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Spatial variability of some chemical properties of a Cambisol soil with cocoa (*Theobroma cacao* L.) cultivation

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ABSTRACT

Objective: To evaluate the spatial variability of some chemical properties of a Cambisol soil, in order to establish specific agronomic management zones for cocoa cultivation.

Methodology: A sampling of 42 georeferenced points equidistant at 40 m was carried out. Geostatistical variability maps were made with the results of the chemical analysis of the soil properties, using the ordinary Kriging interpolation technique.

Results: It was found that the percentage of saturation of acidity (PSA), acidity and H+ showed high variability; P-Olsen and interchangeable K, Ca and Mg displayed medium variability, and pH, MO, CIC and Al presented low variability. Soil properties pH, PSA; Exchangeable P-Olsen, Ca and Mg showed high spatial dependence (<25%) and OM, exchangeable K and CIC moderate spatial dependence (25-75%).

Study limitations/Implications: The generated maps allowed the identification of partial areas with different variability, as well as the direction of greatest variability of the property as a function of distance.

Conclusions: With the maps, it was possible to make recommendations for agronomic management depending on each specific management area.

Keywords: Cambisol, variability, recommendations, site-specific, cocoa, Kriging.

INTRODUCTION

The variability of the chemical and physical properties of the soil is an inherent condition, due to the fact that several processes intervene in its formation that, in turn, are controlled by the formation factors (climate, parent material, organisms, topography and time) (Jaramillo, 2010; Ovalles, 1992). In the state of Tabasco, the area cultivated with high-density cocoa plantations is expanding, which will imply a greater consumption of nutrients in the future. As there are no studies on the management of the spatial variability of the chemical properties of soils, the objective of this study was set to determine the spatial variability of the chemical properties of a Cambisol soil cultivated with cocoa to establish specialized management zones, which will allow the proper use of fertilizers, contributing to improve or maintain soil fertility.

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MATERIALS AND METHODS

The study was carried out in a 7-ha area cultivated with cocoa (the INIFAP-8 clone) at a high (2700 plants ha^{-1}) plantation density; with drip irrigation, located in Ranchería Caobanal, 2nd section, in the municipality of Huimanguillo, Tabasco.

Sampling sites were established from of a grid of 42 equidistant nodes (set every 40m), which were plotted at the office and subsequently, reframed in a field by using a GPS +/− 1 m accuracy. Samples were collected from 0 to 30 cm soil depth with a stainless-steel auger (Dutch type). For each sample, two subsamples were taken to obtain a weight of 1.0 kg soil (Salgado *et al*., 2013). The samples were analyzed in the soil fertility laboratory of Colegio de Postgraduados, Campus Montecillo. Determinations of soil reaction (pH) in water 1: 2 relation, electrical conductivity (EC), organic matter (OM), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and interchangeable Aluminum (Al) were carried out with the methods established in the NOM-021-RECNAT (2001). The percentage of acidity saturation (PSA) was calculated with equation 1:

$$PSA = \frac{Acidity\ meq/100g}{(Acidity + Ca + Mg + k)\,meq/100g} \times 100 \quad (1)$$

For the chemical properties, the variability analysis was performed according to descriptive statistics, and the measures of central tendency and dispersion were determined. With these, the number of samples that should be taken to obtain the value of each parameter was calculated (Acevedo *et al*., 2008). Shapiro-WilK and Kolmorov-Smirnov (Jaramillo, 2011) normality tests were performed while outliers were determined by the box-and-whisker plot, and these were replaced by the mean of the neighbors following Jolliffe (2002). The geostatistical analysis was performed, calculating the experimental semi-variance values with Equation 2:

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

Then, the experimental semivariogram was fitted to the theoretical semivariogram using the graphical method (Gotway and Hartford, 1996). With the theoretical model and the value of the parameters of the experimental semivariogram, the Kriging interpolation method was applied to obtain the distribution maps of the values of the variables in the study area, using the Vesper geostatistical program as well as the geostatistical modules of R (R Team, 2015) and ArcGis v. 9.0. (ESRI, 2012).

RESULTS

Statistical analysis of the data

The values of central tendency and dispersion for each of the variables are presented in Table 1. The pH presented the lowest variability (3.5%), while the highest variability was presented by Acidity (92.9%), H+ (92.7%) and PSA (154.6%). The observed variability values are similar to those found by Acevedo *et al*. (2008) and Salgado-Velázquez *et al*. (2020), with less variability pH (3.7%) and OM (25.5%); and with the highest variability, P-Olsen (53.6%) and K (70%).

Most of the analyzed properties had a distribution where the means and medians were similar (slightly asymmetric) except pH, MO, P-Olsen and K.

In all the studied properties, the kurtosis was greater than two except Ca and Mg, that showed a bias towards the right. This asymmetry is greater for P-Olsen, K, Zn and Mg. Regarding the bias, only the pH, MO, P-Olsen, K, Ca and Mg, presented values very close to zero. This means a clear asymmetric behavior of the data distributions. To corroborate the above, the Shapiro-Wilk and Kolmogorov-Smirnov goodness-of-fit tests were performed (Acevedo *et al*., 2008). Of the two tests, it was only agreed that the P-Olsen, K and the CIC, were adjusted to a normal distribution. The box-and-whisker plot and the analysis of the spatial distribution showed that the detected outliers were the main cause of the high values of asymmetry, kurtosis and CV, as well as of the non-normality at these distributions (Rodrigues *et al*., 2013a). Outliers then were replaced by the mean of the neighbors following Jolliffe (2002).

The minimum number of samples (n) to obtain the average value of the variable with a 5% error rate, except for the pH, MO and CIC, proved excessive, expensive and impractical (Table 2), underestimating in this study, P-Olsen, K, Mg, PSA, Acidity, Ca, H and Al, while pH, OM, and CIC were overestimated.

Geostatistical analysis of soil chemical properties

For all properties, the variograms were adjusted considering the distribution as isotropic. The best fitted variograms were selected based on the mean

Table 1. Central tendency and dispersión values for the soil chemical and physical properties.

Soil property	Min. value.	Max. value.	Range	1st. Q	3rd. Q	M	Me	Variance	SD	CV(%)	S	K	SW	KS
pH	3.9	4.5	0.6	4.1	4.3	4.2	4.1	0.02	0.14	3.5	-0.04	2.5	0.061	0.0035
PAS (%)	0.0	35	35	1	6.5	6.2	2.0	91.3	9.5	154.6	1.8	4.9	<0.001	<0.001
SOM (%)	1.5	2.8	1.36	2.0	2.4	2.2	2.1	0.08	0.29	13.3	0.09	2.7	0.866	0.0432
P (ppm)	4	46	42	17	29	23	24	72.1	8.5	36.9	0.02	3.1	0.891	0.4484
K (meq/100 g)	0.28	0.99	0.70	0.43	0.68	0.56	0.53	0.03	0.18	33.1	0.47	2.2	0.080	0.2435
Ca (meq/100 g)	0.82	14.8	13.9	3.1	10.1	6.7	6.4	15.9	3.9	59.7	0.18	1.9	0.040	0.1339
Mg (meq/100 g)	0.37	5.1	4.7	1.4	3.7	2.5	2.6	1.7	1.3	52.2	-0.07	1.7	0.043	0.1209
CEC (meq/100 g)	13.5	24.0	10.5	17.3	19.9	18.6	18.5	5.6	2.4	12.8	-0.08	2.8	0.8375	0.4775
Acidity (meq/100 g)	0.0	1.2	1.2	0.13	0.50	0.35	0.25	0.10	0.32	92.9	1.07	3.1	<0.001	<0.001
H (meq/100 g)	0.0	0.5	0.5	0.013	0.19	0.12	0.10	0.01	0.11	92.7	1.1	4.4	<0.001	0.035
Al (meq/100 g)	0.0	0.7	0.7	0.07	0.36	0.22	0.15	0.21	0.05	20.9	0.98	2.7	<0.001	<0.001

M=Median, Me=Media, S=Skewness, K=Kurtosis, SD=Standar deviation, SW=Shapiro-WilK y KS=Kolmogorov-Smirnov.

square error (RMSE) and the Akaike criteria (AIC) using VESPER 1.6 (Minasny *et al*., 1999; Rodrígues *et al*., 2013a). In addition, the Spatial Dependency Index (SDI) was calculated, which is the relationship between the variance of the nugget effect and the sill (Cambardella *et al*., 1994) for each variogram, and expressed as a percentage (Table 3).

The semivariograms indicated that the semi-variance increases as distance increases (Figures not shown). These results agree with what was reported by Acevedo *et al*. (2008), who estimated the distribution of K, P, OM and pH, and found that the semivariograms presented spatial correlations; that is, the semi-variance increases as the distance increases. It is observed that the pH, PSA, P-Olsen, Ca and Mg presented an SDI that is considered high according to Cambardella *et al*. (1994), and moderate for the other soil properties. These results were similar to those reported by Arévalo-Hernández *et al*. (2019), in a cocoa plantation established as an agroforestry system.

Kriging

The distribution of the variability of the chemical and physical properties of the soil is depicted in Figure 1, and the cross-validation to all the adjusted semivariograms and the prediction errors are shown in Table 3, which are discussed below for each soil property.

Table 2. Calculation of the mínimum number of determinations to be made to obtain the averege value of the variables with certain presicion.

Soil property	t value 0.05/2	Error	Error (d^2)	NS
pH	2.0195	0.05	0.0441	1.0
PAS (%)	2.0195	0.05	0.0955	3901.0
SOM (%)	2.0195	0.05	0.0123	28.0
P (ppm)	2.0195	0.05	1.3225	222.0
K (meq/100 g)	2.0195	0.05	0.0007	203.0
Ca (meq/100 g)	2.0195	0.05	0.1102	591.0
Mg (meq/100 g)	2.0195	0.05	0.0163	443.0
CEC (meq/100 g)	2.0195	0.05	0.8714	27.0
Exchangeable acidity (meq/100 g)	2.0195	0.05	0.0003	1437.0
H (meq/100 g)	2.0195	0.05	0.00004	1346.0
Al (meq/100 g)	2.0195	0.05	0.0001	8715.0

d^2=mean value × 0.05,
NS=number of samples to collect to obtain the mean value ($P \leq 0.05$).

The Hydrogen potential (pH) is adjusted to an exponential spatial variability model (Table 3) and generates two management zones (Figure 1a). Both pH classes were classified as strongly acidic (<5.0), which restricts the availability of nutrients in the Cambisol soil (Letelier, 1967). The annual application of 1.0 t ha^{-1} of dolomitic lime is suggested to raise the average unit the pH of the Cambisol soil.

The percentage of acidity saturation (PSA), organic matter

(OM), exchangeable potassium (K), exchangeable calcium (Ca), exchangeable magnesium (Mg) and cation exchange capacity (CEC) were adjusted to a Gaussian-type spatial variability model. On the contrary, phosphorus (P-Olsen) is adjusted to a spherical-type spatial variability model (Table 3) and, in general, they generated three agronomic management zones on the site (Figures 1b, 1c, 1d, 1e, 1f and 1g) except the CIC that generated two areas of agronomic management (Figure 1i). The PSA of 0-20 coincides with the highest class of soil pH which would reflect lower toxicity from IA to the crop. The latest PSAs also match the lowest pH. The foregoing reinforces the idea of improving the liming program, applying dolomitic lime 1.0 and 1.5 t ha^{-1} for the pH zones >4.8 and <4.3, respectively; supplemented with 0.5 t ha^{-1} of gypsum ($CaSO_4$), this salt is soluble and allows calcium to pass deeper into the soil (Kingston *et al*., 2007).

Table 3. Criteria for model selection, model characteristics and prediction errors of the selected semivariograms for the soil physical and chemical properties.

Variable	Criteria for model selection		Modelo	Nugget (Co)	Partial sill (C)	Sill (Co+C)	Range (Ao)	Model prediction errors				SDI (%)
	RMSE	AIC						1	2	3	4	
pH	0.001	-188.9	Exponential	0	0.021	0.021	106.85	0.125	-0.019	0.977	0.130	0
PAS (%)	2.34	133.4	Gaussia	0.280	1.463	1.744	286.41	0.696	-0.018	1.124	0.614	16
SOM (%)	0.006	-128.3	Gaussian	0.063	0.109	0.172	613.72	0.259	-0.009	0.987	0.264	37
P (ppm)	4.32	117.6	Spherical	0	75.938	75.938	78.46	6.475	0.006	0.896	7.489	0
K (meq/100 g)	0.004	-203.1	Gaussian	0.020	0.029	0.050	395.29	0.154	0.012	0.998	0.154	41
Ca (meq/100 g)	1.79	84.06	Gaussian	0.066	0.702	0.768	209.02	2.061	0.011	1.022	2.026	9
Mg (meq/100 g)	0.203	1.36	Gaussian	0.264	1.841	2.105	183.04	0.696	0.007	1.029	0.679	13
CEC (Cmol (+) kg-1)	0.870	56.68	Gaussian	0.009	0.008	0.018	113.65	2.040	-0.019	0.986	2.087	51

1. Standardized mean error; 2. Mean square error; 3. Averege standard error and 4. Standardized quadratic mean error.
SDI=[Co/(Co+C)]×100

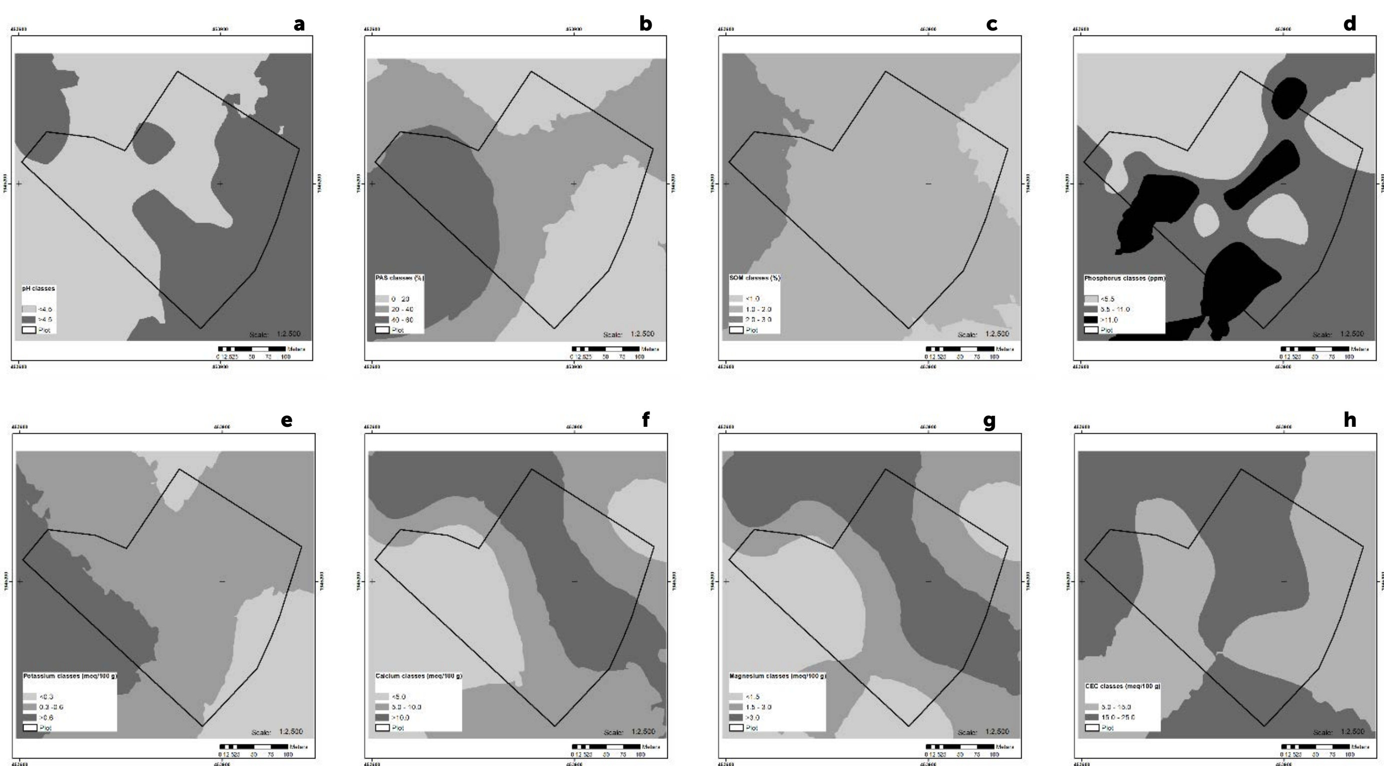

Figure 1. Maps generated by the kriging interpolation method: a) pH, b) PAS, c) SOM, d) Phosphorus, e) Potassium, f) Calcium, g) Magnesium y h) CEC.

The OM classes were classified as very poor (<1.0%), poor (1.0-2.0%) and medium (2.0-3.0%); for k it is considered low (<0.20 meq/100 g), medium (0.3-0.6 meq/100 g) and high (>0.6 meq/100 g); for Ca as low (<5.0 meq/100 g), medium (5.0-10.0 meq/100 g) and high (>10.0 meq/100 g); and for Mg, is classified as low (<1.5 meq/100 g), medium (1.5-3.0 meq/100 g) and high (>3.0 meq/100 g) in Cambisol soil, according to the classification of Tavera (1985). Conserving OM ensures the long-term supply of nutrients to the soil, which is why the application of compost is recommended. Since the plantation is at high density, it is recommended to apply 100 kg ha^{-1} of nitrogen per year. Silva *et al*. (2016) found that the apparent density of the soil, the total volume of pores and the geometric mean diameter depend on the total amount of organic carbon in the soil cultivated with cocoa.

The middle and upper class reflect the accumulation of phosphorus through chemical fertilization carried out on crops such as watermelon and habanero pepper, before establishing the cacao plantation. It is recommended to supply 100, 75 and 50 kg ha^{-1} of P_2O_5 per year for the low, medium and high class, respectively. And for K, it is recommended to apply 150, 100 and 50 kg ha^{-1} of K_2O per year. The low class of Ca is located from southeast to northeast, this coincides with the class with the lowest pH. As well as the low class of Mg coinciding with the low classes of Ca and pH; the middle class of Mg coincides with the highest classes of Ca and pH.

The low class of CIC (5.0 - 15.0 meq/100 g) is associated with the low classes of pH, PSA, Ca and Mg; in this case, it is necessary to apply compost or to leave pruning remains on the soil surface to increase the CEC in the long term. In this regard, Daymond *et al*. (2002) found that the pruning of shade trees resulted in an accumulation of plant debris in the cocoa crop. The middle class (15.0-25.0 meq/100 g) is recommended for cocoa cultivation.

CONCLUSIONS

The PSA, Acidity and interchangeable H+ presented high variability; P-Olsen, interchangeable K, Ca and Mg showed medium variability; and pH, OM, CEC, and IA, low variability.

The geostatistical analysis established specific agronomic management areas on the site. It was determined that the properties of the soil pH, PSA; P-Olsen, Ca and Mg showed high spatial dependence (<25%) and OM, K and CEC moderate spatial dependence (25-75%). With the maps generated by the ordinary Kriging method, partial areas with different variability were identified, as well as the direction of the greatest variability of the property as a function of distance. With these maps, it was possible to define agronomic management recommendations based on the needs of each specific management area.

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