SOIL AND PLANT NUTRITION
Article

https://doi.org/10.1590/1678-4499.20210131

Impact of different crops on the spatial variability of the chemical attributes of Indian black earth in Southern Amazonas

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Received: May 5, 2021 | **Accepted:** Jul. 28, 2021

Section Editor: Hector Valenzuela

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How to cite: Silva, J. J. C., Campos, M. C. C., Brito Filho, E. G., Brito, W. B. M., Leite, A. F. L., Simões, E. L., Cunha, J. M. and Oliveira, F. P. (2021). Impact of different crops on the spatial variability of the chemical attributes of Indian black earth in Southern Amazonas. Bragantia, 80, e5121. https://doi.org/10.1590/1678-4499.20210131

ABSTRACT: In the Amazon region, soil patches with an anthropic A horizon are found, called Indian black earths (IBEs). Indian black earths are highly fertile and, therefore, are deforested by small local farmers to cultivate without basic management that maintains soil and crop sustainability. Therefore, in order to evaluate the effect of using different cultures on the spatial variability of soil chemical attributes, three cultivated IBEs and one IBE under natural forest were selected for georeferencing and sample collection. The collection was made with a mesh system with 88 points per IBE, stratified in three layers: 0–0.05, 0.05–0.10 and 0.10–0.20 m. The soil was sampled, dried in the shade and sieved to obtain the fine earth fraction for analysis of chemical attributes. Descriptive statistical and geostatistical analyses were applied to the results. The use and management of soil influenced the spatial behavior of the chemical attributes of IBEs. The cultivation of Brachiaria over many years favored the reduction of the spatial variability of chemical attributes. The use of cacao and coffee crops also favored the homogeneity of the IBEs in relation to the natural forest, but not as much as for Brachiaria, likely due to the succession of crops that preceded these crops. The IBE in the forest contains a high natural spatial correlation in the first 0.1 m of the surface; however, more than 70% of this correlation is linked to a random variation.

Key words: Amazon soils, use and management, anthropization.

INTRODUCTION

Human-modified soils are recognized as anthrosol or anthroposols according to the World Reference Base (FAO 2015), or are part of soils with anthropic A horizons (Santos et al. 2018). In the Amazon region, the increment of materials of various origins, such as plant remains (pyrogenic charcoal), animals (fish, bones, chelonian carapaces), and lytic (ceramic) fragments, over time allowed the formation of a thick superficial A horizon that gave rise to the archaeological black earth (*terra preta arqueológica*), Indian black earth (*terra preta de índio*), or black earth (*terra preta*) (Campos et al. 2012; Glaser 2007).

The Indian black earths (IBEs) are distributed in discontinuous patches across the Amazon, being normally located at an interval of 5 to 25 m in height in relation to water courses, and can also occur in areas higher than 40 m in altitude for places that required better visualization of the area. Still, they have the peculiarity of maintaining high fertility even after successive years of cultivation, even with little or no replacement of nutrients (German 2003; Kern et al. 2017; Teixeira et al. 2009).

Knowing these characteristics, many producers who practice small-scale (subsistence) agriculture have been deforesting these areas for the cultivation of grains, vegetables and fruits (Clement et al. 2009). Farming practices bring imbalance to the local ecosystem, changing the heterogeneity and spatial distribution of soil attributes (Shang et al. 2014). According to Souza et al. (2006), successive soil management influences the distribution of attributes, leading to variability even in highly homogeneous soils. In addition, both attribute values and their variability characteristics can be affected by management (Kravchenko et al. 2005).

The important issue with the use of spatial variability in soil science is that they are a continuum, and many properties vary in their values temporally and systematically, dependent on space (Wilding et al. 1994). Litter decomposition processes, vegetation composition, soil moisture content, topographic position and history of land use can govern this variability (Baldrian 2014). The greater the variability of the soil, the greater the difficulty in establishing mapping units for prescribing fertility and management zones with precision by conventional statistical methods. Therefore, this work focuses on the immediate quantification of the magnitude of changes in the spatial variability of IBEs attributes, considering that many sites have been under cultivation for several years and that is not known whether that management is benefiting the gain of homogeneity or heterogeneity of the attributes; nor the rhythm with which the heterogeneity of the properties reaches a landmark in its variability, capable of altering a defined diagnosis for a given management zone.

With the introduction of digital soil mapping, the geostatistics technique defined by Matheron (1963) was improved, allowing to identify the existing variability in the environment, the characterization of its random and spatial aspects (Santos et al. 2017; Silva Neto et al. 2011), and enabling the planning of sustainable soil management alternatives (Ziadat and Taimeh 2013). Geostatistics has been an important tool to investigate the variation and spatial dependence on the physical, chemical and hydrological properties of the soil, in addition to having been the focus of soil science in recent decades (Wang et al. 2021). Their study has been an alternative to reduce the effects of soil variation on agricultural production and to estimate the responses of soil attributes as a function of certain management practices (Souza et al. 2004).

Many studies have verified the existence of spatial dependence structures applying geostatistical analyzes to assess the spatial behavior of IBEs attributes in Amazonas (Brito et al. 2018; Campos et al. 2016; Cunha et al. 2019; Gomes et al. 2017; Oliveira et al. 2014; Soares et al. 2015). This technique not only allowed the evaluation of the aspects of spatial variation of the soil properties, but also guaranteed a good interpolation of the data and the generation of isoline maps with accuracy to better indicate the management zones.

However, studies with spatial variability of the soil require dense and numerous samplings, increasing the costs and time involved in sampling and analyzing soil attributes. In addition to this obstacle is the enormous amount of experimental semivariograms obtained, usually one for each attribute, which need to be analyzed for the sampling method for each attribute to be valid (Montanari et al. 2012). Less dense samples are cheaper; however, they can lead to an inaccurate assessment of spatial patterns and important aspects of spatial variability can be missed (van Groenigen et al. 1999). To work around these problems, Vieira et al. (1997) developed the scaled method, which integrates semivariograms of a region into a single experimental semivariogram, facilitating interpretation and reducing processing time. This method does not affect the estimated values in the interpolation; therefore, it better represents the sampling unit, saving time and money (Ferreyra et al. 2002).

Therefore, the aim here was to evaluate the effects of using different crops on the spatial variability of the chemical attributes of IBEs in Southern Amazonas, through classical statistics and geostatistical techniques represented by scaled semivariograms.

MATERIAL AND METHODS

Description and IBEs historical use

The study was carried out in areas with different soil uses and the presence of an anthropic A horizon. The collection sites are located in the south of Amazonas, close to the BR 230 – Transamazônica highway, in the municipalities of Apuí, Manicoré and Novo Aripuanã (Fig. 1). Four areas of IBE were selected in rural settlement properties belonging to family farmers, cultivated with cacao (*Theobroma cacao* L.), coffee (*Coffea canephora* [Pierre ex A. Froehner]), pasture with Brachiaria (*Brachiaria brizantha* [Hochst ex A. Rich.]) and natural forest.

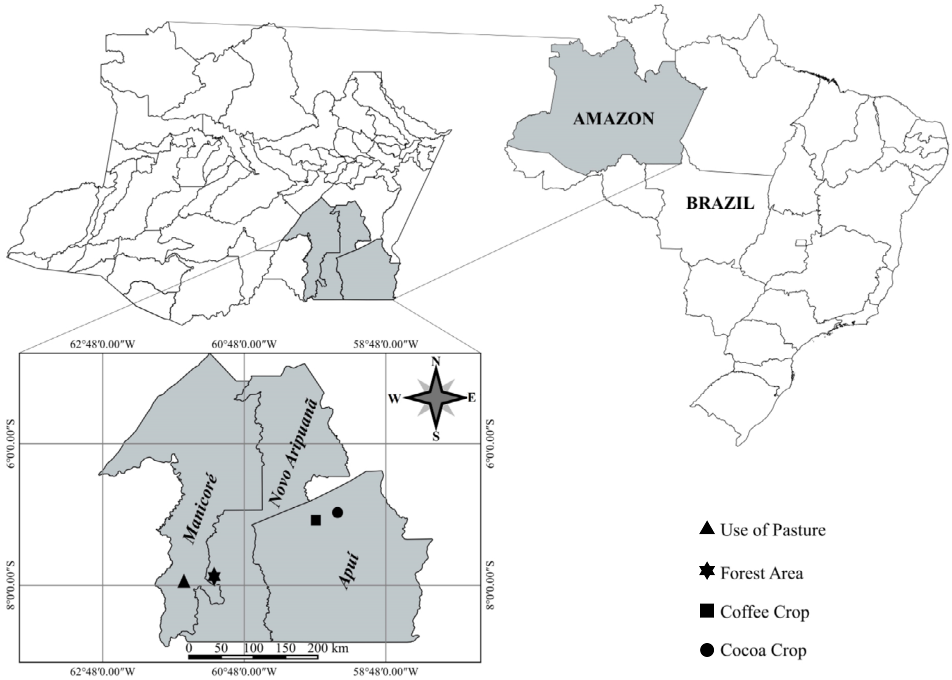

Figure 1. Location of the study IBEs and their respective uses in southern Amazonas.

The IBEs under coffee and cacao are located in the municipality of Apuí, under the geographical coordinates 7°12’05”S latitude and 59°39’35”W longitude. The IBE under coffee cultivation has been cultivated for six years, the first two under pasture cultivation and the last four years with coffee cultivation, until present. The IBE under cacao has been cultivated for fourteen years and, in the first six years, it was cultivated with rice, corn, beans and watermelon, and, subsequently, with cacao. No type of machinery has been used in the implantation and maintenance of crops. The soils of both IBEs were classified as Eutrophic Yellow Argisol according to Santos et al. (2018) or Typic Haplohumult (Soil Survey Staff 2014).

The IBE under Brachiaria is located in the municipality of Manicoré, under the geographical coordinates of 7°59’22”S and 61°39’51.2”W with an average altitude of 83 m, with cultivation of Brachiaria (*Brachiaria brizantha*), in ten years of extensive grazing and animal support capacity of around one unit/animal per hectare. The soil was classified as Eutrophic Red-Yellow Argisol (Santos et al. 2018) or Typic Haplohumult (Soil Survey Staff 2014), and the region primary vegetation is characterized as dense tropical forest. The IBE area under natural forest, on the other hand, has been preserved for over 25 years, with the beginning of forest recovery with medium sized trees reaching up to 15 m in height. This IBE was classified as argisolic yellow eutrophic latosol (Santos et al. 2018) or typic eutrudox (Soil Survey Staff 2014).

Sample design and laboratory analysis

In the field, sample meshes were marked with the following dimensions: 80 × 56, 80 × 42, 80 × 42 and 60 × 42 m, with spacing of 8 × 8, 6 × 8, 6 × 8 and 6 × 6 m, respectively for the IBE’s of Brachiaria, coffee, cacao and forest. These sampling meshes have a sampling coverage of 4480 m² in the pasture area, and 4228 m² in the cacao and coffee areas, which were chosen based on the representativeness of the sampling points as a whole (collection in the spaces between the lines and plants, relief and size of crops). Each mesh had 88 points, where mini trenches were opened and soil samples were collected at depths: 0–0.05, 0.05–0.10 and 0.10–0.20 m, totaling 264 samples per area. The points were georeferenced using GPSMAP 76CSx equipment, with precision < 10 m.

After sampling, each sample was dried in the shade and slightly deformed to obtain the air-dried fine earth, and then sent to the laboratory to determine the attributes. The analyzed attributes were: pH in water, with a pH meter with a soil:water ratio of 1:2.5; calcium (Ca^{2+}), magnesium (Mg^{2+}) and aluminum (Al^{3+}) — extracted by KCl 1 mol·L^{-1} solution and determined by atomic absorption spectrometry for Ca^{2+} and Mg^{2+}, and titrimetry for Al^{3+}; potassium (K^+) and phosphorus (P) extracted by Mehlich-1 and determined, respectively, by flame photometry and calorimetry; potential acidity (H^+ + Al3$^+$), in 0.5 mol·L^{-1} calcium acetate as extractor and 0.025 mol·L^{-1} NaOH as titrant and; total organic carbon by the oxidation wet method, according to Donagema et al. (2011). Based on these determinations, the following were calculated: potential cation exchange capacity (CEC); sum of bases (SB), base saturation (V) and aluminum saturation (m).

Statistical analysis

The soil attributes were analyzed in the first instance using descriptive statistics, estimating mean, amplitude, coefficient of variation (CV%), coefficient of asymmetry and kurtosis. An analysis of variance was also applied to check if there was any difference between the areas studied, comparing the means of the attributes and applying Tukey's test at 5% probability. The hypotheses of normality of the data were verified by the Kolmogorov–Smirnov (KS) test ($p \leq 0.05$), using the computer software Minitab 14 (Minitab 2004).

Then, geostatistics was performed to assess the spatial variability of the studied attributes, according to Vieira et al. (1983). The presence or absence of a spatial dependency structure was verified using the GS+ software v. 7.0 (Robertson 2008), which plots an experimental semivariogram based on the presupposition of stationary intrinsic hypothesis (Eq. 1).

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

where: $\hat{y}(h)$ = value of the semivariance for a distance h; $N(h)$ = number of pairs involved in calculating the semivariance; $Z(x_i)$ = value of attribute Z in position x_i; $Z(x_i + h)$ = value of attribute Z separated by a distance h from position xi.

The experimental semivariograms were fitted based on the highest coefficient of determination (R^2) and cross-validation (C-V), in order to obtain the best correlation and sill clearly defined (Burrough and McDonnel 2000). Then, for each calculated $\hat{y}(h)$ value, the parameters were extracted: C_0 — nugget effect; $C_0 + C$ — sill and; a — range. With these parameters obtained, scaled semivariograms were built to reduce the individual semivariograms on the same scale and incorporate them into one, facilitating the comparison between the results of different attributes (Vieira et al. 1997). According to the results, two models were fitted, the spherical (Eq. 2) and the exponential (Eq. 3).

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

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

In the analysis of the spatial dependency index (IDE), the examination of the parameters of the semivariograms was conducted according to Cambardella et al. (1994), which calculates the values of $\left[\frac{C_0}{(C_0 + C_1)} \times 100\right]$ and classifies them as: IDE ≤ 25%, 25% < IDE < 75%, and IDE > 75% in strong, moderate and weak spatial dependence, respectively.

RESULTS AND DISCUSSION

Chemical profile of IBEs

In general, the IBEs showed high levels of organic carbon, phosphorus, calcium and magnesium, and low levels of exchangeable acidity and, hence, low saturation with aluminum. In particular, the organic carbon (OC) content showed statistical differences between all types of use (Tables 1 and 2), being higher in the superficial layer of Brachiaria cultivation (OC = 13%) (Table 1), and lower in subsurface of the natural forest area (OC = 1.9%) (Table 3). The growth habit of *Brachiaria brizantha*, as well as the greater coverage of the soil verified *in loco*, when compared to the other uses of the soil, may have favored its higher levels of OC. In addition, when handled correctly, these systems benefit from the C inputs to the system, with improvements in the chemical, physical and biological attributes of the soil as a function of time (Bell and Moore 2012).

Table 1. Descriptive statistics of the chemical attributes of IBEs under different crops in southern Amazonas for the **0.00–0.05 m** layer.

Attributes	pH	OC	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^++Al^{3+}	CEC	SB	V	m
	H_2O	$g{\cdot}kg^{-1}$	$mg{\cdot}kg^{-1}$	------------------------------------ $cmol_c{\cdot}kg^{-1}$ ------------------------------------							----- % -----	
Cacao												
Mean	6.23a	55.32b	93.70a	0.03b	19.57a	2.12b	0.06c	6.54b	28.28a	21.77a	77.25a	0.32c
[1]CV%	7.82	19.77	34.93	33.33	16.35	50.00	16.66	52.59	9.83	15.03	14.56	40.62
Amplitude	2.64	55.80	148.28	0.02	13.50	4.75	0.06	13.90	12.45	14.48	47.07	0.59
Skewness	–0.08	0.19	0.33	0.55	–0.29	0.47	0.26	0.36	0.01	0.53	–0.42	1.42
kurtosis	1.00	0.04	–0.43	–0.29	–0.50	–0.09	–0.54	–0.59	–0.33	–0.09	–0.32	1.89
[2]K–S	0.10*	0.06*	0.08*	0.10*	0.12*	0.12*	0.18*	0.10*	0.05*	0.10*	0.08*	0.34*
Coffee												
Mean	5.37c	39.78c	40.35b	0.01c	8.72b	2.45a	0.11b	8.46a	19.65b	11.19b	56.25b	1.05b
[1]CV%	8.71	32.37	68.12	4.05	36.81	35.91	50.00	23.64	16.33	30.29	17.65	81.90
Amplitude	2.13	53.29	153.20	0.02	15.00	3.75	0.30	10.23	19.10	15.50	45.57	5.29
Skewness	0.27	0.41	2.37	1.32	0.46	0.02	1.93	0.12	0.39	0.32	–0.27	3.15
kurtosis	–0.12	–0.84	6.73	0.83	0.08	–0.47	0.29	–0.11	–0.15	–0.34	–0.11	11.81
[2]K–S	0.08*	0.11*	0.09*	0.08*	0.08*	0.08*	0.14*	0.05*	0.08*	0.06*	0.08*	0.22*
Brachiaria												
Mean	5.48c	137.07a	97.44a	0.02b	9.28b	2.29ab	0.39a	8.52a	20.14b	11.61b	57.54b	2.73a
[1]CV%	4.92	4.06	31.97	33.24	20.30	29.57	32.82	15.66	14.49	18.57	9.16	34.95
Amplitude	1.74	31.19	96.68	0.03	9.25	2.75	0.50	7.10	7.65	10.29	36.24	3.77
Skewness	0.75	–0.72	–0.10	0.20	0.55	–0.02	0.69	–0.08	0.22	0.38	0.35	0.57
kurtosis	2.14	1.50	–0.75	–0.91	0.09	–0.47	–0.02	–0.12	–0.20	–0.24	2.38	–0.37
[2]K–S	0.07*	0.06*	0.09*	0.10*	0.12*	0.12*	0.22*	0.07*	0.07*	0.09*	0.06*	0.08*
Forest												
Mean	5.77b	22.34d	28.48c	0.06a	6.59c	1.39c	0.11bc	5.44c	13.48c	8.04c	37.19c	1.39b
[1]CV%	5.92	20.77	68.25	51.39	22.25	27.92	42.63	29.67	18.95	21.73	9.09	42.56
Amplitude	1.54	19.98	91.95	0.16	7.70	1.70	0.40	8.09	14.91	9.30	15.72	3.79
Skewness	–0.06	0.20	1.58	1.42	–0.65	–0.37	7.54	0.92	0.00	–0.66	–0.66	3.16
kurtosis	–0.36	–0.53	2.34	2.49	0.86	–0.40	25.88	1.52	1.03	0.82	0.36	12.19
[2]K–S	0.06*	0.08*	0.19	0.11*	0.08*	0.11*	0.52	0.09*	0.07*	0.08*	0.07*	0.23

Note. Means followed by the same letter in the column do not differ by Tukey's test at 5%. [1]CV%: coefficient of variation; [2]K–S: Kolmogorov–Smirnov normality test. OC: organic carbon; P: available phosphorus; Ca^{2+}: calcium; Mg^{2+}: magnesium; K^+: potassium; Al^{3+}: aluminum; $H^+ + Al^{3+}$: potential acidity; CEC: potential cation exchange capacity; SB: sum of bases; V: base saturation; m: saturation by aluminum; *: significant at 5% probability by the K–S test.

Table 2. Descriptive statistics of the chemical attributes of IBEs under different crops in southern Amazonas for the **0.05–0.1 m** layer.

Attributes	pH	OC	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^++Al^{3+}	CEC	SB	V	m
	H_2O	$g{\cdot}kg^{-1}$	$mg{\cdot}kg^{-1}$	------------	------------	------------	$cmol_c{\cdot}kg^{-1}$	------------	------------	------------	----- %	-----
Cacao												
Mean	5.92a	41.40b	109.61a	0.03a	11.60a	2.05a	0.07c	9.15a	25.75a	15.89a	63.96a	0.78c
¹CV%	8.61	10.26	30.68	33.33	34.05	36.29	42.85	54.31	7.96	29.26	28.65	91.00
Amplitude	2.10	20.84	163.10	0.04	18.10	6.15	0.14	18.65	8.85	19.65	65.15	3.71
Skewness	–0.21	0.31	0.01	0.40	0.20	0.06	0.19	0.76	–0.14	–0.09	–0.05	2.10
kurtosis	–0.57	–0.09	–0.25	–0.14	–0.32	–0.79	0.33	–1.00	–0.62	–0.74	–1.06	4.78
²K–S	0.09*	0.10*	0.08*	0.08*	0.09*	0.12*	0.13*	0.07*	0.14*	0.08*	0.08*	0.24*
Coffee												
Mean	5.15c	34.54c	32.61c	0.005c	5.19d	1.59b	0.25b	8.62a	15.42c	6.79c	43.46b	4.58a
¹CV%	10.87	32.80	67.24	1.23	62.80	38.99	80.00	33.52	27.56	49.92	20.95	95.63
Amplitude	2.54	46.65	100.60	0.02	18.00	2.75	0.80	12.38	21.99	18.70	63.21	19.03
Skewness	0.58	–0.32	1.22	0.57	1.94	0.17	0.99	0.09	0.55	1.73	0.37	1.37
kurtosis	–0.19	–0.70	1.25	–1.10	6.01	–0.54	0.26	–0.41	0.63	5.02	–0.36	1.31
²K–S	0.08*	0.18*	0.08*	0.17*	0.13*	0.10*	0.21*	0.05*	0.07*	0.10*	0.07*	0.23*
Brachiaria												
Mean	5.75b	135.28a	52.42b	0.01b	10.09b	1.36b	0.44a	5.46b	23.18b	11.47b	67.74a	3.71b
¹CV%	3.50	1.69	41.79	40.73	19.03	38.37	19.64	21.04	15.03	17.83	9.57	28.95
Amplitude	0.93	11.30	79.92	0.01	8.50	2.50	0.30	4.79	12.46	8.51	38.88	4.36
Skewness	0.60	–0.69	0.36	1.04	0.40	0.02	–0.28	0.00	0.42	0.34	0.49	0.10
kurtosis	–0.23	0.42	–0.90	0.95	–0.37	–0.17	–0.32	–0.72	0.19	–0.35	1.72	–0.84
²K–S	0.10*	0.09*	0.13*	0.13*	0.09*	0.12*	0.27*	0.07*	0.08*	0.09*	0.09*	0.08*
Forest												
Mean	5.88b	22.25d	28.16c	0.02a	5.90c	0.96c	0.12c	6.40b	13.29d	6.89c	33.95c	2.09c
¹CV%	8.41	21.31	78.64	37.70	23.23	38.89	38.59	25.15	18.23	23.32	10.50	67.00
Amplitude	1.96	19.21	106.65	0.05	6.70	1.90	0.20	8.75	14.32	8.40	17.13	8.01
Skewness	0.38	–0.15	1.80	0.56	–0.66	0.66	1.67	0.21	–0.85	–0.48	–0.57	2.77
kurtosis	–0.43	–0.93	3.69	0.00	0.68	0.19	2.07	0.15	1.69	0.49	0.22	9.05
²K–S	0.09*	0.08*	0.15	0.12*	0.06*	0.14*	0.44	0.08*	0.11*	0.08*	0.12*	0.22

Note. Means followed by the same letter in the column do not differ by Tukey's test at 5%. ¹CV%: coefficient of variation; ²K–S: Kolmogorov–Smirnov normality test. OC: organic carbon; P: available phosphorus; Ca2+: calcium; Mg2+: magnesium; K+: potassium; Al3+: aluminum; H+ + Al3+: potential acidity; CEC: potential cation exchange capacity; SB: sum of bases; V: base saturation; m: saturation by aluminum; *: significant at 5% probability by the K–S test.

As for the pH values in water, contrary to what was expected, they were not lower (more acidic) in the forest area. Considering the 0.0–0.1 m layer (Table 1 and 2), pH in water showed the following order of decline: cacao > forest > Brachiaria > coffee, respectively with mean values of 6.0, 5.8, 5.6, and 5.2. What is intriguing is that in a 0.1–0.2 m layer (Table 3), the IBE of forest, Brachiaria and cacao are more homogeneous, with pH values statistically equal by the used Tukey's test ($p \leq 0.05$). The values of Ca^{2+}, Mg^{2+} and K^+, in general, decrease with depth, reflecting the effect of nutrient cycling of each particular soil use acting as a function of time and according to the litter inputs, as well as the contributions deposited from past anthropic actions. According to Schumacher et al. (2013), the contribution and transformation of litter are fundamental for maintaining soil attributes for both native forest and planting commercial species.

Except for the K^+ levels, the available p values, CEC, SB and base saturation (V) for all IBEs are considered high when compared to adjacent soils in the region (Santos et al. 2013). Among the IBEs evaluated, the one cultivated with cacao showed CEC, SB and V superior to the other areas (Tables 1, 2 and 3). These superior results are a consequence of the high pH values in water, Ca^{2+} and Mg^{2+}, and the low levels of Al^{3+} and potential acidity ($H^+ + Al^{3+}$), allowing greater availability of nutrients to the exchange complex. Falcão and Borges (2006), Campos et al. (2012), Santos et at. (2013) and Oliveira et al. (2014) obtained results similar to these and explain that the low K^+ contents are due to their high mobility in the soil; and that the high values of CEC, SB, V and available p result from the bone and shell remains and complexes of stable organic matter, associated with pyrogenic charcoal.

Table 3. Descriptive statistics of the chemical attributes of IBEs under different crops in southern Amazonas for the **0.1–0.2 m** layer.

Attributes	pH	OC	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^++Al^{3+}	CEC	SB	V	m
	H_2O	$g \cdot kg^{-1}$	$mg \cdot kg^{-1}$	------------------------------------- $cmol_c \cdot kg^{-1}$ -------------------------------------							----- % -----	
						Cacao						
Mean	5.59a	31.31b	124.34a	0.02a	10.47a	1.99a	0.20c	11.53a	24.46a	14.97a	52.65b	1.94b
¹CV%	10.73	17.40	24.44	50.00	40.97	50.25	37.50	43.19	7.68	34.94	36.20	93.00
Amplitude	2.39	23.34	143.35	0.05	17.63	4.50	0.16	20.79	8.89	17.27	70.71	10.57
Skewness	0.65	−0.15	0.04	0.91	0.40	0.43	1.12	−0.22	−0.25	0.31	0.33	2.12
kurtosis	−0.59	−0.35	−0.22	0.26	−0.44	−0.15	0.51	−0.96	−0.12	−0.85	−1.04	4.78
²K–S	0.14*	0.07*	0.12*	0.15*	0.11*	0.12*	0.20*	0.10*	0.14*	0.09*	0.11*	0.25*
						Coffee						
Mean	4.98b	33.04b	32.70c	0.01b	3.88c	1.33b	0.58a	9.76b	14.98c	6.79c	35.18c	11.14a
¹CV%	11.04	22.36	65.68	3.88	55.92	39.17	25.85	33.29	24.03	43.86	38.57	90.57
Amplitude	2.84	34.71	113.84	0.01	8.50	3.00	0.30	14.68	17.46	10.50	56.23	40.12
Skewness	0.83	−0.94	1.39	3.89	0.74	0.72	0.16	0.22	0.23	0.86	0.72	1.10
kurtosis	0.51	0.68	3.04	13.48	−0.38	1.50	−0.58	−0.35	−0.55	0.38	0.08	0.63
²K–S	0.12*	0.13*	0.10*	0.18*	0.16*	0.17*	0.24*	0.06*	0.09*	0.16*	0.14*	0.17*
						Brachiaria						
Mean	5.71a	133.91a	50.43b	0.00c	9.41a	1.47b	0.33b	5.44c	16.62b	10.89b	65.48a	2.92b
¹CV%	4.02	1.56	39.02	54.13	20.84	35.32	28.12	21.31	15.31	18.82	10.00	30.11
Amplitude	1.09	12.04	73.03	0.01	10.50	2.75	0.40	4.29	12.65	11.25	27.84	3.90
Skewness	0.31	0.51	0.43	0.79	0.47	0.09	0.53	−0.23	0.57	0.69	−0.15	0.33
kurtosis	−0.24	1.17	−0.81	−0.67	0.59	0.38	0.33	−1.27	0.02	0.94	−0.81	−0.51
²K–S	0.10*	0.09*	0.09*	0.22*	0.11*	0.12*	0.19*	0.14*	0.10*	0.10*	0.08*	0.08*
						Forest						
Mean	5.76a	19.15c	28.02c	0.02a	5.56b	0.80c	0.29bc	6.02c	12.40d	6.37c	33.47c	4.35b
¹CV%	7.13	36.22	65.43	37.07	31.36	41.78	68.96	30.87	22.51	30.93	14.76	62.36
Amplitude	1.67	34.86	100.77	0.03	7.80	1.60	1.00	10.73	13.63	8.89	21.92	13.92
Skewness	0.65	0.94	1.65	0.89	−0.41	0.85	1.93	0.70	−0.49	−0.32	−0.69	1.70
kurtosis	−0.25	1.27	3.63	0.50	−0.09	0.61	3.57	1.48	0.17	−0.09	0.24	3.12
²K–S	0.11*	0.10*	0.16	0.14*	0.08*	0.14*	0.28	0.07*	0.09*	0.08*	0.13*	0.20

Note. Means followed by the same letter in the column do not differ by Tukey's test at 5%. ¹CV%: coefficient of variation; ²K–S: Kolmogorov–Smirnov normality test. OC: organic carbon; P: available phosphorus; Ca2+: calcium; Mg2+: magnesium; K+: potassium; Al3+: aluminum; H+ + Al3+: potential acidity; CEC: potential cation exchange capacity; SB: sum of bases; V: base saturation; m: saturation by aluminum; *: significant at 5% probability by the K–S test.

From an agronomic point of view, in a quantitative interpretation of the IBEs fertility for crop development, it is possible to classify active acidity as "good" for the areas of cacao, Brachiaria and forest; toxicity by exchangeable acidity from very low to low (except for the 0.1–0.2 m layer of IBE under coffee); very low saturation by aluminum (m); general base saturation low to average, which can be good in cacao and Brachiaria and; CEC ranging from good (in the forest) to very good (in the crops) (Ribeiro et al. 1999).

Variability of properties with classical statistics

The variability in this current study, assessed by the Warrick and Nielsen (1980) criterion, showed a previous diagnosis of the spatial distribution of the chemical attributes of IBEs. The CV% ranged from 1.56 to 95.63% for all evaluated areas, ranging from low (CV < 12%), medium (12% < CV < 60%) to high variability (CV > 60%). The pH in water was the only attribute to present low variability in all IBEs (average CV of 7.6%), in contrast to m%, which showed high variability (CV of 73.8%) in IBEs, except for Brachiaria, which did not show attributes with high variability. Beyond the pH in water, the CEC (8.5%) in cacao, K+ (3.0%) in coffee, OC (2.4%) and V (9.5%) in Brachiaria, and V (11.4%) in the forest also showed low variability in the IBEs (Tables 1, 2 and 3).

Comparing the CV% between the different crops, where the attributes are evaluated as one, the variability increased following Brachiaria < cacao < forest < coffee in the superficial layer; while in the 0.05–0.1 m layer, variability increased from Brachiaria < forest < cacao < coffee. The 0.1–0.2 m layer is more homogeneous, denoting a uniformity between attributes in which similar crops did not interfere in the variability of the IBEs sites, in which the IBE with Brachiaria (the most homogeneous; CV = 23%) and the other coverages (both with CV = 37%) present moderate variability.

The values of the normality test, asymmetry and kurtosis coefficient (Tables 1, 2 and 3) prove that this mesh sampling was sufficient to predict the variability of chemical attributes. As can be seen, all attributes of the cultivated areas showed normal data distribution by the K–S test ($p \leq 0.05$), as well as asymmetry and kurtosis are around zero (± 2.0), despite some exceptions, indicating that the median is close to the mean of each attribute, and ensuring the normality of the data (Cortez et al. 2011).

Thus, this lower variability in the Brachiaria area and greater in other coverings is probably due to its history of use. The Brachiaria had been under a monoculture for over 10 years, the cacao and coffee areas were planted with other cereal crops in succession in previous years, requiring different management practices, which increases the variability of soil attributes (Raiesi and Kabiri 2016).

Another factor to consider is the habit of aggressive growth by Brachiaria, which provides greater soil coverage, softening the heterogeneity of the attributes. Thus, the authors infer that in natural IBEs converted to agricultural uses, the change in variability is dependent on the size, cycle and growth habit of the crop in relation to the predominant vegetation in the forest, so that the monoculture of forage for long years can reduce its heterogeneity, while perennial crops (e.g., cacao and coffee) suffer less variation over the years.

Spatial variability of properties with geostatistics

An individual geostatistical analysis for each chemical attribute was performed to determine which ones were spatially correlated, using experimental semivariograms. The forest was the area that showed the most spatial dependence structure for most of the attributes analyzed (except for V% and m% in the subsurface layer), followed by Brachiaria and cacao. On the other hand, the IBE that showed the least spatial correlation structure was the coffee area, in which attributes, such as available P, Mg^{2+} and SB, did not manifest the phenomenon in any of the evaluated layers and, therefore, were not incorporated into the scaled semivariograms (Fig. 2).

It is important to highlight that the input parameters of the individual semivariograms reflect the sensitivity in the output of the scaled model adjustment. Because it contains several variables of different natures, geostatistical parameters (e.g., C_0, $C_0 + C$ and a) which have great variation in a certain stratified layer of this work may have little sensitivity in the generation of the final model. If they show little variation, the fitted model may have a high sensitivity and, thus, better represent the spatial variability of the attributes.

In this sense, only the attributes that showed spatial dependence defined with a model fitted under minimum residue parameters and with a determination coefficient (R^2) and cross-validation (C-V) greater than 70% were used in the scaled semivariograms (Fig. 2). For attributes without defined spatial structures, only nugget effects can be distinguished and, therefore, the use of geostatistics is irrelevant (Kravchenko et al. 2005). So, classical statistics can better express the spatial variability of these attributes, through the estimates of means, CV% and amplitude presented.

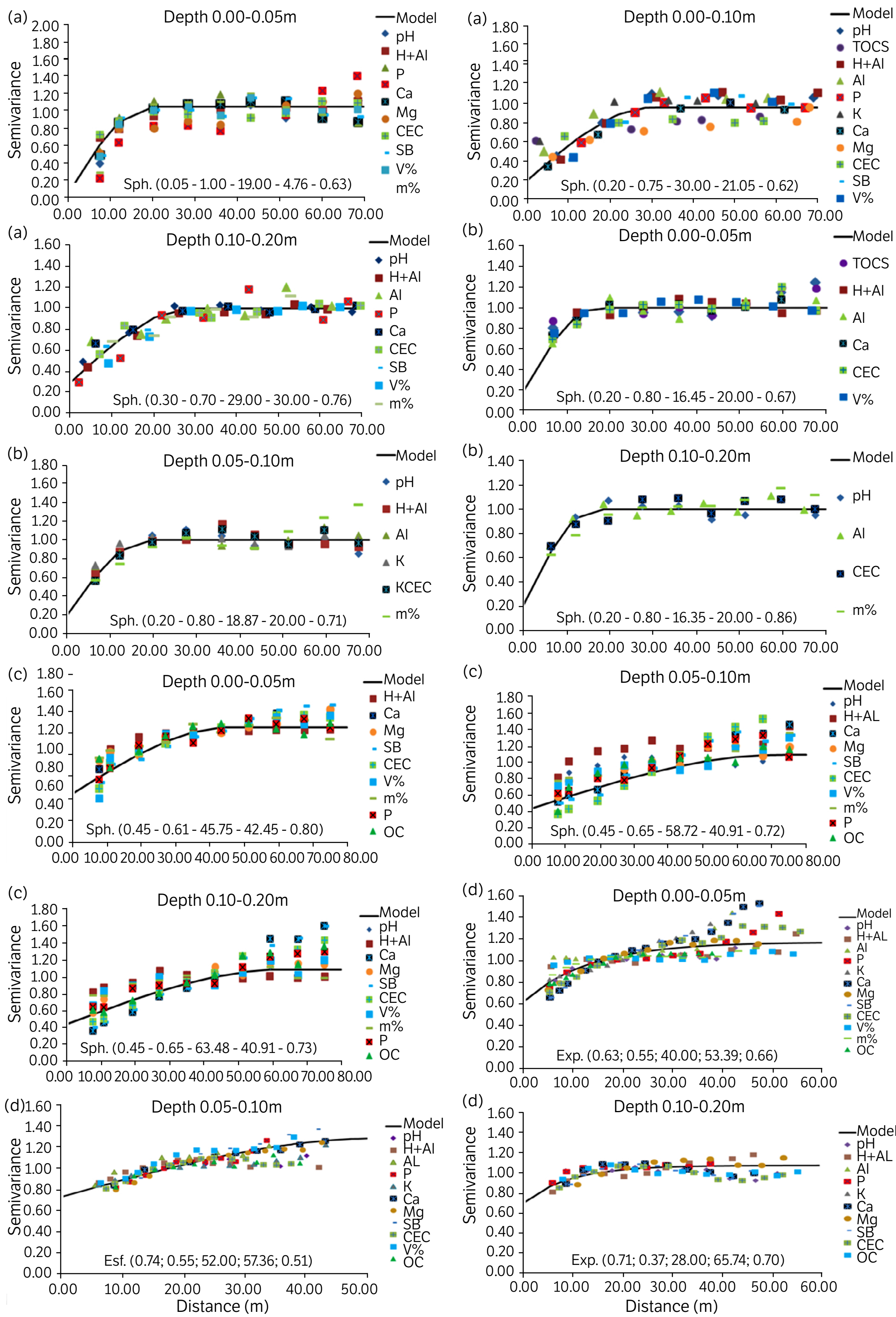

Figure 2. Scaled semivariograms of the chemical attributes of IBEs under uses with cacao (a), coffee (b), Brachiaria (c) and forest (d).

Note. Values in parentheses preceded by the model are, respectively: nugget effect, contribution, range (m), spatial dependency index and determination coefficient.

In the adjustment of the scaled semivariograms, the spherical model was the best in estimating the semivariance of all IBEs (Fig. 2), except for the 0.0–0.5 and 0.1–0.2 m forest layers, in which the exponential model fits better. According to Carvalho et al. (2002), the adjustment of the spherical model predominates in soil science works. However, the exponential model has also been widely used in both soil science and environmental science (Bertolani and Vieira 2001; Siqueira et al. 2010).

Despite the number of attributes, the adjustment of the models taking into account the variations of nugget effects and sills returned good results. This can be seen through the obtained R^2 values, which estimate the percentage of variation of a final variable by an explanatory variable (Renaud and Victoria-Feser 2010). From the fitted models, the extreme values of R^2 are situated between 0.51 (in the forest) to 0.86 (in coffee) (Fig. 2), meaning that the linear relationships of these models with the spreading of the pairs of points are able to explain at least 51% and a maximum of 86%, respectively, of the natural semivariance of the chemical attributes of IBEs. These results allow a good estimate in kriging interpolation to generate reliable spatial distribution maps (Santos et al. 2017).

Analyzing the different soil uses by layers, the Brachiaria IBE obtained the highest values of R^2 (80, 72 and 73%), in the three sampled layers (0.0–0.05, 0.05–0.1, 0.1–0.2 m), in addition to presenting the lowest variation of R^2 between layers (8%) (Fig. 2). This means that the spatial variability of this area increases from the surface to the subsurface and that, as shown in classical statistics, IBE cultivated with Brachiaria is the most homogeneous among IBEs. Conversely, the models fitted for the forest IBE present the lowest R^2, with values of 66, 51 and 70% of the area semivariance, and greater amplitude between layers (19%), so that it is not possible to predict the vertical variability, but only in the first 0.2 m of soil. Therefore, the forest has the greatest spatial variability among IBEs.

The cacao and coffee IBEs have characteristics of intermediate variability between Brachiaria and forest. However, they showed a better-defined spatial dependence structure, where the ranges varied from 19 to 30 and 16 to 18 m of spatial dependence between points in the cacao and coffee areas, respectively. Still, both have a strong spatial dependency index (IDE > 25%), except for the 0.1–0.2 m cacao layer (IDE = 30%). Furthermore, the nugget effects of these IBEs varied from 5 to 20 and 30% between the cacao layers, and around 20% in coffee. This means that the variation due to both analytical measurement errors and uncontrolled microvariation in the adjustment for small distances in which there are no estimates of $\hat{y}(h)$ (< 6 m in both IBEs), did not exceed 30% of the spatial correlation of the data (Silva et al. 2011; Oliver and Webster 2014).

In contrast, the areas of Brachiaria and forest showed the highest ranges of spatial dependence, with values of 45, 58 and 63 m between layers of Brachiaria, and 40, 52 and 28 m between layers of forest. These range values provide fundamental information about the heterogeneity and spatial distribution of properties in each management system (Trangmar et al. 1986). Despite that, it does not mean that the forest has provided the best homogeneity as found in Brachiaria, because one must take into account the percentage of random discontinuity present in each area (C_0). While Brachiaria maintains a 45% variation at random horizontally and does not vary vertically up to 0.2 m, the forest has an average proportion of 72.6% and varies around 3% vertically. This explains that, from point-to-point, there is a variation of 72.6% at random, and in relation to the sills of semivariograms, there is a spatial discontinuity of 4.3 m in range for every 6 m sampled by the mesh, being impossible to discern individual errors of types of variation by sampling and analytics (Silva et al. 2011).

Therefore, corroborating the observed values of R^2 and C-V%, the range values in relation to the nugget effects confirm the greater homogeneity found in Brachiaria, despite having a moderate spatial dependency index (25% < IDE < 75%). This behavior may also be due to the intrinsic characteristics of the crop, such as its better developed and distributed root system, which provides greater OC input and soil cover (Cardoso et al. 2010), and its short life cycle with rapid and aggressive growth. The areas of cacao and coffee showed intermediate variability, in which the reach values were not as high as in the other IBEs, but were obtained with low random variation, a strong spatial dependency index and with a range greater than twice the spacing defined in their sample meshes.

CONCLUSION

The use of geostatistics with the scaled semivariogram technique was efficient and essential in predicting the effect of different crops on the spatial variability of the chemical attributes of IBEs in southern Amazonas. However, the authors recommend its adoption to be always accompanied by classical statistics, mainly for soils sampled in a random system without theoretical bases of the optimal sample density capable of presenting high micro-scalar variation.

The IBE cultivated with cacao showed greater fertility, however, the IBE of Brachiaria shows OC levels higher than the other IBEs, which it is concluded that comes from the root system and the greater soil coverage by its culture. Nevertheless, no associations were verified between the degree of fertility and the spatial variability of the areas.

The use and management of the soil influenced the spatial behavior of the chemical attributes of IBEs. The monoculture of Brachiaria for many years favored greater homogeneity and, hence, decreased spatial variability of chemical attributes, followed by the use of medium-sized crops (cacao and coffee) in relation to the natural forest, as proved through its high range values and fit of the modeled semivariograms. The forest IBE contains a high natural spatial correlation in the first 0.1 m of the surface; however, more than 70% of this correlation is linked to a random variation.

AUTHORS' CONTRIBUTION

Investigation: Silva, J. J. C., Campos M. C. C., Brito Filho, E. G., Brito, W. B. M. Cunha, J. M., Oliveira, F. P.; **Writing – Original Draft:** Silva, J. J. C., Campos M. C. C., Brito Filho, E. G., Brito, W. B. M. Cunha, J. M., Oliveira, F. P.; **Methodology:** Lima, A. F. L., Simões, E. L.; **Writing – Review and Editing:** Brito Filho E. G. and Brito, W. B. M.

DATA AVAILABILITY STATEMENT

All data sets were generated and analyzed in the current study.

FUNDING

Conselho Nacional de Desenvolvimento Científico e Tecnológico
https://doi.org/10.13039/501100003593

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
https://doi.org/10.13039/501100002322

Fundação de Amparo à Pesquisa do Estado do Amazonas
https://doi.org/10.13039/501100004916

ACKNOWLEDGMENTS

The authors thank the Universidade Federal do Amazonas for their technical support during the research.

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