

# USE OF SCALED SEMIVARIOGRAMS IN THE PLANNING SAMPLE OF SOIL PHYSICAL PROPERTIES IN SOUTHERN AMAZONAS, BRAZIL

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## ABSTRACT

There is a great lack of information from soil surveys in the southern part of the State of Amazonas, Brazil. The use of tools such as geostatistics may improve environmental planning, use and management. In this study, we aimed to use scaled semivariograms in sample design of soil physical properties of some environments in Amazonas. We selected five areas located in the south of the state of Amazonas, Brazil, with varied soil uses, such as forest, archaeological dark earth (ADE), pasture, sugarcane cropping, and agroforestry. Regular mesh grids were set up in these areas with 64 sample points spaced at 10 m from each other. At these points, we determined the particle size composition, soil resistance to penetration, moisture, soil bulk density and particle density, macroporosity, microporosity, total porosity, and aggregate stability in water at a depth of 0.00-0.20 m. Descriptive and geostatistical analyses were performed. The sample density requirements were lower in the pasture area but higher in the forest. We concluded that managed-environments had differences in their soil physical properties compared to the natural forest; notably, the soil in the ADE environment is physically improved in relation to the others. The physical properties evaluated showed a structure of spatial dependence with a slight variability of the forest compared to the others. The use of the range parameter of the semivariogram analysis proved to be effective in determining an ideal sample density.

**Keywords:** sample density, spatial variability, physical properties, scaled semivariograms.

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**RESUMO: USO DE SEMIVARIOGRAMAS ESCALONADOS NO PLANEJAMENTO AMOSTRAL DE ATRIBUTOS FÍSICOS DO SOLO EM AMBIENTES NA REGIÃO SUL DO AMAZONAS**

*A carência de informações referentes a levantamento de solos na região sul do Amazonas é muito grande. O uso de ferramentas, como a geoestatística, pode auxiliar no melhor planejamento, uso e manejo desses ambientes. Neste trabalho, objetivou-se utilizar semivariogramas escalonados no planejamento amostral de atributos físicos do solo em ambientes na região Sul do Amazonas. Foram selecionadas cinco áreas, localizadas ao sul do Estado do Amazonas, com diferentes usos: floresta, terra preta arqueológica (TPA), pastagem, cana-de-açúcar e agrofloresta. Nessas áreas, foram estabelecidas malhas regulares contendo 64 pontos espaçados de 10 m entre si. Determinaram-se composição granulométrica, resistência do solo à penetração, umidade, densidade do solo e das partículas, macro e microporosidade, porosidade total e estabilidade dos agregados em água, nas profundidades de 0,0-0,20 m. Foram realizadas análises estatísticas descritivas e geoestatística. O ambiente que necessitou de menor densidade amostral foi o de pastagem e o que demonstrou a necessidade de maior densidade amostral foi o de floresta. Concluiu-se que os ambientes manejados evidenciaram diferenças nos seus atributos físicos em relação à área de floresta, com destaque a área com TPA que se apresentou melhor fisicamente em relação aos demais. Os atributos físicos avaliados apresentaram estrutura de dependência espacial com pequena variação na sua variabilidade da floresta para os demais ambientes, e o uso do parâmetro alcance do semivariograma se evidenciou eficiente para determinar a densidade amostral ideal.*

*Palavras-chave: densidade amostral, variabilidade espacial, atributos físicos, semivariogramas escalonados.*

## INTRODUCTION

Soil in its natural state, under natural vegetation, provides physical conditions that can favor the growth of native species (Andreola et al., 2000). In contrast, the physical properties of cropped soils are altered (Neves et al., 2007), leading to soil degradation (Bertol et al., 2004). Therefore, assessment and monitoring of soil physical properties play an important role in sustainability of agricultural systems (Silva et al., 2005).

Moreover, two close points within the same taxonomic unit may show significant variations in these physical properties (Santos et al., 2012), which may be associated with the management system and the crops planted, but is primarily related to intrinsic soil characteristics (Schaffrath et al., 2008).

Thus, knowing the spatial variability of soil properties is crucial in implementing proper management, including consideration of sampling strategies for soil surveys. For this purpose, geostatistical techniques are used to study the spatial variability of soil and plant properties (Zanão Júnior et al., 2007; Marins et al., 2008; Vieira et al., 2011; Campos et al., 2012, 2013; Camargo et al., 2013; Bottega et al., 2013). However, these techniques require a previous sample design with the exact spatial position of each sample point (Montanari et al., 2012).

One of the great difficulties found in spatial variability studies has been determination of adequate sample spacing to characterize temporal and spatial variations and to represent them accurately, optimizing resources and, consequently,

reducing costs (Lima et al., 2010). Thus, studying the characteristics of soil sampling to better define adequate sampling density in distinct environments has been a constant concern of researchers (Lark, 2000; Montanari et al., 2005; Souza et al., 2006; Coelho et al., 2009; Lima et al., 2010).

Considering the limited information on techniques such as geostatistics for the south of the State of Amazonas for mapping soil characteristics and, especially, for designing sample density, the aim of this study was to use scaled semivariograms in sample design of soil chemical properties at five different environments in the south of Amazonas.

## MATERIAL AND METHODS

The study was carried out on farms located in the south of the state of Amazonas in Brazil, some farms near Santo Antônio de Matupi, in the municipality of Manicoré, AM, and others in the municipality of Humaitá, AM. The mapping of five Amazonian soil environments was carried out, namely, anthropic soil or archaeological dark earth (ADE), soil under natural environment or forest, soil under pasture management with brachiaria (*Brachiaria brizanta*) grass, soil in an agroforestry environment, and soil from a area planted to sugarcane.

The forest area at 7° 54' 44.5" S, 61° 31' 44.7" W and average altitude of 140 m is characterized as a dense Tropical Rain Forest fragment with 20 to 50 m high trees. Surrounding the forest area, there is an area of ADE at 07° 55' 02.1" S, 61° 31' 45.2" W

and 102-m altitude and, at the time of this study, at approximately 120 days after sowing maize. There is also a pasture area at 07° 54' 42" S, 61° 31' 50" W and average altitude of 135 m cultivated with brachiaria (*Brachiaria brizanta*) grass under approximately 10 years of extensive pasture with 1.0 animal ha<sup>-1</sup>. All these experimental areas are located in Manicoré. The environments located in the municipality of Humaitá are agroforestry at 7° 28' 29" S, 63° 02' 07" W and 63-m average altitude, with coffee, cocoa, palm trees, and andiroba, among other crops for about 20 years. Finally, there is the sugarcane field at 7° 54' 38" S, 63° 14' 27" W and 70-m average altitude under burned sugarcane for 10 years (Figure 1).

Environments in the municipality of Manicoré are on weathered soil originating from Rondonia granite from the Late Precambrian Eon (Brasil, 1978). Yet Humaitá environments have their source material from old alluvial sediments, which are chronologically from the Holocene Epoch (Brasil, 1978). According to the Köppen classification, the climate is rainy tropical with a short dry season (*Am*), mean temperatures ranging from 25 to 27 °C, and mean annual rainfall from 2,250 to 2,750 mm, with rains concentrated from October to June (Brasil, 1978). Soil types are classified as Red Ultisol in Manicoré and Haplic Cambisol in Humaitá (Embrapa, 2013).

A 70 × 70-m grid covering 0.49 ha was set up in these areas. Soil samples were collected at crossover points within the grid, with regular intervals of 10 m, for a total of 64 sample points per grid (Figure 1). These points were georeferenced by Garmin Etrex GPS equipment (South American '69). Subsequently, soil samples were collected from each point in the 0.0-0.1 m depth layer to analyze soil physical properties. A detailed description of the chemical properties characterization was given by Oliveira et al. (2015).

Particle size analysis was performed by the pipette method using a 0.1 mol L<sup>-1</sup> NaOH solution as a chemical dispersant and mechanical shaking at high speed for 15 min as proposed by Embrapa (1997). Total carbon was determined by the Walkley-Black method altered by Yeomans and Bremner (1988).

Undisturbed soil samples for physical analyses were collected by the volumetric ring method, with the use of a 0.045-m ring in the 0.0-0.10-m layer. They were then saturated by the capillary rise method until reaching 2/3 of ring height (tension-table method). Total porosity, microporosity, and macroporosity, and soil bulk density (SBD) were thereby determined by the Embrapa (1997) method; particles density was determined by the volumetric flask method also according to Embrapa (1997).

For aggregate distribution, undisturbed soil blocks were collected from the 0.0-0.10 m layer, air dried, manually broken up into smaller sizes, passed through a 9.52 mm sieve, and retained in

a 4.76 mm sieve. The retained aggregates were used for determining aggregate stability in water according to Kemper and Chepil (1965), which was performed by placing the samples over a set of sieves with mesh sizes of 2.0, 1.0, 0.5, 0.25, and 0.063 mm and then subjecting them to vertical oscillations for 15 min at a frequency of 32 oscillations per minute. Geometric mean diameter (GMD) and weighted mean diameter (WMD) were adopted as stability indices, with calculations made according to Kemper and Rosenau (1986).

Gravimetric moisture content was determined from disturbed soil samples (Embrapa, 1997). Soil resistance to penetration (SRP) was measured by an IAA/Planalsucar impact penetrometer with a 30° cone angle. Rod penetration into soil (cm per impact) was transformed into SRP according to formula designed by Stolf (1991):

$$SRP = \frac{Mg + mg + \left(\frac{M}{M+m} \frac{Mg h}{x}\right)}{A}, \quad (1)$$

where SRP = soil resistance to penetration, kgf cm<sup>-2</sup> (kgf cm<sup>-2</sup> × 0.098 = MPa); M<sub>p</sub> = pounder weight, 4 kg (Mg - 4 kgf); m = instrument weight without pounder, 3.2 kg (Mg - 3.2 kgf); h = height of fall of the pounder, 40 cm; x = rod penetration into soil, cm/impact, and A = cone area, 1.29 cm<sup>2</sup>.

Data was subjected to analysis of variance and mean values were compared by the Tukey test at 5 % probability, which was performed by the Minitab statistical software (Minitab, 2000). Data exploratory analysis was performed by calculating means, median, coefficient of variation (CV), skewness, and the Kolmogorov-Smirnov test. The CV (%) was calculated based on the Warrick and Nielsen (1980) criterion that classifies the CV as low (CV < 12 %), medium (from 12-24 %) and high (CV > 24 %).

Semivariograms were designed to determine spatial dependence through geostatistics (Matheron, 1963; Vieira et al., 1983; Isaaks and Srivastava, 1989). Under the theory of intrinsic hypothesis, the experimental semivariogram was estimated by equation 2:

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

where  $\gamma(h)$  = semivariance value at distance h; N(h) = number of pairs of experimental Z observations; Z(x<sub>i</sub>) = value of the Z property at location x<sub>i</sub>; and Z(x<sub>i</sub> + h) = value of the Z property separated by a distance h from location x<sub>i</sub>.

The scaled semivariogram was built based on parameters of experimental semivariograms of soil properties, which were scaled through division of semivariances by statistical variance (Guimarães, 1993; Vieira et al., 1997). In this study, semivariograms were scaled to reduce them to the same scale, facilitating comparison among results of

different variables. Moreover, we aimed to represent several semivariograms simultaneously to better understand patterns of similarity and causes of spatial variability (Ceddia et al., 2009).

Spherical (Equation 3) and exponential (Equation 4) models were fitted to the scaled experimental semivariograms, which were identified within the figures as Sph. ( $C_0, C_1 + C_0, [(C_0/(C_0 + C_1)) \times 100], a, R^2$ ):

$$\begin{cases} \hat{\gamma}(h) = C_0 + C_1 \left[ \frac{3}{2} \left( \frac{h}{a} \right) - \frac{1}{2} \left( \frac{h}{a} \right)^3 \right], & \text{se } 0 < h < a \\ \hat{\gamma}(h) = C_0 + C_1, & \text{se } h \geq a \end{cases} \quad (3)$$

$$\gamma(h) = C_0 + C_1 \left[ 1 - \exp\left(-\frac{3h}{a}\right) \right], \quad h \geq 0 \quad (4)$$

where  $C_0$  = nugget effect;  $C_0 + C_1$  = sill;  $h$  = distance between experimental observations; and  $a$  = spatial dependence range.

Subsequently, scaled semivariograms served as information source to calculate the minimum number of soil samples to determine the variability of all properties within the areas under study (Equation 5):

$$N = \frac{A}{(a^2) / 10000} \quad (5)$$

where  $N$  = minimum number of samples necessary to determine a sample grid;  $A$  = total area (ha); and  $a$  = semivariogram range (m).

In analysis of the degree of spatial dependence (DSD) of the variables under study, we used the classification proposed by Cambardella et al. (1994) in which values of  $[(C_0/(C_0 + C_1)) \times 100]$  lower than

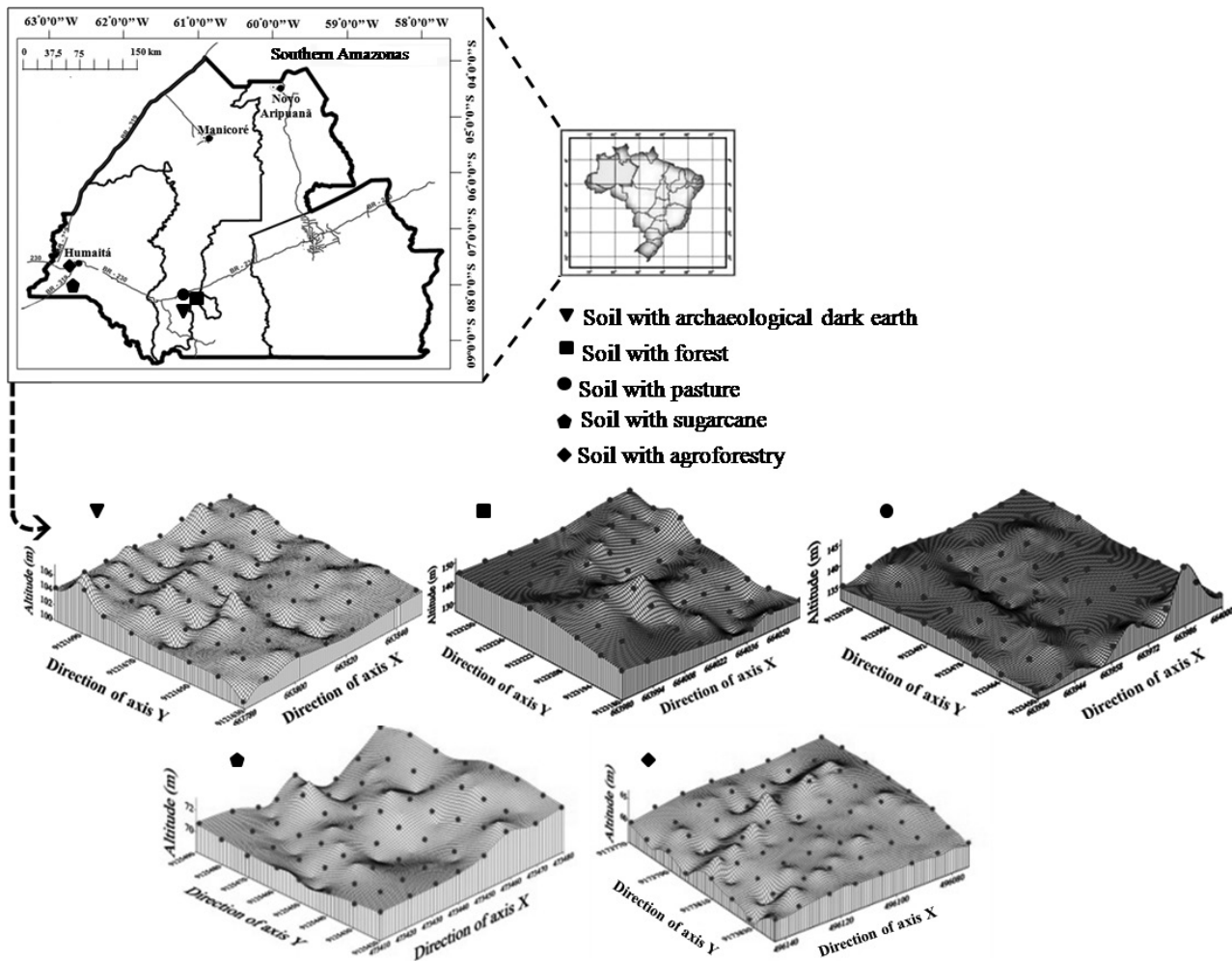


Figure 1. Area location and Digital Elevation Model (DEM) of the environments in southern Amazonas.

25 % are considered strongly spatial dependent, values from 25 to 75 % indicate moderate dependence, and values greater than 75 % indicate poor spatial dependence.

## RESULTS AND DISCUSSION

The mean values of the variables under study showed statistical differences among the environments evaluated, especially when compared to the forest (Table 1). Macro- and microporosity, and particles density (PD) of areas with archaeological dark earth (ADE) did not differ from the forest. Moreover, in the pasture area, soil resistance to penetration (SRP) and soil moisture also did not differ statistically from the forest area. It may be observed that ADE has the best soil physical quality, which may be represented by macro- and microporosity, total porosity, soil bulk density (SBD), SRP, and soil moisture in relation to the other areas. In addition, the forest area had values near those registered for the ADE area, as opposed to the others that were managed. These results were observed by Barros et al. (2012), who found values of physical properties in the ADE environment, such as macro- and microporosity, total porosity, SBD, and SRP, which were considered non-limiting to root growth. Steinbeiss et al. (2009), who studied ADE soil, also found similar physical properties considered non-restrictive to root growth. These same authors explained that the low SBD in the ADE soil areas is due to high levels of organic carbon

and intense biological activity (roots and fauna), with digging of tunnels, cavities, and galleries.

It is also important to observe the low macroporosity and high microporosity values in the sugarcane and agroforestry lands (Table 1). This may be explained by the increased silt content in the sugarcane area, and clay in the agroforestry area, which contribute to macropore filling. This leads to higher soil compaction from agricultural practices, as shown by higher SRP values for both areas, whose mean values did not show statistical differences.

The forestry area differed statistically from the other managed environments for variables such as geometric mean diameter (GMD), weighted mean diameter (WMD), and organic carbon (OC). ADE had lower values for GMD and WMD. Soares (2007) found WMD values from 0.9 to 2.2 mm, and GMD values from 0.88 to 1.02 mm. The high OC value in relation to other areas is explained by the anthropogenic origin of ADE, as confirmed by various authors (Campos et al., 2011; Silva et al., 2011; Barros et al., 2012).

It is important to note that increased GMD and WMD values indicate better soil structure stability, although it does not mean these environments are under ideal conditions since most of the results shown for macroporosity (macro) and microporosity (micro), total porosity (TP), SBD, and SRP are restrictive to root development. Bertol et al. (2004) stated that aggregates with high WMD do not always have proper internal pore size distribution.

**Table 1. Means test of physical properties for the environments evaluated from the municipalities of Humaitá and Manicoré in the south of Amazonas**

Property <sup>(1)</sup>	Forest	ADE	Pasture	Agroforestry	Sugarcane
		Red Ultisol		Haplic Cambisol	
Macro (%)	21.4 A	22.0 A	17.1 B	2.9 D	7.0 C
Micro (%)	19.8 C	28.4 B	20.6 C	30.9 A	29.1 B
TP (%)	41.2 A	50.4 B	37.7 C	33.8 D	36.1 C
SBD (kg dm <sup>-3</sup> )	1.3 B	0.8 A	1.3 C	1.3 D	1.2 C
PD (kg dm <sup>-3</sup> )	2.6 AB	2.6 B	2.4 C	2.6 AB	2.6 A
SRP (MPa)	2.55 B	0.92 C	2.91 B	4.48 A	4.46 A
Moisture (kg kg <sup>-1</sup> )	21.06 C	38.30 A	24.30 C	30.91 B	32.94 B
GMD (mm)	2.2 C	1.7 E	2.7 A	2.0 D	2.6 B
WMD (mm)	2.8 B	2.5 C	3.1 A	2.7 B	3.1 A
OC (g dm <sup>-3</sup> )	10.82 D	39.54 A	15.92 B	11.93 C	17.68 B
Sand (g kg <sup>-1</sup> )	358.8 B	434.1 A	410.7 A	220.7 C	240.5 C
Silt (g kg <sup>-1</sup> )	313.2 C	444.3 B	227.6 D	230.1 D	474.4 A
Clay (g kg <sup>-1</sup> )	327.9 C	121.5 E	361.6 B	549.0 A	284.9 D

<sup>(1)</sup> Macro: macroporosity; Micro: microporosity; TP: total porosity; SBD: soil bulk density; PD: particle density; SRP: soil resistance to penetration; GMD: geometric mean diameter; WMD: weighted mean diameter; OC: organic carbon; and ADE: archaeological dark earth. Mean values followed by the same uppercase letter at the same depth do not differ from each other significantly by the Tukey test at 5 %.

The forest environment differed from the others in terms of particle size. However, predominance of the sand fraction was found in the forest, ADE, and pasture areas, while silt was predominant in the sugarcane area and clay in the agroforestry environment. This may be related to their soil type (Table 1). Martins et al. (2006), Marques et al. (2010), and Campos et al. (2010, 2011) observed similar results in their studies.

Mean and median showed similar values in the forest and ADE environments for all physical properties, except for particle size, which showed statistical distancing for all environments, showing

more serious cases of non-symmetric values for these properties (Table 2). Non-symmetric values for physical properties were observed for pasture (macro, TP, SRP, moisture), agroforestry (micro and TP), and sugarcane (macro and TP) areas. Asymmetry follows the same trend as the mean and median values, with distancing from the central value (zero) in physical properties. In this case, all properties have non-symmetric values, and this is more severe for variables such as moisture, GMD, and WMD, with values of 1.18, -2.4, and -2.8, respectively. Souza et al. (2004, 2009), studying physical properties of the

**Table 2. Descriptive statistics for soil physical attributes in the municipalities of Humaitá and Manicoré in the south of Amazonas**

	Macro	Micro	TP	SBD	PD	SRP	Moisture	GMD	WMD	OC	Sand	Silt	Clay
	%		%	kg dm <sup>-3</sup>		MPa	kg kg <sup>-1</sup>	mm		g dm <sup>-3</sup>	g kg <sup>-1</sup>		
Forest – Red Ultisol													
Mean	21.4	19.8	41.2	1.3	2.6	2.55	21.06	2.2	2.8	10.82	358.8	313.2	327.9
Median	21.5	19.7	41.2	1.3	2.6	2.49	21.42	2.3	2.8	11.90	355.6	312.4	324.9
CV (%)	15.0	14.9	7.5	5.9	2.6	0.21	0.15	17.7	8.0	35.31	16.5	18.9	12.6
Ass.	-0.1	0.3	0.6	-0.3	0.1	1.17	0.16	0.4	0.6	-0.28	1.7	-1.2	0.1
Nt	0.10*	0.08 <sup>ns</sup>	0.10*	0.07 <sup>ns</sup>	0.05 <sup>ns</sup>	0.10*	0.16	0.11*	0.11*	0.12*	0.09 <sup>ns</sup>	0.09 <sup>ns</sup>	0.06 <sup>ns</sup>
Archaeological Dark Earth – Red Ultisol													
Mean	22.0	28.4	50.4	0.8	2.6	0.92	38.30	1.7	2.5	39.54	434.1	444.3	121.5
Median	22.8	28.0	50.9	0.8	2.6	0.92	37.29	1.7	2.5	39.40	442.4	432.9	120.0
CV (%)	37.8	11.2	12.7	9.4	3.0	0.16	0.35	20.0	10.0	19.86	13.5	16.5	35.0
Ass.	0.2	0.8	0.7	-0.4	0.3	0.23	1.07	0.3	-0.3	-0.27	-1.1	1.1	0.6
Nt	0.09 <sup>ns</sup>	0.08 <sup>ns</sup>	0.14*	0.08*	0.07 <sup>ns</sup>	0.10*	0.11*	0.10*	-0.07 <sup>ns</sup>	0.06 <sup>ns</sup>	0.12*	0.12*	0.09 <sup>ns</sup>
Pasture – Red Ultisol													
Mean	17.1	20.6	37.7	1.3	2.4	2.91	24.30	2.7	3.1	15.92	410.7	227.6	361.6
Median	18.0	20.5	38.1	1.2	2.3	3.13	23.81	2.8	3.1	15.70	411.8	224.0	360.0
CV (%)	35.4	13.0	11.0	8.7	5.5	0.49	0.17	14.9	5.9	13.57	9.3	16.6	10.4
Ass.	-0.8	0.1	-0.9	0.6	0.2	0.57	1.18	-2.4	-2.8	0.42	0.1	-0.6	0.1
Nt	0.11*	0.05 <sup>ns</sup>	0.09 <sup>ns</sup>	0.11*	0.05 <sup>ns</sup>	0.13*	0.09 <sup>ns</sup>	0.12*	0.15*	0.07 <sup>ns</sup>	0.05 <sup>ns</sup>	0.08 <sup>ns</sup>	0.08 <sup>ns</sup>
Agroforestry – Haplic Cambisol													
Mean	2.9	30.9	33.8	1.3	2.6	4.48	30.91	2.0	2.7	11.93	220.7	230.1	549.0
Median	2.6	31.6	34.0	1.3	2.6	4.46	30.22	2.0	2.8	11.90	210.2	228.7	558.8
CV (%)	69.0	11.6	9.2	7.2	3.3	0.08	0.11	34.8	19.3	15.52	22.6	25.9	11.9
Ass.	0.2	-0.06	-0.7	0.1	-0.04	-0.24	2.63	-0.3	-3.3	0.78	1.4	0.5	-0.4
Nt	0.18*	0.14*	0.14*	0.06 <sup>ns</sup>	0.10*	0.09 <sup>ns</sup>	0.11*	0.09 <sup>ns</sup>	0.19*	0.08 <sup>ns</sup>	0.15*	0.12*	0.11*
Sugarcane – Haplic Cambisol													
Mean	7.0	29.1	36.1	1.2	2.6	4.46	32.94	2.6	3.1	17.68	240.5	474.4	284.9
Median	6.0	29.2	35.3	1.2	2.7	4.45	32.84	2.5	3.0	17.70	240.4	467.2	287.9
CV (%)	59.5	6.8	9.0	6.7	5.2	0.12	0.08	0.1	3.1	20.52	18.0	7.2	9.9
Ass.	1.3	-0.8	1.6	-0.2	-0.2	1.95	-0.02	-0.4	-0.6	-0.05	0.2	-0.09	-0.8
Nt	0.14*	0.07 <sup>ns</sup>	0.12*	0.11*	0.08 <sup>ns</sup>	0.16*	0.09 <sup>ns</sup>	0.11*	0.11*	0.07 <sup>ns</sup>	0.06 <sup>ns</sup>	0.10*	0.09 <sup>ns</sup>

CV: coefficient of variation; Ass: Asymmetry; Nt: normality test at 5 % significance by the Kolmogorov-Smirnov test; Macro: macroporosity; Micro: microporosity; TP: total porosity; SBD: soil bulk density; PD: particle density; SRP: soil resistance to penetration; GMD: geometric mean diameter; WMD: mean weight diameter; \* and <sup>ns</sup>: significant and non-significant, respectively.

soil under sugarcane cropping, found symmetric distributions for these properties.

Soil property variability (Table 2) measured by coefficient of variation (CV) can be considered the first indication of data heterogeneity. The physical properties analyzed showed CV values ranging from low to medium to high values although, in this study, there was a predominance of low and high ones. Our results are in agreement with the results found by Vieira et al. (2011) and Santos et al. (2012), who studied soil physical properties and found medium and high CV values.

Soil bulk density, PD, SRP and moisture content presented low CV values for all five environments; TP showed medium CV for ADE and low for the others. In contrast, macroporosity showed high CV for all environments except for forest, which obtained a medium CV. In general, forest (CV = 9.84 %) and sugarcane (CV = 11.27 %) environments have low variability in physical properties, while ADE (CV = 14.57 %), pasture (CV = 12.25 %) and agroforestry (CV = 19.93 %) environments have medium variability (Table 2). This implies that in forest and sugarcane environments, there is more

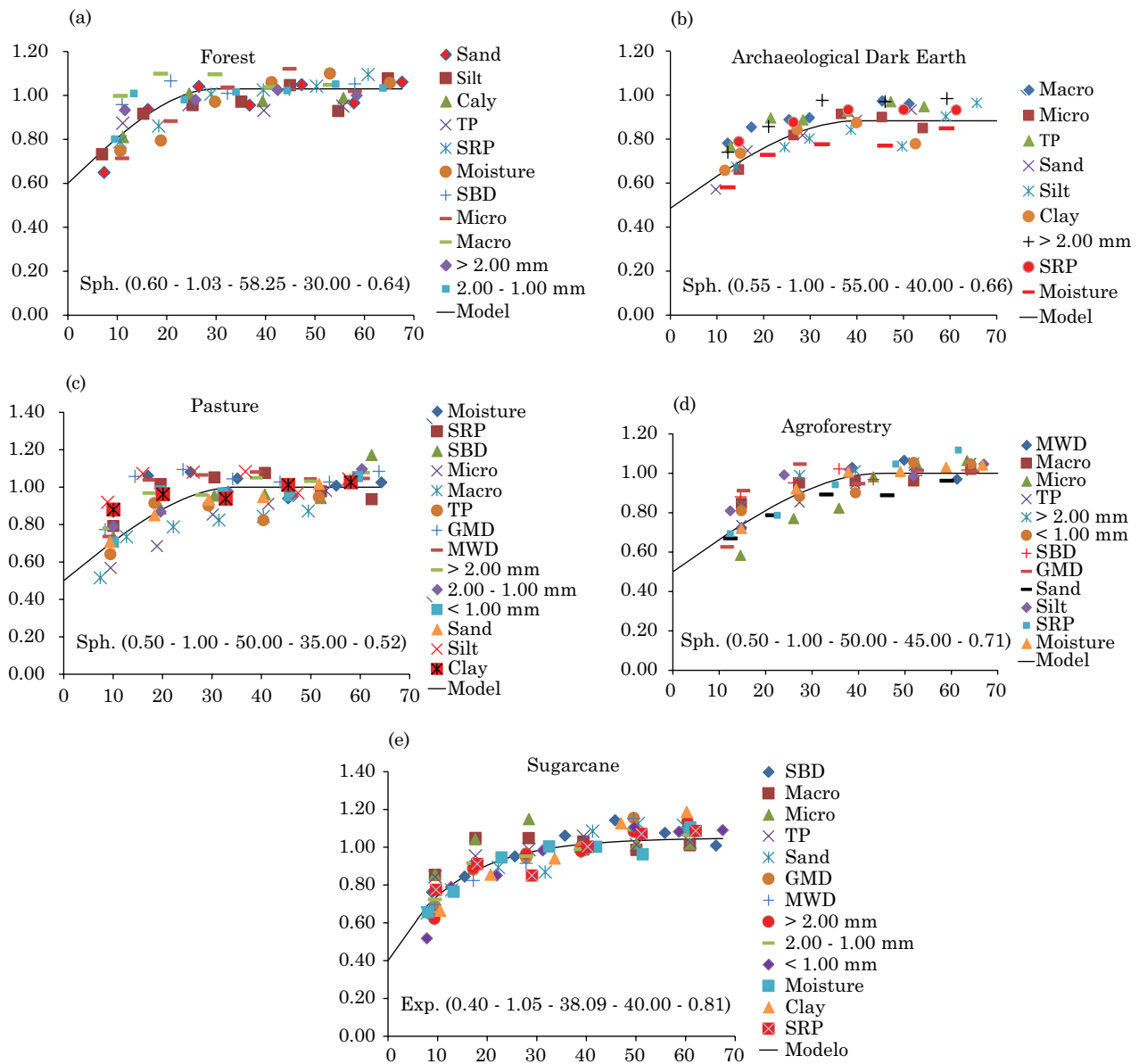


Figure 2. Scaled semivariograms for physical properties of environments in the municipalities of Humaitá and Manicoré in the south of Amazonas. Exp: exponential; Sph: spherical; [model (nugget effect - sill - DSD - R<sup>2</sup> - range - residue)]. DSD: Degree of Spatial Dependence; R<sup>2</sup>: coefficient of determination.

**Table 3. Ideal sampling density and spacing based on estimated range from the scaled semivariograms for soil physical properties in the south of Amazonas**

Sample design	Forest	ADE	Pasture	Agroforestry	Sugarcane
Sampling density (points ha <sup>-1</sup> )	11	6	5	8	6
Spacing (m)	30	40	45	35	40

ADE: archaeological dark earth.

homogeneity for the properties compared to the other environments.

The Kolmogorov-Smirnov test data showed variations among environments and their properties. Macroporosity had non-normal distribution in all environments, except for ADE. For microporosity, inverse behavior was observed, with non-normal distribution only for agroforestry data. Soil resistance penetration and GMD had normal distribution in the agroforestry area, while WMD showed normality in ADE (Table 2). Campos et al. (2007), studying soil texture in different parent materials, found normality for these properties.

Data normality is not required for application of geostatistical techniques; however, it is advisable that the distribution not have very elongated tails, which could compromise analysis (Isaaks and Srivastava, 1989; Cressie, 1991). Thus, prior exploratory data analysis helps to ensure that these distributions are suitable for geostatistical study.

The continuity of spatial variability of soil texture is less than the continuity of spatial variability of the other physical properties since soil texture is related to the source material, and other physical properties are more easily exchangeable, which may occur, for example, due to tillage and land use (Bottega et al., 2013). Spherical models were fitted to the scaled semivariograms for all areas, with the exception of sugarcane, which was best described by an exponential model (Figure 2). Exponential and spherical models represent medium and low continuity of spatial variability, respectively (Silva and Chaves, 2001). Isaaks and Srivastava (1989) indicate that exponential models are better fitted to erratic phenomena on the small scale, whereas spherical models describe properties with high spatial continuity, i.e., less erratic at short distances.

Similar behavior of geostatistical parameters is observed in the environments under study (Figure 2). In general, the adjusted models showed mean values close to 0.51 nugget effect. Vieira (2000) points out that the greater the nugget effect, the greater the discontinuity among samples. Range values were from 30 m (forest) to 45 m (agroforestry). All environments had moderate degrees of spatial dependence (Cambardella et al., 1994). These results are in agreement with results found by Mercante et al. (2003) and Silva Cruz et al. (2010).

Archaeological dark earth and pasture areas showed some dispersal of the experimental semivariograms, indicating different patterns of spatial variability for the variables analyzed (Figure 2). In the other environments, very similar behaviors were observed. On comparing the parameters of the scaled semivariograms of the forest area, a slight variation was seen in relation to the managed environments.

According to Ortiz (2002), knowledge of soil spatial variability, in addition to allowing characterization of a region, may indicate the number and distribution of soil samples to be taken, assisting in detailing the area and in results. Range is an important measure for experimental design and evaluation since it may assist in definition of sampling procedures (Mcbratney and Webster, 1983; Souza et al., 2009). This parameter represents the maximum distance within which sample points are intercorrelated.

Based on range values, the results for minimum sample density and minimum spacing were higher in the forest environment (Table 3). We note that forested areas require a greater number of sample points per hectare (11 points ha<sup>-1</sup>) compared to areas under anthropogenic management (e.g. ADE, pasture, agroforestry, and sugarcane) for best representation of variability. This may be explained by the absence of human impact within this environment, resulting in greater variability; the agroforestry area likewise follows this trend as it has a forest-like behavior, so its properties have a variability closer to the forest variability.

Obtaining these results presupposes the use of these sampling density and spacing values as a basis for further surveys of soil properties in this region since the locations studied are quite representative in regard to soil type, management practices, and environments across the south of the state of Amazonas.

## CONCLUSIONS

The managed environments showed differences in their physical properties compared to the forest area, especially ADE, which provided better soil physical conditions than the other environments due to its anthropogenic formation.



All the physical properties evaluated showed a spatial dependence structure, there being a slight variation in the variability of physical properties of the forest compared to the anthropogenic environments. Thus, it can be stated that human practices (soil management) led to changes in the natural variability of soil physical properties.

Use of the range parameter of the scaled semivariogram proved to be effective in determining the optimal sampling density for the environments under study, which may serve as a basis for further soil survey studies in the south of Amazonas.

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