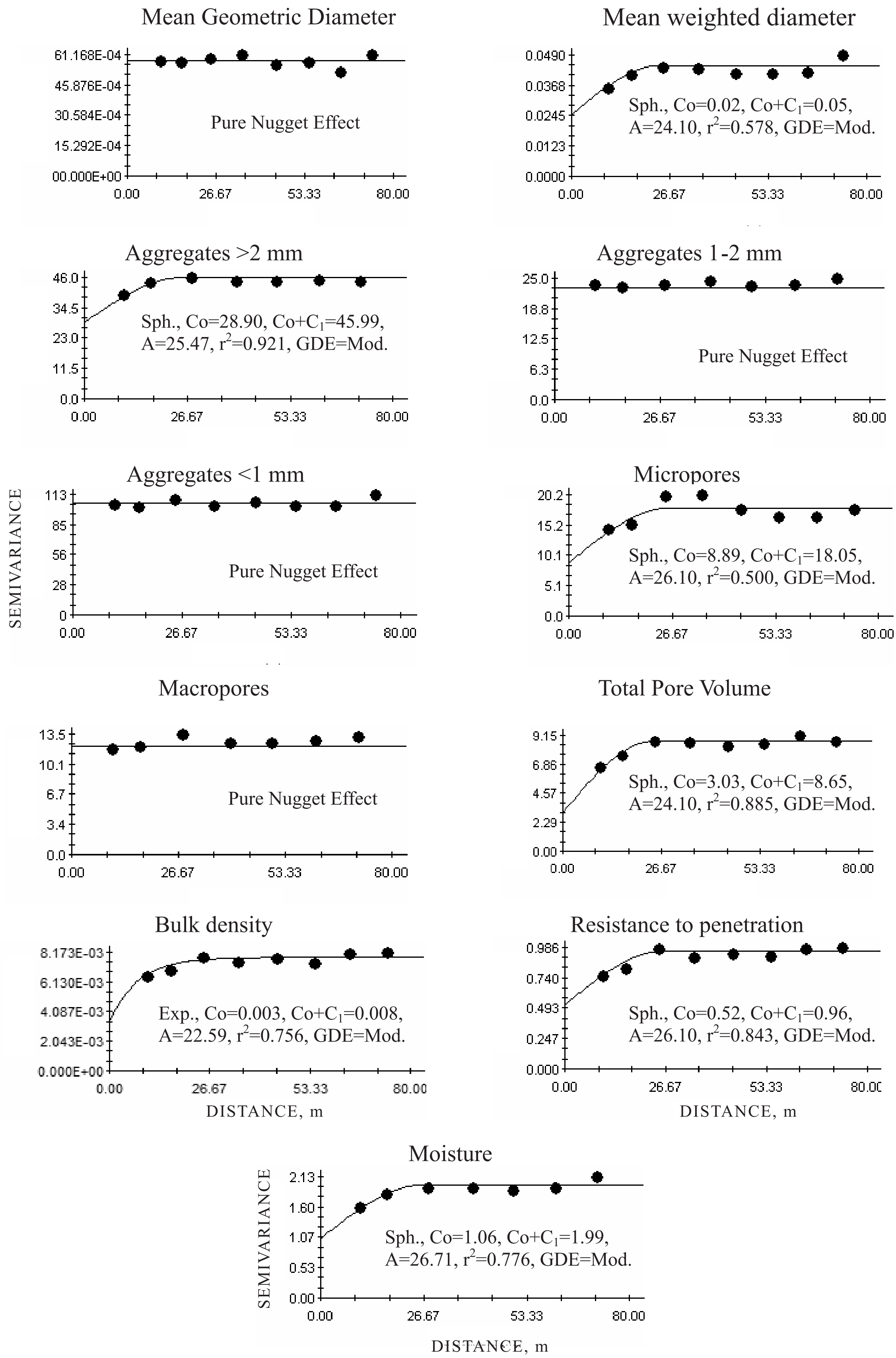

Figure 3. Semivariograms of the studied attributes of the convex area (0.2–0.4 m). Exp.: exponential; Sph.: spherical; Co: Nugget Effect; C_1: sill; a: range (m); r^2 = coefficient of determination.

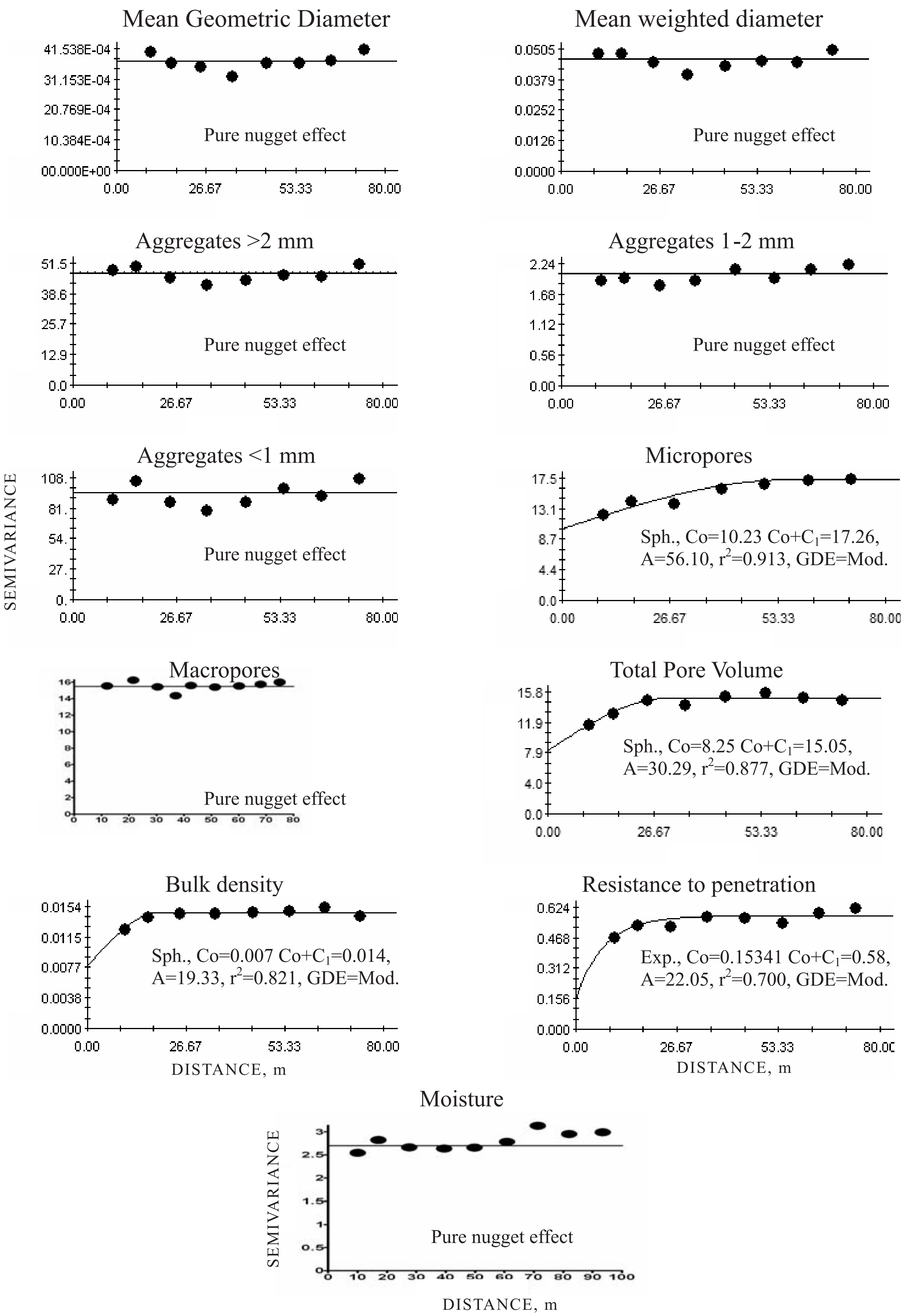

Figure 4. Semivariograms of the studied attributes of the concave area (0–0.2 m). Exp.: exponential; Sph.: spherical; Co: nugget effect; C_1: sill; a: range (m); $r^{2:}$ coefficient of determination.

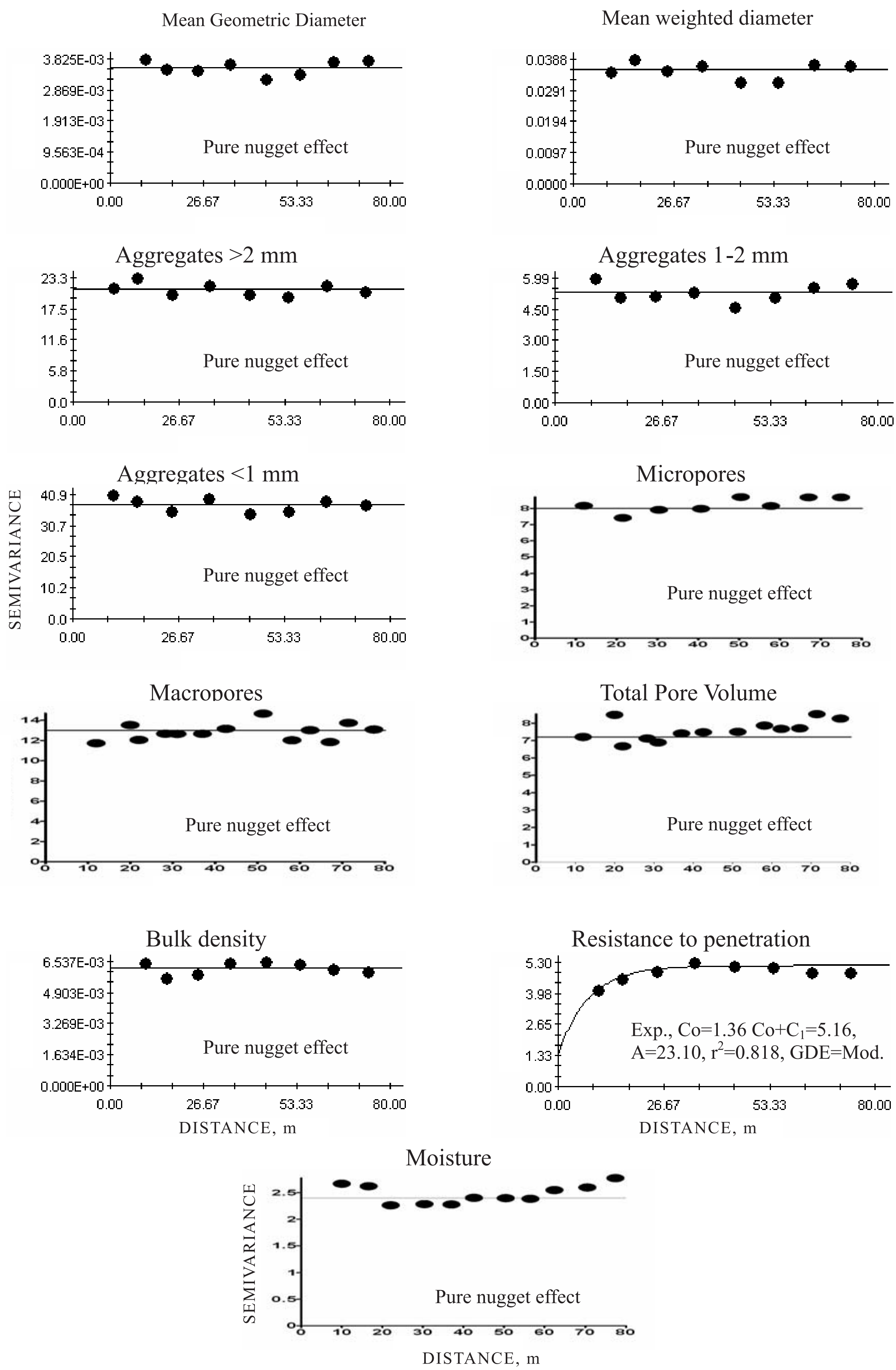

Figure 5. Semivariograms of the studied attributes of the concave area (0.2–0.4 m). Exp.: exponential; Co: nugget effect; C_1: sill; a: range (m); r^2 = coefficient of determination.

found that for Oxisol, the range of aggregates >2mm and aggregates between 1–2 mm were greater than observed in this study. This reflects the greater heterogeneity of Alfisols, which typically occupy less stable positions in the landscape (Miller & Mehlich, 1960).

In this sense, the discontinuity of the physical attribute distributions and consequently the spatial variability of these attributes is greater in the concave area. This result matches the heterogenous water flow characteristic of this area.

When comparing the results of the studied depths, it was observed that a greater number of attributes with PNE occurred in the 0.2–0.4 m depth in both areas. Higher range values were observed in the surface depth, except for aggregates > 2 mm and micropores in the convex area and RP in the concave area. Grego & Vieira (2005) and Berner et al. (2007) also observed a prevailing spatial dependence of physical attributes in the upper soil depths, and these results were attributed to soil tillage, which in the conventional system favors a greater similarity among points that are close than among those that are far away from each other.

These results support decision-making in the planning of soil sampling. In addition, they send a warning about the variability of physical attributes within the same soil class and with the same management history. Therefore, the use hillslope curvatures can be useful in outlining similar management areas in the field and in determining the sampling scheme, acknowledging the need to determine the number of samples and spacing between them, which is a constant concern in soil science (Webster & Oliver, 1990).

CONCLUSIONS

1. The hillslope curvatures in this study scale influenced the spatial variability of the soil physical attributes.

2. The concave area presented a greater number of soil attributes with a greater spatial variability.

3. The convex area is relatively better as the physical quality of soil for crop development.

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