CHEMICAL ATTRIBUTES OF AMAZON FOREST SOIL UNDER CONVERSION FOR DIFFERENT CULTIVATION SYSTEMS IN THE SOUTH OF AMAZONAS, BRAZIL

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Abstract. In the Amazon, the change in land use, with the withdrawal of native vegetation and the implantation of agricultural crops, has caused numerous changes in the chemical properties of the soil, in addition to changing the processes that control the sustainability of its ecosystems. We aim to verify the impacts caused to soil chemical attributes as a function of the conversion of forests to cultivated area with Amazonian species in the municipality of Canutama, southern region of Amazonas. Meshes were established according to the size of the crop and, in each area, samples with a preserved structure were collected at the crossing points of the meshes, at depths of 0.00-0.05; 0.05-0.10; and 0.10-0.20 m, with 80 sampling points in each area, generating 240 samples per area and totalizing 960 samples for determination of chemical attributes and organic carbon. The multivariate analysis of soil chemical attributes is adequate to identify the nutrients that present the greatest alteration after the forest/agriculture conversion process. There were more changes in the chemical attributes in the superficial layers (0.00-0.05 and 0.05-0.10 m), which demonstrates the importance of above-ground biomass in nutrient cycling.

Keywords: *soil attributes, soil degradation, multivariate analysis, conversion, changes*

Introduction

The amazon for the researchers is highlighted in the biodiversity issue (Melo et al., 2017). Soils of the Brazilian Amazon generally have low fertility, low levels of P, Ca^{2+} and Mg^{2+}, and high acidity and Al^{3+} saturation (Enck et al., 2022). Another highlight concerns the deforestation that has exceeded borders because of its global significance. The process of vegetation overturning and burning has been widely used as a practice in agricultural and livestock production systems, with significant impacts on the chemical properties of different soil classes (Lima et al., 2022a).

The substitution of native forest areas in pastures and agricultural plantations, when done improperly, causes drastic changes in the functional system of the original ecosystem and consequently changes in the set of soil attributes. It also promotes the disruption of the balance between the soil and the environment, modifying their chemical, physical and biological properties (Souza et al., 2023).

The cultivation methods in the Amazon are based mainly on extensive livestock (pasture), coffee and secondary forest. For some areas, farmers consorted species and

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secondary forest after cutting and burning forest areas. This practice is based on the indigenous agricultural system, which is characterized by long fallow periods after a short growing period (Reichert et al., 2016).

Thus, it is noticed that the soil is one of the most used natural resources, and its study is of great importance, both in understanding the internal processes in the provision of ecosystem services, as well as in the evaluation of possible impacts of use and management on the soil attributes (Owuor et al., 2018).

Another tool proposed for the study of the behavior of soil attributes in sites under management is the use of multivariate statistics and it is possible to describe the relations of intra and interdependence in the agricultural systems (Sales et al., 2022). With the use of multivariate statistics, it is possible to observe the difference in behavior of soil attributes in relation to its area, as well as to provide a view and diagnosis of the soil management reflex, using factorial analysis in conjunction with cluster analysis (Brito et al., 2022).

In addition, for simultaneous analysis for many information the multivariate analysis ends up becoming the best tool, considering that it allows obtaining and interpreting data more efficiently, when compared to univariate statistics, presenting satisfactory results in studies applying this technique for evaluation of soil variables (Jordão et al., 2020).

Despite the great importance of multivariate statistical methods for interpretations of variations in soil attributes, there are few studies that use this tool, since most researchers still adopt univariate statistical methods (Pantoja et al., 2019). Thus, the present study aimed to verify the impacts to soil chemical properties due to the conversion of forests into cultivated areas with Amazonian species in the south of the Amazon region.

Material and methods

Location and characterization of the study area

The study was developed in two rural properties that are part of the São Francisco settlement located in the municipality of Canutama, Amazonas, Brazil under the geographic reference coordinates (8º 13’ 23’’ S; 64º 00’ 50’’ W) and (8º 13’ 25’’ S; 64º 00’ 23’’ W), for both properties. Four areas were selected, with three areas under different crops Annatto (*Bixa orellana* L.), Cupuaçu (*Theobroma grandiflorum* (Willd. ex. Spreng) Schum), Guaraná (*Paullinia cupana* (Mart.) Ducke) and a forest area (*Figure 1*).

The soil of the study area were classified according to criteria established by the Brazilian Soil Classification System (Santos et al., 2018) as Argissolo Vermelho-Amarelo Distrófico and the World Reference Base of Soils (IUSS Working Group WRB, 2022) as Chromic Abruptic Acrisol, located in the Amazon Plains between the Purus and Madeira rivers, also associated to recent and old alluvial deposits, of the Quaternary period, characterized by the presence of tabular geography of great dimensions, defined by talwegs of very weak deepening, that is, the embossed terrain displays very smooth slopes, and the natural drainage is deficient (Campos et al., 2012). In regard to the climatic characterization, the region’s climate is Rainy Tropical, displaying a dry period of short duration. The partial average rainfall ranges from 2250 and 2750 mm per year, with a rainy period between October and June. The average annual temperatures range from 25 to 27°C and the relative humidity of the air between 85 and 90% (Alvares et al., 2013).

As to the history of the areas under different systems of traditional uses in the Amazon region selected for the study (*Figure 1*), it was possible to gather some important and relevant information:

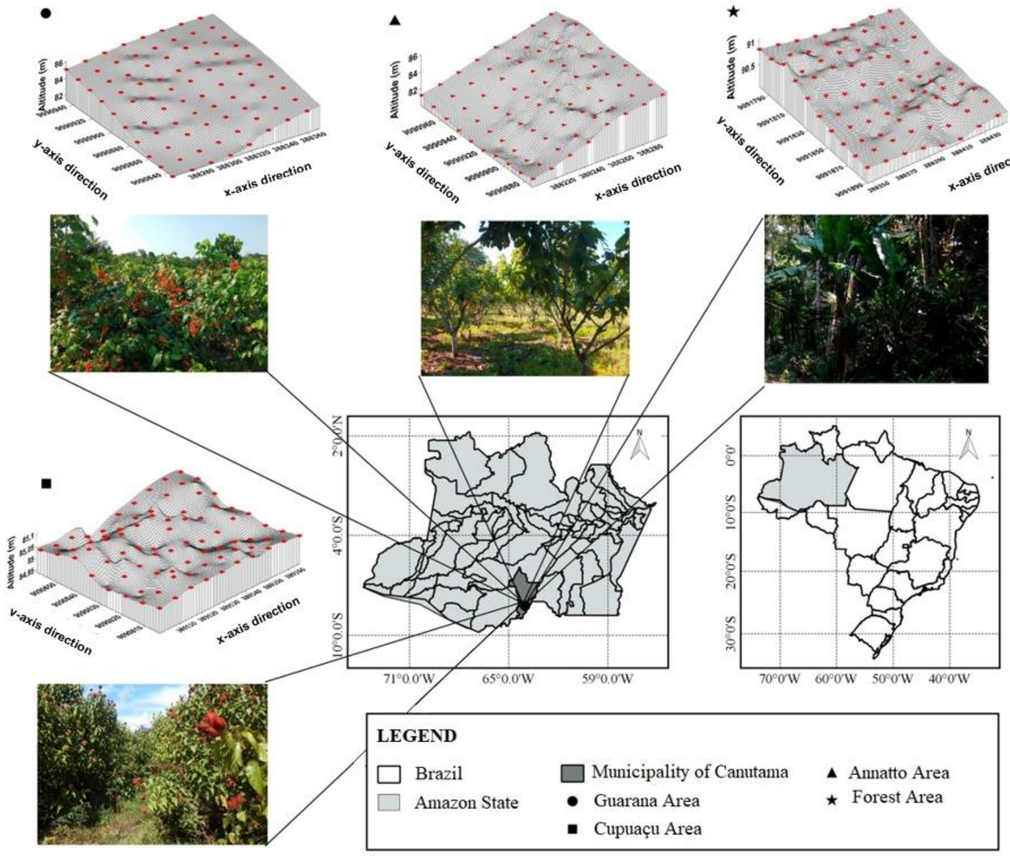

Figure 1. *Location and digital elevation model of the areas with guaraná, cupuaçu, annatto and forest in the municipality of Canutama, southern Amazonas - AM*

Areas cultivated with guaraná, annatto and cupuaçu: The areas cultivated with guaraná and cupuaçu have 7 years of effective cultivation, and the area of annatto only 3 years. It is important to highlight that the respective areas are derived from felling and burning of the forest, with consequent manual clearing to clean the area in the first year of cultivation, without the adoption of agricultural machinery for soil preparation.

The respective areas cultivated with Amazonian species have never received any type of fertilization and/or liming, in both only weed control with the use of a motorized ridge, in addition to spraying with glyphosate herbicides for the control of the hemp (*Imperata brasiliensis*). The areas of guaraná and annatto present an average slope around 3%. The cupuaçu area is located in a flatter area, and it is possible to observe only the actual accumulation of biomass of the crop in great quantity.

Native Forest Area: It is characterized as dense ombrophilous tropical forest, whose vegetation is perennial characterized by the presence of phanerophytes (plants whose renewal buds are more than 25 cm from the ground), besides being composed of densified and multi-layered trees between 20 and 50 meters high.

Field methodology

Meshes were established according to the size of the crop. In the areas of guaraná and forest, 90 x 70 m meshes were established with regular spacing between the sampling points of 10 x 10 m, in the area of annatto the established mesh was 90 x 56 m with spacing between the sample points of 10 x 8 m, and for the cupuaçu area the mesh had 54 x 42 m, with regular spacing between the sampling points of 6 x 6 m. The samples were collected at the crossing points of the meshes, in the depths of 0.00-0.05; 0.05-0.10; and 0.10-0.20 m, with 80 sample points in each area, samples were collected between October and December of the 2017. The points were georeferenced with a Garmin GPS equipment model Etrex (*Datum South American´*69).

At each sampling point, samples were collected in the three layers evaluated for determination of chemical attributes and organic carbon, making a total of 960 samples in the four areas. The samples were dried in the shade and slightly deformed, passed through a sieve of 4.76 mm mesh diameter, separating the material retained in the sieve of 2.00 mm, which was used for determination of the chemical properties of the soil.

Laboratory determinations and analyzes

After the soil underwent a shade drying process and was sieved in a 2 mm mesh, characterizing an air-dried soil, the chemical analyzes were carried out according to the methodology proposed by Teixeira et al. (2017). It was analyzed: water pH, potential acidity (H^++Al^{3+}), exchangeable aluminum (Al^{3+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), phosphorus (P), potassium (K) and organic carbon (OC). The pH in water was determined potentiometrically using pH meter in the soil:water ratio of 1:2.5.

The exchangeable aluminum (Al^{3+}) was extracted with 1 mol.L^{-1} KCl solution, with values determined by titrations, using 0.025 mol.L^{-1} NaOH and bromothymol blue as acolorimetric indicator.

Potential acidity (H+Al) was extracted with calcium acetate at pH 7.00 and determined by titration using 0.025 mol.L^{-1} NaOH and phenolphthalein as indicator.

Phosphorus (P), potassium (K^+), and magnesium (Mg^{2+}) were extracted by the ion exchange resin method. Based on the determinations of the exchangeable cations and potential acidity were calculated: effective and potential cation exchange capacity (CEC); sum of bases (SB), base saturation (V) and aluminum saturation (m).

Organic carbon (OC) was determined by the Walkley-Black method, modified by Yeomans and Bremner (1988), using *Eq. (1)* proposed by Teixeira et al. (2017).

$$Corg = \frac{0{,}003\ x\ Vd\ x\ (40-\text{Va})\ \text{x}\ \frac{40}{Vb}\ x\ 10}{m} \qquad \text{(Eq.1)}$$

In which:
Corg - concentration of organic carbon in the soil, in g kg^{-1}.
Vd - total volume of potassium dichromate solution added in the digestion of the sample, in ml.
Va - volume of the ammoniacal ferrous sulphate solution used in the titration of the sample, in mL.
Vb - volume of the ammoniacal ferrous sulphate solution spent on titration of the heated blank, in mL.
Value 0.003 – milliequivalent of the mass of carbon (atomic weight/valence - 12/4, divided by 1,000).
Value 10 - transformation from % to g kg^{-1}.
m - mass of the soil sample, in g.

Statistical analyzes

After obtaining the data of the chemical attributes, descriptive statistics were analyzed, where the mean, median, standard deviation, variance, coefficient of variation, asymmetry coefficient and kurtosis coefficient were calculated. The coefficient of variation (CV%) was evaluated according to a classification proposed by Warrick and Nielsen (1980), which classifies soil variables as CV <12%, 12 <CV <60%, and CV> 60% for low, medium and high variability, respectively.

Then, univariate and multivariate statistical analysis were performed. The univariate analysis of variance (ANOVA) was used to verify if there is a difference between the studied areas, to know which area is different from the other and to compare the means of the attributes, using the Tukey test at 5% of probability, through the software SPSS 21 (SPSS Inc., 2001). Afterwards, the multivariate analysis of variance (MANOVA) was used, through factorial analysis, in order to find statistical significance of the sets of soil attributes that more discriminate the environments, as a reference the environment under forest, obtaining as a response attribute that suffer greater influence on land use.

The adequacy of the factorial analysis was made by the Kaiser-Meyer-Olkin (KMO) measure, which evaluates the simple and partial correlations of the variables, and by the Barlett sphericity test, which is intended to reject the equality between the correlation matrix and identity. The extraction of the factors was performed by the principal components, incorporating the variables that presented commonalities equal to, or greater, than five. The choice of the number of factors to be used was made by the Kaiser criteria (factors that have eigenvalues greater than 1). In order to simplify the factorial analysis, the orthogonal rotation (*Varimax*) of the factors was performed and represented in a factorial plane of the two components. Pearson's correlation was used to evaluate the strength and direction of map correlation of the distribution pattern of these variables.

Results and discussion

The descriptive statistics, as well as analysis of variance of the chemical attributes evaluated in areas cultivated with guaraná, annatto and cupuaçu in comparison to the forest area are presented in tables 1, 2 and 3, for the respective depths 0.00-0.05 m, 0.05-0.10 and 0.10-0.20 m. According to the results shown in the tables, it was observed that the coefficients of asymmetry and kurtosis expressed the normality of data distribution, since they presented values close to zero, in all depths and for all the studied areas. Studies have shown that asymmetry and kurtosis serve as indicators of the distribution of analyzed values, whether they have symmetric values or not, where the ideal is that these values are close to the zero central value (Lima et al., 2022a).

The mean and median central tendency measurements of the chemical attributes showed a symmetrical distribution, both values were very close to all attributes and their respective depths, which justifies normal or near normal distributions of the data. The results for the Kolmogorov-Smirnov test indicated normal condition data for all chemical attributes from 0.00 to 0.05 m, 0.05-0.10 m, and 0.10-0.20 m (*Tables 1, 2 and 3*), a fact that occurs with the observation of the proximity of the mean in relation to the median. Similar results were found by Soares et al. (2018). Regarding the values of standard deviation and variance, it was possible to verify that some attributes presented high values for both depths and areas studied, highlighting attributes V%, m% and OC.

Table 1. *Descriptive statistics and mean test for the layer 0.00 – 0.05 m of the pH in water, potential acidity (H+Al), exchangeable aluminum (Al^{3+}), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sum of bases (SB), effective CEC (t), potential CEC (T), base saturation (V%), aluminum saturation (m%), phosphorus (P), organic carbon (CO), in areas of Cupuaçu, Guaraná, Annatto and Forest in the municipality of Canutama-AM*

Descriptive statistics	**pH**	**H+Al**	**Al^{3+}**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**SB**	**t**	**T**	**V%**	**m%**	**P**	**OC**
	(H_2O)	------------------------------------ $cmol_c kg^{-3}$------------------------------------										mg kg^{-1}	g kg^{-1}
Area	**Cupuaçu**												
Maximum	4.39	19.14	8.60	0.11	2.10	0.40	2.76	10.29	21.50	18.15	94.73	5.84	36.65
Minimum	3.22	7.10	2.00	0.02	0.21	0.05	0.31	3.83	8.71	2.80	52.23	0.84	10.68
Mean	3.84ab	12.44b	5.54a	0.06c	1.09b	0.24c	1.41b	6.98a	14.30a	10.06c	79.21b	3.33d	23.42a
Median	3.83	12.05	5.35	0.06	1.16	0.25	1.43	6.98	13.82	10.06	79.37	3.33	23.42
¹SD	0.26	2.86	1.27	0.02	0.54	0.09	0.60	1.42	3.19	3.95	9.36	1.15	6.25
Variance	0.07	8.19	1.61	0.00	0.29	0.01	0.36	2.02	10.18	15.59	87.68	1.31	39.12
²CV%	6.77	23.00	22.95	30.17	49.43	35.78	42.79	20.37	22.32	39.26	11.82	34.42	26.70
Asymmetry	0.34	0.59	0.35	0.31	-0.01	-0.40	0.02	0.23	0.51	-0.08	-0.66	0.09	0.12
Curtose	-0.33	0.00	0.28	-0.15	-0.80	-0.30	-0.71	0.12	-0.47	-0.71	0.47	-0.53	-0.29
³K-S	0.09*	0.13*	0.10*	0.13*	0.09*	0.10*	0.08*	0.10*	0.11*	0.06*	0.07*	0.06*	0.10*
Area	**Guaraná**												
Maximum	4.85	18.15	7.40	0.25	2.09	1.05	3.15	9.33	19.88	31.15	92.64	10.23	19.64
Minimum	3.31	4.95	3.10	0.06	0.19	0.10	0.39	4.56	5.51	3.56	54.72	4.17	7.37
Mean	3.78b	8.95c	4.98b	0.11b	1.02b	0.39b	1.54b	6.51ab	10.49c	14.75b	76.57b	6.64c	14.04d
Median	3.74	8.25	4.80	0.11	0.95	0.36	1.55	6.38	10.09	13.58	76.32	6.56	14.04
¹SD	0.27	2.73	0.89	0.04	0.46	0.19	0.60	1.00	2.83	6.27	8.33	1.44	2.94
Variance	0.07	7.42	0.80	0.00	0.21	0.03	0.36	1.00	8.00	39.30	69.46	2.08	8.64
²CV%	7.05	30.45	17.93	34.49	44.69	47.70	39.19	15.36	26.96	42.50	10.88	21.73	20.93
Asymmetry	0.94	0.99	0.48	0.94	0.28	0.88	0.28	0.31	0.93	0.55	-0.35	0.70	-0.03
Curtose	2.09	1.12	-0.03	0.92	-0.48	1.47	-0.37	-0.35	1.10	-0.15	-0.12	-0.02	-0.60
³K-S	0.11*	0.14*	0.10*	0.14*	0.09*	0.09*	0.07*	0.07*	0.11*	0.09*	0.08*	0.09*	0.09*
Area	**Annatto**												
Maximum	4.25	13.86	7.50	0.30	2.75	1.45	4.26	10.65	17.95	36.13	86.51	11.06	24.83
Minimum	3.50	6.43	2.40	0.07	0.57	0.24	0.82	4.22	9.07	8.91	39.73	4.67	10.05
Mean	3.88a	9.65c	4.18c	0.15a	1.63a	0.75a	2.56a	6.93a	12.425b	20.93a	62.76c	7.43b	16.52c
Median	3.91	9.73	4.30	0.14	1.65	0.74	2.59	6.85	12.50	21.00	62.50	7.50	16.36

Descriptive statistics	**pH**	**H+Al**	**Al^{3+}**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**SB**	**t**	**T**	**V%**	**m%**	**P**	**OC**
	(H_2O)	------------------------------------ $cmol_c kg^{-3}$ ------------------------------------										mg kg^{-1}	g kg^{-1}
¹SD	0.17	1.77	0.91	0.05	0.53	0.32	0.80	1.11	1.95	6.23	10.76	1.47	3.28
Variance	0.03	3.15	0.84	0.00	0.28	0.10	0.65	1.25	3.81	38.84	115.86	2.18	10.76
²CV%	4.59	18.39	21.29	32.93	32.47	42.61	31.53	16.12	15.72	29.77	17.15	19.87	19.86
Asymmetry	-0.12	0.37	0.35	1.06	0.07	0.54	0.54	1.12	0.53	0.11	-0.08	-0.01	0.44
Curtose	-0.33	-0.33	1.04	1.05	-0.82	-0.69	-0.69	2.78	0.13	-0.56	-0.32	-0.19	0.05
³K-S	0.08*	0.09*	0.09*	0.17*	0.09*	0.10*	0.10*	0.10*	0.10*	0.07*	0.15*	0.08*	0.12*
Area	**Forest**												
Maximum	3.88	15.84	6.90	0.21	1.42	0.49	1.98	7.63	17.49	13.98	93.87	14.57	30.22
Minimum	3.24	9.57	4.20	0.06	0.19	0.05	0.33	4.53	6.26	2.49	71.41	7.43	13.37
Mean	3.63c	12.61a	5.22ab	0.11b	0.59c	0.21c	0.92c	6.14b	13.44b	6.70d	85.57a	10.85a	20.22b
Median	3.64	12.65	5.24	0.11	0.28	0.15	0.55	6.22	13.56	4.66	89.32	10.93	20.34
¹SD	0.13	1.47	0.56	0.03	0.46	0.12	0.59	0.77	1.80	3.67	7.64	1.61	3.59
Variance	0.01	2.16	0.32	0.00	0.21	0.01	0.35	0.59	3.24	13.51	58.41	2.59	12.90
²CV%	3.62	11.65	10.90	27.24	78.04	59.06	64.31	12.56	13.40	54.82	8.93	14.83	17.76
Asymmetry	-0.55	0.07	0.73	0.89	0.69	0.61	0.70	0.02	-0.65	0.65	-0.69	0.21	0.43
Curtose	0.92	-0.62	0.75	1.00	-1.29	-1.09	-1.28	-0.65	2.08	-1.19	-1.14	-0.48	0.46
³K-S	0.09*	0.08*	0.11*	0.13*	0.29*	0.22*	0.24*	0.06*	0.06*	0.22*	0.22*	0.08*	0.09*

¹SD: standard deviation; ²CV: coefficient of variation; ³K-S: Kolmogorov-Smirnov normality test. *significant at 5% probability; means followed by same letter do not differ statistically column (Tukey $p < 0.05$)

Table 2. *Descriptive statistics and mean test for the layer 0.05 – 0.10 m of the pH in water. potential acidity (H+Al), exchangeable aluminum (Al^{3+}), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sum of bases (SB), effective CEC (t), potential CEC (T), base saturation (V%), aluminum saturation (m%), phosphorus (P), organic carbon (CO) in areas of cupuaçu, guaraná, annatto and Forest in the municipality of Canutama-AM*

Descriptive statistics	**pH**	**H+Al**	**Al^{3+}**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**SB**	**t**	**T**	**V%**	**m%**	**P**	**OC**
	(H_2O)	--------------------------------- $cmol_c kg^{-3}$-------------------------------										mg kg^{-1}	g kg^{-1}
Area	**Cupuaçu**												
Maximum	4.34	11.80	7.50	0.11	2.48	0.45	2.84	9.38	15.14	30.80	94.58	6.01	29.44
Minimum	3.23	3.55	2.50	0.03	0.20	0.05	0.31	3.18	4.46	2.89	49.30	0.38	14.45
Mean	3.82a	8.73c	5.07b	0.06c	0.81b	0.17c	1.06b	6.26b	10.04b	12.11b	80.94b	3.24d	23.30a
Median	3.82	8.73	5.10	0.05	0.79	0.15	1.05	6.19	10.04	10.93	83.32	3.36	23.30
¹SD	0.23	1.57	0.83	0.02	0.43	0.09	0.52	1.08	1.87	6.89	10.39	1.40	3.10
Variance	0.05	2.47	0.69	0.00	0.19	0.01	0.27	1.17	3.48	47.46	107.89	1.96	9.61
²CV%	6.04	17.99	16.34	27.65	53.18	52.33	49.22	17.28	18.58	56.90	12.83	43.21	13.30
Asymmetry	-0.04	-0.37	0.06	0.78	1.09	1.00	1.20	0.31	0.37	0.91	-1.33	-0.36	-0.22
Curtose	-0.34	0.40	1.07	0.85	1.92	1.04	2.00	1.30	1.13	0.15	1.63	-0.57	0.07
³K-S	0.09*	0.06*	0.09*	0.17*	0.12*	0.12*	0.11*	0.12*	0.07*	0.11*	0.12*	0.07*	0.11*
Area	**Guaraná**												
Maximum	4.28	14.69	7.00	0.12	1.52	0.75	2.74	8.74	16.21	22.38	94.80	9.30	19.49
Minimum	3.38	6.60	3.90	0.02	0.19	0.08	0.32	4.63	8.50	1.29	68.65	2.87	7.37
Mean	3.82a	10.60a	5.53a	0.07b	0.80b	0.30b	1.22b	6.75a	11.82a	10.25b	82.34b	4.94c	12.11d
Median	3.83	10.56	5.50	0.07	0.86	0.30	1.21	6.86	11.78	9.95	82.06	4.82	11.82
¹SD	0.19	1.60	0.72	0.02	0.38	0.13	0.51	0.93	1.64	4.34	6.28	1.26	2.55
Variance	0.04	2.56	0.51	0.00	0.15	0.02	0.26	0.87	2.68	18.86	39.49	1.58	6.48
²CV%	5.03	15.08	12.94	30.38	47.45	44.19	42.03	13.85	13.84	42.37	7.63	25.45	21.02
Asymmetry	-0.20	0.25	-0.08	0.48	0.01	0.68	0.22	-0.11	0.17	0.30	0.09	0.82	0.45
Curtose	-0.24	-0.09	-0.37	0.22	-0.87	0.87	-0.14	-0.09	-0.37	-0.08	-0.55	1.38	-0.16
³K-S	0.07*	0.06*	0.09*	0.12*	0.07*	0.09*	0.06*	0.07*	0.05*	0.05*	0.05*	0.08*	0.09*
Area	**Annatto**												
Maximum	4.33	11.71	6.90	0.18	3.36	1.09	3.46	10.14	14.62	31.57	87.35	10.08	19.86
Minimum	3.57	7.09	2.70	0.03	0.57	0.14	1.09	4.43	8.90	10.90	45.33	2.04	10.29
Mean	3.90a	9.37b	4.56c	0.10a	1.73a	0.44a	2.31a	7.08a	11.65a	20.15a	66.77c	6.46b	16.16b
Median	3.90	9.28	4.60	0.10	1.81	0.46	2.40	7.06	11.68	20.46	67.06	6.50	16.66

Descriptive statistics	**pH**	**H+Al**	**Al^{3+}**	**K^{+}**	**Ca^{2+}**	**Mg^{2+}**	**SB**	**t**	**T**	**V%**	**m%**	**P**	**OC**
	(H_2O)	---------------------------------- $cmol_c kg^{-3}$--------------------------------										mg kg^{-1}	g kg^{-1}
¹SD	0.17	1.07	0.75	0.03	0.52	0.16	0.58	1.16	1.30	4.77	8.53	1.63	2.24
Variance	0.02	1.16	0.57	0.00	0.27	0.02	0.33	1.36	1.70	22.80	72.91	2.68	5.02
²CV%	4.41	11.51	16.60	30.21	30.27	37.88	25.11	16.48	11.21	23.70	12.79	25.32	13.86
Asymmetry	0.58	0.01	-0.07	0.46	-0.14	0.69	-0.35	0.29	0.15	0.14	-0.28	-0.08	-0.51
Curtose	0.11	-0.60	0.64	-0.23	0.25	1.63	-0.62	0.20	-0.12	-0.37	0.01	0.01	-0.15
³K-S	0.12*	0.07*	0.09*	0.09*	0.09*	0.07*	0.13*	0.07*	0.08*	0.07*	0.09*	0.08*	0.12*
Area	**Forest**												
Maximum	3.99	10.80	6.90	0.19	0.35	0.17	0.64	8.17	12.93	7.62	95.86	9.71	19.32
Minimum	3.07	7.00	3.50	0.02	0.19	0.05	0.26	3.51	6.55	2.73	87.92	3.80	6.39
Mean	3.68b	9.21bc	5.21b	0.07b	0.25c	0.08d	0.42c	5.75c	9.84b	4.35c	92.54a	7.05a	13.66c
Median	3.74	9.30	5.20	0.07	0.23	0.08	0.40	5.76	9.81	4.24	92.57	7.10	13.66
¹SD	0.19	0.77	0.68	0.04	0.06	0.03	0.10	0.93	1.11	1.08	1.69	1.19	2.65
Variance	0.04	0.60	0.46	0.00	0.00	0.00	0.01	0.86	1.23	1.17	2.85	1.40	7.04
²CV%	5.27	8.40	13.01	51.69	24.61	32.93	24.38	16.13	11.28	24.88	1.82	16.81	19.42
Asymmetry	-1.25	-0.18	0.27	0.64	0.57	1.11	0.10	0.45	0.13	0.45	-0.32	-0.04	-0.20
Curtose	1.29	-0.10	-0.05	0.11	-1.28	1.79	-1.28	0.47	0.93	-0.33	-0.34	0.02	0.21
³K-S	0.15*	0.07*	0.09*	0.14*	0.28*	0.18*	0.13*	0.07*	0.06*	0.10*	0.06*	0.05*	0.11*

¹SD: standard deviation; ²CV: coefficient of variation; ³K-S: Kolmogorov-Smirnov normality test. *significant at 5% probability; means followed by same letter do not differ statistically column (Tukey $p < 0.05$)

Table 3. *Descriptive statistics and mean test for the layer 0.10 – 0.20 m of the pH in water. potential acidity (H+Al), exchangeable aluminum (Al^{3+}), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sum of bases (SB), effective CEC (t), potential CEC (T), base saturation (V%), aluminum saturation (m%), phosphorus (P), organic carbon (CO), in areas of cupuaçu, guaraná, anatto and Forest in the municipality of Canutama-AM*

Descriptive statistics	**pH**	**H+Al**	**Al^{3+}**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**SB**	**t**	**T**	**V%**	**m%**	**P**	**OC**
	(H_2O)	------------------------------------cmol$_c$kg^{-3}-------------------------------										mg kg^{-1}	g kg^{-1}
Area	**Cupuaçu**												
Maximum	4.61	10.73	6.00	0.09	1.39	0.60	1.68	9.35	13.77	30.47	94.58	5.39	13.94
Minimum	3.31	6.11	3.90	0.02	0.20	0.05	0.26	4.48	6.89	2.92	52.91	1.68	1.8
Mean	4.00a	8.50b	4.75a	0.06b	0.61d	0.17b	0.78d	5.91b	9.84b	10.76bc	82.00a	2.97b	8.05c
Median	4.05	8.58	4.70	0.06	0.61	0.13	0.78	5.58	9.69	9.25	84.48	2.91	8.24
[1]SD	0.27	0.96	0.40	0.02	0.26	0.14	0.29	1.07	1.57	6.78	10.52	0.75	3.06
Variance	0.07	0.93	0.16	0.00	0.07	0.02	0.08	1.15	2.46	45.91	110.65	0.56	9.35
[2]CV%	6.81	11.35	8.42	29.59	42.91	81.65	36.85	18.17	15.94	63.00	12.83	25.27	37.99
Asymmetry	-0.38	-0.44	0.46	-0.05	0.52	1.70	0.56	1.43	0.40	1.59	-1.39	0.43	-0.49
Curtose	-0.06	0.27	0.61	-0.15	0.04	1.99	0.27	1.45	-0.33	1.97	1.09	0.08	-0.52
[3]K-S	0.10*	0.10*	0.11*	0.15*	0.13*	0.24*	0.11*	0.21*	0.09*	0.20*	0.21*	0.08*	0.13*
Area	**Guaraná**												
Maximum	4.33	15.02	5.70	0.15	1.81	0.38	2.30	7.25	16.18	22.82	93.86	8.83	15.92
Minimum	3.03	5.45	3.10	0.02	0.19	0.05	0.28	3.61	6.62	2.52	63.81	2.19	6.42
Mean	3.90b	10.10a	4.38b	0.06b	0.84c	0.20b	1.12c	5.50c	11.22a	10.16c	79.94a	4.29a	10.35b
Median	3.92	9.82	4.30	0.06	0.86	0.20	1.11	5.48	10.91	9.69	80.11	4.21	10.71
[1]SD	0.25	2.09	0.56	0.03	0.36	0.11	0.43	0.73	2.17	3.95	6.41	1.35	2.20
Variance	0.06	4.35	0.31	0.00	0.13	0.01	0.18	0.53	4.70	15.57	41.06	1.83	4.84
[2]CV%	6.34	20.66	12.73	44.75	43.08	54.92	37.92	13.21	19.33	38.83	8.02	31.49	21.26
Asymmetry	-0.94	0.33	0.11	0.69	0.13	0.06	0.23	-0.01	0.35	0.58	-0.02	0.89	0.18
Curtose	1.37	-0.47	-0.07	0.25	-0.20	-1.33	0.11	0.22	-0.54	0.91	0.08	0.98	-0.28
[3]K-S	0.08*	0.10*	0.08*	0.15*	0.09*	0.13*	0.05*	0.06*	0.10*	0.06*	0.06*	0.09*	0.08*
Area	**Annatto**												
Maximum	4.33	11.71	6.90	0.18	3.36	1.09	3.46	10.14	14.62	31.57	87.35	10.08	14.78
Minimum	3.57	7.09	2.70	0.03	0.57	0.14	1.09	4.43	8.90	10.90	45.33	2.04	3.90
Mean	3.90b	9.37b	4.56b	0.10a	1.73a	0.44a	2.31a	7.08a	11.65a	20.15a	66.77b	6.46a	7.87c
Median	3.90	9.28	4.60	0.10	1.81	0.46	2.40	7.06	11.68	20.46	67.06	6.50	7.90

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Descriptive statistics	**pH**	**H+Al**	**Al^{3+}**	**K^{+}**	**Ca^{2+}**	**Mg^{2+}**	**SB**	**t**	**T**	**V%**	**m%**	**P**	**OC**
	(H_2O)	------------------------------------cmol$_c$kg^{-3}-------------------------------										mg kg^{-1}	g kg^{-1}
[1]SD	0.17	1.07	0.75	0.03	0.52	0.16	0.58	1.16	1.30	4.77	8.53	1.63	2.09
Variance	0.02	1.16	0.57	0.00	0.27	0.02	0.33	1.36	1.70	22.80	72.91	2.68	4.36
[2]CV%	4.41	11.51	16.60	30.21	30.27	37.88	25.11	16.48	11.21	23.70	12.79	25.32	26.56
Asymmetry	0.58	0.01	-0.07	0.46	-0.14	0.69	-0.35	0.29	0.15	0.14	-0.28	-0.08	0.59
Curtose	0.11	-0.60	0.64	-0.23	0.25	1.63	-0.62	0.20	-0.12	-0.37	0.01	0.01	1.13
[3]K-S	0.12*	0.07*	0.09*	0.09*	0.09*	0.07*	0.13*	0.07*	0.08*	0.07*	0.09*	0.08*	0.13*
Area	**Forest**												
Maximum	4.20	11.00	7.40	0.14	2.28	0.55	2.79	9.90	13.09	25.14	93.66	8.79	19.32
Minimum	3.45	7.20	2.80	0.05	0.23	0.06	0.33	4.47	8.30	3.60	55.54	2.43	6.39
Mean	3.84b	8.59b	4.95a	0.08a	1.43b	0.33b	1.84b	6.79b	10.44b	17.55b	72.99b	4.73a	13.66a
Median	3.86	8.50	4.90	0.08	1.48	0.35	1.93	6.84	10.32	18.21	71.65	4.58	13.66
[1]SD	0.17	0.81	0.82	0.02	0.46	0.10	0.55	0.97	0.90	5.08	7.94	1.41	2.65
Variance	0.03	0.66	0.67	0.00	0.22	0.01	0.31	0.94	0.82	25.78	62.97	1.99	7.04
[2]CV%	4.32	9.45	16.58	24.70	32.44	29.92	30.07	14.32	8.66	28.93	10.87	29.86	19.42
Asymmetry	-0.26	0.69	0.12	0.70	-1.31	-1.23	-1.45	0.19	0.59	-1.48	1.08	0.97	-0.20
Curtose	-0.33	0.06	1.32	0.67	1.77	1.84	2.01	0.56	0.93	2.11	1.56	0.69	0.21
[3]K-S	0.06*	0.15*	0.13*	0.11*	0.22*	0.22*	0.22*	0.09*	0.08*	0.21*	0.19*	0.13*	0.11

[1]SD: standard deviation; [2]CV: coefficient of variation; [3]K-S: Kolmogorov-Smirnov normality test. *significant at 5% probability; means followed by same letter do not differ statistically column (Tukey $p < 0.05$)

Regarding the limits of coefficient of variation (CV%), it is possible to emphasize that the coefficient is dimensionless and allow the comparison of values between the different attributes of the soil, the high CV values can be considered as the first indicators of the existence of heterogeneity in the data (Souza et al., 2023).

Adopting the classification proposed by Warrick and Nielsen (1980), which consider the values of the coefficient below 12% as low variability, between 12% and 60% as average variability and values above 60% as high variability. Based on the values of (CV%) found, it was possible to affirm that the chemical attributes presented low to medium variability for most of the attributes studied, with the exception of the Ca^{2+} and SB attributes in the depth 0.00-0.05 m in the forest area and the attributes Mg^{2+} and V% in the depth 0.10-0.20 m in the area with cupuaçu cultivation. which presented values above 60%, being classified as high variability according to the established limits by Warrick and Nielsen (1980).

When analyzing the results of the analysis of variance of the chemical attributes (*Tables 1, 2 and 3*). Tukey's test ($p < 0.05$) was used to analyze the composition of each attribute. When analyzing the pH attribute in all the studied depths, it was possible to observe an extreme acidity condition in all the evaluated areas, such results were already expected since the respective areas never had liming. The lowest pH value was observed at depth 0.00-0.05 m, with a value around 3.63 for forest area and the highest value occurred in the depth 0.10-0.20 m, with pH around 4.00 in the area cultivated with cupuaçu. Little variation of the soil pH was observed due to the high precipitation of the Amazon region that causes leaching of nutrients from the surface layer to the rest of the soil profile (Sales et al., 2022).

Recent studies have shown that low pH is common in soils of southern Amazonia (Mantovanelli et al., 2015; Aquino et al., 2016), the authors found values of pH below 5.00 which characterizes high acidity to the soils of this region. In the work of Lima et al. (2022b), studying the chemical characteristics of the soils of a toposequence under pasture in a pioneer front of the Eastern Amazon highlighted that the main cause of the low pH values in soils of the Amazon region is due to high loss of exchangeable bases and consequent concentration of H^+ ions to the soil, caused by the process of weathering influenced by the high temperatures and long periods of precipitation.

In relation to the potential acidity (H+Al) results, it was observed that in the depth 0.00-0.05 m the forest area presented a significant difference, when compared to the areas cultivated with cupuacu, guaraná and annatto, presenting value in around 12.61 $cmol_c.kg^{-3}$. The values of H+Al in the forest area were higher among the studied environments, probably due to the higher leaching promoted by the intense water regime associated to better drainage conditions (Oliveira et al., 2015a). When analyzing the values of H+Al at depths 0.05-0.10 m and 0.10-0.20 m. it was possible to observe that the area cultivated with guaraná had higher H+Al levels, differing significantly from the other studied areas, the values varied from 10.60 $cmol_c.kg^{-3}$ at the depth 0.05-0.10 to 10.10 $cmol_c.kg^{-3}$ at depth 0.05-0.10 m, this demonstrates that aluminum, with the hydrogen present in the soil at the respective sub-surface depths, are harmful to the production and the culture itself.

When analyzing the results of Al^{3+}, it was noted that at the depths 0.00-0.05 and 0.10-0.20 m. the forest areas under cupuaçu cultivation showed no significant difference between them by Tukey test 0.05% probability, when compared to the areas of guaraná and annatto. At the depth of 0.05-0.10 m, higher values of Al^{3+} were observed in the area under guaraná cultivation, however, the levels of Al^{3+} in forest and cupuaçu areas were also evident at the respective depth. In order to better understand the results, it is important to highlight that the soils of the area were characterized as Argissolo Vermelho Amarelo, it presents highly evolved and weathered classes, as a consequence of the intense action of the formation processes, there are removal of basic exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and residual concentration of acid exchangeable cations, mainly Al^{3+} (Santos et al., 2018). This soil presents acids, with low availability of nutrients and high saturation by Al^{3+}, which may restrict root development, causing negative effects on nutrition and, especially in dry periods, the extremely hard consistency of these soils may undermine the plants support (Jordão et al., 2020). The high acidification observed in the areas of forest and cupuaçu can also be attributed to the entry of organic acids from the leaching of this material, promoting higher soil respiration, nitrification and nitrate losses (Pantoja et al., 2019).

When the values of bases (Ca^{2+}, Mg^{2+} and K^+) were analyzed, it was possible to observe that both were relatively low in all studied depths. Lima et al. (2022b), analyzing the forest to pasture conversion, also found low levels of Ca^{2+}, Mg^{2+} and K^+ in the first layers of soil in cultivated areas. In relation to the contents of K^+ it was observed that the area cultivated with annatto showed a significant difference when compared to areas of cupuacu, guaraná and forest, a fact observed both in the depths 0.00-0.05 m, and 0.10-0.20 m. In the depth of 0.10-0.20 m the results followed the trend of the previous depths, with exception only of the area of forest that along with the culture of the annatto presented higher values in relation to the areas under cultivation of cupuaçu and guaraná. The low levels of K^+ found in the studied soils may be associated with the easy leaching of this element by rainwater (Aquino et al., 2016), as well as by the nutrient characteristic, since it is considered the element with greater soil mobility.

In relation to the attributes Ca^{2+}, Mg^{2+} and SB, they showed that in the three depths evaluated 0.00-0.05 m, 0.05-0.10 m and 0.10-0.20 m, the area cultivated with annatto presented a significant difference by the Tukey test at 0.05% probability level, when compared to the areas of cupuacu, guaraná and forest. It is important to note that the values of Ca^{2+} in the area of annatto showed a slight tendency to increase in depth. Probably the high values of calcium can be related to the little time of cultivation in the area, since it presents only three years of cultivation, being originated from the process of burning of the forest area.

Work by Lima et al. (2022b) observed a significant increase in Ca^{2+} and Mg^{2+} levels under different uses (different types of pasture) in relation to the native area. It is important give attention to such results, in view that the Ca^{2+} and Mg^{2+} have an antagonistic effect, the excess of one impairs the absorption of other (Enck et al., 2022). The lower Ca^{2+} levels and Mg^{2+} were observed in the forest area, such results can be explained due to the leaching caused by precipitation of the region, such fact can also relates to the forest area presents a large vegetation, which have the capability to extract large nutrients quantities, such conditions explain the low Mg^{2+} values in relation to other areas studied with Amazon species, as well as the higher concentration of H+Al, because when exporting cations from the soil, the plants release H^+, predominantly (Lima et al., 2021).

As for the results of the effective CEC (t), it was possible to observe that in the depth 0.00-0.05 m the highest values occurred in the cultivated areas with cupuaçu with 6.98 $cmol_c.kg^{-3}$. guaraná 6.38 $cmol_c.kg^{-3}$ and annatto 6.93 $cmol_c.kg^{-3}$, both presented a significant difference when compared to the native forest area with 6.14 $cmol_c.kg^{-3}$. At depths characterized as subsurface (0.05-0.10 m and 0.10-0.20 m) the results were more restrictive, so that the highest values were observed in the area of annatto with 7.08 $cmol_c.kg^{-3}$.

Regarding the results related to CEC (T), observed that at the most superficial depth of 0.00-0.05 m, the area cultivated with cupuaçu showed a value of 14.30 $cmol_c.kg^{-3}$, presenting a significant difference when compared to the areas of guarana, urucum and forest. At depths 0.05-0.10 m and 0.10-0.20 m, the results showed that the areas of guaraná and annatto did not show any significant difference between them. It is important to emphasize that CEC is an indicator of retention of positive charges important for plant nutrition and. Therefore, presents a relation directly proportional to the exchange of basic cations, being considered an important characteristic to the decision making in relation to the method adopted (Martins et al., 2015).

When analyzing the results referring to base saturation (V%), it was observed that the area cultivated with annatto presented higher values of (V%) for all depths evaluated, with values ranging from 20.15% to 20.93%, results that indicated a significant difference in relation to the other areas studied. Probably the low levels of Ca^{2+}, Mg^{2+} and K^{+} were responsible for low base saturation (V) of the soil exchange complex. Similar results were found by Fonseca et al. (2021) in soils of a topossequence in the southeast of the state of Amazonas.

When the aluminum saturation (m%) values were analyzed. it was observed that the native forest area presented higher values, both in the depth 0.00-0.05 m and 0.05-0.10 m. For the depth 0.10-0.20 m the highest values were evidenced in the area cultivated with guarana, Moreira and Fageria (2009) reported that the soils of the state of Amazonas present, on average, 76% of aluminum saturation, high or very high, being attributed this fact, to the advanced stage of weathering of the soils of this region. In the present study the values found ranged from 62.76% to 92.54%, this only confirms the reports of the authors mentioned above.

After analysis of the P levels, it was observed that the highest values were found under native forest, a fact diagnosed in all depths studied, for the first depths 0.00-0.05 and 0.05-0.10 m, the forest area presented significant difference in relation to the areas cultivated with Amazonian species. In the depth of 0.10-0.20 m the forest area also presented higher values of P, but without presenting significant difference when compared to the areas of guaraná and annatto. The higher levels of P in the forest area in relation to the other plant formations can be explained by high levels of organic C, that is, this higher content of organic matter reduces the adsorption of P by the action of organic acids resulting from the decomposition of organic residues, root exudation and microbial synthesis, which form complexes with Fe and Al and/or are adsorbed to the surface of oxides, by exchange of ligands and consequently, block the adsorption of P thus increasing their availability (Giácomo et al., 2015). Similar results were found by Oliveira et al. (2015b), who found levels of P high for the Amazonian standards, with values around 6.09 $cmol_ckg^{-3}$ in native forest areas.

When analyzing the OC contents, it was possible to observe that there were significant differences among all the analyzed areas, with higher values found in the area under cupuaçu cultivation in the depths 0.00-0.05 m and 0.05-0.10 m, with except for the depth of 0.10-0.20 m, which the forest area presented higher value. The high values of OC in the cupuaçu area may be associated with the high vegetation cover provided by the crop residues, which can also be attributed to the 7 years of cultivation with the crop without undergoing intensive soil practices. Current studies point out that the opening of new areas in the Amazon for agriculture implies a significant reduction of the organic matter content deposited in the superficial layers (Paula et al., 2023), which results in negative changes in the availability of nutrients, which together with the improper soil management, decreases the productivity of crops in general.

In the multivariate analysis, we observed the chemical attributes of the soil that suffered the greatest change after the process of forest conversion to cultivated areas with Amazonian species. After analysis, it was evident that the chemical attributes presented different behavior for each analyzed depth (*Table 4* and *Figure 2A, B and C*). The adequacy of the factorial analysis was significant at depth 0.00-0.05 m with (KMO equal to 0.81), 0.05-0.10 m (KMO equal to 0.78) and at depth 0.10 to 0.20 m the (KMO was equal to 0.65), both with $p < 0.05$ for the Bartlett sphericity test, this test suggests that the evaluated data attributes are suitable for factor analysis (*Table 4*). The Kaiser-Meyer-Olkin (KMO) measure assesses the adequacy of the factorial analysis. The KMO index values that indicate that factor analysis is adequate vary from author to author. However, the minimum of 0.5 is used as an acceptable limit by the authors. Studies developed by Brito et al. (2022), confirm that values between 0.5 and 1.0 are acceptable, they observed that values below 0.5 indicate that the factorial analysis is unacceptable.

In the Principal Components Analysis (PCA), with the variables of higher scores, two principal components were extracted, which generally explained the total variability of the data for the three depths studied: 0.00-0.05; 0.05-0.10 and 0.10-0.20. The number of extracted factors was established in order to explain above 60% of the total data variance (*Table 4* and *Figure 2A, B and C*). It is important to say that the PCA focus on explaining the variance and covariance structure of a random vector by means of linear combinations of the original variables. In general, what is desired is to obtain a reduction in the number of variables and interpretation of the linear combinations obtained, aiming to explain most of the variability in the original data (Pantoja et al., 2019).

According to Lima et al. (2022a), only variables with eigenvalues above 1 were considered, since they are those that generate components with relevant amount of information of the original variables. Based on this, the depth 0.00-0.05 m showed eigenvalues of the covariance matrix of 4.28 at PC1 and 2.45 at PC2, at depth 0.05-0.10 m the eigenvalues of the matrix were 4.30 at PC1 and 1.54 at PC2, at the most subsurface depth of 0.10-0.20 m the values were 4.03 at PC1 and 1.95 at PC2 (*Table 4*).

In detail, after analysis, it was possible to observe that the principal component 1 related to the depth 0.00-0.05 m explained 54.64% of the total data variability, this component presented percentage of explanation for attributes more oriented the conditions of exchangeable bases and percentage of soil saturation, such as: Ca^{2+}, Mg^{2+}, SB, V% and m%. Through the results it was observed that the attributes Ca^{2+}, Mg^{2+}, SB, V% correlated positively with each other, and negatively with aluminum saturation (m%) (*Table 4*). The inverse correlation between attributes in relation to aluminum saturation indicates that the higher the aluminum saturation in the soil the lower the Ca and Mg contents, and consequently, lower the exchangeable bases of the soil (Lima et al., 2022b). The second principal component presented a percentage of explanation of 29.66% of the data variability, with characteristics more related to conditions of soil acidification and relevant organic concentrations, such as H+Al, T and OC, both of which attributes presented positive correlation (*Table 4*), similar results were observed by Jordão et al. (2020). Overall, the two principal components at depth 0.00-0.05 m retained a percentage of the explained variance of 80.30% (*Table 4* and *Figure 2A. B and C*).

Table 4. *Correlation between each principal component (PC) of the analyzed variables of soil chemical attributes in the three studied depths corresponding to the areas under forest conversion in cultivated areas in the South of Amazonas - AM*

Depth 0.00-0.05 m			
Attributes	Common Variance	Factors	
		PC1	PC2
H^++Al^{3+}	0.88	-0.14	0.93 *
Ca^{2+}	0.86	0.91 *	0.09
Mg^{2+}	0.73	0.85 *	-0.11
SB	0.93	0.97 *	0.03
T	0.88	0.17	0.94 *
V%	0.86	0.90 *	-0.29
m%	0.83	-0.94 *	0.05
OC	0.37	-0.17	0.75 *
	Eigenvalue	4.28	2.45
	Explained variance (%)	**54.64**	**29.66**
Depth 0.05-0.10 m			
Attributes	Common Variance	Factors	
		PC1	PC2
H^++Al^{3+}	0.25	-0.03	0.62 *
Ca^{2+}	0.92	0.94 *	-0.05
Mg^{2+}	0.69	0.83 *	0.21
SB	0.95	0.97 *	0.01
V%	0.90	0.94 *	-0.18
m%	0.85	-0.93 *	0.09
P	0.12	0.04	0.71 *
OC	0.16	0.05	-0.74 *
	Eigenvalue	4.30	1.54
	Explained variance (%)	**53.90**	**19.20**
Depth 0.10-0.20 m			
Attributes	Common Variance	Factors	
		PC1	PC2
H^++Al^{3+}	0.87	0.06	0.95 *
Al^{3+}	0.46	-0.05	0.35 *
Ca^{2+}	0.96	-0.90 *	-0.04
Mg^{2+}	0.69	-0.79 *	0.09
SB	0.97	-0.91 *	-0.01
T	0.88	-0.28	0.92 *
V%	0.90	-0.91 *	-0.21
m%	0.90	0.90 *	0.06
	Eigenvalue	4.03	1.95
	Explained variance (%)	**24.42**	**50.41**

(H+Al): potential acidity; (Al^{3+}): exchangeable aluminum; (K^+): potassium; (Ca^{2+}): calcium; (Mg^{2+}): magnesium; (SB): sum of bases; (t): effective CEC; (T): potential CEC; (V%): base saturation; (m%): aluminum saturation; (P): phosphorus

When verifying the components referring to depth 0.05-0.10 m, it was observed that they behaved similarly to the previous depth, so that the first component showed percentage of explanation for attributes more focused on the exchangeable base conditions and percentage of saturation present in the soil, which explained 53.90% of the total variability of the data. Among the attributes Ca^{2+}, Mg^{2+}, SB, V% and m%, only the attribute related to aluminum saturation (m%) correlated negatively, evidence also observed in the previous depth. The second component had a percentage of explanation of 19.20% of the data variability, as well as the previous depth, presented a trend towards the soil acidification characteristic and relevant organic concentrations, however in this present condition the attributes H+Al and P correlated positively and OC negatively to the respective component. For this depth, the two principal components had a percentage of variance explained around 73.10% (*Table 4* and *Figure 2A, B and C*).

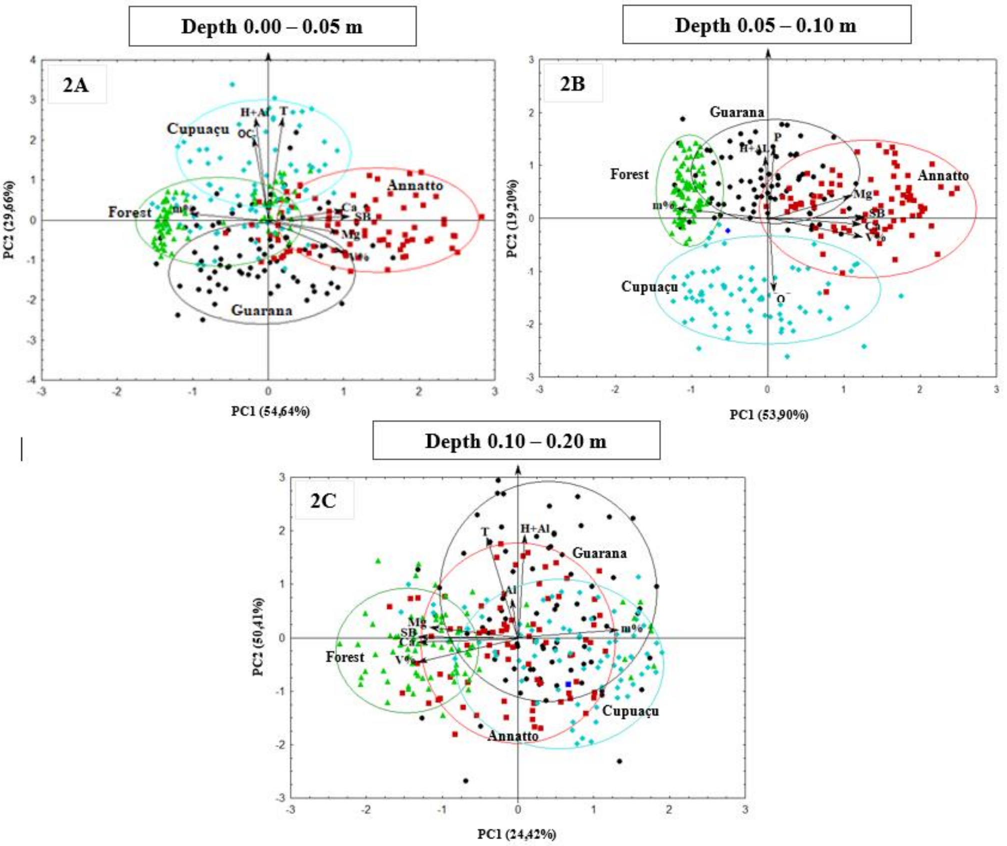

Figure 2. *Principal components analysis of soil chemical attributes in the three studied depths corresponding to areas under forest conversion in cultivated areas in Southern Amazonas-AM*

When analyzing the components at depth 0.10-0.20 m, it was possible to observe that, as in the previous depths, the explanatory potential turned to the conditions of exchangeable bases and percentage of saturation present in the soil, the difference was in the inverse correlation of attributes compared to the depths previously analyzed, as Ca^{2+}, Mg^{2+}, SB and V% presented negative correlation and aluminum saturation (m%), positive correlation. In the present situation PC1 presented a percentage of the data variability of 24.42%. When analyzing the second component, it was observed that it had a percentage of explanation of 50.41%, with an evident characteristic of soil acidification, where in this depth the attributes H+Al, Al^{3+} and T correlated positively. Overall, both principal components at this depth presented a percentage of variance explained of 74.83% (*Table 4* and *Figure 2A, B and C*).

In *Figure 2*, the analyzes of principal components are represented by the distribution of the scores of the different areas studied and the arrangement of the factorial loads of the soil chemical attributes formed by the PC1 and PC2. Based on the results, when analyzing the depth of 0.00 to 0.05 m, it was possible to observe greater densification of the annatto area scores in the first and fourth quadrant, which discriminates that the respective area obtained values of the attributes Ca^{2+}, Mg^{2+}, SB and V%, above the mean (*Figure 2A*). On the other hand, the area cultivated with cupuaçu was more distributed in the second and third quadrant, with the attributes H+Al, T and OC presenting values above the average for the respective attributes (*Figure 2A*).

Based on the results, it was also possible to identify that the higher density of the forest area was concentrated in the second and third quadrant, with aluminum saturation (m%) values above average. In the forest, low levels of nutrients can be explained in part by the fact that in this environment a large part of the nutrients are allocated to the vegetation, besides the chemical poverty of the Argissolos and their high degree of weathering in the environment (Sales et al., 2022). In the general interpretation of the principal components, it was observed that the highest densification of the guaraná scores occurred respectively in the third and fourth quadrant, presenting below-average values for the attributes Ca^{2+}, Mg^{2+}, SB, V%, m%, H+Al, T and OC. Such results in the area of guarana already evidences a high degree of chemical degradation in the superficial depth promoted by the process of forest conversion in cultivated area. Probably a large part of the CEC is occupied by potentially toxic cations such as H^+ and Al^{3+}, which makes it easy to characterize the soil of this area as poor.

When analyzing the results related to depth 0.05-0.10 m, it was observed a greater densification of the annatto area scores in the first quadrant, which discriminates that the present area obtained values of Ca^{2+}, Mg^{2+}, SB and V% above the mean (*Figure 2B*). It is important to note that, when checking the behavior of the forest and guaraná areas, the results showed that the highest concentrations of the scores occurred in the first and second quadrant for the guaraná area and in the second quadrant for the forest area. The guaraná area showed values of the H+Al and P above the average, and the area of forest discriminated values above the average for aluminum saturation (m%). When the area of cupuaçu was analyzed, it was identified a higher densification of the scores in the third and fourth quadrant, presenting value above the average for the OC attribute (*Figure 2B*).

When the principal components were analyzed at depth 0.10-0.20 m, a marked dispersion of the scales of the areas cultivated with guarana, annatto and cupuaçu between the first and fourth quadrant was observed, which discriminates that both areas obtained values attribute H+Al, T and Al^{3+}, above average (*Figure 2C*). When analyzing the forest area, it was possible to observe densification of the scores concentrated in the second and third quadrant, identifying the opposite condition of the one observed in the first two depths. so that in this situation the forest area presented values above average for the attributes Mg^{2+} and SB and below average for the attributes V% and Ca^{2+}. Probably the low organic matter content and the low clay fraction activity at this depth favored a high loss of basic cations by leaching, causing the accumulation of acidic cations (Al^{+3} and H^+) in the soil (Enck et al., 2022).

Conclusions

The chemical attributes OC, H+Al, Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, SB, T, V%, m% and P suffered major changes and degradations after the conversion of forest to cultivated area.

Changes in chemical attributes were more evident in the superficial layers (0.00-0.05 m and 0.05-0.10 m).

The process of converting the forest area into agricultural areas resulted in a significant reduction of the OC attribute in the superficial layers, with the exception of the area cultivated with cupuaçu in the 0.00-0.05 m layer.

Competing interests. The authors declare that they have no conflict of interests.

REFERENCES

[1] Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. M., Sparovek, G. (2013): Köppen's climate classification map for Brazil. – Meteorologische Zeitschrift 22(6): 711-728.

[2] Aquino, R. E., Campos, M. C. C., Soares, M. D., Oliveira, I. A., Franciscon, U., Silva, D., Cunha, J. (2016): Chemical soil attributes evaluated by multivariate techniques and geostatistics in the area with agroforestry and sugarcane in Humaitá, AM. Brazil. – Bioscience Journal 32: 61-72. https://doi:10.14393/bj-v32n1a2016-29421.

[3] Brito, W. B. M., Campos, M. C. C., Souza, F. G., Silva, L. S., Cunha, J. M., Lima, A. F. L., Martins, T. S., Oliveira, F. P., Oliveira, I. A. (2022): Spatial patterns of magnetic susceptibility optimized by anisotropic correction in different Alisols in southern Amazonas, Brazil. – Precision Agriculture 22: 1-18. https://doi.org/10.1007/s11119-021-09843-6.

[4] Campos, M. C. C., Ribeiro, M. R., Souza Júnior, V. S., Ribeiro Filho, M. R., Almeida, M. C. (2012): Topossequência de solos na transição campos naturais-floresta na região de Humaitá, Amazonas. – Acta Amaz 42(03): 387-398. https://doi.org/10.1590/S0044-59672012000300011.

[5] Enck, B. F., Campos, M. C. C., Pereira, M. G., Souza, F. G., Santos, O. A. Q., Diniz, Y. V. F. G., Martins, T. S., Cunha, J. M., Lima, A. F. L., Souza, T. A. S. (2022): Forest-fruticulture conversion alters soil traits and soil organic matter compartments. – Plants 11: 2917-2930. https://doi.org/10.3390/plants11212917.

[6] Fonseca, J. S., Campos, M. C. C., Brito Filho, E. G., Mantovanelli, B. C., Silva, L. S., Lima, A. F. L., Cunha, J. M., Simões, E. L., Santos, L. A. C. (2021): Soil-landscape relationship in a sandstone-gneiss topolithosequence in the State of Amazonas, Brazil. – Environmental Earth Sciences 80: 713-728. https://doi.org/10.1007/s12665-021-10026-9.

[7] Giácomo, R., Pereira, M. G., Guareschi, R., Machado, D. (2015): Atributos químicos e físicos do solo, estoques de carbono e nitrogênio e frações húmicas em diferentes formações vegetais. – Ciência Florestal 25: 617-631. https://doi:10.5902/1980509819613.

[8] IUSS Working Group WRB. (2022): World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. – 4th edition. International Union of Soil Sciences (IUSS), Vienna. Austria.

[9] Jordão, H. W. C., Campos, M. C. C., Cunha, J. M., Oliveira, I. A., Silva, L. S., Brito Filho, E. G., Mantovanelli, B. C., Freitas, L., Gomes, R. P. (2020): Fractal features of soil texture and physical attributes in Indian Dark Earth under different uses in western Amazon. – Bioscience Journal 36: 1961-1974. https://doi.org/10.14393/BJ-v36n6a2020-47894.

[10] Lima, A. F. L., Campos, M. C. C., Martins, T. S., Brito Filho, E. G., Cunha, J. M., Souza, F. G., Santos, E. A. N. (2021): Soil attributes and root distribution in areas under forest conversion to cultivated environments in south Amazonas, Brazil. – Bragantia 80: 1-17. https://doi.org/10.1590/1678-4499.20210106.

[11] Lima, A. F. L., Campos, M. C. C., Enck, B. F., Simões, W. S., Araújo, R. M., Santos, L. A. C., Cunha, J. M. (2022a): Physical soil attributes in areas under forest/pasture conversion in northern Rondônia, Brazil. – Environmental Monitoring and Assessment 194: 34-43. https://doi.org/10.1007/s10661-021-09682-y.

[12] Lima, A. F. L., Campos, M. C. C., Martins, T. S., Silva, G. A., Brito, W. B. M., Santos, L. A. C., Oliveira, I. A., Cunha, J. M. (2022b): Soil chemical attributes in areas under conversion from forest to pasture in southern Brazilian Amazon. – Scientific Reports 12: 2255. https://doi.org/10.1038/s41598-022-25406-9.

[13] Mantovanelli, B., Silva, D., Campos, M. C. C., Gomes, R., Soares, M. D., Santos, L. A. C. (2015): Avaliação dos atributos do solo sob diferentes usos na região de Humaitá, Amazonas. – Revista de Ciências Agrárias 58: 122-130. https://doi:10.4322/rca.1822.

[14] Martins, E., Peluzio, J., Oliveira Junior, W., Tsai, S., Navarrete, A., Morais, P. (2015): Alterações dos atributos físico-químicos da camada superficial do solo em resposta à agricultura com soja na várzea do Tocantins. – Biota Amazônica 5: 56-62. https://doi:10.18561/2179-5746/biotaamazonia.v5n4p56-62.

[15] Melo, V., Orrutéa, A., Motta, A., Testoni, S. (2017): Land use and changes in soil morphology and physical-chemical properties in southern Amazon. – Revista Brasileira Ciência do Solo 41: 1-14. https://doi:10.1590/18069657rbcs20170034.

[16] Moreira, A., Fageria, N. (2009): Soil chemical attributes of Amazonas state. Brazil. – Communication in Soil Science and Plant Analysis 40: 2912-2925. https://doi:10.1080/00103620903175371.

[17] Oliveira, I., Campos, M. C. C., Freitas, L., Soares, M. (2015a): Caracterização de solos sob diferentes usos na região sul do Amazonas. – Acta Amazônica 45: 1-12. https://doi:10.1590/1809-4392201400555.

[18] Oliveira, I., Marques Junior, J., Campos, M. C. C., Aquino, R. E., Freitas, L., Siqueira, D. S., Cunha, J. M. (2015b): Variabilidade espacial e densidade amostral da suscetibilidade magnética e dos atributos de Argissolos da região de Manicoré, AM. – Revista Brasileira de Ciência do Solo 39: 668-681. https://doi:10.1590/01000683rbcs20140496.

[19] Owuor, S., Butterbach-Bahl, K., Guzha, A., Jacobs, S., Merbold, L., Rufino, M., Breuer, L. (2018): Conversion of natural forest results in a significant degradation of soil hydraulic properties in the highlands of Kenya. – Soil and Tillage Research 176: 36-44. https://doi:10.1016/j.still.2017.10.003.

[20] Pantoja, J. C. M., Campos, M. C. C., Lima, A. F. L., Cunha, J. M., Simões, E. L., Oliveira, I. A., Silva, L. S. (2019): Multivariate analysis in the evaluation of soil attributes in areas under different uses in the region of Humaitá, AM. – Revista Ambiente e Agua 14: 1-16. https://doi.org/10.4136/ambi-agua.2342.

[21] Paula, E. M. B., Cunha, J. M., Campos, M. C. C., Silva, D. M. P., Silva, C. L., Lima, A. F. L., Mantovanelli, B. C. (2023): Accumulation and decomposition of cultural residues of Theobroma grandiflorum, Paullinia cupana, Bixa orellana and forest in the southern region of Amazonas. – Brazilian Journal of Biology 83: 1-9. https://doi.org/10.1590/1519-6984.264237.

[22] Reichert, J., Rodrigues, M., Bervald, C., Kato, O. (2016): Fire-free fallow management by mechanized chopping of biomass for sustainable agriculture in eastern Amazon: effects on soil compactness. Porosity, and water retention and availability. – Land Degradation and Development 27: 1403-1412. https://doi:10.1002/ldr.2395.

[23] Sales, M. C. G., Brito Filho, E. G., Campos, M. C. C., Relvas, C. H. G., Santos, L. A. C., Gomes, M. M., Cunha, J. M., Oliveira, F. P., Almeida, R. G. (2022): Seasonality, soil attributes and root biomass in cerrado, cerradão and forest environments, Western Amazon. – Bioscience Journal 38: 1-15. https://doi.org/10.14393/BJ-v38n0a2022-53707.

[24] Santos, H., Jacomine, P., Anjos, L., Oliveira, V., Lumbreras, J., Coelho, M., Almeida, J. (2018): Sistema Brasileiro de Classificação de Solos. – 5th ed., rev. e ampl., Embrapa, Brasília.

[25] Soares, M., Campos, M. C. C., Cunha, J. M., Mantovanelli, B. C., Oliveira, I. A., Brito Filho, E. G., Leite, A. L. F. (2018): Variabilidade espacial da estabilidade dos agregados e matéria orgânica do solo em terra preta arqueológica sob pastagem. – Gaia Scientia 12: 125-133. https://doi:10.22478/ufpb.1981-1268.2018v12n2.34416.

[26] Souza, F. G., Campos, M. C. C., Oliveira, E. S., Lima, A. F. L., Pinheiro, E. N., Cunha, J. M., Martins, T. S., Silva, D. M. P., Oliveira, F. P. (2023): Impacts of native forest conversion on soil erodibility in areas of Amazonic species cultivation. – Applied Ecology and Environmental Research 21: 21-39. https://doi.org/10.15666/aeer/2101_021039.

[27] SPSS Inc (2001): Statistical Analysis Using SPSS. – Chicago.

[28] Teixeira, P., Donagema, G., Ademir, F., Teixeira, W. (2017): Manual de métodos de análise de solo. – 3rd ed., revisada e ampliada. Embrapa Brasília, 573p.

[29] Warrick, A., Nielsen, D. (1980): Spatial variability of soil physical properties in the field. – In: Hillel, D. (ed.) Applications of soil physics. New York, 344p.

[30] Yeomans, J., Bremner, J. (1988): A rapid and precise method for routine determination of organic carbon in soil. – Communication in Soil Science and Plant Analysis 19: 1467-1476. https://doi:10.1080/00103628809368027.