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Spatial variability of soil physical and chemical aspects in a Brazil nut tree stand in the Brazilian Amazon

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The Brazil nut is considered one of the noblest trees of the Amazon biome and contains social, ecologic and economic importance to this region. The study of the spatial variance of the edaphic properties in native nut trees can direct future researches about more efficient samplings. The Geostatistics is the methodology utilized for this type of study, once that it considers the structural and random characteristics of a variable spatially distributed. This work sought to get a higher knowledge about the distribution of the nutrients in the soil, verifying the relationship with the occurrence of this species, to thereby provide subsidies to future forest management and maintenance/enlargement of the productivity in these areas. The soil samples were collected from 30 × 30 m on the line, in all of the lines in part of the study, totaling 60 samples. All of the points were georeferenced. The preparation of the samples for the sample preparation for the chemical analysis and the methods and calculations to determine the physicochemical variables studied were described by Nogueira and Souza (2005). The statistical and geostatistical analysis were conducted using the R computational environment, version 3.2.2. Most of the studied variables presented defined level. For the physical variables, there was predominance of the adjustment to the model of the gaussian variogram, follower by the spherical model. In the case of the chemical variables, there were two occurrences for each adjustment model (spherical, exponential and gaussian). The variables that best presented spatial relation with the occurrence of Brazil nut trees were the silt, clay, macroporosity, pH, phosphorus, zinc and copper.

Key words: Geostatistics, Brazil nut, soil, physical properties, chemical properties.

INTRODUCTION

The soil is characterized by the heterogeneity and presents variations in its morphological, physical, chemical and mineralogical properties (Oliveira et al., 2000). The diversity of the geomorphological aspects, the high temperatures and the elevated indexes of precipitation are the factors that justify these variations and the existence of different classes of soils of the Amazon Biome (Chig et al., 2008).

Spatial variation of edaphic aspects as it relates to the analysis of soil fertility could provide a basis for future research in order to conduct more efficient sampling in the field (Vieira, 2000). Detailed knowledge of variability in soil variables could provide a solid basis for making sound decisions with respect to choosing adequate management schemes (Silva et al., 2013). In managed systems, such as those of Brazil nut harvesting areas, there could be additional sources of soil heterogeneity besides those inherently natural (Camargo et al., 2010), and therefore quantifying soil spatial variation would permit better control over factors that control production and also over environmental monitoring (Silva Neto et al., 2012; Oliveira et al., 2013). According to Souza et al. (2009), the use of geostatistiscal techniques allows for interpretation of results using as a base the natural variability inherent in the system. For this reason there are a growing number of studies published that focus on spatial variation, especially in monoculture production systems (Machado et al., 2007; Lima et al., 2013) and agroforest systems (Campos et al., 2013; Oliveira et al., 2013).

The geostatistics is the methodology utilized for this types of study, once that it considers the structural and random characteristics of a variable spatially distributed (Moolman and Van Huyssteen, 1989). The main tool of geostatistics to describe and model the spatial pattern of a variable is a graph that associates distances with semivariances, named semivariogram (Seidel and Oliveira, 2014). To predict values in not sampled locations the geostatistics uses the kriging that allows the knowledge of continuity of the variable in interest in the study area. Kriging is realized through the interpolation in sites not sampled and it also produces variability (Santos et al., 2011). The geostatistics is one of the main tools of the MapCast project that studies spatial approach on Brazil nut in the Amazon forest.

The MapCast Project “Mapping of native nut trees and socioambiental and economic characterization of systems of production of the Brazil nut in the Amazon”, coordinated by the Brazilian Company of Agricultural Research (Embrapa) from 2014, searches to characterize the factor and systems of production of the *Bertholletia excelsa* Bonpl., Lecythidaceae family, also known as the Amazon nut and “Para nut”, through geospatial information to contribute to the management and adaption of good practices to the different realities of Amazon. One such site is localized in the Tapajós National Forest (FLONA) in the State of Pará, Brazil, which is a natural stand that serves as a food and income source for local families engaged in the extraction and sale of the Brazil nuts.

The Brazil nut is considered one of the noblest trees of the Amazon biome and contains social, ecologic and economic importance to the region. Its almonds are much very appreciated in the European, Asiatic and American continents (Salomão, 2014). Tonini and Pedroso (2014) consider it to be a key species for the management of the direct and indirect benefits of the forest. Due to these factors and also the indexes of the increasing deforestations, in 2008 this species was included in the list of endangered species of the Ministry of the Environment (MMA) and of the State of Para. Considering these aspects and the existence of extensive areas of primary and secondary forests in the Amazon, that house the chestnut tree, it has become urgent to advance in the ecologic, economic and social knowledge of this species (Salomão, 2014) and also provide regionalized informations for future actions of management that foment its production.

In 2011, the total Brazilian production of the Brazil nut was of 39,917 tons. In 2012 and 2013 the production presented reduction to 38,805 and 38,300 tons, respectively (IBGE, 2013). The gains with the Brazil nut can be expanded, in case the producing areas receive investments to develop its productive capacity.

The present work presents an geostatistic analysis of soil nutrient spatial distribution in a natural Brazil nut stand in the FLONA Tapajós. The aim was to obtain higher knowledge about the nutrients distribution in this environment, verifying the relation with the occurrence of Brazil nut trees, to thereby provide subsidies to future practices of forest management and maintenance/enlargement of the productivity of this area.

MATERIALS AND METHODS

Study area

The study site consists of a small stand (300 × 300 m) that was demarcated as part of the MapCast project, with six 50 m transects.The portion was installed in a native forest area with a natural density of Brazil nut, where every individual of the species were georeferenced (Figure 1). The soil was classified as a Clayey Dystrophic Yellow Oxisol (Oliveira Júnior and Corrêa, 2001) using the Brazilian Soil Classification System (EMBRAPA, 2001), and as a Typic Haplustox using the Soil Classification System of the United States (USDA, 1999). This forest fragment is inside the territorial limits of FLONA of the Tapajós, between the parallels 2°45’ and

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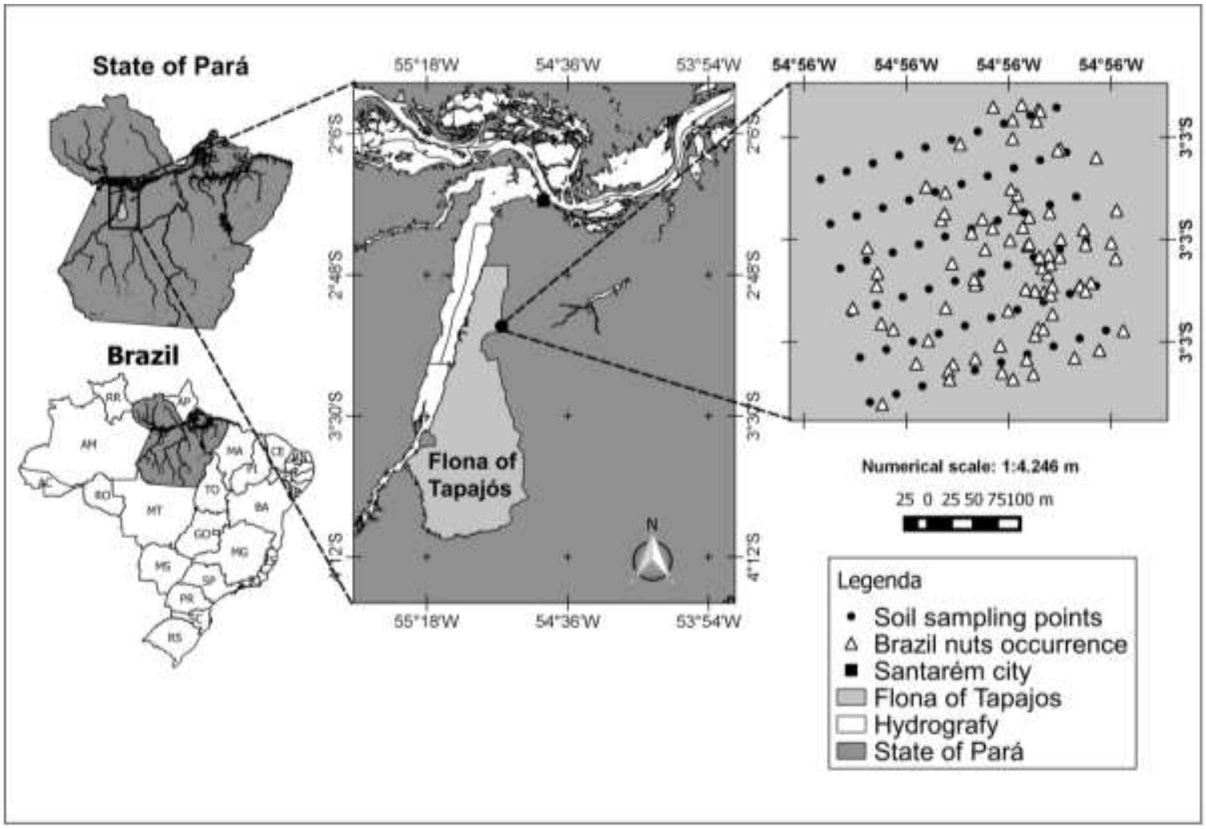

Figure 1. Localization of the study area in the FLONA Tapajós, Belterra-Para, with soil collection points following a systematic grid of 30 m × 50 m.

4º10' S and the meridians 54º45' and 55º30' W (Espirito-Santo et al., 2005), State of Para (north region of Brazil), in the central portion of the Amazon forest (Figure 1).

The region's climate, according to the classification of Köppen, is of the Type Ami (IBAMA, 2004). Through the common precipitation of the period from 1950 to 2000 of the station of Belterra-PA, Espirito-Santo et al. (2005) identified the presence of a rainy seasonal period (January - June) and other less rainy (July - December) well defined.

The area of the FLONA of the Tapajós covers part of the cities of Belterra, Aveiro, Ruropolis and Placa, extending through an area of approximately 545,000 ha (MMA, 2002). It was formed in the region of stratigraphic unit named Formação Barreiras (Barriers Formation), composed by rocks of fine sandstones and grey shales calciferous, being constituted mainly by red continental sediments and formed by intercalations of sandstones and mudstones with conglomerates subordinated (Damasceno, 2001; IBAMA, 2004). There are found Dystrophic Yellow Latosol, Argissolos Red-Yellow, Petric Plinthosols dealers and Entisol. The classes Argissolos Red-Yellow and Dystrophic Yellow Latosol occupy respectively, 37.1 and 25.34% of the FLONA (Espirito-Santo et al., 2005).

The region's vegetation is classified as Ombrophilous Dense Forest (Veloso et al., 1991), with abundance of large arboreal individuals of woody lianas, palmtrees and epiphytes. IBGE (1997) inform the predominance of the genus *Hevea*, *Bertholletia* and *Dinizia*. Guimarães (1999) and Gonçalves and Santos (2008) present more detailed floristic information of the FLONA Tapajós.

The anthropic actions in the area (extractive activities, hunting, fishing, wood extraction, family farm system in agriculture, and others) are promoted, in part, by the residents of communities. According to estimates, there are approximately 10,696 people living in the FLONA, distributed in 26 communities (IBAMA, 2004).

Collection, preparation and physicochemical analysis of the soil samples

The soil samples were collected in intervals of 30 m in line, in all of the lines from the grid of the study area, totalizing 60 sampling points (Figure 1). All of the points were georeferenced. For the determination of texture, and bulk and particle densities samples were collected at depths of 0-15, 15-30, 30-45 and 45-60 cm. For aggregate analysis and determination of the water retention curve, sampling was done in the two superficial layers. For the soil chemical determination, the sampling collection was conducted with a dutch auger at a depth of 0-20 cm. The preparation of the samples for the chemical and physical analysis and the calculation of the studied variables were done as in Nogueira and Souza (2005).

Soil texture was determined by the nugget method, and the density particle density (Dp), by the volumetric balloon method, utilizing ethyl alcohol, as the penetrating liquid, to measure the soil volume. The bulk density (Bd) was determined by the volumetric ring method. The total porosity (Tp) was calculated by the equation $Tp = (1 - Bd/Dp)$. The microporosity was obtained by the curve of water retention in the soil, in tension equivalent to 6 kPa. The macroporosity resulted from the difference between total porosity and microporosity. The water retention in the tensions of -10, -33, -100, -500, -1,000 and -1500 kPa was determined with sampling, previously saturated with water, on a porous ceramic plate by the application of these tensions, inside of a pressure cooker.

With these points (q, ym) determined, the adjustment of the retention curves of water, was done according to the proposed model by Van Genuchten (1980). This adjustment was realized by the method that considers: qs = qmax, with ym = 0 and, qr = qmin, with ym = - 1,500 kPa. With these curves, the distribution of the size of the pores was calculated using the following system: (a) pores = 50 mm - by the difference between the total porosity value and the volumetric humidity obtained in the pressure of -6 kPa; (b) pores between 50 and 30 mm - difference of volumetric humidities between 6 and 10 kPa; (c) pores between 30 and 10 mm - difference of volumetric humidities between -10 and -30 kPa; (d) pores between 10 and 3 mm - difference of volumetric humidities between -30 and -100 kPa; (e) pores between 3 and 0.2 mm - difference of volumetric humidities between -100 and -1,500 kPa; (f) pores < 0.2 - value of the volumetric humidity in the pressure of -1,500 kPa.

The pH was determined using a suspension of soil: water with relation of 1:2.5, and the Walkley-Black method (redox volumetry) was used to determine the organic carbon. The total nitrogen was determined by sulfuric acid digestion, Kjeldhal distillation and titration, and potential acidity was determined through the neutralization volumetry method, using as an extractor a solution of acetate of calcium, pH 7.0. For the calcium, the manganese and exchangeable aluminium extraction a potassium chloride solution (pH 7.0) was used. The value of calcium and manganese were obtained through atomic spectrophotometric absorption and aluminium was determined by volumetry utilizing 0.025N sodium hydroxide. Phosphorus, the potassium, the sodium and micronutrients (copper, zinc, iron and manganese) were analyzed utilizing the Melich I extractor solution with phosphorus determined by colorimetry, the sodium and potassium by flame spectrophotometer and micronutrients by atomic absorption spectrophotometry (Nogueira and Souza, 2005).

Data analysis

The statistical data analysis was conducted using an exploratory analysis of the data to verify the central and dispersal tendency measures, aiming to improve the efficiency of the spatial analysis through the identification of discrepant values and the removal of outliers. Statistics used in this analysis were: Maximum, minimum, medium, standard deviation and the coefficient of variation. The normality of the variables was verified by the statistical test of normality Shapiro-Wilk, with a level level of significance of 5% (Zar, 1999).

To describe and model the spatial patterns geostatistical analysis was used with the adjustment of the semivariogram (Equation 1), which corresponds to a mathematical tool that allows study of the spatial dispersal of a variable in function of the distance (Isaaks and Srivastava, 1989; Vieira, 2000).

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

In which, $\hat{\gamma}$(h) = semivariance of the Z(x_i) variable; h = distance; N(h) = number of pairs of measured points Z(x_i) and Z(x_i+ h), separated by a h(lag) distance.

For the experimental semivariogram generated the theoretical models were adjusted that provided the Nugget effect, landing and reach parameters. These parameters were estimated by the adjustment methods of the theoretical models, by the Ordinary Least Square (OLS) method and Weighted Least Square (WLS) methods. The statistical theoretical models adjusted for the comparison were the spherical (Equation 2), the exponential (Equation 3) and the gaussian (Equation 4), according to Isaaks and Srivastava (1989) and Vieira (2000).

$$\hat{\gamma}(h) = Co + C1\left[\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right], \text{Spherical} \qquad (2)$$

$$\hat{\gamma}(h) = Co + C1\left[1 - e^{\left(-3\frac{h}{a}\right)}\right], \text{Exponential} \qquad (3)$$

$$\hat{\gamma}(h) = Co + C1\left[1 - e^{-3\left(\frac{h}{a}\right)^2}\right], \text{Gaussian} \qquad (4)$$

In which, $\hat{\gamma}(\boldsymbol{h})$= is the value of the estimated semivariance for the h distance; a = reach, corresponds to the distance after the one in which the spatial semivariance stabilizes; h = distance between measures; Co = nugget effect; C = landing, it is the value spatial semivariance that corresponds to its (a) reach; C1 = contribution, corresponds to the difference between the landing (C) and the nugget effect (Co).

In the Index of Spatial Dependency (ISD) of the variables, the classification of Cambardella et al. (1994) was used that proposed the following intervals to evaluate the index of spatial dependence of the phenomena: Values lower than 25% are considered as having strong spatial dependence; those between 25 and 75% indicated moderate spatial dependence, and values higher than 75% determine weak spatial dependence. The ISD value was obtained by Equation 5.

$$ISD = \frac{Co}{Co + C1} \, x \, 100 \qquad (5)$$

From each one of the adjusted models, the interpolation by the simple kriging was conducted which generated the mapping of all of the soil variables in the area of the Brazil nut trees. The simple kriging implicitly evaluated the medium in the sampling space by neighborhood (Isaaks and Srivastava, 1989; Yamamoto and Landim, 2013), therefore, the estimated value in a random spatial x_0 position was obtained by the Equation 6.

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \qquad (6)$$

In which: $\hat{z}(x_0)$ = is the estimated value for the point x_0; λ_i = are to the weight of the kriging defined according to the semivariogram's parameters; $z(x_i)$ = are the values observed in the sampled points (sampling space by neighborhood).

Definition of the best model utilized the technique of cross-validation, that consists in prediction of the known value z(x_i) of the random variable, comparing to the observed value. The errors of the observed and predicted values were analyzed through the statistics: Mean error (ME), root mean square standardized (RMSS) and absolute error (AE) described by Vieira (2000).

The analysis were realized in the computational environment R (R-Development-Core-Team, 2015), associated to the outliers packages (Komsta, 2006) for the identification and removal of the outliers, nortest (Ross and Ligges, 2015) for the test of the normality and geoR (Ribeiro and Diggle, 2001) for the geostatistical analysis with the semivariogram adjustment and realization of the simple kriging.

RESULTS AND DISCUSSION

The results of the descriptive statistics and the geostatistics analysis for the physicochemical properties of the studied soil are presented in Table 1.

The obtained values for the variables presented a normal distribution by the Shapiro-Wilk (significance of 5%) test except for the phosphorus, potassium, sodium, calcium, zinc, manganese and copper. According to

Table 1. Descriptive statistics and results of the geostatistical analysis of the physicochemical properties of the soil under native Brazil nut trees in the FLONA Tapajós, Para.

Variable	**Descriptive statistics**			**Geostatistical analysis**				
	Average	**SD**	**CV (%)**	**Model**	**Nugget effect**	**Landing**	**Practical reach (m)**	**ISD (%)**
Physical								
Total sand (g.kg^{-1})	372.4	23.2	11.1	Spherical	77.82	544.72	115.09	14.3
Silt (g.kg^{-1})	102.7	16.9	17.3	Gaussian	180	304	71.71	59.2
Clay (g.kg^{-1})	524.9	27.2	7.4	Spherical	240.56	740.66	92.12	32.5
TP (g.cm^{-3})	0.559	0.04	7.3	Gaussian	0.0009	0.00177	111.31	50.9
Macrop. (g.cm^{-3})	0.208	0.03	23.5	Gaussian	0.0005	0.00101	132.02	49.5
Microp. (g.cm^{-3})	0.352	0.04	10.2	Gaussian	0.001	0.00144	48	71.4
CC	0.329	0.03	10.7	Gaussian	0.00093	0.00117	72.47	80.6
PWP	0.235	0.02	11.2	Spherical	0.00038	0.00059	55.29	63.8
Chemical								
pH (H_2O)	4.08	0.18	4.5	Exponential	0.0245	0.00335	179.74	73.1
Carbon (g.kg^{-1})	13.4	2.01	19.0	PNE	-	-	-	-
Nitrogen (g.kg^{-1})	1.13	0.12	13.8	PNE	-	-	-	-
C/N	11.92	1.46	14.1	PNE	-	-	-	-
Phosphorus (mg.dm^{-3})	2.75	0.38	18.0	Gaussian	0.078	0.142	79.26	54.9
Potassium (mg.dm^{-3})	21.27	6.7	32.6	Spherical	76.28	92.38	54.16	66.0
Sodium (mg.dm^{-3})	3.29	1.29	53.0	PNE	-	-	-	-
Calcium (cmol$_c$.dm^{-3})	0.175	0.12	84.8	PNE	-	-	-	-
Magnesium (cmol$_c$.dm^{-3})	0.209	0.08	46.8	PNE	-	-	-	-
Alumínio (cmol$_c$.dm^{-3})	1.59	0.35	22.1	PNE	-	-	-	-
Iron (mg.dm^{-3})	225.2	44.3	23.7	PNE	-	-	-	-
Zinc (mg.dm^{-3})	0.727	0.16	35.2	Exponential	0.0193	0.0283	272.16	68.7
Manganese (mg.dm^{-3})	3.14	2.06	80.1	Spherical	3.33	4.98	180.3	66.9
Copper (mg.dm^{-3})	0.341	0.18	75.3	Gaussian	0.024	0.034	227.30	70.8

TP, Total porosity; Macrop., macroporosity; Microp., microporosity; CC, camp capacity; PWP, permanent wilting point; C/N, relation carbon/nitrogen; ISD, index of spatial dependency; SD, standard deviation; CV, coefficient variation; m, meters; PNE, pure nugget effect.

Isaaks and Srivastava (1989), normality is not the determinant factor for the realization of the geostatistical analysis, being more important the existence of sills well defined in the semivariograms. Rachid Junior et al. (2006), and Souza et al. (2010), realize the geostatistical evaluation of the variables that did not present normality and obtained well defined sills.

The coefficient of variation (CV) obtained for the physical variables of the soil samples was considered low (CV < 12%), as proposed by Warrick and Nielsen (1980), except for the silt and macroporosity, that presented moderate variation (12% < CV > 60%). The silt presented more expressive variability due to its greater mobility in the soil and deposition in the floodplain (Santos et al., 2012). The soil chemical variables showed a more heterogeneous behavior, with only pH in the interval of low variation; calcium and manganese presented high variability (CV > 60%) and the remaining variables presented moderate variation. Aquino et al. (2014), studying the spatial distribution of chemical properties of soil in the Amazon forest, also registered moderate and high variation. For Carvalho et al. (2003), it is common that the variability of the soil properties presents moderate to high values, because there are many environmental factors that interfere in its dynamics of such. Souza et al. (2014) highlights that the mapping of the soil properties with higher variability can be less precise.

After the exploratory analysis, the values obtained for the physicochemical variables were submitted to the geostatistical analysis with the aim to verify its spatial dependence. The variables: carbon, nitrogen, C/N, sodium, calcium, magnesium, aluminium and iron presented a Pure Nugget Effect (Figure 2), meaning that, they are spatially independent and it was not possible to determine the variogram components. For Silva et al. (1989) that happens when the spacing adopted in the sampling is higher than needed to reveal the spatial

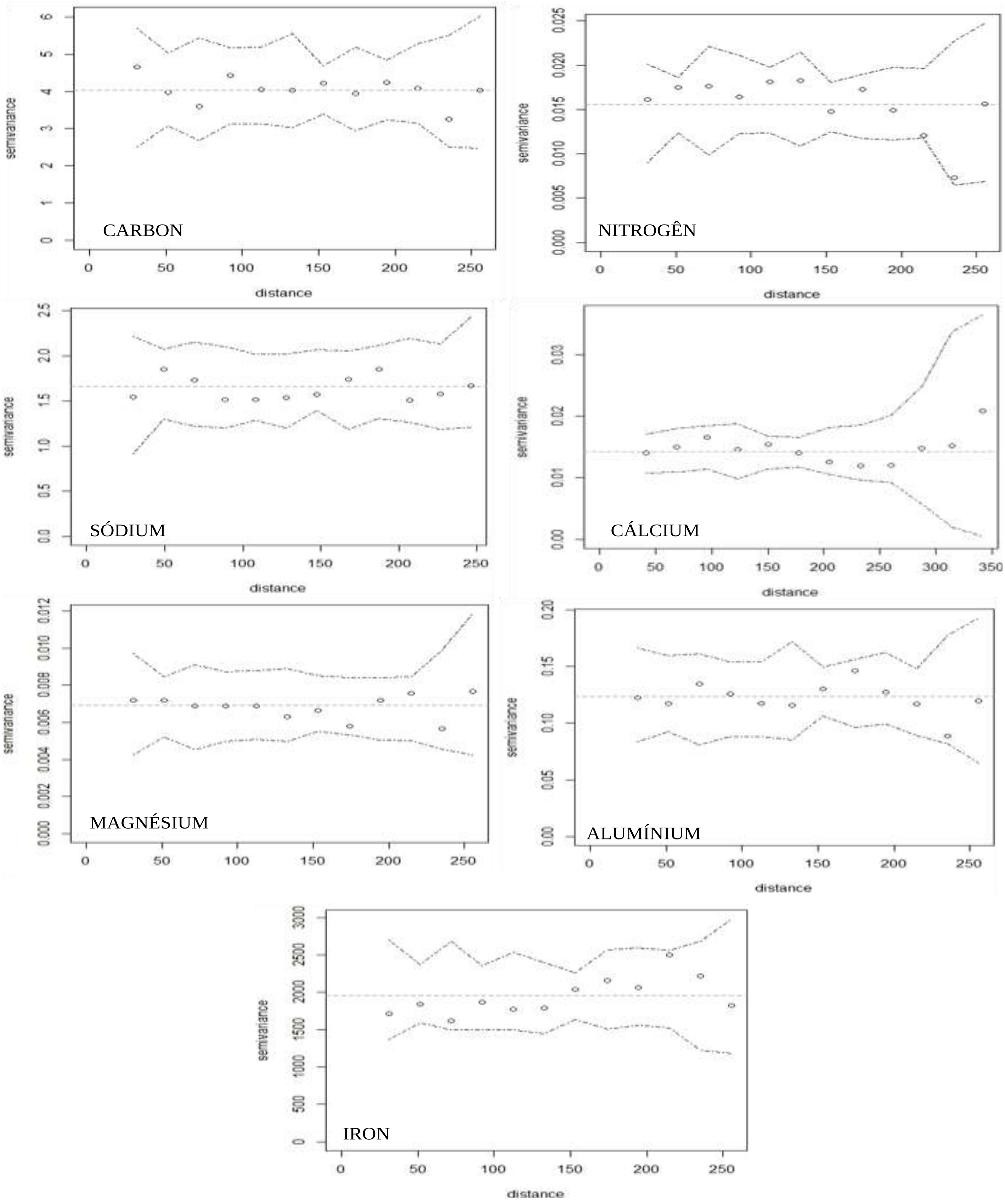

Figure 2. The spatial dependence analysis presenting only the sill (pure nugget effect), for the variables: Carbon, nitrogen, sodium, calcium, magnesium, aluminium and iron.

dependence. The nugget effect indicates the variability not explained or the variation not detected and occurs due to measurement errors and or when the sampling configuration was not robust enough (Cambardella et al., 1994). Therefore, the nugget effect can show the nature of spatial dependence (Chaves and Farias, 2008), the continuity of the phenomena, and the confidence in the estimate (Vieira, 2000; Yamamoto and Landim, 2013).

For the other studied variables, the sampling configuration was sufficient to determine the spatial dependence. The variables that presented a more expressive nugget effect were microporosity, phosphorus, zinc, manganese and copper. Cerri et al. (2004), studying the variables of a soil in the state of Rondonia, adopted sampling with distance between the points of 25 m and also obtained an elevated nugget effect in most of the variables. That indicates that there is high variability inside a small space, in a shorter distance to that practiced in the collections (Novaes Filho et al., 2007).

The majority of the studied variables presented good semivariogram behavior, allowing for semivariogram adjustment for the gaussian, spherical and exponential models. Thus, the choice of the model was determined by the best adjustment of the line to the points located in the contribution band of the semivariogram, by the cross-validation methodology (through the relation: predicted/observed). For the physical variables (Figures 3 to 5), there was predominance of the adjustment to the gaussian semivariogram model, followed by the spherical model. In the case of the chemical variables (Figures 6 and 7), there were two occurrences for each model of adjustment (spherical, exponential and gaussian).

The gaussian model was the most prevalent model in the works of Machado et al. (2007) and Souza et al. (2008) that studied physical variables of a Red Latosol and a Fluvisol, respectively. This model has a large reach and its landing presents equal values to the exponential model; it is a transitive model, appropriate for modelling continuous phenomena (Isaaks and Srivastava, 1989). The spherical and exponential models describe properties with high spatial continuity, or less erratic in short distance (Isaaks and Srivastava, 1989) and are considered the most common when working with soil and plant variables (Carvalho et al., 2003; Lima et al., 2013).

As in the established intervals by Cambardella et al. (1994), the physical variables presented moderate spatial dependence (25% < ISD > 75%), except the total sand and the field capacity, which obtained the values of 14.3 and 80.6%, being categorized in the strong (< 25%) and weak (> 75%) classifications, respectively. The percentual values obtained for the chemical variables did not present high discrepancy and are considered moderate. The strong spatial dependence demonstrates that the semivariograms explain the greater part of the variance of the experimental data with high confidence in the estimate (Souza et al., 2010) and generally are more influenced by factors of formation of the soil. According to Cambardella et al. (1994), values of weak spatial dependency can indicate sites that are suffering higher external pressure and moderate spatial dependency occurs when there is homogenization of the soil. In this study, 86% of the variables presented moderate spatial dependence. Campos et al. (2013) and Aquino et al. (2014) also found moderate spatial dependence for the majority of the physical variables of their soil sampling in the Amazon.

The range is another important parameter in the study of the semivariogram, because it corresponds to a maximum distance (influence zone) in which a variable is spatially correlated, meaning that, the model establishes a maximum distance to where the value of a variable demonstrates spatial dependence with its neighbors (Santos et al., 2012; Oliveira et al., 2013). Therefore, analyses done at higher distances than the established range will have random distribution and, because of that, they are independent between themselves. In a practical way, the range of a variable guarantees that all of the neighbors are so similar that they can be used to estimate values for any point (Machado et al., 2007). A lower interval than the range provides soil samples with superposition of the spatial characteristics; on the other hand, a higher interval than the range does not comprise the spatial variability, while the medium value obtained does not reflect the area studied (Motomiya et al., 2011).

In the current study, the higher ranges for the physical variables were registered for macroporosity (132.02 m), total sand (115.09 m) and total porosity (111.31 m) and the lower range (48 m) for microporosity. Within the chemical variables, the higher ranges were identified for zinc (272.16 meters) and copper (227.30 meters) and lower for the potassium (54.16 m). A future experiment that will be conducted in the same area under the same conditions will generate Geostatistical results (Table 1) that will serve to better estimate the necessary number of samples necessary for each variable. According to Carvalho et al. (2002), in order to guarantee spatial dependence, sample points should be collected at a distance equal to half the reach value and in a systematic grid arrangement.

Relation of the variables with the Brazil nut trees

Through simple kriging it can be estimated the concentration of the studied nutrients for the area of the sampling grid (interpolation), was delimited due to the expressive occurrence of Brazil nut trees. All of the individuals of this species were georeferenced and their coordinates were plotted in the simple kriging maps, in order to visualize their occurrence in relation to the concentration of the variables of the soil. A higher concentration of Brazil nut trees was identified in the areas with higher values for the silt and clay variables

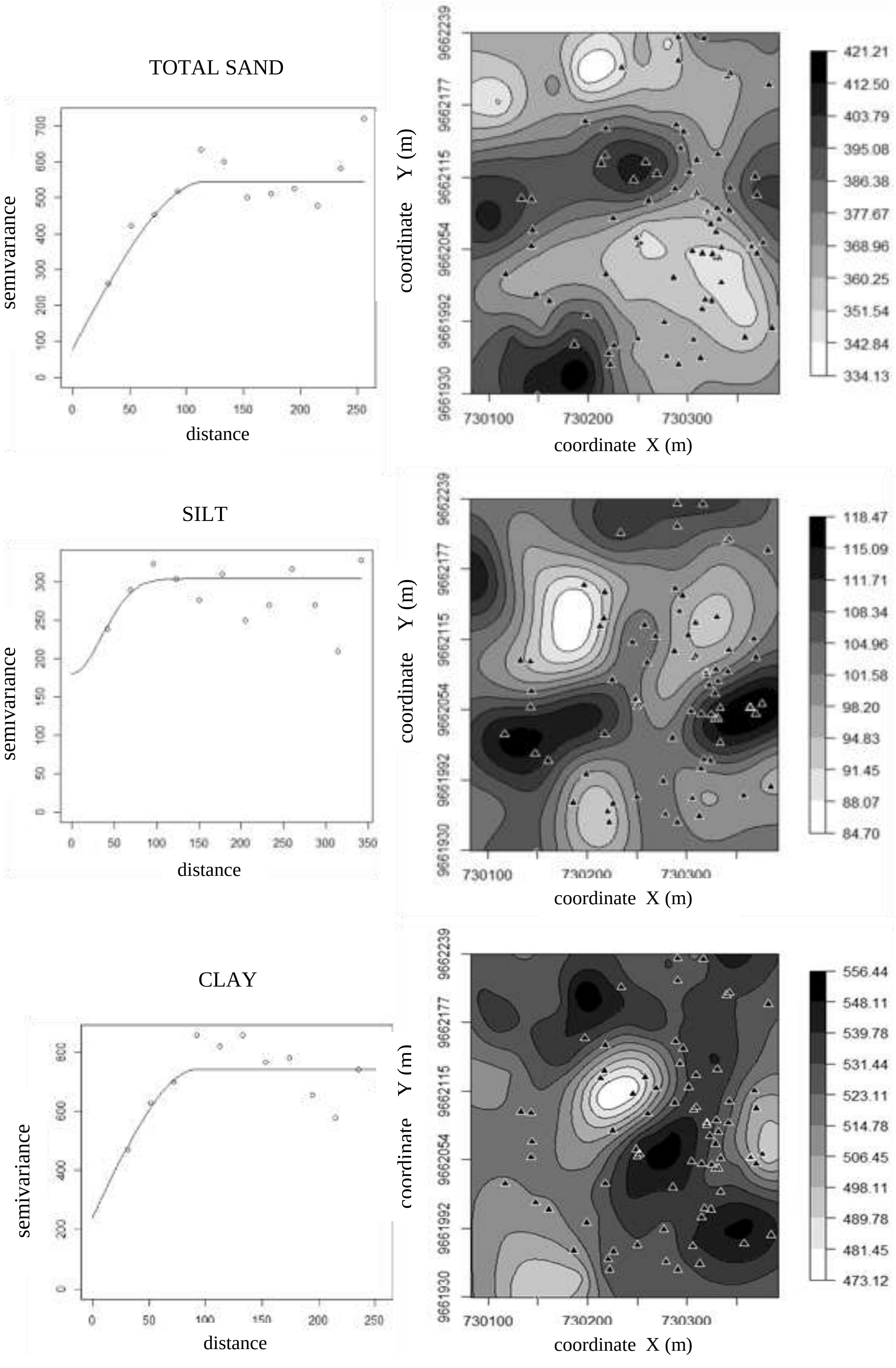

Figure 3. Semivariograms adjusted for the spherical (total sand and clay) and gaussian (silt) models and their related maps obtained through the simple kriging process. The symbol in the shape of a triangle represents the georeferenced Brazil nut trees in the study area.

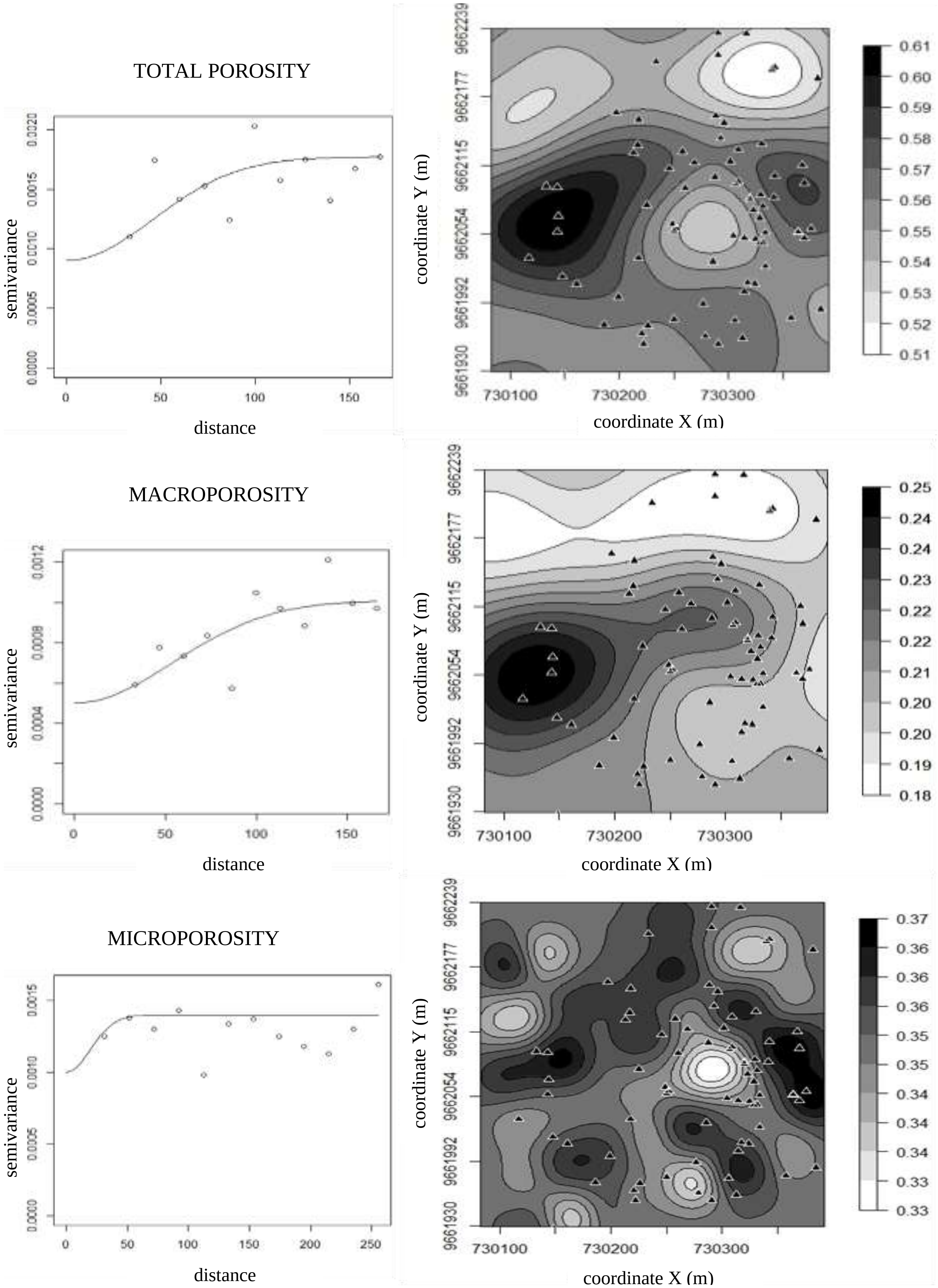

Figure 4. Semivariograms adjusted for the gaussian model (total porosity, macroporosity and microporosity) and its related maps obtained through the process of simple kriging. The symbol in the shape of the triangle represents the georeferenced Brazil nut trees in the study area.

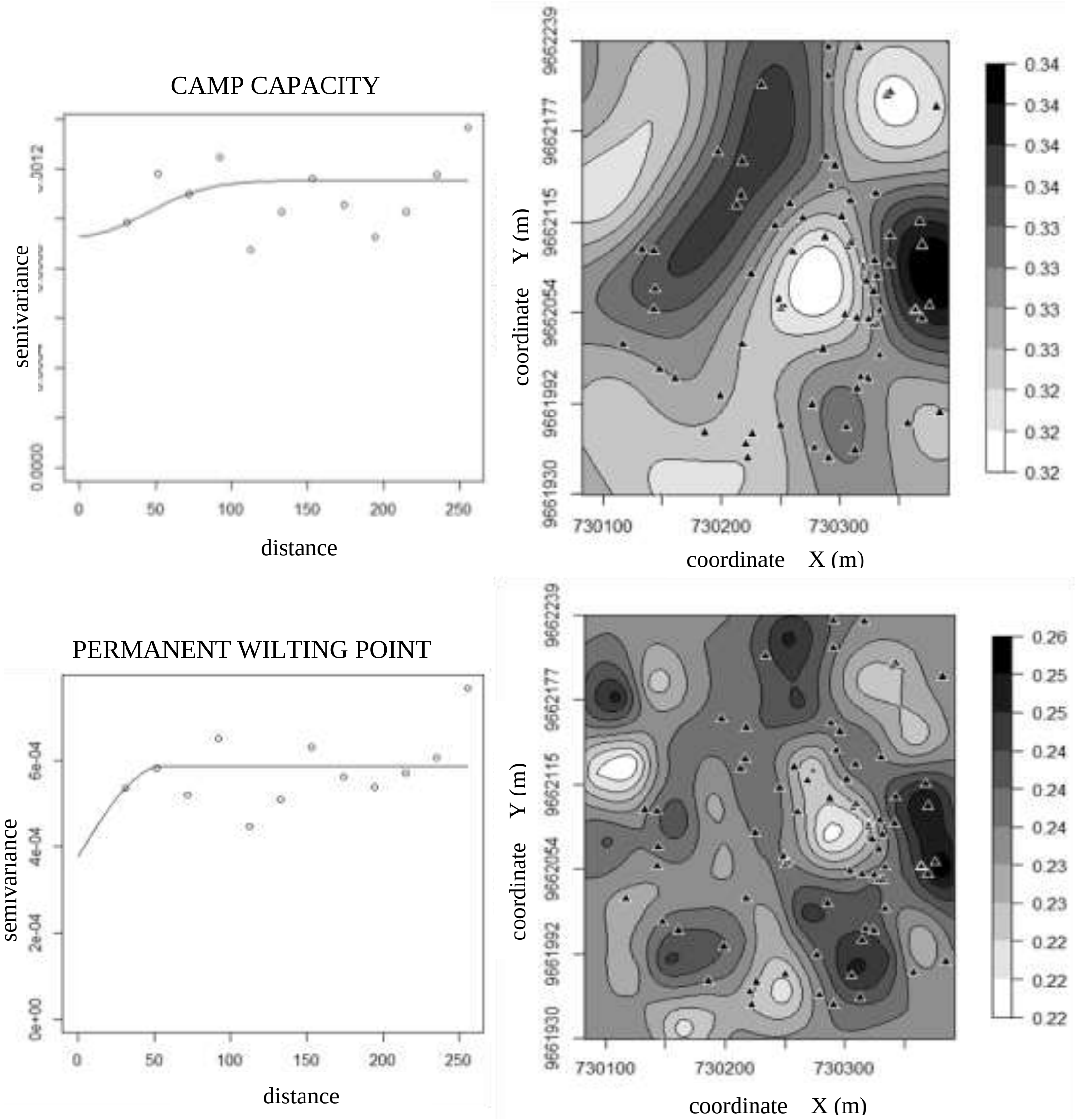

Figure 5. Semivariograms adjusted for the gaussian (camp capacity) and spherical (permanent wilting point) models and their related maps obtained through the simple kriging process. The symbol in the shape of a triangle represents the georeferenced Brazil nut trees in the study area.

(Figure 3) and smaller values for the macroporosity (Figure 4), pH, phosphorus (Figure 6), zinc and copper (Figure 7).

The predominance of individuals in the more clayey part in study area corroborates with the studies of Fernandes and Alencar (1993), Muller (1995) and Espirito-Santo et al. (2005). The results of these authors indicated that this species presents better production in soils with clayey to very clayey texture and soils of sandy texture are unsuitable to maximize the growth potential of this species.

The lower values obtained for phosphorus, zinc, and copper levels in the area of higher Brazil nut tree population indicates the demand that this species has for these nutrients. Lima and Azevedo (1996), studying the Brazil nut tree in agroforestry systems on a yellow Latosol, in the State of Amazonas, identified around 200% greater growth of three-year old individuals after the incorporation of nitrogen, phosphorus, potassium, magnesium and micronutrients. Lima et al. (2004), evaluated the growth response of Brazil nut trees with respect to the soil physicochemical variables and concluded that the variables total sand, silt, available water, phosphorus, zinc, sodium, aluminium and magnesium were the ones that influenced its growth.

As there is generally predominance of individuals in areas with lower pH values, the study of Locatelli et al. (2002) analyzed the chemical variables of an Argisol in a

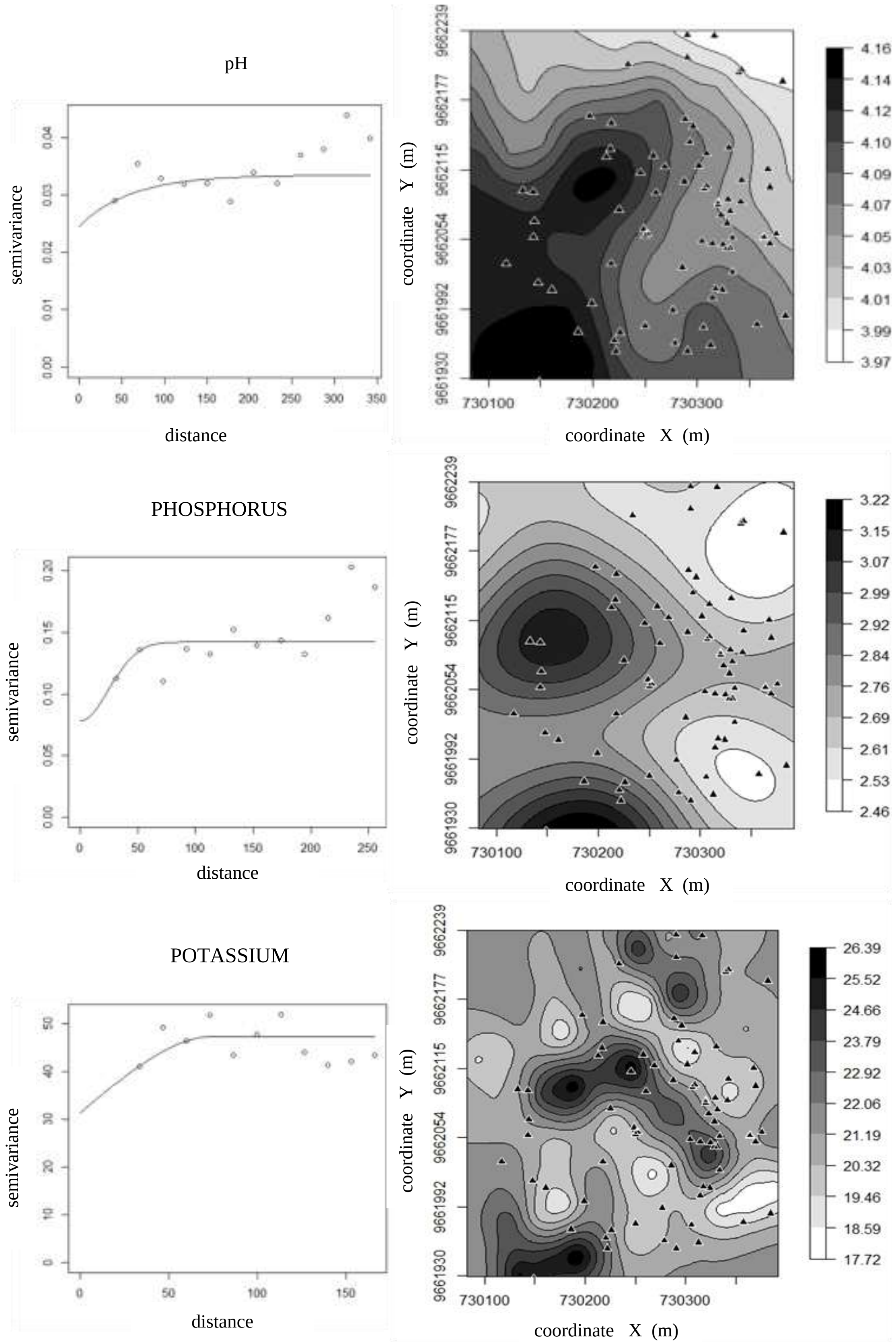

Figure 6. Semivariograms adjusted for the exponential (pH), gaussian (phosphorus) and spherical (potassium) models and their related maps obtained through the simple kriging process. The symbol in the shape of a triangle represents the georeferenced Brazil nut trees in the study area.

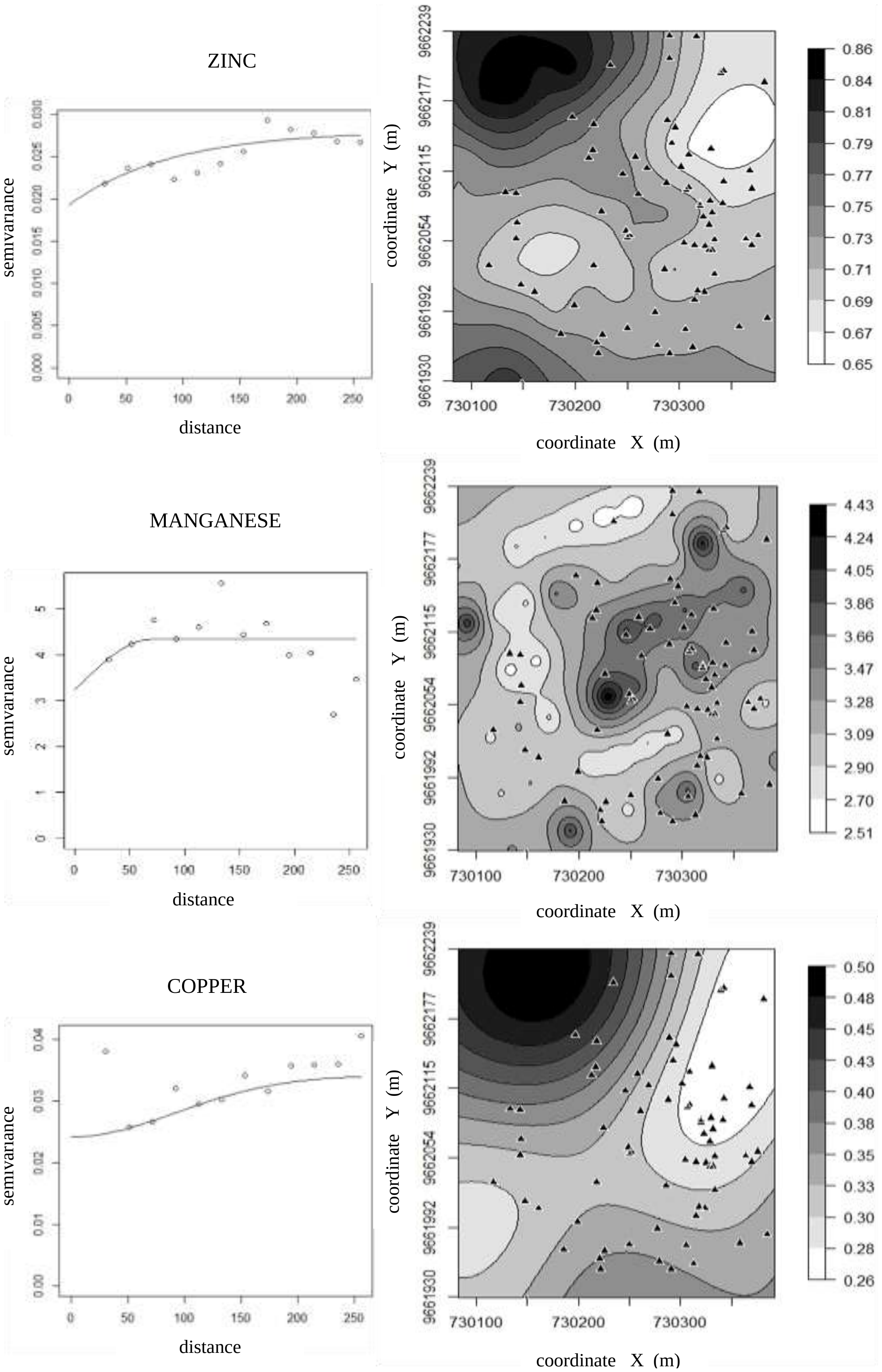

Figure 7. Semivariograms adjusted for the exponential (zinc), spherical (manganese) and gaussian (copper) models and their related maps obtained through the Simple Kriging process. The symbol in the shape of a triangle represents the georeferenced chestnut trees in the area of study.

Brazil nut tree plantation, and identified a good development in height and diameter of individuals on soil with low values of pH, cation exchange capacity and high values of aluminium saturation.

Considering that the quantity of nutrients in the soil also is an important factor in the production of fruits of the Brazil nut tree (Zuidema, 2003), highlights the importance of the products (simple kriging maps generated in this research) of the above variables, because they can direct management decisions aiming to foment the production of fruits in the area. Another study that reinforces this idea is the study by Kainer et al. (2007), that identified that the nutritional variable of the soil that best explained the variation of the yearly production of the fruits of the Brazil nut tree, in the State of Acre, was the cation exchange capacity (positive correlation) and the phosphorus concentration (negative correlation).

The kriging maps presented in this study provided information that can help to generate better practices for forest management that aim to maintain and/or enlarge the production of these Brazil nut trees in the FLONA Tapajós. The remaining variables, that do not present a more defined spatial behavior in relation to distribution of the Brazil nut trees, require more detailed studies to determine their correlation with this species.

The results for each variable presented in the kriging maps, in relation to the distribution of the Brazil nut trees, provide basic information that can be used to compare to other studies done in areas of Brazil nut tree production, and using these correlations it is possible to meet several of the objectives of the MapCast project, especially those whose goal is to understand whether or not there exists a pattern between the distribution of Brazil nut trees and soil physical and chemical properties in different regions of the Amazon basin, and also to identify environmental characteristics that should be taken into consideration in defining Brazil nut tree management practices.

The kriging maps can also be used to elucidate forest management practices that have the goal of maintaining and increasing the production of this area in the FLONA Tapajós since the results show the areas that have lower nutrient concentration in relation to the occurrence of Brazil nut trees.

Conclusions

Geostatistical analysis helped to elucidate to discern the spatial distribution of soil physical-chemical characteristics in the study area which will serve as a base for comparison for future studies in the same area to help to understand environmental aspects of other Brazil nut tree stands. The reach values obtained demonstrate lower variability for zinc, copper, and pH, and greater variability for microporosity, potassium, and silt. The simple krieging maps can help to more effectively choose areas in which future management actions should be focussed in order to optimize costs for fertilizers and soil sampling for variables that present reach values higher than those established by the 30 × 50 grid. For the variables that presented a pure nugget effect (carbon, nitrogen, sodium, calcium, magnesium, aluminum, iron) future spatial analyses should be done on a reduced grid of 15 × 50 m in size. This result is a reflection of the 120 sampling points used in the study area, and the viability of the use of geoestatistics and krieging in the elaboration of thematic maps that can be used in management of agricultural production systems. The variables that show a stronger spatial relationship with Brazil nut trees were silt, clay, macroporosity, pH, phosphorus, zinc, and copper. These are pioneering results that will be generated by the MapCast project, and will help to characterize and understand the environmental factors that influence production in Brazil nut tree stands in the Brazilian Amazon through geospatial data in order to contribute to adoption of good management practices.

Conflicts of Interests

The authors have not declared any conflict of interests.

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