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SOIL SCIENCE

Pedotransfer functions to estimate some soil properties in Indian Black Earth, south of Amazonas State

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Abstract: Agriculture needs methodologies that assist in the determination of soil attributes and variability mapping attributes with greater levels of detail. Therefore, the objective of this research was to evaluate magnetic susceptibility as auxiliary variable for estimating soil attributes in areas of Indian Black Earths in the south of Amazonas State. Three Indian Black Earth areas are located in the municipalities of Apuí and Manicoré - Amazonas, under uses with coffee, cocoa and pasture. The soils were collected at the crossing points in the depth of 0.00 - 0.20 m, making a total of 88 sampling points/area, and totaling 264 samples. The points were georeferenced for geostatistical modeling. After that, physical and chemical analyzes were performed to obtain the values of soil and magnetic susceptibility attributes. Descriptive statistics, Pearson correlation, linear regression and geostatistical analyzes were applied for Pedotransfer Function modeling and the spatial variability of the analyzed attributes. Magnetic susceptibility showed a high degree of spatial dependence in the study areas, high range values, correlating with most of the assessed attributes, mainly physical, indicating potential in the prediction of the attributes in these environments. Pedotransfer functions vary among IBE's sites in attribute prediction, ensuring moderate estimates for predicting soil attributes in IBE's areas.

Key words: Customized methodology, environmental impacts, IBE's, pedotransfer function.

INTRODUCTION

The detailed studies related to the soil are subsidized by techniques aimed at providing information to support the sustainability of agricultural activities. In order to obtain this information, a large volume of samples is required, high cost, time needed to process and acquire information and generation of residues caused by the use of reagents, generating great economic and environmental discomfort (McBratney et al. 2003).

In this context, pedometry emerges as a tool through the Pedotransfer Functions (PTF), being predictive functions of the soil properties from other easily measured and routinely obtained at lower costs, and minimizing the time spent collecting and analyzing (McBratney et al. 2003, Ramos 2015). Agriculture requires methodologies to determine soil attributes less aggressive to the environment, less onerous, and that help in mapping the variability of these attributes with higher levels of detail (Siqueira 2010). Pedometry fits in this context, allowing to increase the precision in the studies, besides the number of samples collected without increasing the cost and time of analysis.

Magnetic Susceptibility (MS or χρ) appears as an alternative to evaluate soil attributes in a practical way, without environmental impact and relatively low cost, because it is an easily acquired mineralogical attribute and easy to apply method (Ramos 2015). MS is a characteristic present in rocks and soil, and is defined as a tendency for a material to magnetize (Verosub & Roberts 1995), resulting from the rotation and translation of the electrons that constitute the minerals present in rocks, sediments and soils. (Oliveira et al. 2015). In this principle, it is influenced by the soil formation factors, pedogenic process (Dearing et al. 2001, Ayoubi et al. 2018, Gholamzadeh et al. 2019), climate (Dearing et al. 2001, Ayoubi & Mirsaidi 2019), fauna / flora (Dearing et al. 1995) and relief (Jong et al. 2000), soil drainage (Asgari et al. 2018;), industrial and urbanized activities (Dankoub et al. 2012, Naimi & Ayoubi 2013, Ayoubi et al. 2014, 2018, Karimi et al. 2017).

Several researches have been applied in this line aiming the determination of MS of soils, by direct or indirect methods. Siqueira (2010) evaluated the potential of MS to estimate soil attributes and map management areas for sugarcane cultivation; Cortez et al. (2011) applied MS to identify management areas in citriculture; Cervi (2013) quantified the spatial variability of tropical soils with MS; Peluco et al. (2013b) used the MS to predict the physical, chemical and mineralogical properties of Oxisols under sugarcane management; Barbosa (2014) evaluated the efficiency of MS to estimate the erodibility of Ultisols, and Oliveira (2017) used MS to identify pedogenic environments and as an agricultural and environmental indicator of Indian Black Earths (IBEs) or Archaeological Dark Earths (ADEs).

Most studies involving MS, Preetz et al. (2008) use sensors for these purposes in which the main equipment is the Bartington Instrument coupled to a sensor (Bartington Instruments 1997). However, other authors present alternative methods for the determination of MS, such as the magnetometer (Fabris et al. 1998) and analytical balance (Carneiro et al. 2003, Siqueira et al. 2010). Occasionally, the analytical balance efficiency for MS reading (χρ) has been demonstrated for most minerals with magnetic behavior. (Fabris et al. 1998, Carneiro et al. 2003). The advantage of this alternative method is flexibility and simplicity, allowing its use by researchers of different levels of technification, which is why this same methodology will be adopted to determine MS in this research.

Even with several studies for the use of MS in predicting soil attributes, the development of PTF is a difficult task for applications at different sites from which they were developed. It is not recommended to use PTF outside the geomorphic region, soil type or specific management area from which it was developed (McBratney et al. 2002). Studies are needed to investigate the spatial correlation of MS with soil attributes at different sites and scales. The results are validated, and MS can be used as PTF for the use and management of the soil in a sustainable way, since it considerably reduces the impact of the study of soils (Freitas 2014, Siqueira 2010).

Therefore, the objective of this research was to evaluate magnetic susceptibility as auxiliary variable for estimating soil attributes in areas of Indian Black Earths in the south of Amazonas State.

MATERIALS AND METHODS

Characterization of the studied area

In this research, three IBE areas were selected, cultivated with coffee, cocoa and pasture, located in the municipalities of Apuí and Manicoré, Amazonas. The parent material from the alteration of Rondonian granites, from the Upper Pre-Cambrian, colluvial deposits in the lower parts of the landscape, and tertiary coverings (Brazil 1978). The climate according to the classification of Köppen is tropical rainy type, with a dry period of short duration (Am). It has a temperature range of 25 – 27 °C, this zone has a mean rainfall 2,250 to 2,750 mm, rainfall concentrated in the period October to June (Brazil 1978). Vegetation of the region is rain forest consisting of densified and multi-layered trees from 20 to 50 meters high (ZEE / AM 2008).

Pasture area (*Brachiaria brizanta*), located (7° 53 '36, 84 "S and 61º 23' 54,49" W), with an average height of 83 m, cultivated at seven years of extensive grazing and support capacity of animals around of one unit/animal/ha (Fig. 1). The soil classified as Argissolo Vermelho-Amarelo Eutrófico (Campos 2009) or Typic Hapludalf (Soil Survey Staff 2014), primary vegetation of the region characterized as rain forest.

The IBE under cocoa and coffee are located (7° 12' 05" S and 59° 39' 35" W). IBE under cocoa has been cultivated for fourteen years, and in the first six years it has been used to rice, maize, beans and watermelon culture, and the cocoa

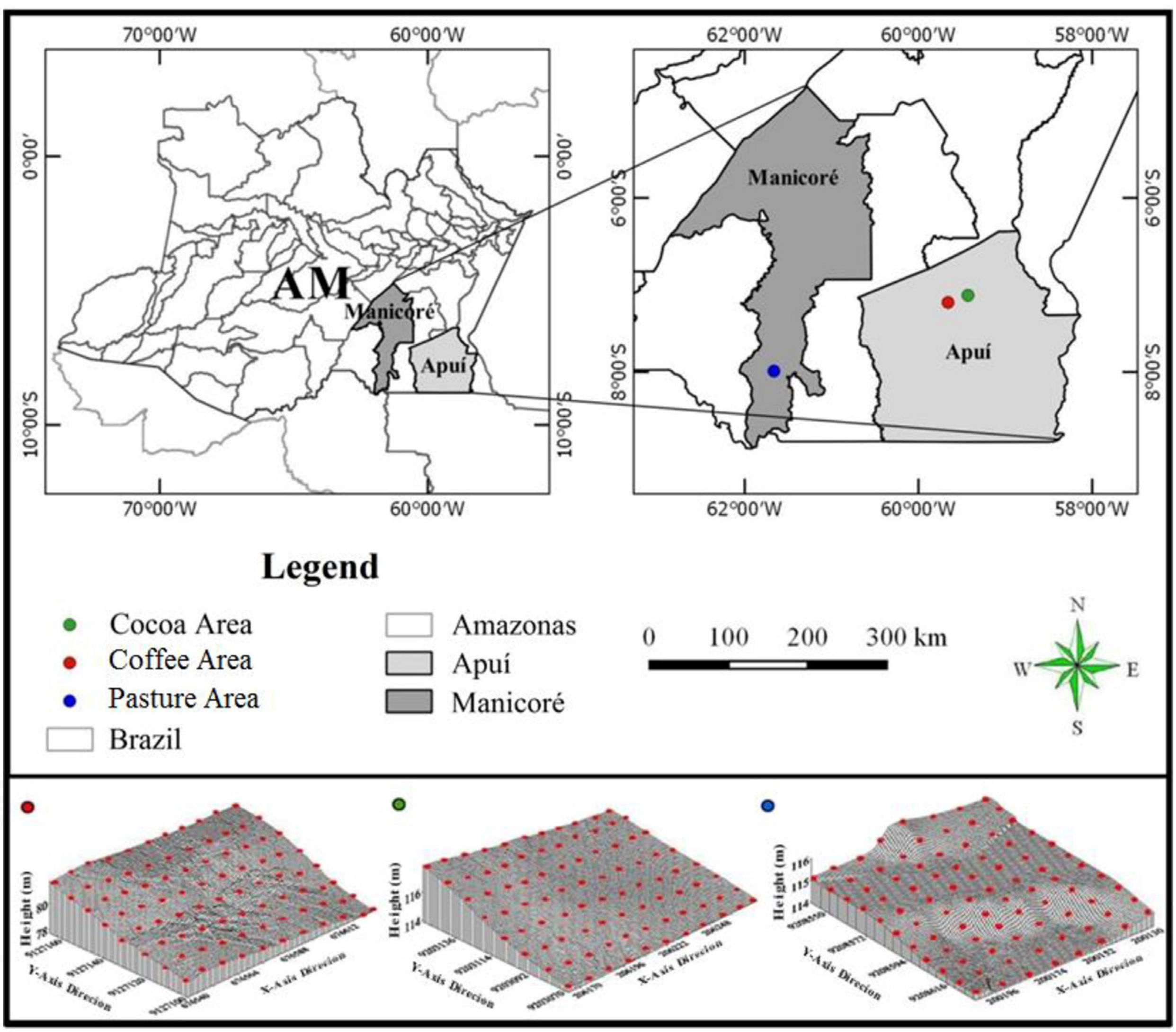

Figure 1. Location map and digital elevation model of the studied areas in southern Amazonas State, Brazil.

culture that remained until the present study was inserted (Fig. 1). IBE under coffee, cultivation has been cultivated for six years, the first two years under pasture cultivation and the last four years with coffee cultivation, and no agricultural implements are used in the implantation and maintenance of the cultivated areas. The soil of these two areas were classified as Argissolo Amarelo Eutrófico according to Embrapa (2013) and a Typic Hapludalf (Soil Survey Staff 2014).

Field methodology

Grids were established, with a dimension of 80 x 56 m and regular spacing of 8 x 8 m between the sampling points for the pasture area; 88 x 48 m and spacing of 6 x 8 m for the cocoa and coffee area. The soils were sampled at intersection points in the grids at a depth of 0.0 - 0.20 m, totaling 88 sampling points in each area. Points were georeferenced with a GPSMAP 76CS equipment (Garmin International, USA) for the construction of the Digital Elevation Model (DEM).

Physical analyses

The distribution of particle sizes (soil texture) was measured by sieving and using the pipette method, using 0.1 NaOH mol L^{-1} solution as a chemical dispersant and mechanical stirring in low speed apparatus for 16 h using a soil dispersion mixer Wagner type. The clay fraction was separated by sedimentation, the coarse and fine sand by sieving and silt calculated by difference (Donagema et al. 2017).

Macroporosity, microporosity, total porosity, soil density and soil moisture were determined from undisturbed samples collected in soil core with a known volume of 98.36 cm^3, at a depth of 0.0 - 0.20 m. The samples were prepared by removing the excess soil from its ends, then saturated by raising a water slide in an aluminum tray until it reached 2/3 of the height of the soil core.

Total porosity (TP) determined by the saturation method (Eq. 1). Macroporosity (Macro), applying matric potential of -6 kPa to sand tension table (Eq. 2). Microporosity (Micro) obtained after subtraction of the soil core weight to -6 kPa and its respective dry weight in the oven dried at 105° C (Eq. 3).

The soil penetration resistance (SPR) was measured in the laboratory using the same penetrometer model MA-933 / Marconi, constant velocity of 0.1667 mm s^{-1}, equipped with a load cell of 200 N, a 4 mm diameter cone with a 30º semi-angle, a receiver and interface coupled to a microcomputer, to record the readings by means of the equipment own software (Dalchiavon et al. 2011). Assays were performed after equilibration of the samples to a -6 kPa matric potential.

Soil moisture (θ) was obtained by the difference between the wet soil mass and the dry soil mass in the oven dried at 105 ° C for 24 h (Eq. 4), (Donagema et al. 2017). The bulk density (BD) was measured by the soil core method in which core samples were oven dried at 105 °C until a constant weight was achieved. The dry weight of the soil was expressed as the fraction of the volume of the core as described by Grossman & Reinsch (2002) (Eq. 5).

$$\text{Total Porosity} = \frac{V_{pore}}{V_{soil}} = \frac{V_{saturation}}{V_{soil}} \quad (1)$$

$$\text{Macro} = \frac{\text{Vmacro}}{\text{Vsolo}} = \frac{(\text{saturated soil weight - balanced weight -1 kPa})}{\text{Vsoil}} \quad (2)$$

$$\text{Micro} = \frac{\text{Vmicro}}{\text{Vsoil}} = \frac{(\text{balanced weight at -6 kPa - balanced weight at 105 °C})}{\text{Vsoil}} \quad (3)$$

$$Soil\ Moisture\ (\theta) = \frac{S.moist - S.dry}{V\ soil} \quad (4)$$

$$\text{Bulk Density} = \frac{\text{S. dry}}{\text{V soil}} \quad (5)$$

where: Vpore = pore volume; Vsaturation = volume saturation; Vsoil = Volume soil; Vmacro = volume macroporosity; Vmicro = volume microporosity; S. moist = soil moisture; S. dry = soil dry

Samples were collected with an undisturbed structure in the form of clod to determine the stability of soil aggregates. The samples were dried in the shade, lightly handwrecked, and passed through a 4,76 mm mesh screen for aggregation analysis. Stability of the aggregates were evaluated according to Kemper & Chepil (1965), with modifications in the following diameter classes: > 2.0 and < 2.0 mm. The aggregates from the 4.76 mm sieve were placed in the Yoder apparatus for 15 minutes, the mass of the material retained in each sieve (2; 1; 0.5; 0.25; 0.125 and 0.063 mm) was placed in a greenhouse at 105 °C. The results were expressed as: mean weighted diameter (MWD) and geometric mean diameter (GMD).

Chemical analysis

Potential acidity (H+Al) was determined volumetrically by titration of NaOH in calcium acetate at pH 7.0 as a reagent, in addition to phenolphthalein as indicator (Campos et al. 2017). The pH was determined potentiometrically using a 1:2.5 soil ratio in KCl solution (Teixeira et al. 2017a). Exchangeable aluminum (Al^{3+}), 1 mol L^{-1} KCl was used as the extractor and 0.025 mol L^{-1} NaOH as titrant in the presence of bromothymol blue as a colorimetric indicator (Teixeira et al. 2017b).

Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) were determined by complexiometry using KCl solution. Phosphorus (P) and potassium (K^{+}) were extracted with solution of Mehlich-1, being P read by light spectrophotometry at 840 nm absorbance and K^{+} in flame spectrophotometry (Teixeira et al. 2017c). The organic carbon (OC) was determined by the humid oxidation method, with external heating (Yeomans & Bremner 1988).

Magnetic Susceptibility (χρ)

Magnetic susceptibility was determined using 10 grams in the 2mm sieve air-dried soil fraction. An analytical balance, coupled from a set (magnet holder-sample holder) was used according to Carneiro et al. (2003), modified by Cano et al. (2008) and adapted by Siqueira et al. (2010). The analytical balance has a maximum capacity of 220g and its sensitivity is 10µg. The specific mass of χρ (mass magnetic susceptibility), was measured in the analytical balance according to Cano et al. (2008) and Siqueira et al. (2010).

A cylindrical magnet of neodymium-ferro-boron, with dimension 18 x 5 mm that generates a magnetic field in the distance of 3 mm next to 2275 Gauss, was used like source of magnetization. For the arrangement of the magnet in the balance, the criterion of Carneiro et al. (2003) to define the distance between magnet and sample port, in which the value to be chosen will depend on the interaction force between magnet and the magnetic property of the sample. In this procedure, the change of weight in the balance caused by the allocation of the sample on the support is negative for paramagnetic, ferromagnetic and ferrimagnetic samples, since the interaction of the magnetic fields of the magnet with the magnetic field of the sample will attract the support upwards; and positive for diamagnetic samples, as the support is pushed down by pressing the plate.

Sample-magnet interaction generates a force-weight on the scale expressed in unit cgs. This force was converted to a unit of the International System of Units (SI) (m^3 kg^{-1}), using a standard curve. This curve was constructed using tabulated MS of pure reagents (Lide 2005). However, the same standard curve presented by Siqueira et al (2010), ammonium sulfphate, potassium chloride, ferrous sulfphate, nickel sulfphate and, which presented a high correlation with the measurement performed by a proprietary equipment (MS2 Bartington Instrument 1997) for χρ reading ($r = 0.97$; P value < 0.001). To the values corrected by the curve a transformation factor [4π/(1000 x molecular mass)] was used.

Statistical procedures

Results were first evaluated by the exploratory analysis of the descriptive statistics, calculating the mean, coefficient of variation and hypothesis of normality of the data (1% Kolmogorov-Smirnov test). The coefficient of variation (CV%) was evaluated according to Warrick & Nielsen (1980), where: CV < 12%, 12 < CV < 60%, and CV > 60% for low, medium and high variability, respectively.

The modeling of the Pedotransfer Functions (PTF) to estimate the soil attributes as a function of the χρ, were analyzed by linear regression and Pearson correlation using 70 sample points. Simple linear regression and Pearson correlation analysis between χρ and the other variables involved in this study were performed in SPSS 21 software (SPSS 2001).

The attributes were then estimated by χρ with the PTF for a set of 18 points of the different sample meshes of the original model. These new values were correlated with the calculated values. Procedure is known as external validation and avoids error due to feedback of models (Barbosa 2014, Freitas 2014).

In order to verify the accuracy of the calibration of PTF's and to evaluate the external validation, were used as parameters the standardized standard error (RMSE) and Coefficient Residual Mass (CRM) (Loague & Green 1991). It was considered that when predicted and observed values are equal, RMSE and CRM values equal to zero (Aragão et al. 2013, Santos et al. 2013).

For the external validation tests proposed by Loague & Green (1991), Eq. 6 and 7 were used:

Standard error of the normalized estimate (RMSE):

$$RMSE = \left[i = \sum_{i=1}^{n} (P_i - O_i)^2 / n \right]^{0,5} (100 / O) \quad (6)$$

Coefficient Residual Mass (CRM):

$$RMC = \left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i \right) / \sum_{i=1}^{n} O_i \quad (7)$$

where: O_i - observed value; P_i - Predicted value; i- index from 0 to n; n - sample space; *O* - mean of the observed values.

The results of the observed and estimated attributes were used in the geostatistical analysis to evaluate their spatial distribution by means of semivariogram adjustment using the GS[+] software version 7 (Robertson 2004), under the theory of the intrinsic hypothesis the experimental semivariogram was estimated by Eq. (8).

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(x_i) - Z(x_i + h) \right]^2 \quad (8)$$

where: h is the value of semivariance for a distance h; N (h) is the number of pairs involved in the calculation of the semivariance; Z (xi) is the value of the attribute Z at the position xi; Z (xi+h) is the value of the attribute Z separated by a distance h from the position xi.

Based on the experimental semivariograms parameters of the soil attributes, scaled semivariograms were constructed with the objective of reducing them to the same scale, which facilitated the comparison of the results among different areas, as used by Oliveira et al. (2015). The experimental semivariograms were adjusted to the spherical (Eq. 9) and exponential (Eq.10) models, considering R² (coefficient of determination) and CV (cross validation) above 70%:

$$\begin{cases} \hat{\gamma}(h) = C_0 + C_1 \left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3 \right], se\, 0 < h < a \\ \hat{\gamma}(h) = C_0 + C_1, se\, h \geq a \end{cases} \quad (9)$$

$$\gamma(h) = C_0 + C_1\left[1-\exp\left(-\frac{3h}{a}\right)\right], se\, h \geq 0 \quad (10)$$

A mathematical model with the calculated values of $\hat{\gamma}(h)$ was fitted and the coefficients were defined for the semivariogram (nugget effect, C_0; structural variance, C_1; sill, C_0 + C_1; and range, a). The nugget effect is the value of the semivariance for a distance greater than zero and lower than the shortest distance of sampling and represents the component of random variation; the sill is the value of the semivariance at which the curve stabilizes over a constant value; and the range is the distance from the origin to where the sill reaches stable values, expressing the distance beyond which the samples are not correlated (Trangmar et al. 1986).

The individual and scaled semivariograms served as an information base to calculate the minimum sample density to estimate each soil attribute, using the expression: N = [A / (a² / 10000)] (Oliveira et al. 2015). Where: N is the minimum number of samples required for the determination of a sampling grid; A: total area, in ha; and a, the range of the semivariogram in meters.

Table I. Descriptive statistics and Tukey averages test at 5% of the analyzed variables of soil attributes and magnetic susceptibility in areas of Indian Black Earth under uses with cocoa, coffee and pasture.

Attributes (0.0-0.2 m)	COCOA			COFFEE			PASTURE		
	Mean	[1]CV%	[2]KS	Mean	CV%	KS	Mean	CV%	KS
χ_ρ (10^{-6} m³/kg)	5.83 c	17.70	*	0.90 a	33.60	*	1.40 b	32.40	*
Sand (g/kg)	201.4 c	16.50	*	375.50 b	7.10	*	709.60 a	3.00	*
Silt (g/kg)	553.3 b	2.90	*	607.90 a	4.30	*	225.40 c	9.40	*
Clay (g/kg)	243.9a	13.30	*	16. 90 c	8.70	*	64.00 b	20.40	*
SPR (MPa)	1.0 c	19.80	*	1.10 b	19.10	*	1.40 a	17.20	*
BD (Mg/m³)	0.9 c	6.80	*	1.10 b	8.80	*	1.20 a	6.00	NS
Macro (m³ m^{-3})	0.2 a	17.00	*	0.19 a	0.17	*	0.17 b	10.00	*
Micro (m³ m^{-3})	0.47 a	5.50	*	0.38 b	3.60	*	0.24 c	6.90	*
TP (m³ m^{-3})	0.67 a	3.60	*	0.57 b	5.10	*	0.42 c	6.10	*
θ (m³ m^{-3})	0.47 a	5.50	*	0.44 c	19.50	*	36.10 b	8.30	*
MGD (mm)	2.60 b	8.00	*	2.50 c	7.90	*	2.70 a	6.40	*
MWD (mm)	2.80 c	5.50	*	3.00 b	2.90	*	3.10 a	2.30	*
pH KCl	5.90 a	9.60	*	5.00 c	7.50	*	5.60 b	2.20	*
H+Al ($cmol_c$/dm³)	9.60 a	38.70	*	9.10 a	24.70	*	6.50 b	14.30	*
Al^{3+} ($cmol_c$/dm³)	0.10 c	57.00	NS	0.20 b	74.80	*	0.30 a	17.20	NS
P ($mmol_c$/dm³)	116.0 a	25.60	*	32.30 c	43.60	*	68.20 b	35.50	*
K^+ ($cmol_c$/dm³)	0.02 a	32.80	*	0.007 c	29.70	NS	0.013 b	38.80	*
Ca^{2+} ($cmol_c$/dm³)	13.60 a	20.80	*	5.30 c	35.60	*	9.30 b	14.50	*
Mg^{2+} ($cmol_c$/dm³)	2.60 a	26.70	*	1.80 b	27.40	*	1.70 b	22.10	*
O.C (g/kg)	42.00 b	11.90	*	36.90 c	15.20	*	135.70 a	1.62	*

Means followed by the same lowercase letter in the row compared by management do not differ from each other by the Tukey test at 5%. [1]CV%: coefficient of variation; [2]KS: normality test; * 99% confidence (α = 1%); NS: not significant. χρ: susceptibility magnetic (analytical balance method); SPR: soil penetration resistance; BD: bulk density; Macro: macroporosity; Micro: microporosity; TP: total porosity; θ: soil moisture; MGD: mean geometric diameter; MWD: mean weighted diameter; H+Al: potential acidity; Al^{3+}: exchangeable aluminum; P: phosphorus available; K^+: available potassium; Ca^{2+}: exchangeable calcium; Mg^{2+}: exchangeable magnesium; O.C.: organic carbon.

Determining the magnitude of spatial dependence, applied Spatial Dependency Index (SDI) proposed by Seidel & Oliveira (2014), which is given as: SDI_{model} (%) = [FM x (C1 / C0 + C1) x (a / q.MD) x 100], followed by classification proposed by the same authors the following year (Seidel & Oliveira 2015), in which, for the spherical model: SDI ≤ 9 spatial dependence, SDI between 9 and 28 moderate spatial dependence and SDI > 28 strong spatial dependence; for the exponential model: IDE ≤ 8 weak spatial dependence, SDI between 8 and 24 moderate spatial dependence, and SDI > 24 strong spatial dependence.

RESULTS AND DISCUSSION

Descriptive statistics

Silt fraction was higher in areas of cocoa and coffee, with a silt texture, the sand fraction predominated in the pasture area, presenting sand texture (Table I). Silt textural classification, due to the high silt content, is a common feature of the transition from Inceptisols to Ultisols, being a common factor in archaeological soils in the Western Amazon. The soil penetration resistance (SPR) was low for the areas of cocoa and coffee, and moderate for the pasture area, with values of 1.0; 1.1 and 1.4 MPa respectively. Bulk density (BD) presented values of 0.9; 1.1 and 1.2 Mg m^{-3} for the areas of cocoa, coffee and pasture, respectively. SPR and BD values in the different systems of use demonstrate the tendency and effects of organic composition in IBEs, thus favoring the maintenance of soil moisture and thus attenuating the effects of cohesion or densification in these areas. This issue also influences the variability of these soils, since the range of spatial distribution is long distances (meters), thus reducing the trend and monitoring future practices regarding these physical variables.

Organic carbon (OC) in pasture was higher compared to cultivated areas, value of 135.7 g kg^{-1}. Active acidity was of medium to high, varying from 5.0 to 5.9, indicating that areas have pH in a range suitable for the good development of the cultures. Exchangeable acidity and potential acidity were low, favoring the hypothesis that these soils possess adequate physical and chemical characteristics for agriculture. The magnetic susceptibility (χρ) presented significant differences at 5% between the areas, with values ranging from 0.9×10^{-6} to 5.83×10^{-6} m^3 kg^{-1}.

Most of the attributes presented significant differences by the Tukey test at 5%, except for macroporosity and potential acidity. According to Warrick & Nielsen (1980) the coefficient of variation, considering the three crops, the variables silt, density, microporosity, total porosity, GMD, WMD and pH presented low variability, whereas the variables magnetic susceptibility, resistance to penetration, potential acidity, phosphorus, potassium, calcium and magnesium presented moderate variability.

Geostatistics

Most of the attributes presented spatial dependence structure, exceptions for θ, GMD and K^+ in the area of cocoa, P, K^+ and Mg^{2+} in the coffee area, and sand, SPR, BD, GMD, MWD, pH KCl, H + Al, P and Mg^{2+} in the pasture area. To the attributes in a spatial correlation condition, we obtained semivariance with a coefficient of determination (R^2) of more than 70%, with predominance of the spherical and exponential models, the most indicated in the configuration of the parameters analyzing the data.

Following the classification of Seidel & Oliveira (2015) and analyzing the three areas together (Table II), the variables silt, Al^{3+}, Ca^{2+} and OC presented moderate spatial dependence between the areas; IBE's with coffee and cocoa did not present variables with poor spatial dependence. Comparing the management (cultivated vs. pasture), it was observed that SPR had a strong spatial dependence for cultivated areas, while pasture had a pure nugget effect (PNE), that is, the sampling points were larger than ideal to satisfy the condition in which it could correlate with each other. The range values between the correlations obtained, within the cocoa area, ranged from 15.5 to 80 m; in the coffee area ranged from 14 to 85 m; and in pasture area ranged from 11.5 to 85 m. The pasture area was the one with the greatest variation in spatial distribution, presenting several attributes in the condition of pure nugget effect, although there is not as much discrepancy in its reach in relation to the cultivated areas. Variations evidenced the heterogeneity of the spatial correlations of soil attributes, even among the IBE's own sites, as a function of the influence of management as a modifying and transforming of soil properties.

Sample density

Sample density (Table III), determined based on the reach of the individual and scaled semivariograms, presented high variability in IBE's. IBE under cocoa, sampling density ranged from 2 to 44 sampling points/ha, the lowest sampling density required to obtain the variables sand, clay, SPR, macroporosity and Mg^{2+}, and the highest sampling density required for microporosity, silt and OC in IBE cultivated with coffee obtained the highest sample density heterogeneity, ranged from 2 to 54 sample points ha between the SPR and χρ variables. IBE under pasture presented values of controversial sampling density between soil aeration, in which the macro and microporosity variables presented values of 1 and 77 points/ha^{-1}. These variables are dependent on the same analysis to be obtained, it is recommended to use lower density in the determination.

Mean values of sample density vary from 11.4 sample points in the cocoa area, 23.0 sample points in the coffee area and 31.3 sample points in the pasture area. A minimum sample density can be defined for determination of soil attributes in future diagnoses in other IBE's under the same conditions. For greater reliability, it is recommended to use the sampling density of the attribute that presented the highest value (maximum sample density), which in these cases are 44; 54 and 77 sampling points/ha^{-1} for cocoa, coffee and pasture, respectively.

Pedotransfer functions

In the evaluation of Pearson correlation values between χρ and soil attributes (Table IV), only the variables sand, SPR, BD, macro, TP, GMD, pH, H + Al, Ca^{2+} and Mg^{2+} presented some form of correlation; in coffee area only silt, clay, θ, Ca^{2+} and Mg^{2+} presented correlation; and for the pasture area there was only the variable K^{+} correlating with the χρ. It is observed the particularities of each management in the prediction of soil attributes through the χρ.

Pearson's correlation was able to formulate pedotransfer functions to estimate soil attributes that correlated with χρ, with their respective standard errors (RMSE) and coefficient residual mass (CRM) (Table IV). In the cocoa area, chemical variables that showed a correlation with χρ (pH, H + Al, Ca^{2+} and Mg^{2+}) exhibited negative CRM values, while physical variables alternated between positive and negative values. Loague & Green (1991) tendency to overestimate and underestimate the predicted variable, respectively, by a model. Thus, CRM's > 0.0 indicate the observed values underestimated by the predicted values, which occurred only with SPR, TP, GMD and Al^{3+}. For the pasture area, the K^{+}, single significant variable, presented CRM of 0.029 cmolc dm^{-3}, indicating that the model is underestimating the value of the predicted variable.

Table II. Models and parameters estimated to semivariograms of soil attributes and magnetic susceptibility in areas of Indian Black Earth under uses with cocoa, coffee and pasture.

Attributes	COCOA						COFFEE						PASTURE					
(0.0-0.2 m)	Mod.	[1]C_0	[2]C_0+C_1	[3]a (m)	[4]r^2	[5]SDI%	Mod.	C_0	C_0+C_1	a (m)	r^2	SDI%	Mod.	C_0	C_0+C_1	a (m)	r^2	SDI%
χ_p	Sph.	0.65	1.23	67.0	0.90	25	Sph.	0.005	0.12	14.0	0.87	10	PNE	-	-	-	-	PNE
Sand	Sph.	100.0	1550.0	80.0	0.89	58	Sph.	60.0	597.1	16.5	0.83	11	PNE	-	-	-	-	PNE
Silt	Exp.	30.0	330.6	19.0	0.85	11	Sph.	35.0	731.3	16.0	0.86	12	Exp.	6.0	580.5	14.8	0.75	8
Clay	Sph.	220.0	1800.0	80.0	0.80	55	Sph.	0.075	3.04	15.8	0.66	12	Exp.	6.0	230.5	16.0	0.75	9
SPR	Sph.	0.015	0.055	80.0	0.78	45	Sph.	0.039	0.10	85.0	0.98	40	PNE	-	-	-	-	PNE
BD	Exp.	0.0005	0.0055	50.0	0.76	30	Sph.	0.0007	0.02	19.0	0.82	14	PNE	-	-	-	-	PNE
Macro	Sph.	6.76	16.9	80.0	0.84	37	Sph.	4.8	16.3	36.5	0.89	20	Sph.	2.6	5.54	85	0.70	35
Micro	Sph.	1.5	7.94	15.5	0.86	10	Sph.	1.76	3.06	31.0	0.91	10	Exp.	0.18	3.5	11.5	0.80	6
TP	Exp.	1.59	9.56	55.0	0.77	30	Exp.	5.20	12.56	55.5	0.93	21	Sph.	1.1	5.75	16.0	0.85	10
θ	PNE	-	-	-	-	PNE	Exp.	0.25	1.13	30.0	0.88	15	Exp.	0.3	10.2	15.0	0.75	8
MGD	PNE	-	-	-	-	PNE	Sph.	0.017	0.065	21.0	0.75	12	PNE	-	-	-	-	PNE
MWD	Exp.	0.013	0.0357	57.0	0.85	24	Sph.	0.005	0.0145	27.0	0.86	14	PNE	-	-	-	-	PNE
pH KCl	Sph.	0.008	0.457	25.0	0.90	19	Sph.	0.009	0.17	19.0	0.70	14	PNE	-	-	-	-	PNE
H+Al	Sph.	0.30	17.2	23.5	0.93	18	Sph.	0.13	6.5	15.5	0.73	12	PNE	-	-	-	-	PNE
Al^{3+}	Exp.	0.0021	0.0053	22.5	0.83	9	Exp.	0.014	0.0764	43.0	0.89	23	Exp.	0.0006	0.0051	30.0	0.96	15
P^+	Exp.	104.0	2701.0	54.0	0.90	34	PNE	-	-	-	-	EPP	EPP	-	-	-	-	PNE
K^+	PNE	-	-	-	-	PNE	PNE	-	-	-	-	EPP	Exp.	1.3×10^{-5}	4.5×10^{-5}	24.5	0.70	10
Ca^{2+}	Sph.	0.27	11.48	27.0	0.90	20	Exp.	0.72	4.92	21.0	0.78	12	Exp.	0.08	2.31	23.0	0.90	12
Mg^{2+}	Sph.	0.11	0.78	78.0	0.90	52	PNE	-	-	-	-	EPP	PNE	-	-	-	-	PNE
O.C	Sph.	5.10	31.1	19.5	0.80	12	Exp.	8.2	38.45	30.0	0.92	15	Exp.	0.5	6.47	27.0	0.90	14

Mod: model; Sph: Spherical; Exp.: Exponential; [1]C0: nugget effect; [2]C0 + C1: sill; [3]a: range (m); [4]r^2: coefficient of determination; [5]SDI%: spatial dependence index; PNE: pure nugget effect; χρ: susceptibility magnetic (analytical balance method); SPR: soil penetration resistance; BD: bulk density; Macro: macroporosity; Micro: microporosity; TP: total porosity; θ: soil moisture; MGD: mean geometric diameter; MWD: mean weighted diameter; H+Al: potential acidity; Al^{3+}: exchangeable aluminum; P: phosphorus available; K^+: available potassium; Ca^{2+}: exchangeable calcium; Mg^{2+}: exchangeable magnesium; O.C.: organic carbon.

Table III. Minimum sample density based on the reach of semivariograms adjusted of soil attributes and magnetic susceptibility in areas of Indian Black Earth under uses with cocoa, coffee and pasture.

Attributes	COCOA		COFFEE		PASTURE	
	Sill (m)	Sampling (Points/ha^{-1})	Sill (m)	Sampling (Points/ha^{-1})	Sill (m)	Sampling (Points/ha^{-1})
χ_ρ	67	3	14	54	-	-
Sand	80	2	16	39	-	-
Silt	19	29	16	41	15	47
Clay	80	2	16	42	16	40
SPR	80	2	85	2	-	-
BD	50	4	19	29	-	-
Macro	80	2	36	8	85	1
Micro	15	44	31	11	11	77
TP	55	4	55	3	16	40
θ	-	-	30	12	15	45
MGD	-	-	21	24	-	-
MWD	57	3	27	14	-	-
pH KCl	25	17	19	29	-	-
H+Al	23	19	15	44	-	-
Al^{3+}	22	21	43	6	30	11
P^{+}	54	4	-	-	-	-
K^{+}	-	-	-	-	24	17
Ca^{2+}	27	14	21	24	23	19
Mg^{2+}	78	2	-	-	-	-
O.C	19	28	30	12	27	14
S.E	44	6	22	21	17	34

χρ: susceptibility magnetic (analytical balance method); SPR: soil penetration resistance; BD: bulk density; Macro: macroporosity; Micro: microporosity; TP: total porosity; θ: soil moisture; MGD: mean geometric diameter; WMD: mean weighted diameter; H+Al: potential acidity; Al^{3+}: exchangeable aluminum; P: phosphorus available; K^{+}: available potassium; Ca^{2+}: exchangeable calcium; Mg^{2+}: exchangeable magnesium; O.C.: organic carbon; S.E: scaled semivariograms.

Regarding the standard error values represented by the RMSE, the variables correlated with the χρ in the cocoa area presented a variation from 19.38 to 358.3%, inferring that only the attributes that presented the lowest values show a reliability and accuracy of their estimate. In the pasture area, K^{+} presented RMSE of 284.69%, that is, even though it is the only variable correlated with χρ, its estimate is still low, that is, it can not be considered as reliable. Barbosa (2014) and Freitas (2014) obtained RMSE below 25% in the prediction of soil attributes and erodibility, highlighting the perspective of this property in the prediction of attributes of different soils.

Relationship of soil physical and chemical attributes with χρ

Low values of SPR and BD (Table I) can be explained by the incorporation of residues in the cultivated IBE (cocoa and coffee), in IBE with pasture, as a consequence of animal trampling, resulting in decreased porosity, infiltration, percolation and soil water retention. This also explains the high aeration values (macro, micro and total porosity) and low structure values (GMD and MWD) in the areas of cocoa and coffee, and the inversion of these conditions in the pasture, low aeration and high values of structure.

Table IV. Pearson correlation coefficient values, pedotransfer functions and accuracy and precision values calculated by external validation of soil attributes and magnetic susceptibility in areas of Indian Black Earth under uses with cocoa, coffee and pasture.

Attributes	COCOA					COFFEE					PASTURE				
	Variable = A + B * χ_p			Calibration		Variable = A + B * χ_p			Calibration		Variable = A + B * χ_p			Calibration	
	r	A	B	RMSE	CRM ▪	r	A	B	RMSE	CRM ▪	r	A	B	RMSE	CRM ▪
χ_p	0.20**	6.80	159.24	115.91	-0.000004	0.19	16.00	358.94	43.36	0.000000	0.15	8.28	697.38	22.52	0.000000
Sand	0.16	2.90	534.90	19.38	-0.000004	-0.33**	-29.26	635.04	27.46	0.000000	-0.00	-0.31	224.24	68.70	-0.000003
Silt	-0.18	-7.23	288.55	103.94	-0.000002	-0.25*	-1.40	18.44	58.98	-0.000023	0.11	3.21	59.99	143.23	-0.000001
Clay	-0.32**	-0.07	1.49	144.01	0.000837	-0.03	-0.02	1.20	137.72	-0.000202	-0.10	-0.05	1.46	131.65	0.000456
SPR	-0.33**	-0.02	1.06	47.44	-0.002475	0.13	0.05	1.09	66.85	-0.000005	-0.00	-0.001	1.27	46.60	0.000403
BD	0.29**	1.06	14.30	108.31	-0.000142	-0.07	-1.01	19.98	139.24	-0.000013	-0.08	-0.31	17.79	71.59	-0.000054
Macro	-0.03	-0.10	47.67	39.06	0.000036	0.08	0.46	37.63	23.48	0.000002	-0.09	-0.32	25.00	44.62	0.000016
Micro	0.29**	0.88	61.99	27.60	0.000043	-0.11	-1.12	57.82	36.11	0.000001	-0.04	-0.18	42.00	37.12	0.000016
TP	-0.05	-0.18	47.49	44.58	0.000002	-0.22*	-0.75	5.24	133.12	-0.000004	0.04	0.28	35.12	61.48	0.000011
θ	0.24*	0.05	2.29	54.36	0.000709	-0.04	-0.03	2.59	55.69	0.000125	-0.06	-0.02	2.74	46.63	0.000236
MGD	0.19	0.03	2.71	39.70	-0.000720	0.06	0.02	2.99	20.69	-0.000094	0.02	0.003	3.12	16.40	0.000103
MWD	-0.27*	-0.18	7.08	71.61	-0.000241	0.02	0.03	5.08	55.66	0.000071	-0.11	-0.03	5.67	16.25	0.000110
pH KCl	0.30**	1.23	1.54	293.08	-0.000315	0.19	1.44	7.63	160.41	-0.000009	-0.09	-0.16	6.83	83.32	-0.000066
H+Al	0.05	0.003	0.083	358.29	-0.016201	0.03	0.03	0.30	538.38	0.001158	-0.07	-0.01	0.38	109.12	0.000867
Al^{3+}	-0.13	-6.20	161.15	199.25	-0.000008	-0.17	-10.17	42.19	294.89	-0.000009	-0.09	-4.83	74.88	255.41	0.000010
P^{+}	-0.17	-0.003	0.043	298.11	0.056567	-0.02	-0.0001	0.0072	169.31	0.011234	0.25*	0.003	0.009	284.69	0.029150
K^{+}	-0.21*	-0.72	18.38	154.47	-0.000097	0.24*	1.68	3.94	240.93	0.000064	-0.12	-0.40	10.08	102.58	-0.000052
Ca^{2+}	0.23*	0.17	1.67	171.40	-0.000212	-0.37**	-0.56	2.26	153.82	0.000323	0.14	0.10	1.54	144.89	0.000025
Mg^{2+}	0.20	1.09	36.30	83.37	0.000047	-0.10	-1.84	37.12	103.54	0.000002	-0.05	-0.26	136.05	11.99	-0.000003

χ_p: mass magnetic susceptibility (analytical balance method); r: Pearson correlation between χρ (10-6 m³ / kg) and attributes; SPR: soil penetration resistance; BD: bulk density; Macro: macroporosity; Micro: microporosity; TP: total porosity; θ: soil moisture; MGD: mean geometric diameter; WMD: mean weighted diameter; H+Al: potential acidity; Al^{3+}: exchangeable aluminum; P: phosphorus available; K^{+}: available potassium; Ca^{2+}: exchangeable calcium; Mg^{2+}: exchangeable magnesium; O.C.: organic carbon; RMSE: standard error of the normalized estimate,%; CRM: Coefficient Residual Mass; ▪ have the same units of the tested variables; * significant at 95%; ** significant at 99% confidence.

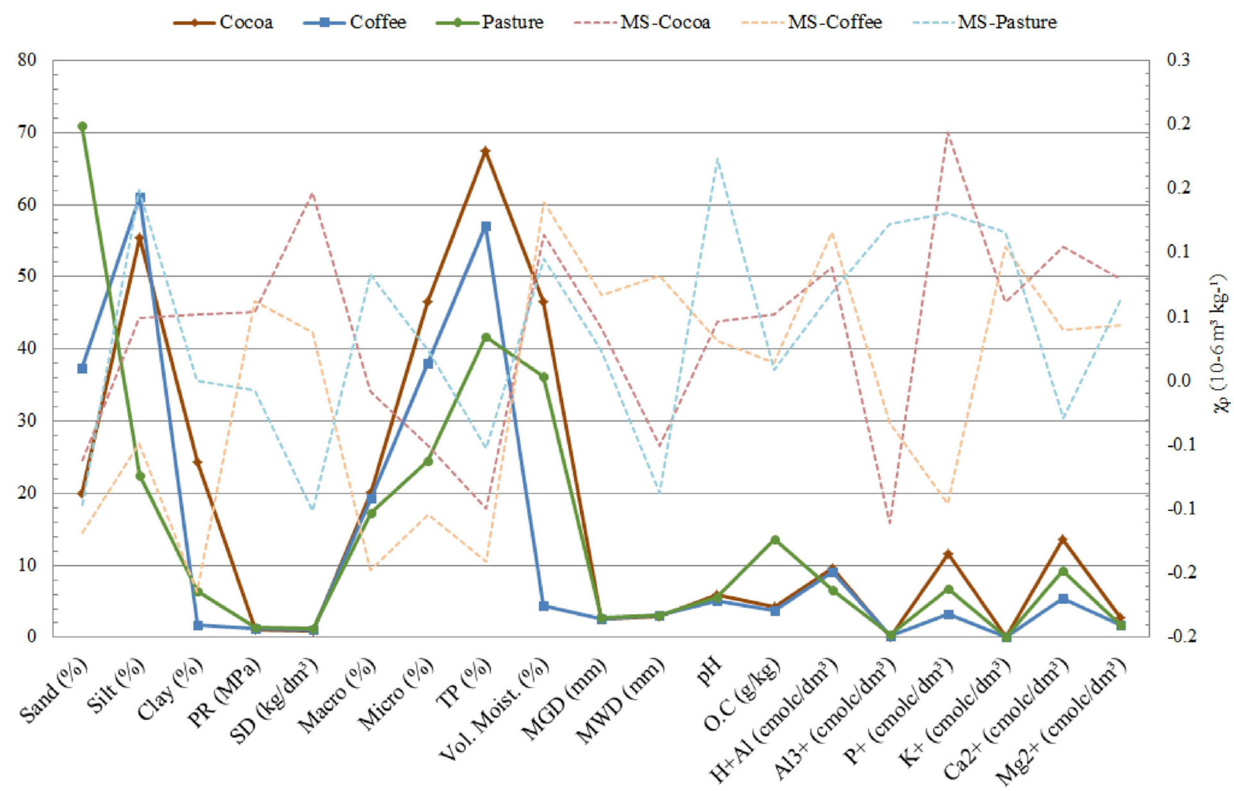

Figure 2. Correlation intensity of DM with physical attributes in soil chemists in IBEs under cultivation.

Although there is no classification restricted to IBE's for BD, through the texture values obtained (Reichert et al. 2009), it can be inferred that these values are found to be absent from restriction to the root growth of the plants, corroborating with Campos et al. (2012), Santos et al. (2013), Aquino (2014), which obtained similar values in studies with physical and chemical properties of IBE's and non-anthropogenic soils in southern Amazonia.

The O.C content in the pasture, as opposed to the low values in the other areas (Fig. 2), can be explained by the greater contribution of organic matter provided by the grass root system, which are well developed and distributed (Cardoso et al. 2010). The higher OC content in the pasture justifies the high values of GMD and MWD in the same area, since the organic molecules act in the stages of formation and stabilization of the aggregates, besides serving as energy source for the microorganisms, which are important agents of aggregation (Wohlenberg et al. 2004, Ayoubi et al. 2012).

Significant differences between the chemical attributes (Table I) were also obtained between the studied areas, in the area of cocoa predominated higher values of phosphorus, potassium, calcium and magnesium, probably due to fertilization and / or liming occurred before the implantation of the crop, coherent when compared to the pasture area, where there is a lack of management, resulting in an acidic pH and high exchangeable aluminum content. The coffee area, however, presented the lowest values of the nutrients phosphorus, potassium, calcium and magnesium between the areas. One of the explanations for this fact is in the history of use of these IBE's, because in the six years of cultivation in the coffee area, only the extensive use of *Brachiaria brizanta* was exhausted, exhausting certain nutrients, despite the nitrogen supply through the BFN process (Biological Fixation of Nitrogen) or greater accumulation of OC (Cardoso et al. 2010), for example; while in the area of cocoa the horticultural cultivation of several annual crops in the first six years of use was preceded, which together with the practices of correction and preparation of the soil, contributed to the maintenance of these nutrients in the area. Another explanation for the occurrence can be attributed to the formation of the IBE site itself, suggesting that it was more intensively used, so that there was a greater deposition of domestic waste, having as main source of calcium and phosphorus microfragments of biogenic appetite and animal bones (Kern et al. 2017).

It observed little variation in χρ values in IBE's (Fig. 2), because its pedogenic factors contained few ferrimagnetic and ferromagnetic minerals. Costa et al. (2004), the presence of magnetic minerals mainly derives from the practice of fire during the formation of IBE's, corroborating with Mullins (1977) and Schwertmann & Cornell (1991), which indicate that the route of formation of magnetic minerals more acceptable occurs formation of maghemite by burning other iron oxides, such as goethite and hematite, in the presence of organic material. Resende et al. (1988) mentions that high values of χρ may be associated with the presence of the magnetic lithogetic mineral. Cervi (2013) mentioned that in addition to the lithological influence, factors such as pedogenesis may be contributing to the differentiation of the values and proportions of ferrimagnetic minerals in tropical soils. Oliveira (2017), evaluated the MS in plants and ceramics of IBE's, the highest values of χρ occur in the antropic horizon, and reduced in depth, possibly due to the use of fire (formation of magnetic minerals such as maghemite) and by the presence of ceramics that contribute to the increase of minerals with high magnetic expression.

Spatial Variability relation of the soil attributes and χρ

The relationship obtained between χρ and soil attributes, shows that the idea about χρ can be applied in the prediction of soil attributes, since it is considered as a micromarcador of the soil and is influenced by the concentrations and characteristics of the minerals present (Peluco et al. 2013b), and to determine the physical, chemical, and mineralogical attributes of the soil (Verosub & Robert 1995), or even in plants and ceramics incorporated into the soil matrix. and / or identify changes in IBE's pedogenetic environments through the accumulation of minerals formed under normal conditions (Oliveira 2017).

In the scaled semivariograms (Fig. 3), in order to understand the variations in soil behavior and χρ, we observed a relationship of soil attributes with χρ. Correlations between similar attributes were also obtained by Oliveira et al. (2015) analyzing the spatial variability of attributes in Ultisols in Amazon region.

The exponential model was fitted to soil and χρ attributes in almost all areas (Figs. 3a, 3b, 3c, 3d and 3e), except for soil attributes in the IBE under pasture, in which the spherical model fitted (Fig. 3f). The lowest values of R^2 (coefficient of determination) and CV (cross validation) were obtained in the cocoa area, with values of 0.54 and 0.74, respectively, while the highest values were found for soil attributes in pasture, with values of 0.83 and 0.91, respectively. This particularity can be explained by the number of variables being analyzed in each area, in the area of cocoa there is an adjustment considering 17 variables, while in the pasture area, the model evaluates 11 distinct variables, so that, in contrast to the parent material, use history, mainly, soil

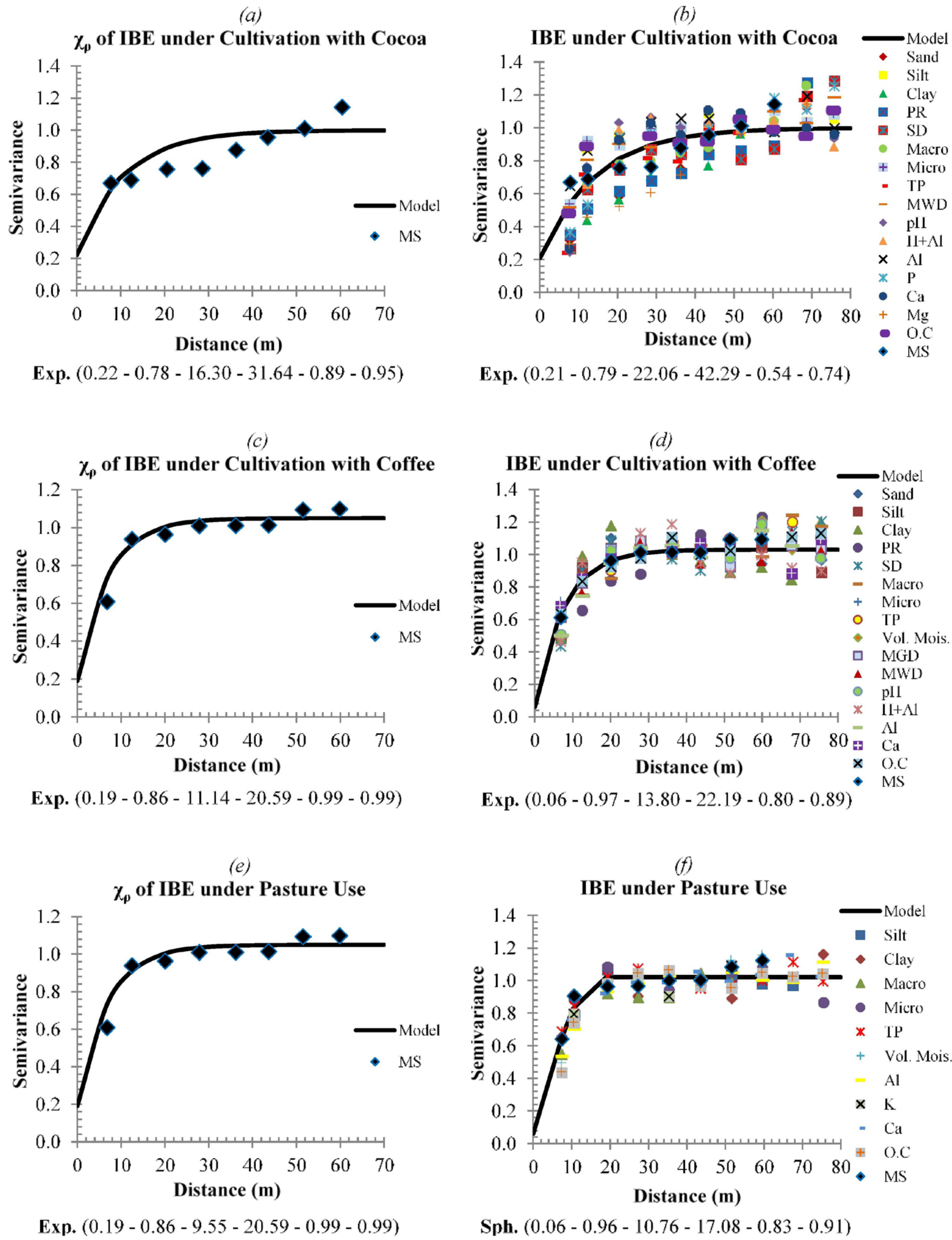

Figure 3. Scaled semivariograms adjusted for magnetic susceptibility - χp [(a), (c) and (e)], and soil attributes [(b), (d) and (f)] of IBE under crops in region of Apuí and Manicoré, Amazonas. [model (C0; C1; SDI%; range (m), R^2; CV)]. Spherical; Exp.: exponential; SDI%: spatial dependence index; R^2: coefficient of determination; CV: cross validation.

management, causes a greater randomness in the attributes of the soil, guaranteeing greater accuracy in the adjustment to the pasture, as can also be verified through CV% values (Table I) between the areas cultivated with pasture, for example, in which the cultivated areas stand out.

The results of the scaled semivariograms (Fig. 3) obtained in the area with cocoa showed greater variability in relation to the other studied areas, similar to the individual semivariograms made, with a value of 42.3 m between attributes and 31.6 m for χp. For IBE under coffee the range was 20.6 and 22.2 m for χp and attributes, respectively. And for pasture the range was 20.6 and 17.0 m for χp and attributes, respectively. Comparing the areas with coffee and pasture, it is observed that there is similarity in the semivariograms adjustments (reach parameters,

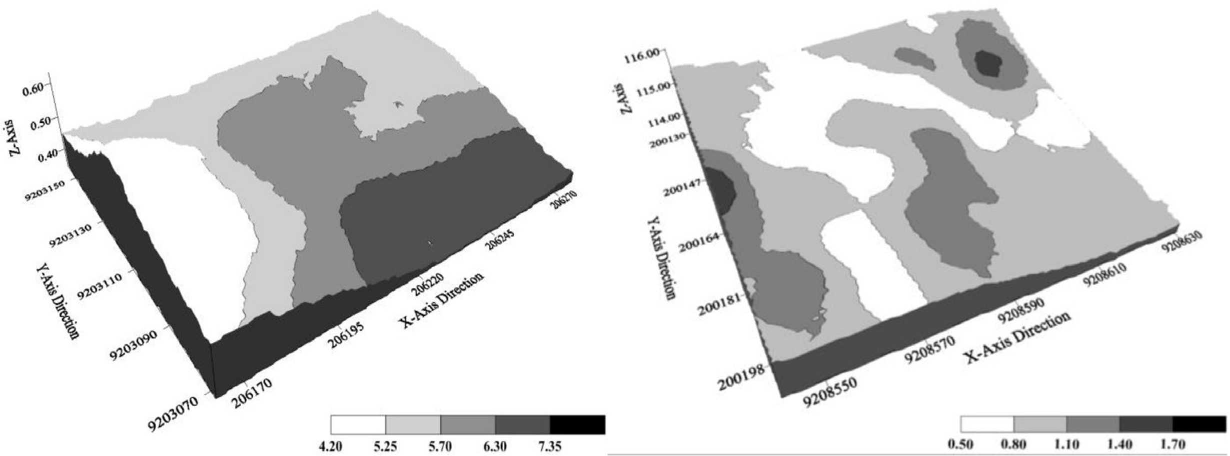

Figure 4. Magnetic Susceptibility kriging maps obtained by interpolation of the geostatistical parameters in IBEs under cultivation. Cocoa area (left) and Coffee cultivation area (right).

R^2 and CV), and difference in relation to the area of cocoa, which is probably due to the difference in vegetal cover, where there is a greater amount of soil cover roots (surface layer) that provide a better balance in its structure through the exudation of chelating substances that act as cements of soil aggregates.

The greater variation in IBE under cocoa use can be explained, as mentioned previously, due to the relief (Fig. 1), which presents a linear slope compartment, as it occurs in the IBE of pasture and coffee, evidencing that there is a deposition of sediment and nutrient leaching directly to the lower part of the land, which consequently causes higher range values and lower R^2 and CV% (Fig. 3).

The interpolation of the data by the kriging technique allowed the generation of the maps of χρ surfaces only for the areas under cultivation (Fig. 4), since in the grazing area there was in the spatial dependence for this attribute, making its interpolation unnecessary (Table I). In cocoa cultivation, it is observed that χρ was the tendency of χρ to be higher in the lower parts of the relief, which is probably due to the deposition of high magnetic expression minerals in the lower parts by sedimentation and / or leaching.

Predictive functions in the estimation of χρ

Analyzing the predictive models (Fig. 5), high remnants of RMSE were observed, which ranged from correlated attributes of 27.26 to 284.69%, obtained in the adjustment of χρ with TP in cocoa area and χρ with K^+ in pasture, respectively. According to Moriasi et al. (2007), during the observations in the RMSE, it is commonly accepted that the models with the lowest values have the best prediction performances. Therefore, the attributes with the highest Pearson coefficient are justified to contain the lowest values of RMSE%, since it is only the indexed statistical error. These values were higher in the area of coffee (RMSE = 240.93%) and potassium in the pasture area (RMSE = 284.69%), are the least reliable models in their estimation, requiring adjustments in their calibration..

Cacao cultivation presented higher attributes correlating with χρ. Possible causes are linked to the formation of the IBE. Specifically, can be said as a result, in the first hypothesis, of the intense use of fire combined

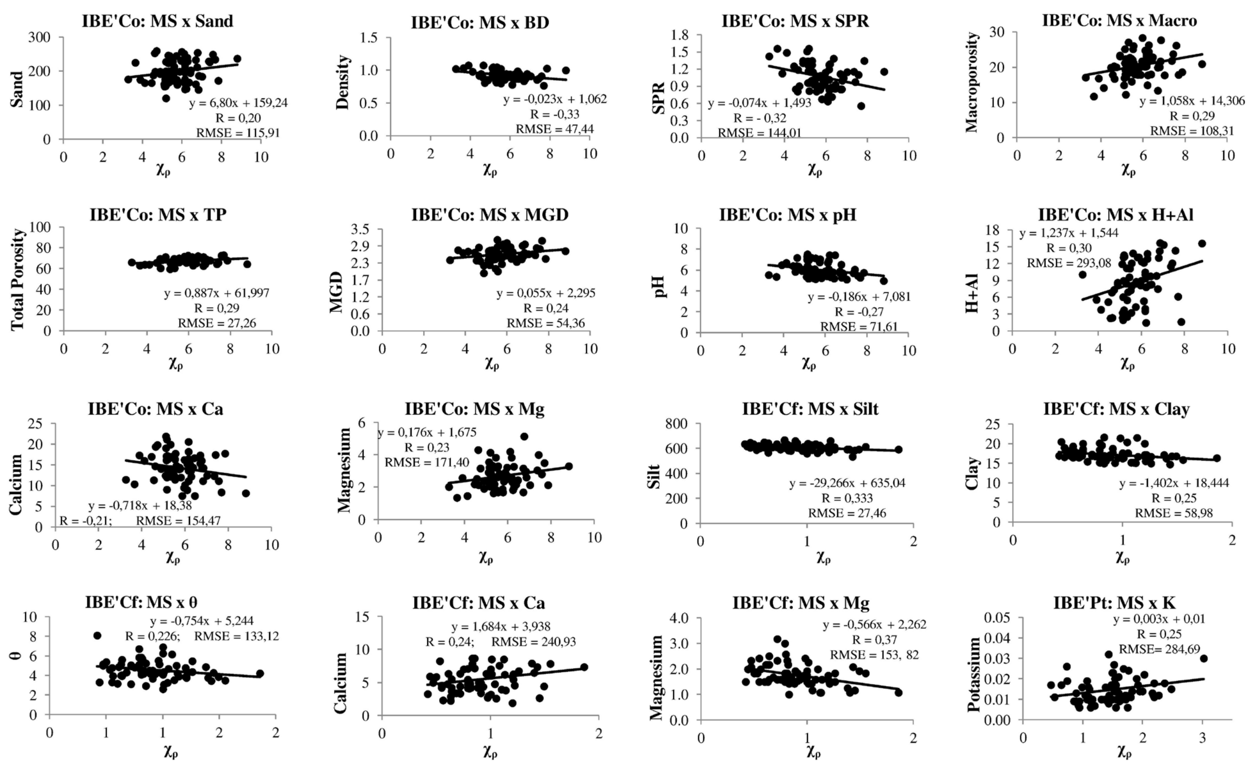

Figure 5. Regression models based on 70 sample points for soil attributes in relation to the mass magnetic susceptibility (analytical balance method) in Indian Black Earth under different crops. IBE'Ca: Indian Black Earth under use with Cocoa; IBE'Cf: Indian Black Earth under use with Coffee; IBE'Pt: Indian Black Earth under pasture use.

with domestic waste during heating of the lepidocrocite (ŷ-FeOOH), from 200 ° C to 300 ° C from ferrihydrite after thermal heating (fire) that release to the soil magnetic iron oxides, either by ceramic fragments or by domestic refusals, directly producing maghemite (Barrón & Torrent 2013). In the second hypothesis, the positive correlations of MS with soil attributes, mainly physical, such as MS x Sand; MS x Micro and MS x TP, negative correlations such as MS x BD and MS x SPR.

The correlations obtained in the majority of cocoa areas show that the study of χρ with soil attributes within IBE's should be specific for each management, because the use of prediction models requires particular soil parameters for each region or use, mainly physical properties such as texture, which can influence soil density, soil penetration resistance and soil porosity, leading to correlation results in its empirical basis.

In the area with cocoa (Fig. 5), the variables most strongly correlated between χρ and Bulk Density (R = -0.33, P <0.01), SPR (R = -0.32; P <0.01), macro (R = 0.29, P <0.01), TP (R = 0.29, P <0.01) and sand (R = 0.20, P <0.01). In the area with coffee, the best correlations were obtained between the χρ with the Mg^+ (R = 0.23, P <0.01) and silt (R = -0.33; P <0.01), Ca^{2+} (R = -0.21, P <0.05) and θ (R = -0.22, P <0.05). In the pasture, K^+ presented correlation with the χρ (R = 0.25, P <0.05).

According to Moriasi et al. (2007), Pearson's correlation coefficient describes the degree of collinearity between measured and estimated attributes, requiring values greater than 0.5 or -0.5 to be considered acceptable, since it varies from -1 to 1. Estimates of this research can be accepted as "moderate", or rather "still in calibration” in the prediction procedure of IBE’s attributes.

This is not to say that χρ is unusable in IBE’s areas, as stated in this study, there is no standard curve for the calibration of the predictive functions made for IBE’s, and for this reason a standard curve is adjusted for Brazilian Ultisols with a high degree of correlation with measurements made in MS2 Bartington Instruments. This assertion shows that if an improper standard curve presented moderate predictions, perhaps calibration curve appropriate to the IBE’s may provide optimal predictions, supporting view design for several researchers like Hartemink (2007), who believes that the scenario to come in the science of solo is moving in the way of the use of the pedotransfer functions. Thus, as Cantarella et al. (2006), on the future of the research carried out in Brazil, since there is a frequent error of laboratory misinterpretation, reaching errors in the order of 3-26% in the determination of macronutrients and of 15-32% in analyzes of particle size.

Studies have been applied using χρ, aiming, in addition to studies of the genesis of tropical soils, the proposal of χρ as: indicator of land use and occupation, assisting strategic planning of agricultural areas; (Leal et al. 2015), rational use of phosphorus (Marques Júnior et al. 2014), soil conservation (Santos et al. 2013), application of residual water (Peluco et al. 2013a, Camargo et al. 2016) and characterization and spatial variability, comparing agricultural area with IBE in the Amazon (Oliveira et al. 2015). In summary, this research indicates that obtaining χρ has the potential to become a promising alternative technique in the future of soil science, whatever the field, simply with the results of magnetic expressions.

CONCLUSIONS

Magnetic susceptibility showed significant correlation with sand, soil penetration resistance, bulk density, macroporosity, total porosity, geometric mean diameter, pH, potential acidity, calcium and magnesium in cocoa area; silt, clay, soil moisture, calcium and magnesium area with coffee; and potassium in the pasture, indicating potential use prediction attributes in these soils.

Magnetic susceptibility showed a high spatial dependence index in the three study areas, with high range values, correlating with most of the evaluated attributes. Such behavior is attributed as characteristic of the antropic genesis of this type of soil. Pedotransfer functions vary among IBE’s sites in attribute prediction, ensuring moderate estimates for predicting soil attributes in IBE’s areas.

Magnetic susceptibility can be used to predict the physical and chemical attributes of IBE’s, but there should be further investigations to standardize better settings of the IBE’s pedotransfer functions to ensure greater precision and accuracy in attribute predictions.

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