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Soil attributes and root distribution in areas under forest conversion to cultivated environments in south Amazonas, Brazil

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ABSTRACT: The objective of this work was to evaluate soil attributes and root distribution in areas under forest conversion to cultivated environments. The study was carried out in four areas: forest, cupuaçu, guarana and annatto, located in the municipality of Canutama, state of Amazonas. Soils and volumetric rings were collected in the layers 0.00 – 0.10; 0.10 – 0.20; 0.20 – 0.30; 0.30 – 0.40; and 0.40 – 0.50 m for analyses of physical and chemical attributes and root distribution. Univariate statistical analyses were carried out, the means were compared with the Tukey's test ($p < 0.05$) and Pearson's correlation ($p < 0.05$ and < 0.01). The forest area and the cultivated environments present soil chemical limitations for agricultural production, whereas the physical attributes presented satisfactory values. The chemical attributes underwent major changes and degradations upon conversion to agriculture. Major changes were observed in the layers of 0.00 – 0.10 and 0.10 – 0.20 m for the studied areas. Cupuaçu cultivation showed higher values of roots dry weight (RDW) and roots distribution (RD), with the highest values found in the 0.00 – 0.10 and 0.10 – 0.20 m layers.

Key words: Amazonian soils, management, effective roots.

INTRODUCTION

The cupuaçu (*Theobroma grandiflorum* [Willd. ex. Spreng] Schum), guarana (*Paullinia cupana* [Mart.] Ducke) and annatto (*Bixa orellana* L.) are plants of Amazonian origin, which have economic, social and cultural importance for the region. They are adapted to deep acid soils with high levels of aluminium and low fertility, and have a pivoting root system, characterized as deep, showing a main axis from which secondary and tertiary roots emerge (Franco et al. 2008).

Currently, the occupation and replacement of forested areas in agricultural areas without proper knowledge and nonobservance of technical criteria has been one of the main problems in the Amazon region. The conversion of natural habitats to agricultural systems, especially monoculture systems, has provoked changes in soil properties and, in most cases, cause adverse environmental impact (Freitas et al. 2015).

According to Moline and Coutinho (2015), opening up new areas in the Amazon for agriculture implies a significant reduction in the organic matter (OM) content deposited on the surface layer, causing negative changes in nutrient availability, which, associated with improper handling of the areas to which they are inserted, decrease crop productivity over time. Magalhães et al. (2013) verified a reduction in the nutrient stock in crop (teak, agroforestry with teak, agroforestry with teak and cocoa, agroforestry with teak cocoa and pasture, extensive pasture) areas in relation to the native forest in Rondônia.

Araújo et al. (2011), analyzing the forest-to-pasture conversion, also found low levels of Ca, Mg, K and P in the first layers of the soil in cultivated areas.

Oliveira et al. (2015) state that soil physical attributes are changed due to the handling to which they are subjected, and this may be exacerbated by the constant use of conventional tillage equipment. In addition, different management and land use practices can cause changes in soil water movement, soil resistance to penetration (SRP), porosity and aggregate classes, serving as soil structure indicators (Sales et al. 2016). A compacted soil does not provide conditions for the growth of the root system, interfering with the absorption of water and nutrients by the root and, consequently, in the production of the crop.

Given that the conversion processes often cause negative changes in soil properties, there is currently a lack of studies that evaluate which attributes undergo major changes and that suggest management practices to reduce soil degradation. Therefore, the objective of this work is to evaluate soil attributes and root distribution under forest conversion to cultivated environments in the municipality of Canutama, state of Amazonas.

METHODS

The study was conducted in the São Francisco settlement located in the municipality of Canutama, Amazonas, Brazil, under the geographical coordinates 8°11'22" S, 64°00'83" W (Fig. 1), in 2017, in four areas: secondary forest, cupuaçu (*Theobroma grandiflorum* [Willd. ex. Spreng] Schum), guarana (*Paullinia cupana* [Mart.] Ducke) and annatto (*Bixa orellana* L.).

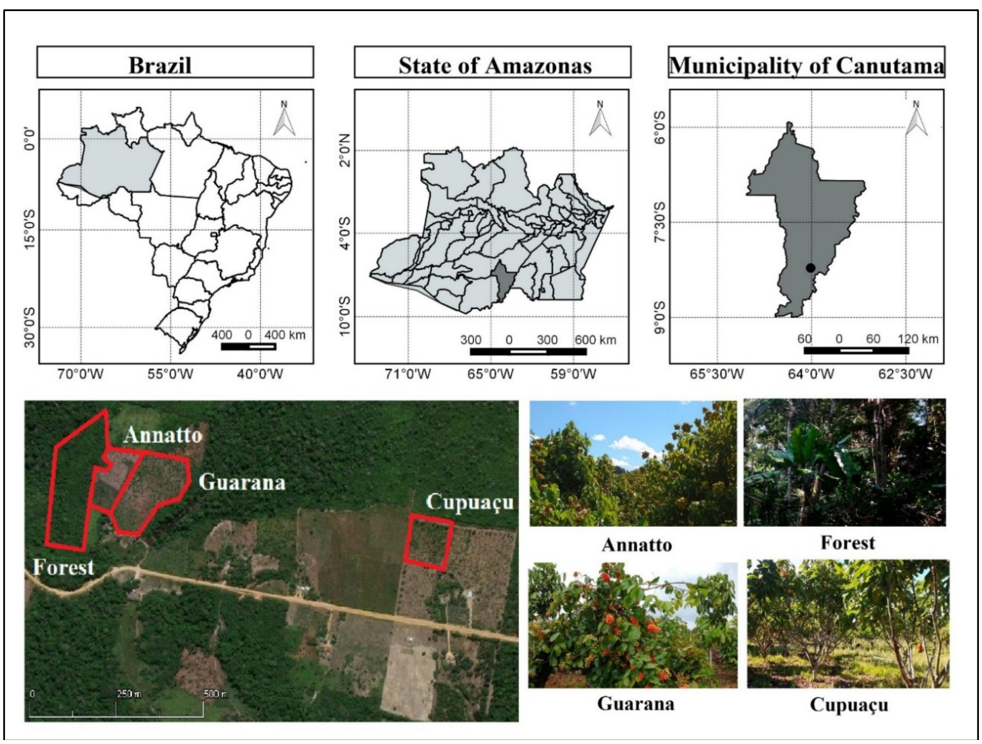

Figure 1. Location map of the areas studied in the southern region of Amazonas.

The common vegetation of this region is dense tropical forest, consisting of densified and multi-layered trees between 20 and 50 m tall. According to Campos et al. (2012), the predominant landscapes of this region consist of natural fields, natural fields/forests and forests.

The soil of the study area is classified as a red-yellow argisol located on the Amazonian plain between the Purus and Madeira rivers. The soil is associated with recent and ancient alluvial sediments from the quaternary period, characterized by the presence of large tabular reliefs, soils of low depth, relief with very smooth slopes, and a deficient natural drainage (Embrapa 1997).

In the field, four areas were selected to be investigated, being formed by secondary forest, cupuaçu, guarana and annatto. In each area, four plants were selected at random to compose the repetitions. In these plants, trenches were made at a distance of 0.5 m from the stem, for collecting soil samples and monoliths for sampling the roots, at depths of 0.00 – 0.10, 0.10 – 0.20, 0.20 – 0.30, 0.30 – 0.40 and 0.40 – 0.50 m, totaling 20 samples per area and a total of 80 samples.

The selected forest area for this study has 4.50 ha and is characterized as a secondary forest, where the natural vegetation was deforested in 1994, but it was not used for agriculture, allowing an ecological succession, reaching its current stage as a secondary forest. Fire was used to clean the area, and then agricultural crops were planted. Fertilization and liming were not used in the area during the whole growing period. The cultivation area with cupuaçu occupies 1.56 ha, is 7 years old, with a spacing of 5 × 4 m, and with yields of 500 $kg \cdot ha^{-1} \cdot year^{-1}$ pulp. The area in cultivation with guarana occupies 2.25 ha, is 7 years old, with a spacing of 5 × 5 m, and with yields of 420 $kg \cdot ha^{-1} \cdot year^{-1}$ of dry seed. The area of cultivation with annatto occupies 1.80 ha, is 3 years old, with a spacing of 5 × 4 m, and with yields of 642 $kg \cdot ha^{-1}$ of seeds.

Samples with a preserved structure and volumetric rings of 4.0 cm height and 5.1 cm of internal diameter were collected in each trench of the four areas, in the 0 – 0.10, 0.10 – 0.20, 0.20 – 0.30, 0.30 – 0.40 and 0.40 – 0.50 m layers, for the determination of the chemical and physical properties of the soil and root distribution.

In each trench, monoliths (soil blocks) were used for the sampling of roots, according to Böhm (1979) and Schuurman and Goedewaagen (1971). They had dimensions of 20 cm of width, 10 cm of length and 10 cm of height, in the layers 0 – 0.10, 0.10 – 0.20, 0.20 – 0.30, 0.30 – 0.40 and 0.40 – 0.50 m. The roots were separated by washing under running water through 2 mm mesh sieves and forceps. After separation of the effective roots (< 1.0 mm), they were taken to the circulation oven for 72 h to obtain the dry mass in grams to calculate the roots dry weight (RDW) in $g \cdot dm^{-3}$ and roots distribution (RD).

The formula in Eq. 1 was used to calculate RDW:

$$RDW = \frac{DW}{VM} \tag{1}$$

where RDW = root dry weight in $g \cdot dm^{-3}$, DW = dry weight of the root in g after 72 h in the circulation oven and VM = the volume of the collected monolith in dm^{-3}.

The formula in Eq. 2 was used to calculate RD:

$$RD = \frac{RDW}{\sum RDW} \times 100 \tag{2}$$

where RD = root distribution in %, RDW = root dry weight in $g \cdot dm^{-3}$ and ΣRDW = sum of the dry weight of the roots of the other layers in $g \cdot dm^{-3}$.

The soil was submitted to the shade drying process and sieved in a 2 mm mesh, characterizing an air-dried soil. Chemical analyses were performed according to the methodology proposed by Teixeira et al. (2017) for pH in water, potential acidity ($H^+ + Al^{3+}$), exchangeable aluminum (Al^{3+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), resin phosphorus (Pr), potassium (K) (Teixeira et al. 2017), and organic carbon wet path by the Walkley–Black method, modified by Yeomans and Bremner (1988), OM was determined by the product of organic carbon (OC) by factor 1.724 (Teixeira et al. 2017). Based on the quantified attributes, the following were calculated: cation exchange capacity effective (t) and potential (T); sum of bases (SB), base saturation (V) and aluminum saturation (m).

The carbon stock (CS) was defined by the Eq. 3:

$$CS = Sd \text{ x } h \text{ x } OC \tag{3}$$

where CS = carbon stock ($t \cdot ha^{-1}$), Sd = soil density ($g \cdot cm^{-3}$), h = corresponds to the depth at which the samples were collected (10 cm) and OC = organic carbon content ($g \cdot kg^{-1}$).

The soil samples collected in the form of a clod were shade dried and manually discharged in a set of sieves (9.51, 4.76 and 2.00-mm diameter). After this, physical analyses were performed, according to methodology proposed by Teixeira et al. (2017) including aggregate stability, geometric average diameter (GAD), weighted average diameter (WAD), aggregate classes > 2 mm, 1–2 mm, < 1 mm and aggregate stability index (ASI) with soil that was retained in the 4.76 mm mesh. With soil that passed the sieve of 2 mm granulometric analysis of sand, silt and clay were performed. The following analyses were performed with the volumetric rings: SRP, Sd, total porosity (TP), microporosity (MiP), macroporosity (MaP) and volumetric humidity (VH).

After obtaining the data on chemical and physical attributes and on RD, descriptive statistics analyses were performed, and the mean and coefficient of variation were calculated.

Analysis of variance was performed to verify if there is a difference between the areas studied. To determine which area is different from the other and to compare the means of the attributes, Tukey's test was performed at 5% probability, using the SPSS 21 software (SPSS Inc. 2001).

RESULTS AND DISCUSSION

Low pH values are common in soils of the southern Amazon region, as observed by Campos et al. (2012) and by Mantovanelli et al. (2015), who found pH values below 5.00 (Table 1). The pH increased in depth for all studied areas (Fig. 2). The lowest pH of the 0.00–0.10 m layer was attributed to the production of organic and inorganic acids, such as H_2SO_4 and HNO_3, and to the decomposition of OM (Galdos et al. 2004), in addition, through the removal of bases by cultures and leaching of the bases in the superficial layers due to high precipitation in the Amazon region (Silva Neto et al. 2019).

Table 1. Mean and coefficient of variation of the chemical attributes in areas under conversion from forest to cultivated environments in the municipality of Canutama, Amazonas, 2017.

AREA		Layer 0.00 – 0.10 m				
		Forest	Cupuaçu	Guarana	Annatto	CV
pH	H_2O	3.74a	3.86a	3.45a	3.64a	6.72
H + Al	$cmol_c{\cdot}kg^{-1}$	12.33a	13.86a	12.83a	11.55a	15.03
Al^{3+}	$cmol_c{\cdot}kg^{-1}$	4.28a	5.40a	4.85a	3.85a	21.78
K^+	$cmol_c{\cdot}kg^{-1}$	0.14a	0.08b	0.14ab	0.16a	30.81
Ca^{2+}	$cmol_c{\cdot}kg^{-1}$	0.52c	1.28a	1.00b	1.02b	31.53
Mg^{2+}	$cmol_c{\cdot}kg^{-1}$	0.41a	0.19b	0.13b	0.36a	49.04
SB	$cmol_c{\cdot}kg^{-1}$	1.07b	1.55a	1.27ab	1.47a	17.11
t	$cmol_c{\cdot}kg^{-1}$	5.34a	6.95a	6.12a	5.32a	17.85
T	$cmol_c{\cdot}kg^{-1}$	13.40a	15.41a	14.10a	13.02a	14.22
V	%	7.94b	10.21ab	9.13ab	11.45a	18.32
m	%	79.46a	77.28a	79.06a	72.24a	5.73
P_R	$mg{\cdot}kg^{-1}$	5.28a	1.98b	4.75a	2.37b	46.67
AREA		Layer 0.10 – 0.20 m				
		Forest	Cupuaçu	Guarana	Annatto	CV
pH	H_2O	3.88a	3.99a	3.53a	3.69a	6.93
H + Al	$cmol_c{\cdot}kg^{-1}$	8.33a	11.10a	10.31a	8.33a	22.61
Al^{3+}	$cmol_c{\cdot}kg^{-1}$	3.58b	4.35ab	4.95a	4.43ab	18.81
K^+	$cmol_c{\cdot}kg^{-1}$	0.07a	0.05a	0.06a	0.08a	47.08
Ca^{2+}	$cmol_c{\cdot}kg^{-1}$	0.39c	1.32a	1.12b	1.20ab	34.59
Mg^{2+}	$cmol_c{\cdot}kg^{-1}$	0.31a	0.19a	0.19a	0.22a	43.20
SB	$cmol_c{\cdot}kg^{-1}$	0.77c	1.57a	1.37b	1.50ab	21.45
t	$cmol_c{\cdot}kg^{-1}$	4.34b	5.92a	6.32a	5.92a	16.89
T	$cmol_c{\cdot}kg^{-1}$	9.10a	12.66a	11.68a	9.83a	21.05
V	%	8.50b	13.02a	11.81ab	15.24a	25.65
m	%	82.30a	73.45c	78.28b	74.63bc	5.33
P_R	$mg{\cdot}kg^{-1}$	2.73a	2.24a	4.09a	2.03a	48.28

continue...

Table 1. Continuation...

AREA		Layer 0.20 – 0.30 m				
		Forest	Cupuaçu	Guarana	Annatto	CV
pH	H_2O	3.87ab	4.22a	3.63b	3.92ab	7.30
H + Al	$cmol_c{\cdot}kg^{-1}$	8.29a	8.37a	8.95a	8.33a	23.97
Al^{3+}	$cmol_c{\cdot}kg^{-1}$	3.95a	4.50a	4.45a	3.95a	18.55
K^{+}	$cmol_c{\cdot}kg^{-1}$	0.06ab	0.04b	0.05ab	0.07a	51.15
Ca^{2+}	$cmol_c{\cdot}kg^{-1}$	0.45b	1.38a	1.36a	1.28a	35.58
Mg^{2+}	$cmol_c{\cdot}kg^{-1}$	0.18a	0.23a	0.21a	0.21a	39.53
SB	$cmol_c{\cdot}kg^{-1}$	0.69b	1.65a	1.63a	1.57a	24.94
t	$cmol_c{\cdot}kg^{-1}$	4.64a	6.15a	6.08a	5.52a	16.75
T	$cmol_c{\cdot}kg^{-1}$	8.98a	10.02a	10.58a	9.90a	21.85
V	%	7.66b	16.63a	15.57a	15.92a	29.98
m	%	84.71a	72.79b	73.12b	71.12b	6.64
P_R	$mg{\cdot}kg^{-1}$	2.66a	2.18a	2.20a	1.82a	48.44
AREA		Layer 0.30 – 0.40 m				
		Forest	Cupuaçu	Guarana	Annatto	CV
pH	H_2O	4.05ab	4.24a	3.86b	4.01ab	7.31
H + Al	$cmol_c{\cdot}kg^{-1}$	8.21a	7.59a	8.09a	7.84a	24.60
Al^{3+}	$cmol_c{\cdot}kg^{-1}$	3.73a	3.93a	4.10a	3.90a	18.23
K^{+}	$cmol_c{\cdot}kg^{-1}$	0.06a	0.04a	0.05a	0.07a	53.24
Ca^{2+}	$cmol_c{\cdot}kg^{-1}$	0.60b	0.90a	1.20a	1.14a	36.21
Mg^{2+}	$cmol_c{\cdot}kg^{-1}$	0.22a	0.18a	0.24a	0.20a	37.37
SB	$cmol_c{\cdot}kg^{-1}$	0.88a	1.12a	1.50a	1.41a	26.77
t	$cmol_c{\cdot}kg^{-1}$	4.61a	5.04a	5.60a	5.31a	17.01
T	$cmol_c{\cdot}kg^{-1}$	9.09a	8.71a	9.58a	9.25a	22.54
V	%	9.68a	12.38a	15.61a	15.34a	29.58
m	%	80.79a	79.04a	72.95a	73.30a	6.86
P_R	$mg{\cdot}kg^{-1}$	2.06a	2.08a	2.12a	1.95a	47.13
AREA		Layer 0.40 – 0.50 m				
		Forest	Cupuaçu	Guarana	Annatto	CV
pH	H_2O	4.26a	4.21a	4.09a	4.12a	7.55
H + Al	$cmol_c{\cdot}kg^{-1}$	6.60a	7.63a	8.50a	7.96a	25.00
Al^{3+}	$cmol_c{\cdot}kg^{-1}$	3.68a	3.65a	3.95a	4.00a	23.07
K^{+}	$cmol_c{\cdot}kg^{-1}$	0.07ab	0.04b	0.07ab	0.08a	51.69
Ca^{2+}	$cmol_c{\cdot}kg^{-1}$	0.57b	0.40b	1.32a	1.35a	39.17
Mg^{2+}	$cmol_c{\cdot}kg^{-1}$	0.24a	0.11a	0.22a	0.16a	40.59
SB	$cmol_c{\cdot}kg^{-1}$	0.88b	0.55b	1.61a	1.59a	30.41
t	$cmol_c{\cdot}kg^{-1}$	4.55a	6.43a	5.56a	5.59a	19.29
T	$cmol_c{\cdot}kg^{-1}$	7.48b	8.18ab	10.11a	9.55a	23.16
V	%	11.63ab	6.88b	16.07a	16.71a	31.22
m	%	80.72ab	90.25a	71.03b	71.12b	8.15
P_R	$mg{\cdot}kg^{-1}$	2.14a	2.06a	2.64a	2.66a	45.11

Means followed by the same letter within the row did not differ significantly (Tukey's $p < 0.05$). Sum of bases (SB); cation exchange capacity effective (t); cation exchange capacity potential (T); base saturation (V); aluminum saturation (m); and resin phosphorus (Pr).

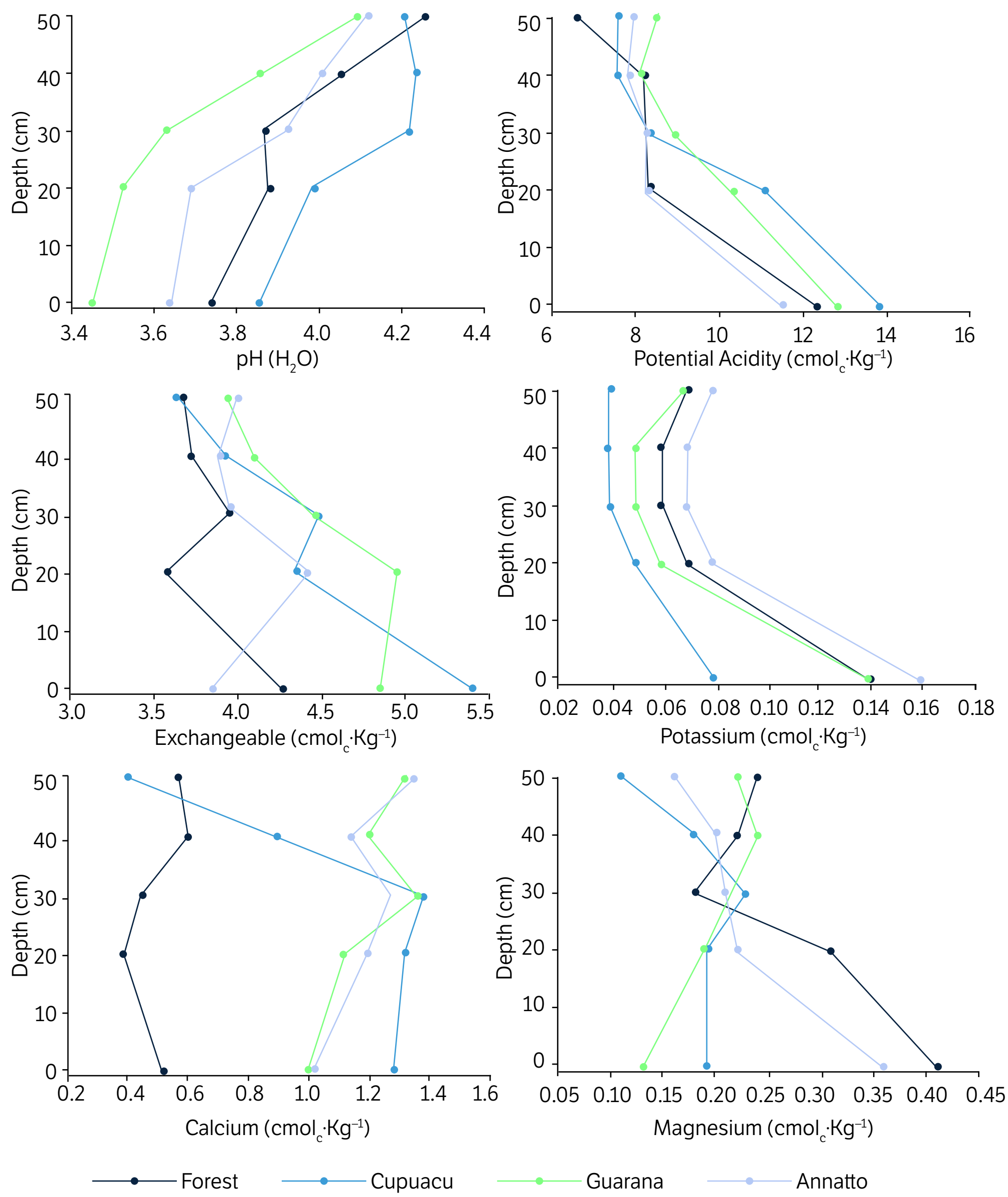

Figure 2. Mean values of soil chemical attributes, at different depths, in areas under conversion from forest to agricultural environments in the municipality of Canutama, Amazonas.

The behavior of exchangeable Al in the studied environments may be an indicator of the effect of systems with low production capacity for organic compounds, which do not show Al^{3+} complexing capacity, as verified by Moline and Coutinho 2015 and Mantovanelli et al. 2015.

The Ca^{2+} presented a significant difference for the studied areas, in all layers, with the highest values in the cupuaçu area, reaching up to 1.38 $cmol_c{\cdot}kg^{-1}$ in the layer 0.20 – 0.30 cm and decreasing in the other layers. The lowest values were observed in the forest area, for all studied layers reaching up to 0.39 $cmol_c{\cdot}kg^{-1}$ (Table 1). This is mainly due to the cleaning process for implanting the crops, where the burning provides the soil with Ca^{2+} present in the native vegetation structures. These values corroborate with Carneiro et al. (2009), who found higher levels of Ca^{2+}, Mg^{2+} and P in managed areas.

Evaluating the Mg^{2+} contents, a significant difference was observed only in the 0.00 – 0.10 m layer for the studied areas, where the highest value was observed on the forest area and the lowest value in the cultivated areas (Table 1). Jakelaitis et al. (2008) reported a decrease of Ca^{2+} and Mg^{2+} due to the removal of the original forest for cultivation, justified by the poor soil management, and the continuous removal of the trees or vegetation, among other factors.

Phosphorus presented statistical difference for the studied areas only in the 0.00 – 0.10 m layer with the highest values found in the forest area, followed by the guarana area (Table 1). In most of the soils of the Amazon region, except areas of black Indian soil, P levels are generally very low, as shown by Campos et al. (2010) and Campos et al. (2012). However, in their study, Oliveira et al. (2015) found high levels of P in forests (6.09 mg·dm^{-3}) and agroforestry areas (8.19 mg·dm^{-3}), values higher than those found in the present study.

Phosphorus had the highest levels, at depths 0.00 – 0.10 and 0.10 – 0.20 m, mainly for the areas of forest and guarana, with little variation at depths below 0.20 m (Fig. 3). The soil P levels corroborate with Galang et al. (2010), who showed that the stocks of inorganic P in the superficial layers of the soil is due to the conversion of organic P. In general, the studied environments have low available phosphorus values. One of the main factors responsible is the phosphorus precipitation with the ions Al and Fe, present in high levels in the soil (Gama-Rodrigues et al. 2014).

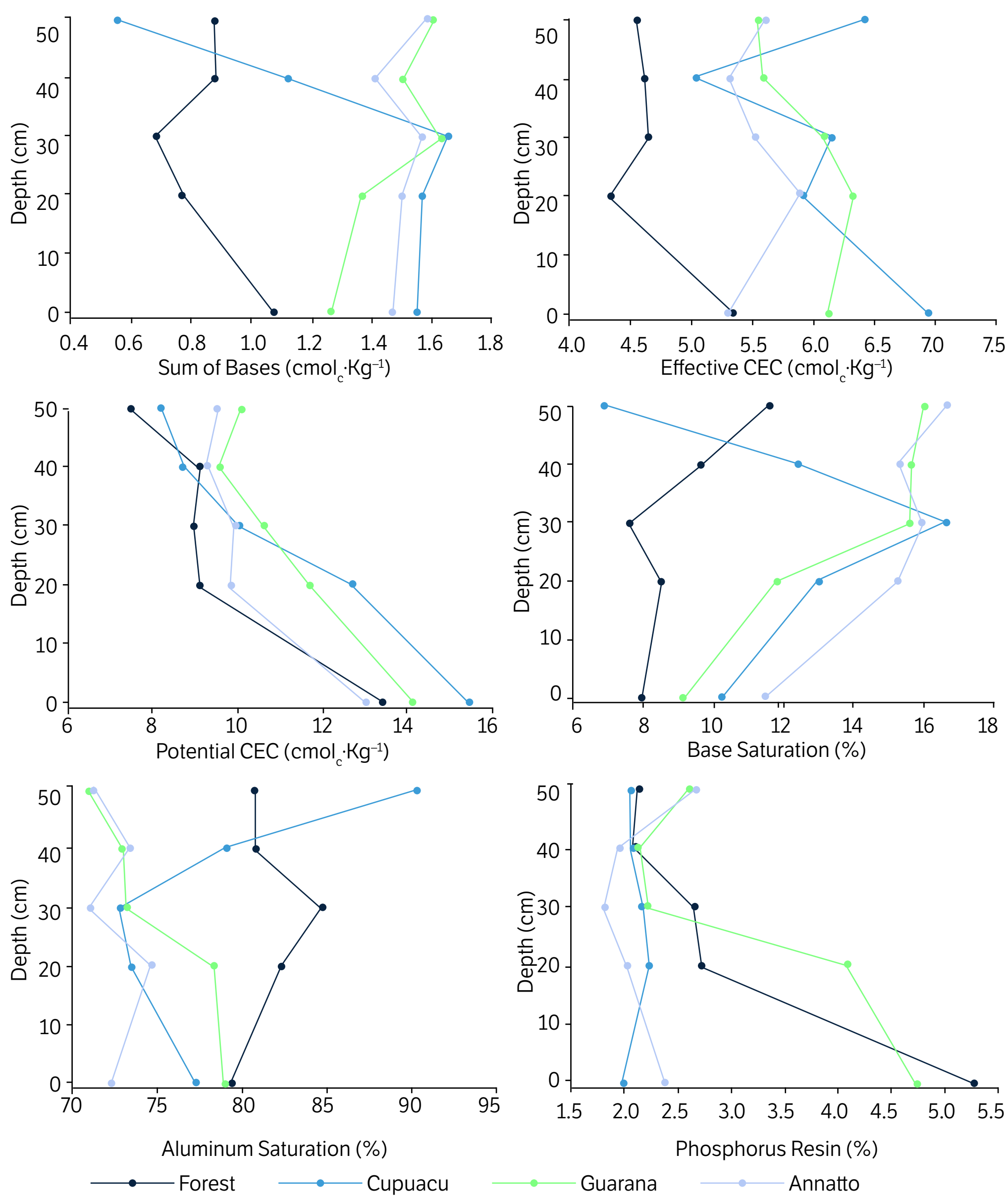

Figure 3. Mean values of soil chemical attributes, at different depths, in areas under conversion from forest to agricultural environments in the municipality of Canutama, Amazonas.

The values of t and T decrease in depth, while SB and V% increase (Fig. 3). These parameters are related to K^+, Ca^{2+} and Mg^{2+}, being strongly influenced by their contents, except for t and T, which are more influenced by Al^{3+} and $H^+ + Al^{3+}$, respectively, and these decreased in depth, which consequently provided a decrease in t and T. The m% varied slightly with soil depth and a significant increase in the cupuaçu area was observed from 0.30 m.

Table 2 presents the mean and coefficient of variation of aggregates, OM, OC and CS in all areas and depths studied. At layer 0.00 – 0.10 m, in the aggregate class > 2 mm, 1–2 mm and < 1 mm, and at layer 0.20 – 0.30 m, for < 1mm, no significant differences were observed between the studied areas. However, a significant difference occurred between the studied areas in the other layers (Table 2). The forest area showed the highest values of aggregates in the class > 2 mm, in relation to the cultivated areas with the different crops studied. According to Soares et al. (2016), soils with larger stable aggregates are considered structurally better and more resistant to erosive processes, aggregation facilitates soil aeration, gas exchange and water infiltration, due to the increase of MaP, and ensures microporosity and water retention within the aggregates. On the other hand, the lowest values of aggregates in the class 1–2 mm were observed for the forest area in all the studied layers and the largest ones were observed in the cupuaçu area, in the lower layers.

Table 2. Average and coefficient of variation of soil aggregates and OC, OM and CS in areas undergoing forest conversion for cultivated environments in the municipality of Canutama, Amazonas, 2017.

AREA		Layer 0.00 – 0.10 m				
		Forest	Cupuaçu	Guarana	Annatto	CV
Classes (%)	> 2 mm	94.64a	92.79a	91.57a	89.43a	4.22
	1–2 mm	0.50a	1.07a	1.10a	1.37a	73.52
	< 1 mm	4.87a	6.13a	7.32a	9.20a	47.62
ASI	%	93.63a	92.49a	88.63a	86.57a	5.92
GAD	mm	2.64a	2.64a	2.32a	2.41a	14.40
WAD	mm	3.09a	3.14a	2.95a	3.04a	6.32
OC	$g \cdot kg^{-1}$	23.91a	20.56ab	17.96ab	15.26b	23.80
OM	$g \cdot kg^{-1}$	41.22a	32.95ab	30.19ab	26.31b	22.01
CS	$t \cdot ha^{-1}$	25.67a	18.43ab	22.76ab	17.72b	25.90
AREA		**Layer 0.10 – 0.20 m**				
		Forest	**Cupuaçu**	**Guarana**	**Annatto**	**CV**
Classes (%)	> 2 mm	84.24ab	90.90a	77.00b	83.15ab	7.36
	1–2 mm	2.54b	3.02ab	7.36a	3.64ab	67.76
	< 1 mm	13.22a	6.07b	15.64a	13.21a	35.40
ASI	%	87.96a	92.89a	87.61a	88.52a	6.36
GAD	mm	2.36a	2.56a	2.04a	2.26a	16.86
WAD	mm	2.95a	3.03a	2.72a	2.91a	7.84
OC	$g \cdot kg^{-1}$	13.18ab	15.13a	11.74ab	9.78b	32.73
OM	$g \cdot kg^{-1}$	22.73ab	26.12a	20.23ab	16.86b	30.96
CS	$t \cdot ha^{-1}$	14.94ab	17.86a	14.30ab	12.14b	30.12
AREA		**Layer 0.20 – 0.30 m**				
		Forest	**Cupuaçu**	**Guarana**	**Annatto**	**CV**
Classes (%)	> 2 mm	82.84a	65.33b	65.92b	79.20ab	13.68
	1–2 mm	3.44b	13.58a	12.36a	6.04ab	61.49
	< 1 mm	13.72a	21.09a	21.72a	14.76a	29.25
ASI	%	90.51a	89.39a	86.49a	89.00a	5.49
GAD	mm	2.30a	1.89a	1.79a	2.06a	18.40
WAD	mm	2.93a	2.55a	2.45a	2.69a	10.12
OC	$g \cdot kg^{-1}$	9.96a	10.29a	10.07a	7.61a	38.64
OM	$g \cdot kg^{-1}$	17.16a	15.47a	17.37a	13.13a	37.98
CS	$t \cdot ha^{-1}$	11.07a	11.14a	12.58a	9.80a	35.68

continue...

Table 2. Continuation...

AREA		Layer 0.30 – 0.40 m				
		Forest	Cupuaçu	Guarana	Annatto	CV
Classes (%)	> 2 mm	74.26a	33.90c	59.56b	59.57b	26.90
	1–2 mm	6.56c	22.84a	13.82b	11.63bc	47.93
	< 1 mm	19.18c	43.26a	26.62b	28.80b	32.19
ASI	%	83.94a	82.05a	85.84a	77.20a	7.44
GAD	mm	1.73a	0.98a	1.61a	1.24a	27.99
WAD	mm	2.58a	1.46b	2.22a	1.96ab	19.03
OC	$g \cdot kg^{-1}$	9.10a	7.38ab	9.67a	6.07b	42.98
OM	$g \cdot kg^{-1}$	15.68a	12.77ab	16.39a	10.47b	42.10
CS	$t \cdot ha^{-1}$	11.32a	10.30ab	12.49a	8.20b	37.52
AREA		Layer 0.40 – 0.50 m				
		Forest	Cupuaçu	Guarana	Annatto	CV
Classes (%)	> 2 mm	43.06b	50.42ab	32.36c	57.53a	22.58
	1–2 mm	13.20b	19.78a	17.93ab	13.03b	24.83
	< 1 mm	43.75a	29.79b	49.71a	29.44b	26.38
ASI	%	81.67a	86.10a	78.30a	82.65a	8.21
GAD	mm	1.15a	1.34a	1.00a	1.42a	33.48
WAD	mm	1.79a	1.95a	1.57a	2.01a	23.78
OC	$g \cdot kg^{-1}$	7.10a	7.59a	5.78a	6.62a	47.19
OM	$g \cdot kg^{-1}$	12.24a	13.08a	9.96a	11.42a	46.16
CS	$t \cdot ha^{-1}$	9.68a	10.80a	8.45a	9.27a	39.37

Means followed by the same letter on the line did not differ significantly (Tukey's $p < 0.05$). Aggregate stability index (ASI); geometric average diameter (GAD); weighted average diameter (WAD); organic carbon (OC); organic matter (OM); and carbon stock (CS).

Geometric average diameter (GAD) showed values lower than those reported by Coutinho et al. (2010) for all areas in all studied layers. Such differences may be related to the root system of crops, since the cultures studied present a pivoting root system, while those studied by Coutinho et al. (2010) had a fasciculate root system, which is more aggressive and covers more areas, resulting in greater soil formation.

Figure 4 presents soil aggregate parameters by depth in the different areas. It can be observed that, for the class of aggregates > 2 mm, ASI, GAD and WAD decrease in depth. This factor can be related to the OC, OM and CS, which also decreased in depth (Fig. 5). These observations corroborate with Vasconcelos et al. (2010), which related the soil aggregation process to the content of OM and with Wendling et al. (2012), who observed a decrease in soil aggregation, with increased depth in soil under native forest.

For groups of aggregates of 1–2 mm and < 1 mm, an increase was observed according to depth (Fig. 4). This is likely due mainly to the decrease in OC, OM and CS with soil depth (Fig. 5), which influence soil aggregation by acting as cementing agents.

The decrease with depth of OC, OM and CS (Fig. 5) was also observed by Mantovanelli et al. (2015), and they attribute this pattern to the higher deposition of OM on the surface, which is intensified due to the contribution of more lignified vegetable residues.

With respect to SRP, the layers 0.00 – 0.10 and 0.10 – 0.20 m showed significantly higher values for guarana and annatto and the lowest for cupuaçu (Table 3). In general, according to Couto et al. (2016), the studied areas, in all the layers that show an SRP lower than 2 MPa, characterize soils without restriction to root growth. This higher SRP value observed on guarana and annatto likely occurred because the soil in these locations had no initial preparation.

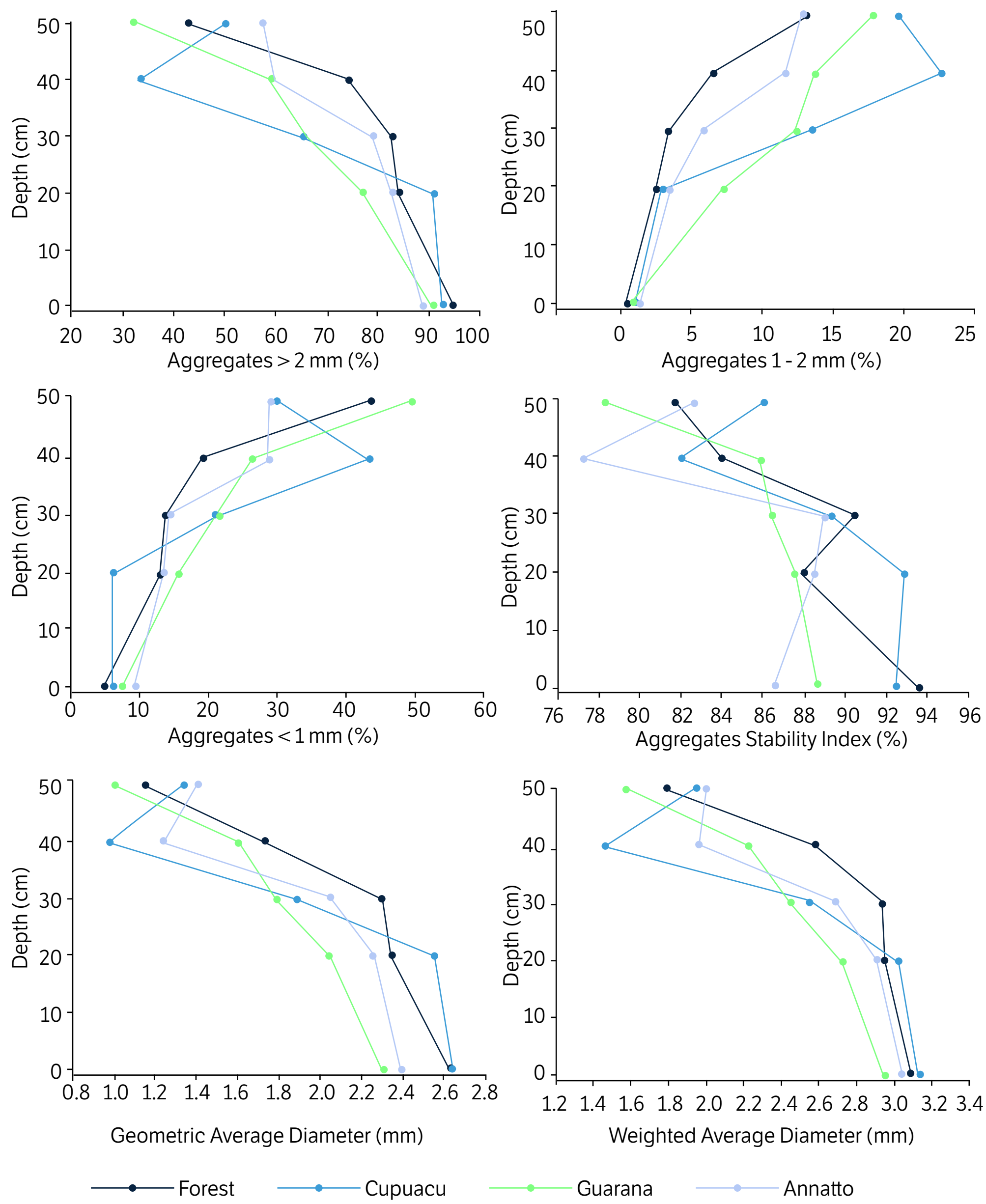

Figure 4. Mean values of soil aggregates, at different depths, in areas under conversion from forest to agricultural environments in the municipality of Canutama, Amazonas.

Vogel and Fey (2016) attributed the higher Sd and SRP in the superficial layers to the low intensity of soil preparation. Another factor is the exposure of the bare soil surface, which has consequently been compacted by rain drops.

Figure 6 shows the compaction parameters, root distribution and soil porosity for the different areas in the studied depths. It can be observed that SRP and Sd, in general, increased according to depth, as observed by Lima et al. (2013), who verified that from the 0.20 m depth there was more soil compaction.

Soil density (Sd) showed a significant difference between areas in the layers of 0.00 – 0.10 and 0.30 – 0.40 m, with the highest values observed for the annatto and guarana areas (table 3). This increased value can be attributed to the use of fire to clean the area. Redin et al. (2011) pointed out that the main alterations that occur with burning include a decrease in the volume of macropores, the weighted average diameter of the stable aggregates and an increase in soil density.

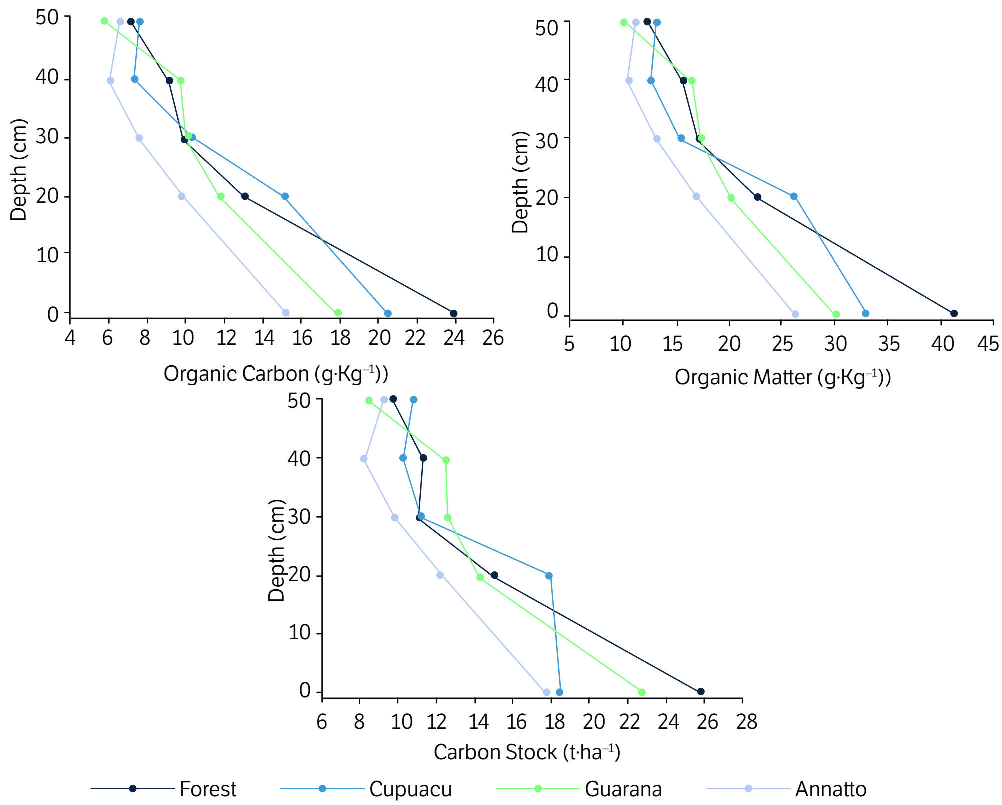

Figure 5. Mean values of OC, OM and CS, at different depths, in areas under conversion from forest to agricultural environments in the municipality of Canutama, Amazonas.

Table 3. Mean and coefficient of variation of the SRP, Sd, soil porosity and root system distribution in areas under forest conversion to cultivated environments in the municipality of Canutama, AM, 2017.

AREA		Layer 0.00 – 0.10 m				
		Forest	**Cupuaçu**	**Guarana**	**Annatto**	**CV (%)**
SRP	MPa	0.81ab	0.42b	1.04a	1.05a	41.52
Sd	$g \cdot dm^{-3}$	1.07ab	0.89b	1.22a	1.15a	14.42
TP	$m^3 \cdot m^{-3}$	0.55ab	0.63a	0.52b	0.53b	10.18
MiP	$m^3 \cdot m^{-3}$	0.35a	0.38a	0.38a	0.35a	6.43
MaP	$m^3 \cdot m^{-3}$	0.20ab	0.25a	0.14b	0.19ab	29.16
VH	$m^3 \cdot m^{-3}$	0.35a	0.38a	0.38a	0.35a	6.43
RDW	$g \cdot dm^{-3}$	1.17ab	2.13a	1.24ab	0.44b	70.14
RD	%	43.45a	54.56a	58.86a	63.32a	23.59
AREA		**Layer 0.10 – 0.20 m**				
		Forest	**Cupuaçu**	**Guarana**	**Annatto**	**CV (%)**
SRP	MPa	0.82ab	0.54b	0.72ab	0.89a	35.11
Sd	$g \cdot dm^{-3}$	1.13a	1.13a	1.22a	1.24a	11.72
TP	$m^3 \cdot m^{-3}$	0.57a	0.58a	0.53a	0.52a	8.52
MiP	$m^3 \cdot m^{-3}$	0.37a	0.38a	0.36a	0.39a	5.89
MaP	$m^3 \cdot m^{-3}$	0.20a	0.20a	0.18a	0.14a	25.27
VH	$m^3 \cdot m^{-3}$	0.37a	0.38a	0.36a	0.39a	5.89
RDW	$g \cdot dm^{-3}$	0.67ab	1.10a	0.42ab	0.10b	87.99
RD	%	21.73a	27.37a	19.10a	14.03a	54.85

continue...

Table 3. Continuation...

AREA		Layer 0.20 – 0.30 m				
		Forest	Cupuaçu	Guarana	Annatto	CV (%)
SRP	MPa	0.81a	0.55a	0.85a	0.92a	33.59
Sd	g·dm^{-3}	1.12a	1.21a	1.25a	1.27a	10.97
TP	m^3·m^{-3}	0.56a	0.54a	0.55a	0.50a	8.87
MiP	m^3·m^{-3}	0.37a	0.36a	0.38a	0.38a	5.43
MaP	m^3·m^{-3}	0.20a	0.18a	0.17a	0.12a	27.56
VH	m^3·m^{-3}	0.37a	0.36a	0.38a	0.38a	5.43
RDW	g·dm^{-3}	0.54a	0.33ab	0.35ab	0.07b	101.12
RD	%	19.31a	7.96b	13.40ab	10.48ab	70.89
AREA		Layer 0.30 – 0.40 m				
		Forest	Cupuaçu	Guarana	Annatto	CV (%)
SRP	MPa	0.94a	1.27a	1.02a	1.14a	32.67
Sd	g·dm^{-3}	1.26b	1.43a	1.35ab	1.35ab	12.00
TP	m^3·m^{-3}	0.52a	0.47a	0.52a	0.49a	9.49
MiP	m^3·m^{-3}	0.37a	0.36a	0.39a	0.38a	5.40
MaP	m^3·m^{-3}	0.15a	0.11a	0.12a	0.11a	32.56
VH	m^3·m^{-3}	0.37a	0.36a	0.39a	0.38a	5.40
RDW	g·dm^{-3}	0.29a	0.20ab	0.12ab	0.04b	116.72
RD	%	9.80a	5.41a	4.86a	7.24a	86.80
AREA		Layer 0.40 – 0.50 m				
		Forest	Cupuaçu	Guarana	Annatto	CV (%)
SRP	MPa	0.94a	1.38a	1.14a	1.27a	36.60
Sd	g·dm^{-3}	1.36a	1.46a	1.46a	1.40a	13.11
TP	m^3·m^{-3}	0.49a	0.48a	0.51a	0.47a	9.89
MiP	m^3·m^{-3}	0.37ab	0.36b	0.40a	0.38ab	5.41
MaP	m^3·m^{-3}	0.12a	0.11a	0.11a	0.09a	36.19
VH	m^3·m^{-3}	0.37ab	0.36b	0.40a	0.38ab	5.41
RDW	g·dm^{-3}	0.17a	0.13a	0.10a	0.03a	130.76
RD	%	5.72a	4.70a	3.77a	4.93a	100.17

Means followed by the same letter on the line did not differ significantly (Tukey's $p < 0.05$). Soil resistance to penetration (SRP); soil density (Sd); total porosity (TP); microporosity (MiP); macroporosity (MaP); volumetric humidity (VH); roots dry weight (RDW); and roots distribution (RD).

The TP and MaP showed significant differences between the studied areas only in the layer 0.00 – 0.10 m, while MiP and VH showed significant differences in the layer 0.40 – 0.50 m. The highest values of PT and MaP were found in the cupuaçu area in the 0.00 – 0.10 m layer and for the MiP and UV in the guarana area (Table 3). According to Soares et al. (2016), the reduction of the TP can reflect the reduction of the MaP, since the MiP does not seem to be influenced directly by the soil management.

Total porosity and MaP decreased in depth, while MIP and VH increased according to depth (Fig. 6). This factor can be attributed to the increase of the Sd and, consequently, of the SRP, which compact the soil reducing TP and MaP, and increase the MiP and VH, where the larger the MiP, the greater the soil capacity to retain water, consequently increasing the VH.

In Table 3 it is possible to observe a significant difference for RDW between the areas for all the layers evaluated, except for layer 0.40 – 0.50 m, and the highest values found were in the area under cupuaçu cultivation in layers 0.00 – 0.10 and 0.10 – 0.20 m. In the other layers, the highest values were found in the forest area. This higher RDW can be attributed to cupuaçu in these layers due to the fact that it has presented smaller SRP and Sd in the superficial layers, and also because the area has 7 years of cultivation.

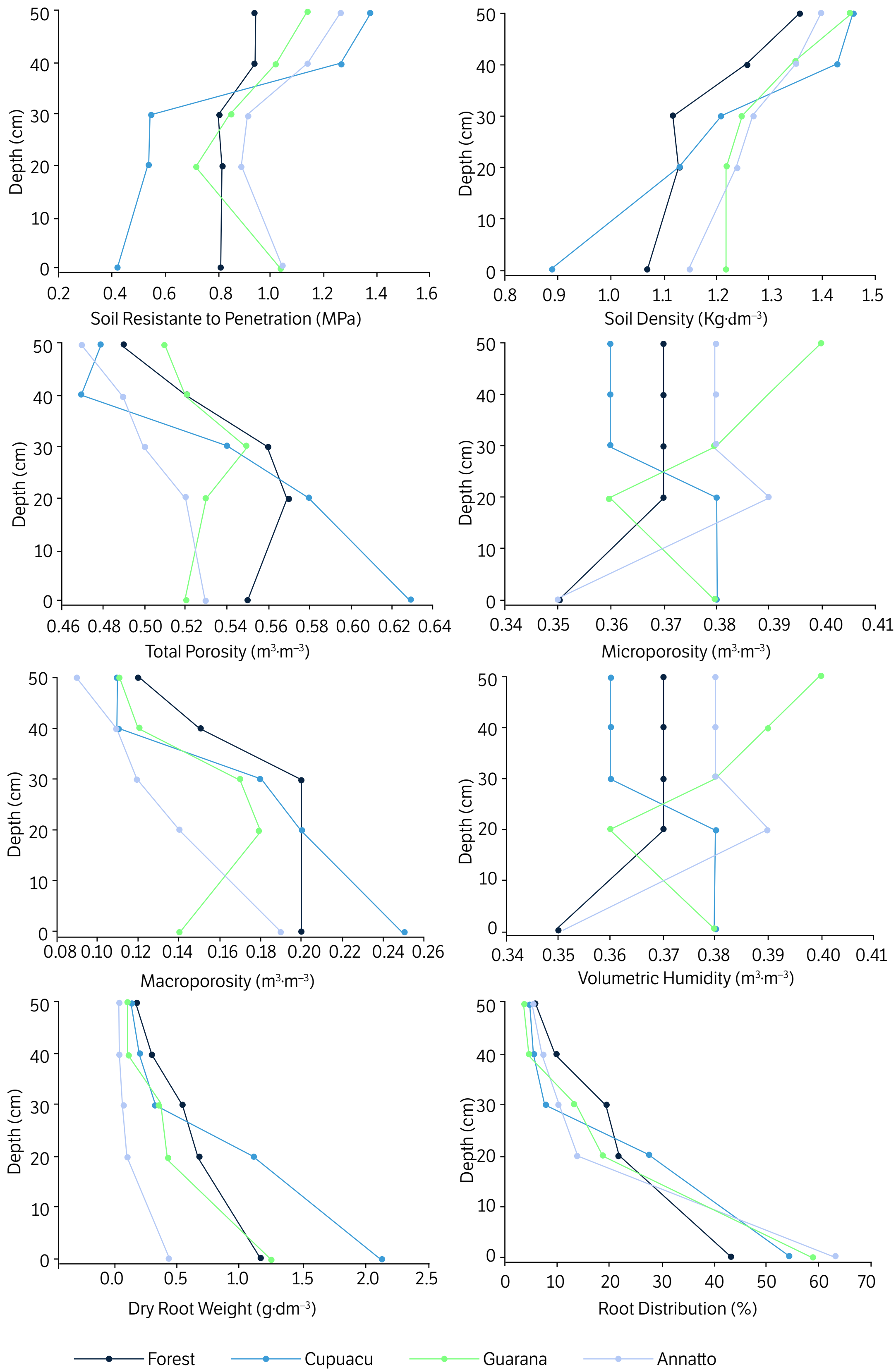

Figure 6. Mean values of SRP, SD, porosity and root distribution, at different depths, in areas under conversion from forest to agricultural environments in the municipality of Canutama, Amazonas.

Roots dry weight (RDW) and RD decreased with depth, with the highest levels observed up to 0.20 m depth. This is likely due mainly to the lower SRP and Sd and the higher TP and MaP, as well as to the greater amount of OM at that depth, contributing to higher levels of P, K, Ca^{2+} and Mg^{2+}, essential nutrients for plant development. According to Pezzoni et al. (2012), the litter from the deposition of dead matter, from the aerial part of the trees, positively affects the soil quality, both physically for the SRP, Sd and aggregate attributes, and chemically through the nutrient cycling process.

The environments cultivated have fertility levels close to those observed in the forest environment, however they require management for exchangeable bases, components of acidity, P and accumulation of OM. Therefore, liming is necessary to reduce acidity, supply Ca and Mg, and provide essential nutrients for plant nutrition (Natale et al. 2012). In addition, it is recommended to apply phosphate fertilizers, as a practice, to increase the phosphorus content in the soil and, consequently, greater availability for plants. However, it is essential to use practices that increase the content of OM in the soil, either through the use of cover plants or the management of plant residues. According to Damasceno et al. (2019), brachiaria, jack beans, millet and their mixtures, are excellent alternatives for use as cover crops in the Amazon region, which in addition to having good coverage, take longer to decompose after cutting, allowing accumulation of OM in the soil. The management of plant residues, through the action of the litter produced by the accumulation of branches, leaves, flowers and fruits of the cultivated species, contributes significantly to the accumulation of OM in the soil and also in the increment of nutrients (Pérez-Flores et al. 2018).

The environment with cupuaçu cultivation showed improvement in porosity, soil aggregation and compaction. These improvements are even superior to those observed in the forest environment. This was attributed to the low use of machines in the cultivated systems, which allowed the maintenance of the physical characteristics of the soil related to compaction, which allowed a greater root growth in the cupuaçu area and, with that, improvements in the porosity and aggregation of the soil (Chaves et al. 2020). The soil compaction observed in the secondary forest area may be due to the soil compression caused by the growth of the roots (Oliveira et al. 2015).

FINAL CONSIDERATIONS

Greater changes were observed in the soil surface, being more influenced by exchangeable bases, organic components and soil compaction. The cultivated environments showed fertility levels similar to those observed in the forest and, often, a superior physical structure. However, management is recommended to improve acidity, exchangeable bases, organic components and soil compaction, mainly for annatto and guarana crops.

The cultivation of cupuaçu increased soil fertility levels, and its greater root development, aggregation, accumulation of organic matter, compaction and soil porosity.

Due to the ecological question that the Amazon Forest weighs in Brazil and the world, further studies should be carried out to evaluate the impacts caused to the soil by the conversion of forest into cultivated environments in the region as a way of generating data, which minimizes the impacts caused by agriculture.

AUTHORS' CONTRIBUTION

Investigation: Lima A. F. L., Campos M. C. C., Cunha J. M. and Brito Filho E. G.; **Writing – Original Draft:** Lima A. F. L., Campos M. C. C., Cunha J. M. and Brito Filho E. G.; **Methodology:** Martins T. S., Santos E. A. N. and Souza F. G.; **Writing – Review and Editing:** Brito Filho E. G.

DATA AVAILABILITY STATEMENT

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

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REFERENCES

Araújo, E. A., Ker, J. C., Mendonça, E. S., Silva, I. R. and Oliveira, E. K. (2011). Impacto da conversão floresta - pastagem nos estoques e na dinâmica do carbono e substâncias húmicas do solo no bioma amazônico. Acta amazonica, 41, 103-114. https://doi.org/10.1590/S0044-59672011000100012

Böhm, W. (1979). Methods of studying root systems. Berlin: Springer-Verlag.

Campos, M. C. C., Ribeiro, M. R., Souza Júnior, V. S., Ribeiro Filho, M. R. and Oliveira, I. A. (2010). Interferências dos pedoambientes nos atributos do solo em uma topossequência de transição Campo/Floresta. Revista Ciência Agronômica, 41, 527-535. https://doi.org/10.1590/S1806-66902010000400004

Campos, M. C. C., Santos, L. A. C., Silva, D. M. P., Mantovanelli, B. C. and Soares, M. D. R. (2012). Caracterização física e química de terras pretas arqueológicas e de solos não antropogênicos na região de Manicoré, Amazonas. Revista Agro@mbiente On-line, 6, 102-109. https://doi.org/10.18227/1982-8470ragro.v6i2.682

Carneiro, M. A. C., Souza, E. D., Reis, E. F., Pereira, H. S. and Azevedo, W. R. (2009). Atributos físicos, químicos e biológicos de solo de cerrado sob diferentes sistemas de uso e manejo. Revista Brasileira de Ciência do Solo, 33, 147-157. https://doi.org/10.1590/S0100-06832009000100016

Chaves, S. F. S., Gama, M. A. P., Alves, R. M., Oliveira, R. P., Pedroza Neto, J. L. and Lima, V. M. N. (2020). Avaliação dos atributos físico-químicos de um latossolo amarelo sob sistema agroflorestal em comparação com floresta secundária na Amazônia Oriental. Agroforestry Systems, 94: 1903-1912. https://doi.org/10.1007/s10457-020-00513-6

Coutinho, F. S., Loss, A., Pereira, M. G., Junior, D. J. R., Torres, J. L. R. (2010). Estabilidade de agregados e distribuição do carbono em Latossolo sob sistema plantio direto em Uberaba, Minas Gerais. *Comunicata Scientiae*, 1: 100.

Couto, W. H., Anjos, L. H. C., Wadt, P. G. S., Pereira, M. G. (2016). Atributos edáficos e resistência a penetração em áreas de sistemas agroflorestais no sudoeste amazônico. *Ciência Forestal*, 26: 811-823. https://doi.org/10.5902/1980509824210

Damasceno, L. A., Carvalho, J. E. B., Xavier, F. A., Santos, A. F., Gonçalves, G. S., Lima, A. F. L., Brito, W. B. M., Azevedo C. L. L. and Silva, J. F. (2019). Weed Suppression by Cover Plants in the Amazonian. Journal of Agricultural Science, 11, 148-159. https://doi.org/10.5539/jas.v11n7p148

[EMBRAPA] Empresa Brasileira de Pesquisa Agropecuária. (1997). Avaliação da aptidão agrícola de áreas de cerrados em municípios do estado do Amazonas. Centro Nacional de Pesquisas de Solo. Rio de Janeiro: Embrapa Solos.

Franco, C. F. O., Silva, F. C. P., Cazé Filho, J., Barreiro Neto, M., São José, A. R., Rebouças, T. N. H. and Fontinélli, I. S. C. (2008). Etnobotânica e Taxonomia do Urucuzeiro. João Pessoa: EMEPA.

Freitas, L., Casagrande, J. C., Oliveira, I. A., Campos, M. C. C. and Silva, L. S. (2015). Técnicas multivariadas na avaliação de atributos de um Latossolo vermelho submetido a diferentes manejos. Revista Brasileira de Ciências Agrárias, 10, 17-26. https://doi.org/10.5039/agraria.v10i1a3928

Galang, M. A., Markewitz, D. and Morris, L. A. (2010). Soil phosphorus transformations under forest burning and laboratory heat treatments. Geoderma, 55, 401-408. https://doi.org/10.1016/j.geoderma.2009.12.026

Galdos, M. V., Maria, I. C. and Camargo, O. A. (2004). Atributos químicos e produção de milho em um latossolo vermelho eutroférrico tratado com lodo de esgoto. Revista Brasileira de Ciência do Solo, 28, 569-577, https://doi.org/10.1590/S0100-06832004000300017

Gama-Rodrigues, A. C., Sales, M. V. S., Silva, P. S. D., Comerford, N. B., Cropper, W. P. and Gama-Rodrigues, E. F. (2014). An exploratory analysis of phosphorus transformations in tropical soils using structural equation modelling. Biogeochemistry, 118, 453-469. https://doi.org/10.1007/s10533-013-9946-x

Jakelaitis, A., Silva, A. A., Santos, J. B. and Vivian, R. (2008). Qualidade da camada superficial de solo sob mata, pastagens e áreas cultivadas. Pesquisa Agropecuária Tropical, 38, 118-127.

Lima, R. P., León, M. J. and Silva, A. R. (2013). Resistência mecânica à penetração sob diferentes sistemas de uso do solo. Scientia Plena, 9, 069903.

Magalhães, S. S. A., Weber, O. L. S., Santos, C. H. and Valadão, F. C. A. (2013). Estoque de nutrientes sob diferentes sistemas de uso do solo de Colorado do Oeste-RO. Acta Amazonica, 43, 63-72. https://doi.org/10.1590/S0044-59672013000100008

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

Moline E. F. V. and Coutinho, E. L. M. (2015). Atributos químicos de solos da Amazônia Ocidental após sucessão da mata nativa em áreas de cultivo. Revista de Ciências Agrárias, 58, 14-20. https://doi.org/10.4322/rca.1683

Natale, W., Rozane, D. E., Parent, L. E. and Parent, S.-É. (2012). Acidez do solo e calagem em pomares de frutíferas tropicais. Revista Brasileira de Fruticultura, 34, 1294-1306. https://doi.org/10.1590/S0100-29452012000400041

Oliveira, I. A., Campos, M. C. C., Freitas, L. and Soares, M. D. R. (2015). Caracterização de solos sob diferentes usos na região sul do Amazonas. Acta amazônica, 45, 1-12. https://doi.org/10.1590/1809-4392201400555

Pérez-Flores, J., Pérez, A. A., Suárez, Y. P., Bolaina, V. C. and Quiroga, A. L. (2018). Leaf litter and its nutrient contribution in the cacao agroforestry system. Agroforestry Systems, 92, 365-374. https://doi.org/10.1007/s10457-017-0096-3

Pezzoni, T., Vitorino, A. C. T., Daniel, O. and Lempp, B. (2012). Influência de *Pterodon emarginatus* Vogel sobre atributos físicos e químicos do solo e valor nutritivo de *Brachiaria decumbens* em sistema silvipastoril. Revista Cerne, 18, 293-301. https://doi.org/10.1590/S0104-77602012000200014

Redin, M., Santos, G. D., Miguel, P., Denega, G. L., Lupatini, M., Doneda, A. and Souza, E. L. (2011). Impactos da queima sobre atributos químicos, físicos e biológicos do solo. Ciência Florestal, 21, 381-392. https://doi.org/10.5902/198050983243

Sales, R. P., Portugal, A. F., Moreira, J. A. A., Kondo, M. K. and Pegoraro, R. F. (2016). Qualidade física de um Latossolo sob plantio direto e preparo convencional no semiárido. Revista Ciência Agronômica, 47, 429-438. https://doi.org/10.5935/1806-6690.20160052

Schuurman, J. J., Goedewaagen, M. A. J. (1971). Methods for the examination of root systems and roots: Methods in use at the Institute for Soil Fertility for eco-morphological root investigations. Wageningen: Centre for Agricultural Publishing and Documentation.

Silva Neto, E. C., Pereira, M. G., Frade Junior, E. F., Silva, S. B., Carvalho Junior, J. A. and Santos, J. C. (2019). Temporal evaluation of soil chemical attributes after slash-and-burn agriculture in the Western Brazilian Amazon. Acta Scientiarum Agronomy, 41, e 42609. https://doi.org/10.4025/actasciagron.v41i1.42609

Soares, M. D. R., Campos, M. C. C., Oliveira, I. A., Cunha, J. M., Santos, L. A. C., Fonseca, J. S. and Souza, Z. M. (2016). Atributos físicos do solo em áreas sob diferentes sistemas de usos na região de Manicoré, AM. Revista de Ciências Agrárias, 59, 9-15. https://doi.org/10.4322/rca.2020

SPSS Inc. Statistical Analysis Using SPSS. Chicago. 2001. [Accessed Jul. 10, 2020]. Available at: https://www.ibm.com/br-pt/analytics/spss-statistics-software

Teixeira, P. C., Donagemma, G. K., Fontana, A. and Teixeira, W. G. (2017). Manual de métodos de análise de solo. Brasília: Embrapa.

Vasconcelos, R. F. B., Cantalice, J. R. B, Oliveira, V. S., Costa, Y. D. J. and Cavalcante, D. M. (2010). Estabilidade de agregados de um latossolo amarelo distrocoeso de tabuleiro costeiro sob diferentes aportes de resíduos orgânicos da cana-de açúcar. Revista Brasileira de Ciência do Solo, 34, 309-316. https://doi.org/10.1590/S0100-06832010000200004

Vogel, G. F. and Fey, R. (2016). Resistência mecânica à penetração em diferentes sistemas de uso do solo. Revista de Agricultura Neotropical, 3, 21-26. https://doi.org/10.32404/rean.v3i1.812

Wendling, B., Vinhal-Freitas, I. C., Oliveira, R. C., Babata, M. M. and Borges, E. N. (2012). Densidade, agregação e porosidade do solo em áreas de conversão do cerrado em floresta de pinus, pastagem e plantio direto. Bioscience Journal, 28, 256-265.

Yeomans, J. C. and Bremner, J. M. (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.org/10.1080/00103628809368027