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Spatial Variability of Soil Properties in Archeological Dark Earth Sites under Cacao Cultivation

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ABSTRACT: Soils with an A horizon formed by human activity, an anthropogenic A horizon, are found in the Amazon Region. Few studies have examined the spatial distribution of the properties of these soils. We mapped the spatial variability of some soil properties in an area of Archaeological Dark Earth (ADE) in the Brazilian Amazon. A sampling grid was defined over an area of 42 × 88 m under cacao cultivation in which sampling points were established at a spacing of 6 × 8 m, for a total of 88 points. Samples were collected from the 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.30 m depth layers. Soil texture, aggregate stability, and organic carbon (OC) analyses were performed on disturbed soil samples. Undisturbed samples were used to determine soil macroporosity (Macro), microporosity (Micro), total porosity (TP), and soil resistance to penetration (RP). The results were analyzed by descriptive statistic, Pearson correlation ($p<0.01$), and geostatistics. Soil bulk density, total pore volume, and geometric mean diameter are dependent on the total amount of OC in the ADE area. Increased soil bulk density and RP are proportional to a decrease in OC content and lower Micro and TP. Moreover, soil resistance to penetration is influenced by soil water and clay content with depth.

Keywords: Indian Dark Earth, management systems, Amazon soils, anthropogenic soils.

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INTRODUCTION

The different types of soil in the Amazon region include soil with an anthropogenic A-horizon, i.e., formed by human activity (Santos et al., 2013b). These soil units, known as Dark Earths, Indian Dark Earths, or Archaeological Dark Earths (ADEs), generally stem from ancient Indian settlements, and stand out through the presence of ceramics and cultural artifacts, as well as dark color and large deposits of stable organic matter (Campos et al., 2011).

Furthermore, ADEs are naturally fertile, with high levels of phosphorous, calcium, magnesium, and stable organic matter and greater biological activity compared to surrounding soils (Glaser, 2007). Soil organic matter has a direct and indirect effect on soil properties (Viana et al., 2011). According to Cunha et al. (2007), the fertility of ADEs is strongly related to the molecular characteristics of the alkali-soluble fraction within organic carbon, the humic substances.

One of the soil physical properties under the influence of organic matter is particle aggregation, which is related to water and air availability to roots and microbes, in addition to mechanical resistance to penetration (Vieira et al., 2010). Besides soil aggregation, organic matter contents play other vital functions in the lifecycle, ranging from microbial and soil fauna activities to positive action on aggregate stability, soil porosity, and soil density, contributing to reduce soil compaction (Spera et al., 2010).

In contrast, soil and crop management practices can degrade soil by reducing total organic carbon content, aggregate stability, and hydraulic conductivity and by increasing density and RP (Hickmann et al., 2012), thus impairing gas exchanges between the soil and the atmosphere (Chaves and Farias, 2008).

Soil properties have natural variation in space because of pedogenic features, and if management practices are taken into account, this variation may increase (Oliveira et al., 2013); therefore, maintenance of soil quality maintenance is of prime importance for stability, sustainability, and plant yield in natural and agricultural ecosystems. Thus, understanding and quantifying the impact of management systems on soil physical quality enables development of sustainable agricultural systems (Silva et al., 2008).

Studying it in Brazilian agroecosystems is the basis for achieving agricultural sustainability (Cunha et al., 2007). Soil use and management and soil variations interfere in the natural balance of ecosystems by changing organic compounds both in quantity and quality (Melo and Schaefer, 2009).

As Terras Pretas Arqueológicas por sua natureza antropogênica podem ter sofrido modificações na variabilidade espacial de seus atributos, entretanto acredita-se que o manejo do solo e uso atual destas terras com espécies cultivadas podem agravar essas alterações.

The Archaeological Dark Earths in its anthropogenic nature may have been changed in the spatial variability of its attributes; however it is believed that the soil management and the current use of these lands with cultivated species, may aggravate these changes. Thus, the aim of this study was to assess the spatial variability of soil properties in an area of Archaeological Dark Earth located in Amazonas, Brazil.

MATERIALS AND METHODS

The areas sampled came from the municipality of Apuí in the state of Amazonas, Brazil. The area is located along the Transamazonian Highway (BR-230) at geographical coordinates of 7° 12’ 05” S and 59° 39’ 37” W. According to the Köppen classification system, local weather belongs to group A (Rainy Tropical) and type Am (monsoon rains), with a short dry period. The area is bounded by isohyets of 2,250 and 2,750 mm, and the rainy season is from October to June. Average annual temperatures range from 25 °C to 27 °C, and relative humidity is between 85 and 90 %.

Local geology consists of sandstones from the *Beneficiente* group, covered with clayey matrix from the tertiary period. Predominant soil classes are *Argissolos* and *Latossolos*, and the area under study is classified as an *Argissolo Amarelo Eutrófico*, according to Santos et al. (2013a), or an Ultisol (Soil Survey Staff, 2014). The area is predominantly primary vegetation formed by dense rainforest, consisting of dense tree cover (SDS, 2004).

The Archaeological Dark Earth (ADE) area had been cropped for 14 years. In the first six years, rice, corn, beans, and watermelon were grown, and later cacao was planted, which remains until now. Over this location, we established a 42 × 88 m grid, demarcating points at a spacing of 6 × 8 m, for a total of 88 sampling points.

Blocks of soil samples with undisturbed structure were collected from grid intersection points, and were removed from the 0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.30 m depth layers for further determination of aggregate stability. Initially, the soil samples were left to air dry and subsequently passed through 9.52 and 4.76 mm sieves. Then, aggregate stability was measured by the wet-sieving method. After that, 20-g samples of aggregates with diameters between 9.52 and 4.76 mm were placed over a set of sieves with meshes of 2.0, 1.0, 0.5, 0.25, 0.105, and 0.063 mm. Next, these samples were subjected to vertical oscillations for 15 min at a frequency of 32 oscillations per minute. Geometric mean diameter (GMD) was adopted as a stability index, which was calculated in accordance with Kemper and Chepil (1965).

The samples collected using volumetric rings and used to test aggregate stability were likewise used for determination of soil macro- and microporosity, bulk density, and total pore volume. In the laboratory, samples were prepared by removing excess soil from ring ends. Subsequently, the samples were saturated by gradually adding water to a plastic tray up to the maximum height of the outer edge of rings from each sample. After saturation, samples were weighed and taken to a tension table and subjected to a pressure of 6 kPa for measurement of soil microporosity (Claessen, 1997).

After reaching equilibrium, samples were weighed and then soil RP (SRP) was measured using an electronic penetrometer (Marconi, Model: MA-933) equipped with a 200-N load cell with a 4-mm base diameter conical rod and a 30° semi-angle. Measurements were made at a constant penetration speed of 0.1667 mm s^{-1}, with the receiver and interface coupled to a computer to record the readings. Readings taken within 5 mm of the upper and lower edges of the samples were discarded to eliminate peripheral effects (Bradford, 1986).

Particle size distribution analysis was performed by the pipette method, using a 0.1 mol L^{-1} NaOH solution as a chemical dispersant and mechanical agitation on a high speed apparatus for 15 min, following the method proposed by Claessen (1997). Total organic carbon was determined by the Walkley-Black method, modified by Yeomans and Bremner (1988).

Data were analyzed by descriptive statistics, determining mean, maximum, and minimum values, skewness and kurtosis coefficients, the coefficient of variation (CV), and data frequency distribution. This analysis was performed using the Minitab 14 statistical software (Minitab, 2000). The relationship among soil properties was calculated by Pearson correlation.

In addition, spatial variability was evaluated by geostatistics. The experimental semivariogram was estimated by equation (1).

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

in which γ(h) is the semivariance value at distance interval h; N(h) is the number of sample pairs within the distance interval h; Z(xi) is the sample value Z at point xi; and Z(xi+h) is the sample value Z separated by the distance interval h from point xi.

Experimental semivariograms were chosen based on the number of pairs involved in semivariance calculation of the first lags, with a clearly defined sill (Burrough and McDonnel, 2000) and the result of the jack-knifing technique (Vauclin et al., 1983).

After validating mathematical models, data were interpolated through kriging analysis. Geostatistical analysis was performed on GS+ software, and kriging maps were produced by Surfer v. 8.0 (Golden Software, Inc.).

RESULTS AND DISCUSSION

All the variables studied had close mean and median values, as well as skewness and kurtosis close to zero, characterizing symmetrical data distribution (Tables 1 and 2). Organic carbon (OC) was an exception in the 0.05-0.10 m layer, silt content in the 0.00-0.05 and 0.10-0.20 m layers, and soil bulk density (BD) in the 0.20-0.30 m layer; all of them had kurtosis values above 1. Mean and median proximity ensure a symmetrical distribution, meaning that the dispersion of values do not have very elongated tails, which could compromise geostatistical analyses (Diggle and Ribeiro Júnior, 2007).

All properties showed normal distribution at all soil layers (Tables 1 and 2), similar to the results of Aquino et al. (2014a), who studied anthropogenic and non-anthropogenic soils in the southern part of Amazonas. Data normality is essential because it indicates that the mean and variance are constant over the area of study (Isaaks and Srivastava, 1989), as we observed, i.e., it satisfies the principle of stationarity required by geostatistical modeling.

According to the coefficient of variation (CV) classification proposed by Warrick and Nielsen (1980), who classified CV <12 % as low variability, CV between 12 and 60 % as medium variability, and CV >60 % as high variability, we noted that part of the properties studied showed low variability, except for GMD, Macro, RP, sand and clay contents for all soil layers, Micro for the 0.00-0.05 m layer, and BD for the 0.20-0.30 m layer, which showed medium variability. These results are considered promising since such variables normally have a high variation in the field, as stated by Aquino et al. (2014b). Conversely, Campos et al. (2011), studying ADEs within the region at the middle part of the Madeira River, claimed that this low to medium variability in physical properties is probably due to the similarity of anthropic factors that had led to the formation of these soils, as well as the population density and time of occupation of these areas by pre-Colombian people.

The GMD was higher in the surface layers and decreased with depth, just as for the OC (Table 1). According to Santos et al. (2013b), OC plays a decisive role in the formation and stabilization of aggregates in areas of ADEs; therefore, reducing OC content in the soil would change its structure, since particle aggregation indirectly affects other properties, such as porosity, aeration, retention capacity, and water infiltration.

Soil bulk density (BD) values reached a maximum of 1 Mg m^{-3} in all the layers analyzed, indicating friable soil with low resistance to penetration of roots and plenty of porous areas (Table 1). The BD and RP increased, whereas OC, Micro, and TP decreased with depth. This trend highlights the role of OC in the behavior of certain soil properties, as already highlighted by Campos et al. (2011). These authors studied ADE profiles from the middle Madeira River region and found OC contents in anthropogenic horizons ranging from 44 to 80 g kg^{-1}, values below those found in our study. Furthermore, Santos et al. (2011) studied soil physical properties in ADEs in the southern Amazon region and observed SBD averages similar to our study in surface layers, increasing with depth.

The RP increased with depth, together with a decrease in moisture, denoting the influence of moisture on soil resistance. In addition, we observed an increase in clay content with depth, which may have occurred through its reach into deeper horizons of pedogenic origin, a fact confirmed by Santos et al. (2013b) in a study of ADEs in the region of Apuí and Manicoré, AM, Brazil.

Table 1. Descriptive statistics for soil macroporosity (Macro), microporosity (Micro), total porosity (TP), soil bulk density (BD), geometric mean diameter (GMD), and organic carbon (OC), for four soil layers, in the area of Archaeological Dark Earth under cacao cultivation

Descriptive statistic	Macro	Micro	TP	BD	GMD	OC
		%		Mg m^{-3}	mm	g kg^{-1}
			0.00-0.05 m			
Mean	19.0	49.0	69	0.9	2.6	114
Median	19.0	49.0	68	0.8	2.6	114
SD[1]	5.6	4.4	4.7	0.1	0.5	8.1
Variance	31.8	19.3	22.7	0.1	0.2	65.9
CV (%)[2]	28.0	9.0	7	11	19	7
Ass[3]	0.4	-0.7	0.2	04	-0.3	-0.1
Kurtosis	-0.5	1.5	0.9	0.2	0.9	-0.8
d[4]	0.07*	0.07*	0.08*	0.09*	0.09*	0.07*
			0.05-0.10 m			
Mean	19	47	66	0.9	2.5	105
Median	18	47	65	0.9	2.5	104
SD[1]	5.3	4.8	4.3	0.1	0.4	4.7
Variance	28.1	23.2	19.0	0.1	0.2	21.9
CV (%)[2]	27	10	6	9	17	4
Ass[3]	0.6	-0.3	-0.2	0.2	0.1	1.0
Kurtosis	0.1	1.3	4.1	0.4	0.6	1.8
d[4]	0.07*	0.07*	0.05*	0.10*	0.05*	0.04*
			0.10-0.20 m			
Mean	22	43	65	0.9	2.5	107
Median	22	42	66	0.9	2.6	101
SD[1]	5.2	3.8	4.3	0.1	0.4	6.4
Variance	27.5	14.7	18.5	0.1	0.2	41.4
CV (%)[2]	23	8	6	10	16	6
Ass[3]	-0.2	-0.1	-0.6	0.6	-0.6	0.7
Kurtosis	-0.3	1.1	0.7	0.3	0.1	0.4
d[4]	0.07*	0.08*	0.08*	0.09*	0.02*	0.07*
			0.20-0.30 m			
Mean	21	41	63	1.0	2.5	101
Median	21	41	63	0.9	2.5	101
SD[1]	4.7	3.6	4.1	0.1	0.4	6.6
Variance	22.9	12.9	16.9	0.1	0.2	44.6
CV (%)[2]	22	8	6	13	18	6
Ass[3]	-0.1	0.3	-0.2	-1.4	-0.2	-0.3
Kurtosis	-0.2	0.7	-0.1	9.2	0.2	0.8
d[4]	0.05*	0.05*	0.07*	0.09*	0.09*	0.10*

[1] SD: standard deviation; [2] CV: coefficient of variation; [3] Ass: asymmetry coefficient; [4] d: Kolmogorov-Smirnov normality test. *: significant at 5 % probability.

The geostatistical results showed spatial dependence for all the properties studied, except for OC at 0.00-0.05 m, and moisture and Micro at 0.00-0.05, 0.05-0.10, and 0.10-0.20 m. These variables showed pure nugget effect, i.e., random variation throughout the study area (Tables 3 and 4). The semivariograms of soil properties that presented spatial dependence were fitted mainly to the exponential and spherical models (Tables 3 and 4), corroborating other studies that indicate these models as the best fit for soil properties (Souza et al., 2009; Cajazeira and Assis Junior, 2011).

Table 2. Descriptive statistics for contents of sand, silt, and clay, as well as soil resistance to penetration (RP) and soil moisture, for four soil layers, in areas of Archaeological Dark Earth under cacao cultivation

Descriptive statistic	Sand	Silt	Clay	RP	Moisture (vol)
	g kg-1			MPa	$m^3 m^{-3}$
			0.00-0.05 m		
Mean	221	573	206	0.89	0.49
Median	217	577	205	0.84	0.48
SD(1)	49.6	32.0	44.1	0.3	4.3
Variance	2458.2	1024.5	1941.3	0.1	19.2
CV (%)(2)	22	5	21	32	8
Ass.(3)	0.3	-0.5	-0.03	0.3	-0.7
Kurtosis	-0.3	1.1	0.10	-0.4	1.5
d(4)	0.06*	0.09*	0.08*	0.08*	0.09*
			0.05 - 0.10 m		
Mean	196	534	270	0.91	0.46
Median	192	544	265	0.85	0.47
SD(1)	38.7	34.5	53.4	0.3	4.8
Variance	1499.6	1192.1	2850.0	0.1	23.4
CV (%)(2)	19	6	20	30	10
Ass.(3)	0.3	-0.1	0.5	-0.1	-0.3
Kurtosis	-0.1	0.8	0.4	-0.5	1.3
d(4)	0.07*	0.09*	0.07*	0.07*	0.06*
			0.10-0.20 m		
Mean	188	527	285	1.1	0.43
Median	181	536	275	1.1	0.42
SD(1)	36.1	37.6	47.9	0.3	3.8
Variance	1302.4	1413.8	2300.9	0.1	14.7
CV (%)(2)	19	7	17	41	8
Ass.(3)	0.5	0.4	-0.1	0.5	-0.1
Kurtosis	0.1	1.2	-0.8	-0.4	1.1
d(4)	0.09*	0.07*	0.06*	0.07*	0.09*
			0.20 – 0.30 m		
Mean	185	511	304	1.13	0.41
Median	182	516	301	1.12	0.41
SD(1)	32.0	48.6	65.3	0.3	3.6
Variance	1025.9	2359.3	4269.2	0.1	13.2
CV (%)(2)	17	9	21	38	8
Ass.(3)	0.5	0.1	0.1	0.4	0.3
Kurtosis	0.1	0.4	-0.4	-0.3	0.6
d(4)	0.06*	0.08*	0.05*	0.08*	0.05*

(1) SD: standard deviation. (2) CV: coefficient of variation. (3) Ass: asymmetry coefficient. (4) d: Kolmogorov-Smirnov normality test. RP: soil resistance penetration. *: significant at 5 % probability.

Cross-validation values started at 0.60 (Table 3). These values range from 0 to 1, with values closer to 1 indicating the most efficient models for representing the phenomenon studied (Wojciechowski et al., 2009).

The degree of spatial dependence (DSD) is the ratio between the nugget effect and sill $[C_0/(C_0+C_1)]$ (Cambardella et al., 1994). This rate was strong (DSD <25 %) for most of the soil properties

Table 3. Models and estimated parameters for semivariograms of macroporosity (Macro), microporosity (Micro), total porosity (TP), soil bulk density (BD), geometric mean diameter (GMD), and organic carbon (OC), for four soil layers, in soils from areas of Archaeological Dark Earth under cacao cultivation

Parameter	Macro	Micro	TP	BD	GMD	OC
			0.00-0.05 m			
Model	Exp	Lin	Exp	Exp	Exp	Lin
Nugget effect	2.60	-	1.50	0.0009	0.041	-
Landing	27.80	-	16.0	0.0089	0.221	-
Reach (m)	24	-	21	22	35	-
$R^{2(1)}$	0.94	-	0.80	0.83	0.94	-
DSD (%)[(2)]	9	-	9	10	19	-
CV (%)[(3)]	0.74	-	0.71	0.81	0.70	-
			0.05-0.10 m			
Model	Exp	Lin	Sph	Exp	Exp	Exp
Nugget effect	3.0	-	3.2	0.0008	0.018	2.70
Landing	20.5	-	14.9	0.0006	0.135	22.67
Reach (m)	24	-	20	30	26	26
$R^{2(1)}$	0.84	-	0.96	0.89	0.94	0.85
DSD (%)[(2)]	15	-	22	13	13	12
CV (%)[(3)]	0.63	-	0.60	0.80	0.80	0.70
			0.10-0.20 m			
Model	Exp	Lin	Sph	Exp	Sph	Exp
Nugget effect	6.3	-	5.3	0.0008	0.009	4.90
Landing	20.5	-	13.8	0.0008	0.194	42.85
Reach (m)	30	-	27	28	43	25
$R^{2(1)}$	0.86	-	0.95	0.97	0.97	0.90
DSD (%)[(2)]	31	-	38	10	5	11
CV (%)[(3)]	0.61	-	0.70	0.75	0.99	0.75
			0.20-0.30 m			
Model	Exp	Exp	Sph	Exp	Sph	Exp
Nugget effect	1.56	1.1	5.0	0.0015	0.017	4.20
Landing	22.4	11.4	16.2	0.0096	0.162	45.63
Reach (m)	22	20	21	20	31	24
$R^{2(1)}$	0.62	0.93	0.92	0.95	0.94	0.91
DSD (%)[(2)]	7	10	31	16	11	9
CV (%)[(3)]	0.62	0.73	0.93	0.71	0.76	0.85

Exp: Exponential model; Lin: Linear; Sph: Spherical model. [(1)] R^2: coefficient of determination; [(2)] DSD: degree of spatial dependence; [(3)] CV: cross-validation.

studied, except for Macro in the 0.10-0.20 m layer, TP in the 0.10-0.20 and 0.20-0.30 m layer, silt in the 0.00-0.05 layer, and RP in the 0.20-0.30 m layer, which exhibited moderate variability (25 to 75 %) (Tables 3 and 4). Organic C at 0.00-0.05 m, Micro at 0.0-0.05, 0.05-0.10, and 0.10-0.20 m, and moisture at 0.05-0.10 and 0.10-0.20 m had pure nugget effect, i.e., exhibited random variation over the study area (Tables 3 and 4). Similar results were found by Oliveira et al. (2013), who studied soils under different uses in the Amazon region.

The range of spatial dependence did not show wide variations. The clay content was the property with the highest variation (26 to 54 m), followed by GMD (26 to 43 m) and sand (30 to 54 m); the other properties showed little variation. Soil BD, Micro, Macro, TP, OC, RP, moisture, and silt ranged from 20 to 31 m (Tables 3 and 4), similar to results found by Aquino et al. (2014a), who studied anthropogenic and non-anthropogenic soils

Table 4. Models and estimated parameters for semivariograms of soil resistance to penetration (RP), moisture, sand, silt, and clay for four different layers of Archaeological Dark Earth under cacao cultivation

Geostatistical parameter	RP	Moisture (vol)	Sand	Silt	Clay
	MPa	%		g kg^{-1}	
		0.05-0.10 m			
Model	Exp	Exp	Sph	Sph	Exp
Nugget effect	0.015	2.80	519	256	256
Landing	0.121	17.74	2235	937	1942
Reach (m)	20	20	30	23	26
$R^{2(1)}$	0.90	0.91	0.97	0.95	0.84
DSD (%)[2]	12	16	23	27	13
CV (%)[3]	0.89	0.70	0.85	0.87	0.95
		0.05-0.10 m			
Model	Exp	Lin	Exp	Exp	Exp
Nugget effect	0.02	-	104	91	484
Landing	0.09	-	1091	910	2245
Reach (m)	34	-	54	31	51
$R^{2(1)}$	0.97	-	0.96	0.94	0.99
DSD (%)[2]	22	-	9.5	10	21.6
CV (%)[3]	0.75	-	0.90	0.91	0.96
		0.10-0.20 m			
Model	Exp	Lin	Exp	Exp	Exp
Nugget effect	0.012	-	67	148	138
Landing	0.110	-	1081	1539	1735
Reach (m)	24	-	35	26	54
$R^{2(1)}$	0.90	-	0.96	0.95	0.94
DSD (%)[2]	11	-	6	10	8
CV (%)[3]	0.87	-	0.94	0.78	0.94
		0.20-0.30 m			
Model	Sph	Exp	Exp	Exp	Exp
Nugget effect	0.044	1.72	129	449	356
Landing	0.110	13.30	863	1880	3392
Reach (m)	26	22	54	21	29
$R^{2(1)}$	0.90	0.84	0.94	0.96	0.98
DSD (%)[2]	40	13	15	24	11
CV (%)[3]	0.89	0.62	0.91	0.76	0.89

Exp.: Exponential model; Sph: Spherical model; Lin: Linear; [1] R^2: coefficient of determination. [2] DSD: degree of spatial dependence. [3] CV: cross-validation.

from the region of Manicoré in the state of Amazonas. Knowledge of range may assist in future studies involving soil sampling with respect to sample density (Aquino et al., 2014b).

In general, all soil properties were correlated (Table 5). Soil density and RP had positive correlation in all soil layers. Moreover, these two variables had a negative correlation with OC, indicating that the higher the OC content, the lower both BD and RP. Therefore, we can emphasize the important role of organic carbon for these properties in areas of ADE, as also reported by Campos et al. (2012).

A positive correlation between GMD and OC in the different layers was observed (Table 5), as also concluded by Vieira et al. (2011) and Coutinho et al. (2010). These results show the great importance of C in aggregation of soil particles (Alho et al., 2014).

Table 5. Coefficients of correlation among the soil properties (n = 352), for four soil layers, in areas of Archaeological Dark Earth under cacao cultivation

	RP	BD	Macro	Micro	TP	GMD	OC
			0.00-0.05 m				
SRP	1.00	0.54*	-0.57*	0.20	-0.49*	0.04	-0.51
SBD		1.00	-0.66*	0.10	-0.79*	0.10	-0.63*
Macro			1.00	-0.57	-0.65*	-0.14	0.68*
Micro				1.00	0.25	0.08	0.02
TP					1.00	-0.09	0.61*
GMD						1.00	0.71*
OC							1.00
			0.05-0.10 m				
SRP	1.00	0.53*	-0.54*	0.25	-0.55*	-0.01	-0.44*
SBD		1.00	-0.62*	-0.15	-0.68*	-0.04	-0.55*
Macro			1.00	-0.63	-0.52*	-0.01	0.49*
Micro				1.00	0.34	-0.03	0.26
TP					1.00	-0.04	0.55*
GMD						1.00	0.60*
OC							1.00
			0.10-0.20 m				
SRP	1.00	0.43*	-0.49*	0.07	-0.49*	-0.15	-0.47*
SBD		1.00	-0.44*	0.10	-0.53*	-0.05	-0.51*
Macro			1.00	-0.59*	0.69*	-0.02	0.44*
Micro				1.00	0.17	-0.09	0.04
TP					1.00	-0.11	0.49*
GMD						1.00	0.51*
OC							1.00
			0.20-0.30 m				
SRP	1.00	0.41*	-0.43*	-0.20	-0.44*	-0.05	-0.44*
SBD		1.00	-0.57*	-0.17	-0.82*	-0.21	-0.45*
Macro			1.00	-0.55*	0.68*	0.01	0.47*
Micro				1.00	0.23	0.18	0.05
TP					1.00	0.16	0.44*
GMD						1.00	0.56*
OC							1.00

* Pearson correlation, significant at 1 % probability by the t test. RP: soil resistance to penetration; BD: soil bulk density; Macro: macroporosity; Micro: microporosity; TP: Total porosity; GMD: geometric mean diameter; OC: organic carbon.

Even in areas of ADE with a history of more than 14 years under cultivation, soil properties had spatial dependence and low spatial variation. Part of this result is probably due to the stability of the cropping system using a perennial crop (cacao) for the last eight years. Another part should be attributed to the pedogenic features of this group of anthropogenic soils, which has a large amount of stable OC and natural fertility, favoring the maintenance of acceptable levels of such properties.

CONCLUSIONS

The soil properties studied exhibited a structure of spatial dependence, except for organic carbon, microporosity, and moisture at some of the layers evaluated, which showed a pure nugget effect, indicating that in areas of ADE with soil management interference and under cocoa use, the soil attributes exhibit distribution dependent on the spatial characteristics.

The soil physical properties showed a range between 20 and 54 m, showing that in the case of a new sampling process in this area under cacao cultivation, we can adopt 20 m as a minimum distance between sample points.

In ADE areas with high organic carbon content, there is an increase of the influence on the soil bulk density, soil resistance to penetration, and particle geometric mean diameter.

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