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Impact of land use on the chemical attributes of the soil, Cruzeiro do Sul, in the Brazilian Amazon[1]

Rodrigo Camara[2]*, Luciélio Manoel Silva[3], Elizio Ferreira Frade Junior[4], Eduardo Pacca Luna Mattar[4], Sandra Bezerra da Silva[4], Eduardo Carvalho da Silva Neto[5], Marcos Gervasio Pereira[6]

ABSTRACT - Vast areas of the Brazilian Amazon have been deforested for the expansion of livestock and the agricultural frontier, which has resulted in soil exhaustion. It is therefore urgent to reduce deforestation and encourage sustainable land use to promote social and economic development in the region. The aim of this study was to evaluate the impact of different land use systems (an agroforestry system, cassava cultivation, non-degraded pasture, native forest) on the chemical properties of the soil (0-40 cm) in the mesoregion of the Juruá Valley, in the state of Acre, Brazil. Principal component analysis showed the soil in the forested area (reference) has greater values for P, Ca^{2+}, Mg^{2+}, K^+, Na^+, sum of bases, and cation exchange capacity; while hierarchical cluster analysis suggested little dissimilarity to the soil in the agroforestry system, and high dissimilarity to the soil in the areas of cassava cultivation and pasture. The results therefore support agroforestry as the most sustainable land use system, compared to cassava cultivation or pasture.

Key words: Soil fertility. Amazon Rainforest. Cassava cultivation. Pasture. Multivariate analysis.

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*Author for correspondence
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[1]Study Research
[2]Departamento de Solos, Universidade Federal Rural do Rio de Janeiro (UFRRJ), Seropédica-RJ, Brasil, rcamara73@gmail.com (ORCID ID 0000-0002-7142-4797)
[3]Embrapa Tabuleiros Costeiros, Rio Largo-Al, Brasil, lucielio.silva@embrapa.br (ORCID ID 0000-0003-1290-515X)
[4]Centro de Ciências Biológicas e da Natureza, Universidade Federal do Acre (UFAC), Rio Branco-AC, Brasil, elizioufac@gmail.com (ORCID ID 0000-0002-2456-0489), eduardo@ufac.br (ORCID ID 0000-0001-9202-9879), sandrinha.czs@hotmail.com (ORCID ID 0000-0002-4907-3441)
[5]Departamento de Solo, Programa de Pós-Graduação em Agronomia, Universidade Federal Rural do Rio de Janeiro (UFRRJ), Seropédica-RJ, Brasil, netocseduardo@gmail.com (ORCID ID 0000-0001-6986-1376)
[6]Departamento de Solos, Universidade Federal Rural do Rio de Janeiro (UFRRJ), Seropédica-RJ, Brasil, mgervasiopereira01@gmail.com, (ORCID ID 0000-0002-1402-3612)

INTRODUCTION

The Brazilian Amazon represents around 40% of the remaining tropical forests on the planet, and has the highest richness values for the most diverse plant and animal species (ALVES *et al*., 2015). Many arboreal species are endemic, and develop strategic functions for maintaining ecosystem services, such as biogeochemical cycles and global climate regulation (GRIMALDI *et al*., 2014). However, vast areas of the Brazilian Amazon have been deforested for expansion of the livestock frontier, leading to soil exhaustion, the deterioration of crop cultivation, water contamination, a reduction in terrestrial carbon stocks, and an increase in greenhouse gas emissions (LAPOLA *et al*., 2014). The expansion of livestock and agriculture in the Brazilian Amazon has even been seen in areas of environmental protection, including in the state of Acre (PRADO; RIBEIRO, 2011).

It therefore becomes urgent to reduce deforestation, and encourage land use to promote sustainable social and economic development in the Amazonian domain, which can be achieved by encouraging the adoption of agroforestry systems. These land use systems consist in forestry plantations together with farming and livestock activities all in the same area, employing a wide variety of species and ecological interactions (MARTINS; RANIERI, 2014). This affords greater ecological sustainability, due to higher soil fertility compared to other types of land use (CAMARA *et al*., 2020), in addition to commercial and subsistence support for family farmers (VIEIRA *et al*., 2007); this is especially true for the state of Acre, considering the total size of the occupied area and the number of establishments that adopt this type of land use (SCHEMBERGUE *et al*., 2017).

Even so, the best soil quality was not always found in areas of agroforestry systems (CAMARA *et al*., 2020; CORRÊA *et al*., 2019), as there is variation in arrangements, which can be staggered in time and space, such as the number and abundance of temporary and permanent species (VIEIRA *et al*., 2007). Soil quality can be assessed via the chemical, physical, or biological attributes that correlate with nutrient cycling (ARAÚJO *et al*., 2012; OLIVEIRA *et al*., 2015). Such soil attributes are relatively easy to access and circulate among specialists and producers (DORAN; PARKIN, 1996), and depend on factors that are intrinsic to soil formation (ARAÚJO *et al*., 2012) and aspects of the climate and management.

Attributes related to nutrient content and availability, such as the sum of bases (SB: Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}), cation exchange capacity (CEC), phytotoxic elements (Al^{3+}), and soil acidity (pH, H^{+}+Al^{3+}), are among the chemical indicators of soil quality (ARAÚJO *et al*., 2012). Studies of this nature contribute by pointing out attributes that indicate the chemical quality of the soil (ARAÚJO *et al*., 2012), which, if identified as suitable, demonstrate that the management in question favours sustainability of production potential.

The aim of this study was to evaluate the impact of different land use systems on the chemical properties of the soil in the Brazilian Amazon. We tested the hypotheses that chemical attributes might indicate differences between land use systems, and that, in the district of Cruzeiro do Sul, in the state of Acre, the fertility of the soil in the area of agroforestry is similar to that of the soil in the area of native forest.

MATERIAL AND METHODS

Study area

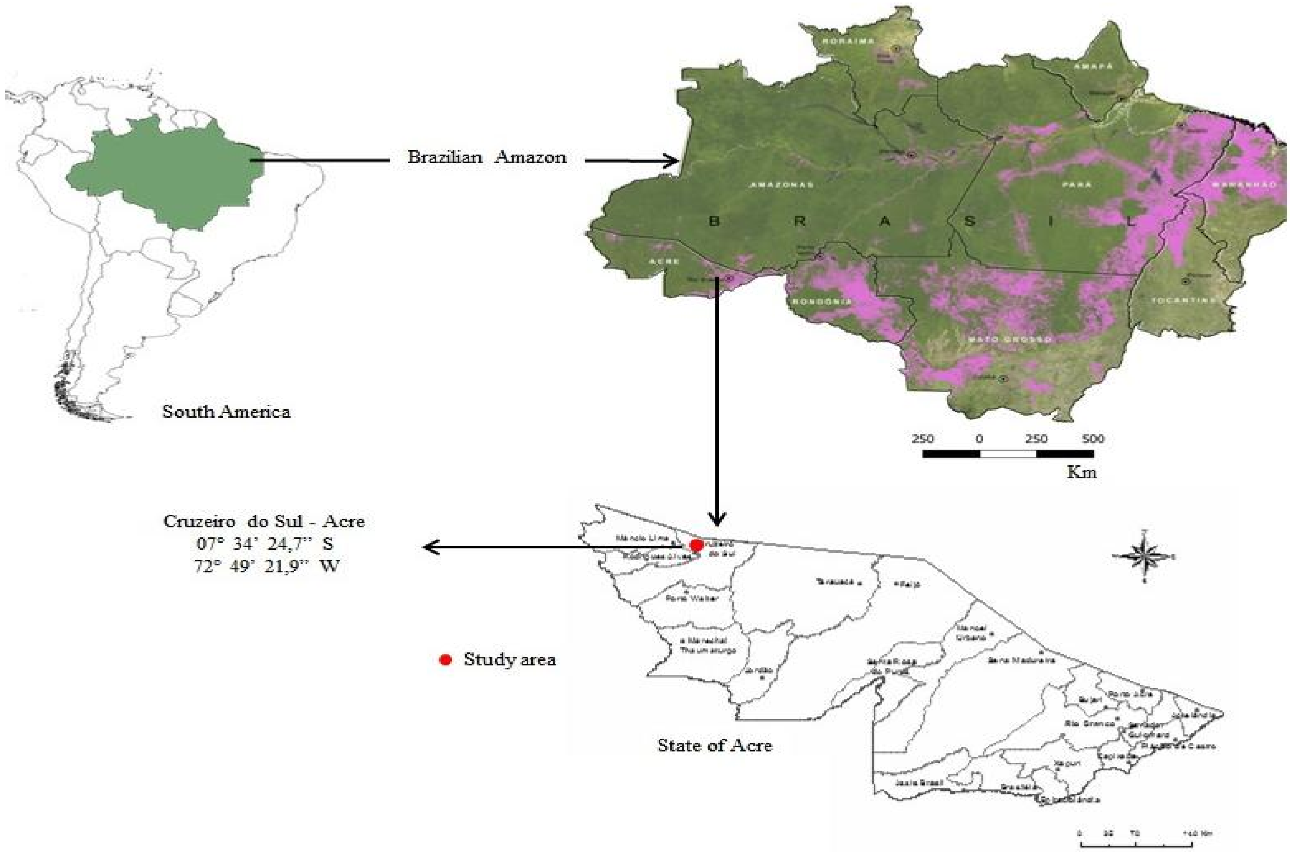
The study area is in the district of Cruzeiro do Sul, the westernmost municipality in Brazil, located in the region of the Juruá Valley, on the banks of the Upper Juruá River, in the state of Acre, bordering Peru to the west and the state of Amazonas to the north, at 7°34’24.7” S and 72°49’21.9” W (Figure 1).

Cruzeiro do Sul is the second largest district in the state (7,781.5 km^2), after the capital Rio Branco. Until the beginning of the 20 th century, rubber extraction was the most prominent economic activity, but currently, cassava flour is the basis of the economy (COSTA *et al*., 2010). The terrain in the region is smoothly undulating, with the original vegetation cover comprising seasonal semideciduous forest. According to the Köppen classification, the climate is type Af, i.e. rainy tropical with no dry season. The region has an average annual temperature of approximately 24.5 °C and average annual rainfall of 2,000 mm, with the driest period from May to September, and a rainy period from October to April (MOREIRA *et al*., 2019).

Areas containing four types of land use were selected for the study: (i) agroforestry system, (ii) cassava cultivation (*Manihot esculenta* Crantz), (iii) pasture, and (iv) native forest. In each of these areas, the soil, which was classified as a Yellow Argisol, is well-drained, is neither stony nor rocky, and shows no apparent erosion. The agroforestry system belongs to the Sítio Progresso Farm (7^{o}34´24.30´´S and 72 49´23.87´´W), a family production unit located on an unpaved road in the Pentecoste Ecological Area, at an altitude of 190 m, with flat terrain.

The agroforestry system has an area of 5.2 ha and was implanted approximately 28 years ago at the initiative of the farmer and his family, with no technical guidance. The area was set up in areas of annual crops (known locally as ‘roças’),

Figure 1 - Localisation of the study area in the district of Cruzeiro do Sul, in the state of Acre, the Brazilian Amazon



employing an intercropping system of perennial species, with no commercial spacing and a high density of *Inga edulis* Mart. This species provides food, the control of spontaneous plants, and perennial green manure, and is characterised by rapid growth in the humid tropics. The slash-and-burn system is not used, and spontaneous plants are controlled by scythe. The agroforestry system is located between 7°34.470' S and 72°49.429' W, and includes 33 species distributed over 19 families, mostly represented by arboreal species (74%) at the expense of the palm (26%) (Table 1).

The species with the greatest relative contribution in the agroforestry system are the avocado (*Persea americana* Mill.), *Inga edulis* Mart, and açaí (*Euterpe precatoria* Mart.), which together represent approximately 64% of all individuals. Under the agroforestry system, annual species, such as the pineapple (*Ananas comosus* (L.) Merr.) and cassava, are grown in cleared areas, following the natural death or cutting down of *Inga edulis* Mart.

Cassava is grown between 7°34.585' S and 72°49.215' W, covers an area of 4.0 ha, and was installed approximately seven years ago in an area of flatly undulating relief at an altitude of 210 m, following the cutting and burning of the native forest. Although cassava farming does not cover the expenses of the farmers, its cultivation stands out among the temporary species of the Brazilian Amazon, as it is a rustic species, easy to grow, a source of food, and generates employment (OLIVEIRA *et al*., 2015; VIEIRA *et al*., 2007). Cassava cultivation in the Brazilian Amazon, which is traditionally implemented under a slash-and-burn system to take advantage of the natural fertility of the soil, aims to meet family consumption, with the surplus destined for the domestic market of the state (VIEIRA *et al*., 2007), in addition to serving as an instrument of cultural reaffirmation of the indigenous and riverine peoples.

The non-degraded area of pasture, which is located between 7°36.702' S and 72°43.214' W and undergoes extensive management, was formed with the installation of *Brachiaria decumbens* Stapf., 25 years after cutting and burning the native forest vegetation in an area of approximately 18.0 ha of flat relief at an altitude of 206 m. According to the history of land use, no pH correctors or soil fertilisers have been used in the area of pasture nor in the area of cassava cultivation.

Table 1 - List of species in the agroforestry system, in the district of Cruzeiro do Sul, in the state of Acre, Brazil

Scientific name	Family	GH	N	RC
Persea americana Mill.	Lauraceae	T	527	28.96
Inga edulis Mart.	Fabaceae	T	336	18.46
Euterpe precatoria Mart.	Arecaceae	P	292	16.04
Cocos nucifera L.	Arecaceae	P	96	5.27
Citrus sp. 1	Rutaceae	T	96	5.27
Pouteria caimito (Ruiz and Pav.) Radlk.	Sapotaceae	T	84	4.62
Bactris gasipaes Kunth	Arecaceae	P	77	4.23
Mangifera indica L.	Anacardiaceae	T	56	3.08
Citrus sp. 2	Rutaceae	T	27	1.48
Theobroma cacao L.	Malvaceae	T	25	1.37
Theobroma subincanum Mart.	Malvaceae	T	22	1.21
Bixa orellana L.	Bixaceae	T	22	1.21
Anacardium occidentale L.	Anacardiaceae	T	18	0.99
Theobroma grandiflorum (Willd. ex Spreng.) K. Schum.	Malvaceae	T	17	0.93
Hevea brasiliensis (Willd. ex A. Juss.) Müll. Arg.	Euphorbiaceae	T	16	0.88
Coffea arabica L.	Rubiaceae	T	15	0.82
Eugenia pyriformis Cambess.	Myrtaceae	T	14	0.77
Carica papaya L.	Caricaceae	T	12	0.66
Syzygium malaccense (L.) Merr. and L. M. Perry	Myrtaceae	T	11	0.60
Mauritia flexuosa L. f.	Arecaceae	P	9	0.49
Annona muricata L.	Annonaceae	T	8	0.44
Psidium guajava L.	Myrtaceae	T	6	0.33
Citrus sp. 3	Rutaceae	T	6	0.33
Artocarpus heterophyllus Lam.	Moraceae	T	5	0.27
Crescentia cujete L.	Bignoniaceae	T	4	0.22
Swietenia macrophylla King	Meliaceae	T	4	0.22
Citrus sp. 4	Rutaceae	T	4	0.22
Rollinia deliciosa Saff.	Annonaceae	T	3	0.16
Citrus sp. 5	Rutaceae	T	3	0.16
Hymenaea courbaril L.	Fabaceae	T	2	0.11
Bertholletia excelsa Bonpl.	Lecythidaceae	T	1	0.05
Citrus sp. 6	Rutaceae	T	1	0.05
Caryocar sp.	Caryocaraceae	T	1	0.05
Total			1,820	100.00

Note: GH - growth habit; T - tree; P – palm; N - number of individuals; RC - relative contribution (%)

The area of native forest, which is considered primary and the reference for original plant cover, is located between 7°34.152’ S and 72°49.408’ W at an altitude of 224 m, and consists of smoothly undulating relief. In the areas of agroforestry, pasture, and native forest, the A horizon is characterised by the abundant presence of fine roots, which reach layers of soil more than 30 cm deep.

Sample collection

We obtained three composite soil samples from a 1.0 ha plot in each land use system. Each sample was formed by a mixture of 10 single samples taken from different layers, at depths of 0-5, 5-10, 10-15, 15-20, 20-30, and 30-40 cm. After collection, the composite soil samples were air-dried, ground, and sieved using a 2.00 mm mesh, resulting in air-dried fine earth, used to characterise the fertility of the soil, which included an analysis of the following chemical attributes: pH in water, exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), available P, Al^{3+}, potential acidity (H^++Al^{3+}), total organic carbon (TOC), total nitrogen (TN), sum of bases (SB), and cation exchange capacity (CEC) (DONAGEMA *et al*., 2011).

We opted to evaluate such chemical attributes of the soil as acidity, nutrient availability, phytotoxic elements (Al^{3+}, for example), and organic matter content, as well as their ratios, expressed by the sum of bases and cation exchange capacity, as they are important for assessing soil quality when comparing different management systems (ARAÚJO *et al*., 2012). We also compared the areas using the ratio between the value of the indicators in each managed system and the value observed in the reference ecosystem, i.e. in the area of native forest (ROCHA *et al*., 2022). The higher this ratio, the greater the sensitivity of the attribute in question to function as an indicator of the changes in soil chemistry in response to the different management systems (ROCHA *et al*., 2022).

Statistical analysis

The data from each level of soil were individually submitted to a simple analysis of variance (One Way ANOVA) to evaluate the effect of the land use system. When there was a significant effect, homogeneity of variance was tested using Levene's test. When this premise was met, the mean values of the treatments were compared using the LSD parametric test, and when the premise was not met, the Kruskal-Wallis non-parametric test was used. Univariate statistical analysis, which considered $p < 0.05$, was carried out with the help of the STATISTICA v8.0 software.

To assist in interpretating the large set of data, principal component multivariate analysis and hierarchical cluster analysis were carried out with the help of the PAST v2.17c software (Oyvind Hammer, Oslo, Norway). The principal component analysis, which is a technique of pattern recognition that reveals the existence or not of relationships considering different areas and a large group of attributes based on linear units of the original attributes, aimed to highlight the soil attributes that contribute more to differentiating each area (SANTOS *et al*., 2015). The hierarchical cluster analysis aimed to estimate dissimilarities between the areas, depending on the influence of the land use system on the soil attributes.

RESULTS AND DISCUSSION

In general, there were no differences between the areas of native forest and pasture, regarding the values for total organic carbon (TOC) in the soil (Table 2). The total organic carbon content (TOC) was higher in the native forest in relation to the area of cassava and the agroforestry system (5-10, 20-30, 30-40, and mean value for 0-40 cm), and higher in the area of pasture, compared to the area of cassava and the agroforestry system (5-10, 10-15, 30-40 cm, and mean value for 0-40 cm, in both comparisons).

Table 2 - Values for pH (H_2O), K^+, Ca^{2+}, Mg^{2+}, Na^+, Al^{3+}, $H^+ + Al^{3+}$, sum of bases (SB), cation exchange capacity (CEC, $cmol_c\ dm^{-3}$), P ($mg\ kg^{-1}$), total organic carbon (TOC, $g\ kg^{-1}$), and total nitrogen (TN, $g\ kg^{-1}$) in the 0-5, 5-10, 10-15, 15-20, 20-30, 30-40, and 0-40 cm layers of soil, the PA/FO, CA/FO, and AFS/FO ratios (0-40 cm) in areas of pasture (PA), cassava cultivation (CA), agroforestry (AFS), and native forest (FO), in the district of Cruzeiro do Sul, state of Acre, Brazil[1]

Chemical attribute	PA	CA	AFS	FO	PA	CA	AFS	FO
	0-5 cm				5-10 cm			
pH	5.29 A (0.65)	5.68 A (0.55)	4.09 B (0.10)	3.66 B (0.16)	4.49 B (0.23)	5.21 A (0.35)	4.01 C (0.05)	3.67 C (0.15)
K^+	0.19 C (0.01)	0.22 B (0.02)	0.20 BC (0.01)	0.27 A (0.01)	0.18 B (0.00)	0.17 B (0.04)	0.17 B (0.02)	0.25 A (0.03)
Ca^{2+}	0.27 C (0.25)	1.47 B (0.32)	0.17 C (0.06)	2.20 A (0.46)	0.13 B (0.06)	0.93 A (0.47)	0.03 B (0.06)	1.13 A (0.21)
Mg^{2+}	1.13 A (0.12)	0.87 A (0.15)	0.43 B (0.06)	1.03 A (0.21)	0.77 B (0.15)	1.10 A (0.17)	0.53 B (0.06)	1.13 A (0.25)
Na^+	0.01 A (0.00)	0.02 A (0.00)	0.02 A (0.00)	0.02 A (0.01)	0.01 B (0.00)	0.01 B (0.00)	0.01 B (0.00)	0.02 A (0.01)
Al^{3+}	0.30 B (0.30)	0.17 B (0.15)	1.37 A (0.15)	1.53 A (0.31)	0.63 C (0.06)	0.30 D (0.00)	1.67 B (0.06)	2.00 A (0.10)
H^++Al^{3+}	3.66 BC (0.83)	2.56 C (1.29)	6.48 A (0.69)	5.85 AB (1.81)	4.73 B (0.95)	2.17 C (0.34)	7.58 A (0.62)	7.08 A (1.20)
SB	1.60 C (0.26)	2.57 B (0.24)	0.82 D (0.09)	3.53 A (0.57)	1.09 B (0.17)	2.22 A (0.62)	0.75 B (0.06)	2.54 A (0.06)
CEC	5.26 B (0.56)	5.12 B (1.34)	7.30 AB (0.78)	9.37 A (2.06)	5.82 B (0.88)	4.39 B (0.64)	8.33 A (0.68)	9.63 A (1.23)
P	4.81 B (0.25)	6.50 B (1.91)	5.24 B (1.29)	10.00 A (1.41)	4.49 A (1.05)	3.38 A (2.15)	4.99 A (0.87)	9.26 A (4.15)
TOC	8.97 A (0.22)	6.64 A (1.01)	8.79 A (4.47)	8.48 A (2.43)	10.40 A (1.74)	7.31 B (1.60)	6.05 B (0.50)	9.85 A (1.06)
TN	1.31 A (0.08)	1.28 A (0.30)	1.04 A (0.18)	1.26 A (0.19)	1.11 A (0.19)	1.09 A (0.15)	1.23 A (0.08)	1.04 A (0.00)

Continuation Table 2

	10-15 cm				15-20 cm			
pH	4.69 AB (0.41)	4.90 A (0.65)	4.12 BC (0.24)	3.71 C (0.02)	4.49 A (0.06)	4.37 A (0.12)	4.11 B (0.22)	3.87 B (0.10)
K^+	0.11 B (0.04)	0.15 B (0.05)	0.12 B (0.01)	0.22 A (0.00)	0.12 A (0.08)	0.12 A (0.02)	0.13 A (0.07)	0.21 A (0.02
Ca^{2+}	0.07 B (0.06)	1.20 A (0.40)	0.07 B (0.06)	1.27 A (0.29	0.03 B (0.06)	0.20 AB (0.10)	0.03 B (0.06)	0.30 A (0.17
Mg^{2+}	0.80 A (0.20)	0.93 A (0.23)	0.60 A (0.10)	1.03 A (0.32)	0.87 A (0.15	0.80 A (0.17)	0.57 A (0.06)	0.77 A (0.40
Na^+	0.00 B (0.00)	0.01 A (0.00)	0.01 A (0.00)	0.01 A (0.00)	0.00 B (0.00)	0.01 A (0.00)	0.01 A (0.00)	0.02 A (0.00)
Al^{3+}	0.57 B (0.21)	0.60 B (0.36)	1.70 A (0.10)	1.90 A (0.10)	0.77 B (0.06)	1.53 AB (0.50)	1.63 AB (0.06)	1.83 A (0.12)
H^++Al^{3+}	3.33 B (1.05)	2.96 B (1.21)	6.73 A (0.60)	6.62 A (0.87)	3.63 B (0.25)	4.43 B (1.06)	7.08 A (0.13)	6.42 A (0.88)
SB	0.98 B (0.24)	2.30 A (0.50)	0.80 B (0.14)	2.53 A (0.35)	1.03 B (0.04)	1.14 AB (0.13)	0.74 C (0.04)	1.30 A (0.25)
CEC	4.31 B (1.00)	5.26 B (1.09)	7.52 A (0.49)	9.15 A (1.17)	4.66 B (0.20)	5.56 B (1.08)	7.82 A (0.11)	7.72 A (1.09)
P	4.43 A (0.18)	3.10 A (1.02)	4.04 A (1.14)	5.86 A (1.60)	3.54 BC (0.37)	3.06 C (0.21)	4.51 A (0.19)	4.11 B (0.68)
TOC	10.75 A (2.16)	6.87 B (1.77)	7.29 B (1.06)	8.91 AB (0.43)	9.60 A (0.68)	7.27 A (1.29)	7.60 A (3.66	7.85 A (0.75)
TN	1.06 A (0.11)	1.40 A (0.34)	1.11 A (0.11)	1.08 A (0.11)	1.16 A (0.15)	0.87 A (0.19)	1.19 A (0.15)	1.20 A (0.15)
	20-30 cm				30-40 cm			
pH	4.62 A (0.05)	4.58 A (0.41)	4.11 B (0.16)	3.92 B (0.04)	4.72 A (0.07)	4.44 AB (0.40)	4.18 B (0.29)	4.02 B (0.12)
K^+	0.16 AB (0.02)	0.12 B (0.02)	0.15 AB (0.03)	0.19 A (0.01)	0.13 A (0.03)	0.13 A (0.02)	0.13 A (0.03)	0.15 A (0.03)
Ca^{2+}	0.00 A (0.00)	0.50 A (0.78)	0.07 A (0.06)	0.47 A (0.55)	0.13 A (0.06)	0.43 A (0.67)	0.00 A (0.00)	0.33 A (0.32)
Mg^{2+}	0.70 AB (0.10	1.30 AB (0.44)	0.50 B (0.10)	1.73 A (0.15)	0.63 A (0.06)	0.97 A (0.72)	0.40 A (0.10)	0.97 A (0.81)
Na^+	0.00 C (0.00)	0.01 B (0.00)	0.02 B (0.00)	0.02 A (0.00)	0.01 B (0.00)	0.01 B (0.00)	0.01 B (0.00)	0.02 A (0.00)
Al^{3+}	0.77 B (0.06)	1.17 AB (0.74)	1.67 A (0.15)	1.87 A (0.15)	0.57 A (0.06)	1.17 A (0.67)	1.37 A (0.23)	1.47 A (0.23)
H^++Al^{3+}	3.71 B (0.08)	4.26 B (1.32)	6.15 A (0.71)	6.26 A (0.72)	3.63 B (0.08)	4.48 B (0.76)	6.15 A (0.45)	5.85 A (0.31)
SB	0.86 B (0.11)	1.94 AB (1.12)	0.73 B (0.09)	2.41 A (0.43)	0.90 A (0.05)	1.54 A (1.36)	0.54 A (0.07)	1.47 A (1.12)
CEC	4.57 C (0.03)	6.20 B (0.74)	6.88 B (0.64)	8.67 A (0.30)	4.53 B (0.04)	6.02 AB (1.18)	6.69 A (0.39)	7.32 A (1.04)
P	3.36 A (0.24)	3.25 A (1.61)	4.23 A (0.93)	3.98 A (0.46)	2.93 B (0.35)	2.35 B (0.67)	3.05 B (0.76)	4.62 A (0.97)
TOC	8.79 AB (0.31)	7.10 BC (0.99	6.32 C (1.95)	9.36 A (0.33)	7.47 A (0.19)	4.44 B (0.25)	5.17 B (0.86)	7.15 A (0.43)
TN	0.97 A (0.11	1.23 A (0.29)	1.14 A (0.11)	1.04 A (0.00)	1.24 A (0.13)	1.23 A (0.29)	1.09 A (0.07)	1.15 A (0.04)
	Mean				PA/FO	CA/FO	AFS/FO	Mean (PA/FO, CA/FO, AFS/FO)
					(0-40 cm)			
pH	4.72 A (0.16)	4.86 A (0.24)	4.10 B (0.12)	3.81 B (0.05)	1.24	1.28	1.08	1.20
K^+	0.15 B (0.01)	0.15 B (0.00)	0.15 B (0.01)	0.22 A (0.01)	0.11	0.83	0.06	0.34
Ca^{2+}	0.11 B (0.07)	0.79 A (0.29)	0.06 B (0.03)	0.95 A (0.17)	0.11	0.83	0.06	0.34
Mg^{2+}	0.82 AB (0.04)	0.99 A (0.22)	0.51 B (0.03)	1.11 A (0.26)	0.74	0.90	0.46	0.70
Na^+	0.00 C (0.00)	0.01 B (0.00)	0.01 B (0.00)	0.02 A (0.00)	0.74	0.90	0.46	0.70
Al^{3+}	0.60 B (0.09)	0.82 B (0.35)	1.57 A (0.09	1.77 A (0.13)	0.34	0.47	0.89	0.56
H^++Al^{3+}	3.78 B (0.39)	3.48 B (0.79)	6.69 A (0.49)	6.35 A (0.79)	0.60	0.55	1.05	0.73
SB	1.08 B (0.27)	1.95 A (0.53)	0.73 B (0.10)	2.30 A (0.82)	0.45	0.87	0.27	0.53
CEC	4.86 B (0.57)	5.43 B (0.66)	7.42 A (0.61)	8.64 A (0.93)	0.65	0.63	0.86	0.71
P	3.93 B (0.28)	3.61 B (0.47)	4.34 B (0.21)	6.30 A (0.64)	0.62	0.57	0.69	0.63
TOC	9.33 A (0.34)	6.61 B (0.68)	6.87 B (0.85)	8.60 A (0.64)	1.09	0.77	0.80	0.88
TN	1.14 A (0.06)	1.18 A (0.15)	1.13 A (0.05)	1.13 A (0.07)	1.00	1.05	1.00	1.02

[1]Mean value of three repetitions. Values followed by different letters indicate significant differences ($p < 0.05$) between areas within the same layer of soil, by the parametric LSD test or non-parametric Kruskal-Wallis test

The greater levels of TOC in the soil under native forest and pasture are due to the continuous input and accumulation of plant residue in the soil (BATTISTI *et al*., 2018). The high levels of TOC in the soil in the areas of pasture, which are comparable to those under native forest, are a consequence of the abundant fasciculate root system (SEGUEL *et al*., 2013), in addition to a high capacity for photosynthetic efficiency, use of nitrogen and use of water, even under low levels of light radiation, atmospheric CO_2, and soil moisture; this is due to the C4 cycle of photosynthetic carbon metabolism in grasses (VISSER *et al*., 2017).

Areas of pasture are an important economic activity in various regions of the country that can efficiently sequester atmospheric carbon when properly managed, in such a way as to completely cover the soil, depending on the period of use and soil properties; this contributes to mitigating concentrations of greenhouse gases (BAYER; BATJES; BINDRABAN, 2010), which is one advantage of pastures in recovering TOC in the soil. On the other hand, degraded pastures function as a source of greenhouse gases, whose recovery demands high investment in fertilisation, which can be financially unviable, in addition to some inputs used in fertilisation possibly acting as gas-release agents (BERNOUX *et al*., 2003).

We registered higher values for Ca^{2+} in the native forest than in the areas of agroforestry and pasture (down to the 0-20 cm layer, and mean value for the 0-40 cm layer), higher values for Mg^{2+} compared to the area of agroforestry (down to 0.10 cm, 20-30 cm, and mean value for 0-40 cm), and higher values for K^{+} compared to the areas of cassava cultivation (0-5, 15-20, 30-40 cm, and mean value for 0-40 cm), pasture and the agroforestry system (down to the 15 cm layer, and mean value for 0-40 cm, in both comparisons) (Table 2). We also recorded higher values for Na^{+} in the native forest compared to the areas of pasture (from 5-40 cm and mean value for 0-40 cm), cassava cultivation, and the agroforestry system (for both land use systems, in the 5-10, 20-30, and 30-40 cm layers, and mean value for 0-40 cm), and higher values for P compared to the areas of cassava and pasture (0-5, 15-20, 30-40 cm, and mean value for 0-40 cm, in both comparisons).

A higher P content in the soil (0-20 cm) was also registered in an area of native forest, compared to the agroforestry system and the area of subsistence agricultural cultivation, which had been planted over two consecutive years with cassava, rice (*Oryza sativa* L.), and maize (*Zea mays* L.) on a rural property located in a rural settlement, six kilometres from the district of Esperantina, in the Cerrado biome of the state of Tocantins (COLLIER; ARAÚJO, 2010). This pattern may be due to the contribution of a more diversified litterfall, and may indicate fewer losses and less extraction of the element by the vegetation (COLLIER; ARAÚJO, 2010).

Higher values for SB were found in the native forest, in relation to all of the other areas (0-5 cm) and areas of agroforestry and pasture (5-10, 10-15, 15-20, 20-30, and mean value for 0-40 cm) (Table 2). In terms of CEC, higher values were found in the native forest, compared to areas of cassava cultivation and pasture (0-5, 5-10, 10-15, 15-20, 20-30, and mean value for 0-40 cm), with no differences between the areas of native forest and the agroforestry system. In the native forest, the higher levels of Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} led to higher values for both SB and CEC in the soil, compared to the other land use systems.

Soils developed under a tropical climate generally present low natural fertility due to weathering of the parent material together with the high leaching of cations, indicating that nutrient availability depends basically on litterfall (MARTINS *et al*., 2018). The higher fertility of the soil (SB and P) in the area of native forest underlines the importance of the nutrient-cycling process, which involves the mineralisation of the elements contained in the shoot and root litter during decomposition. The higher values for CEC in the area of native forest and the agroforestry system compared to the soil in the agricultural areas, which were also recorded in the district of Esperantina, are due to greater efficiency of the charge-exchange reactions and contact with nutrients arranged in deeper layers of the soil, promoted by the root system of trees, a fact that favours nutrient cycling (IWATA *et al*., 2012).

Higher values for Al^{3+} were found in the native forest compared to the areas of pasture (up to 30 cm and mean value for 0-40 cm) and cassava (down to 0.15 m and mean value for 0-40 cm) (Table 2). The values for $H^{+}+Al^{3+}$ were higher in the area of agroforestry, compared to the areas of pasture and cassava cultivation (up to 0.40 cm and mean value for 0-40 cm). In general, there was no difference between the area of native forest and the agroforestry system regarding the values for both Al^{3+} and $H^{+}+Al^{3+}$ in the soil. This pattern is believed to be consistent with the fact that the dissociation of acidic groups from organic matter can increase $H^{+}+Al^{3+}$ values in the soil, especially when pH values are low (BROQUEN *et al*., 2013), as we observed in both the agroforestry system and area of native forest.

The pH values were higher in the area of cassava cultivation compared to the agroforestry system and area of native forest (to a depth of 30 cm and mean value for 0-40 cm) (Table 2). Association of the area of cassava with higher pH values was probably caused by the maintenance of plant residue from earlier crops, which helps the release of bases (Ca^{2+} and Mg^{2+}) to the soil during mineralisation (CORRÊA *et al*., 2019) since there had been no liming.

There was no effect from the type of land use system for the total N content of the soil in any of the layers (Table 2). It was expected that the total nitrogen content of the soil would be lower in the areas of forest and pasture where a higher carbon content was found, compared to the soil in the area of cassava and the agroforestry system. Generally, higher levels of carbon denote more energy available for the microbial community of the soil, which results in an increase in activity and, as a result, in the immobilisation of nitrogen by microorganisms (DVOŘÁČKOVÁ *et al*., 2018).

The lack of any difference between land use systems in relation to the total N content is probably due to the low values of this nutrient in the soil in the form of nitrate (NO^{3-}), which is the most oxidised and available form of N for uptake by plants in non-flooded soils. Nitrate is quickly lost from more superficial soil layers by leaching to underground aquifers under intense rainfall, a process that is enhanced by increased water percolation in sandy soils, conditions that commonly occur in the Amazon region (NAKAGAWA *et al*., 2012). The low values for total N content in the soil may also be due to volatilisation and denitrification (PÉREZ; TORRES-BAZURTO, 2020).

In general, the mean value for the ratio calculated between the chemical attributes of the soil (0-40 cm) in the managed areas (agroforestry system, cassava cultivation and non-degraded pasture) and in the area of native forest (reference area) was less than 1.0 (Table 2). This overall pattern therefore indicates that the value of most of the chemical attributes of the soil tended to be higher in the area of native forest.

On the other hand, the value of this ratio was greater than or equal to 1.0 in the soil (0-40 cm) of each of the managed areas (agroforestry system, non-degraded pasture, and cassava cultivation) with regard to pH and total N content, for H^{+}+Al^{3+} in the agroforestry system, and for total carbon content in the area of pasture (Table 2). The most marked difference between the overall mean value of the ratio obtained for all of the managed areas (Table 2) and the value for the native forest (1.0) indicated that exchangeable K^{+} and Ca^{2+} (-0.66, for both) and sum of bases (-0.47) were the most sensitive chemical attributes to changes caused in the soil (0-40 cm) by the type of management system (ROCHA *et al*., 2022).

Principal component analysis showed how the areas are ordered, using the relation between Principal Component 1 (PC1) and Principal Component 2 (PC2) (Figures 2A and 2B). The area of pasture was positioned on the extreme left (negative eigenvectors) of PC1, which explained a greater proportion of the variability of the results (Table 3), followed by the area of cassava cultivation, also on the left, with the agroforestry system occupying the intermediate position close to the junction between PC1 and PC2; the area of native forest was positioned on the extreme right of PC1 (positive eigenvectors).

The vectors for the attributes Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, SB, P, and TOC pointed to the area of native forest, while the vectors for Al^{3+}, H^{+}+Al^{3+}, and CEC pointed to the areas of native forest and/or agroforestry (Figures 2A and 2B), while the vectors for pH and TN pointed to the area of cassava cultivation. The vectors for Ca^{2+}, SB, and Mg^{2+} pointed in the same direction and practically overlapped to form a very sharp angle. This same pattern was seen for Na^{+} and K^{+}, whose vectors also pointed in the same direction, practically overlapped, and formed a sharp angle. This pattern for the chemical attributes of the soil, pointing in the same direction and again almost overlapping (to form sharp angles), was expected due to the high positive correlation between them. In contrast, the vector for pH was presented in the opposite direction to that of Al^{3+} and H^{+}+ Al^{3+} which confirmed the high negative correlation between these attributes.

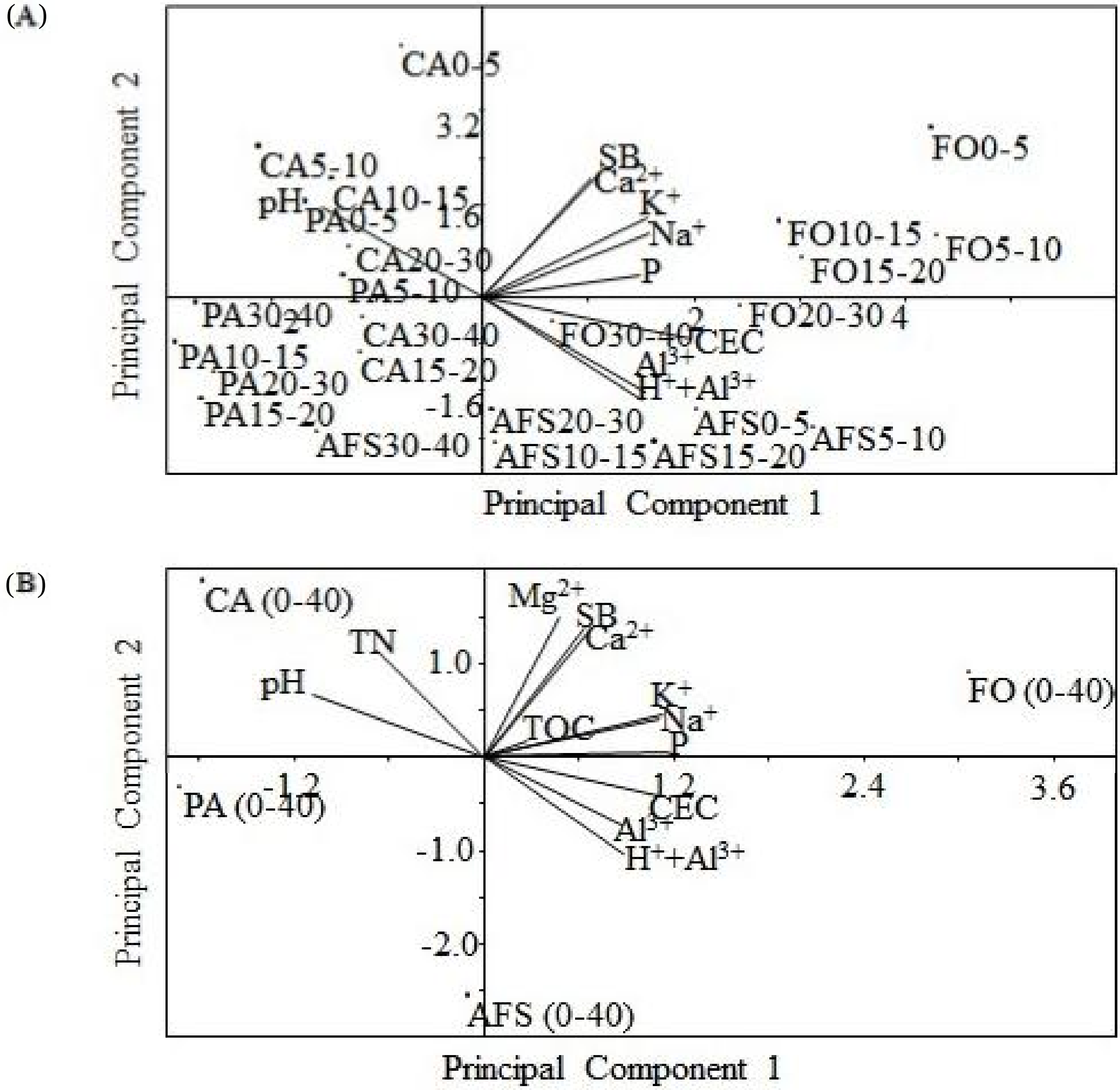
The association of the soil in the agroforestry system with higher values for H^{+}+Al^{3+}, indicated by principal component analysis, was also found in the south of the state of Amazonas between the districts of Manicoré and Humaitá, where an agroforestry system was compared to archaeological black earth, native forest, pasture, and sugar cane and cassava plantations (OLIVEIRA *et al*., 2015). Higher values for H^{+}+Al^{3+} in the soil, which were also recorded in an area under an agroforestry system compared to areas of native forest or subsistence cassava farming intercropped with corn and rice (COLLIER; ARAÚJO, 2010), are probably a consequence of the litterfall having a high rate of decomposition, especially when dealing with sandy soils (COLLIER; ARAÚJO, 2010), as in the present study.

The principal component analysis revealed that the chemical attributes TOC and TN presented eigenvectors (correlation coefficients) that were considered non-significant (< 0.70) for PC1 or PC2, for each of the individual layers of soil (A) and the calculated mean value for 0-40 cm (Table 3). In contrast, the chemical attributes CEC, pH, K^{+}, Na^{+}, and P presented higher values for the eigenvectors with Principal Component 1 (> 0.90).

This result suggests that these five chemical attributes were the most relevant for recognising patterns, and could be identified as indicators of the effect of the land use systems on the soil in the study area to a depth of 40 cm. The availability of nutrients, such as exchangeable K and available P, is important to assess soil quality between different management systems (ARAÚJO *et al*., 2012), due to correlation with the functionality of the ecosystem and susceptibility to variations in management (DORAN; PARKIN, 1996).

Therefore, as TOC and TN were considered soil chemical attributes of low relevance in the individualization of the areas among themselves, its evaluation can be disregarded low relevance, and their evaluation can be disregarded. In this way, a smaller number of variables was necessary to explain the total variation of the obtained results. This procedure could result in savings in time and economic resources, with no significant loss of information, especially in terms of reducing costs with chemical analyses of soil samples in future studies that use this same database and are conducted under similar conditions to those of the present study (HONGYU; SANDANIELO; OLIVEIRA JUNIOR, 2015).

Figure 2 - Multivariate analysis of principal components for the chemical attributes of the soil in the 0-5, 5-10, 10-15, 15-20, 20-30 and 30-40 cm layers (A), and mean value for 0-40 cm (B), in the areas of pasture (PA), cassava cultivation (CA), agroforestry (AFS), and native forest (FO), in the district of Cruzeiro do Sul, state of Acre, Brazil. TOC: total organic carbon, TN: total nitrogen, SB: sum of bases, CEC: cation exchange capacity



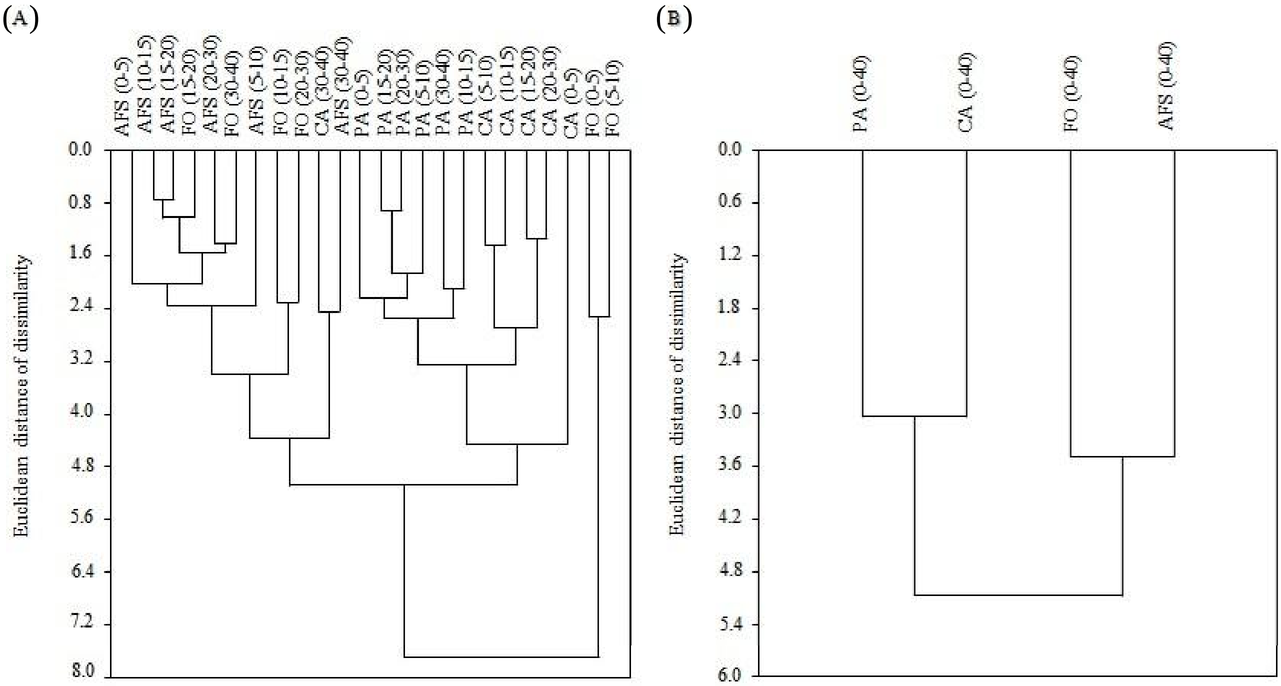
From the hierarchical cluster analysis, considering the chemical attributes in each of the soil layers, the formation of two large dissimilar clusters could be identified, which were divided into subgroups (Figure 3A). The first large group was formed from only the most superficial layers of soil (0-5 and 5-10 cm) in the area of forest, which was distanced from the second large group, formed by deeper soil layers in the area of forest (10-15, 15-20, 20-30 and 30-40 cm), and all the soil layers in the areas of agroforestry, pasture, and cassava, by a distance of dissimilarity of approximately 8.0.

This second group comprised two subgroups, one of which was represented by the areas of pasture and cassava, linked by a distance of dissimilarity of approximately 5.0 to the other subgroup, represented by the agroforestry system and remaining layers of soil deeper than 10 cm in the area of native forest.

Table 3 - Eigenvector of the chemical attributes of the soil in Principal Components 1 and 2, eigenvalue, proportion of variance of PC1 and PC2, and total variance explained by the principal component analysis for each individual soil layer (A), with the calculated mean value for 0-40 cm (B)

Chemical attribute of the soil	A		B	
	PC1	PC2	PC1	PC2
pH	-0.71	0.62	-0.91	0.41
Ca^{2+}	0.58	0.72	0.54	0.79
Mg^{2+}	0.29	0.56	0.40	0.91
K^{+}	0.79	0.41	0.95	0.27
Na^{+}	0.72	0.07	0.95	0.27
Al^{3+}	0.71	-0.64	0.87	-0.36
H^{+}+Al^{3+}	0.68	-0.70	0.75	-0.63
P	0.80	0.29	0.99	0.02
TOC	0.16	0.17	0.22	0.07
TN	-0.03	0.46	-0.57	0.69
SB	0.59	0.76	0.53	0.84
CEC	0.93	0.31	0.93	-0.26
Eigenvalue	4.89	3.28	6.91	3.55
Proportion of variance	40.77	27.30	57.61	29.56
Total variance	68.08		87.16	

Figure 3 - Multivariate analysis of hierarchical clustering for the chemical attributes of the soil in the 0-5, 5-10, 10-15, 15-20, 20-30 and 30-40 cm layers (A) and mean value for 0-40 cm (B), in the areas of pasture (PA), cassava cultivation (CA), agroforestry (AFS), and native forest (FO), in the district of Cruzeiro do Sul, state of Acre, Brazil



According to the hierarchical cluster analysis involving the mean value for the chemical attributes in the 0-40 cm layer of soil, two groups were identified, which were linked to each other by a distance of dissimilarity of approximately 5.0 (Figure 3B). One group was represented by the area of native forest and the agroforestry system, while the second group was formed from the areas of pasture and cassava. As these are cultivated environments, the areas of cassava and pasture can be classified into homogeneous groups, since their soil chemical attributes are similar (OLIVEIRA *et al*., 2015).

Nutrient cycling is more efficient in areas where the plant community presents greater species richness and diversity, because of a high continuous and heterogeneous litterfall that increases the activity of the decomposing microbiota (CEZAR *et al*., 2015; FREITAS *et al*., 2018). Soil fertility is therefore higher in areas such as agroforestry systems (CAMARA *et al*., 2020), and can be similar to that in native areas of forest (CEZAR *et al*., 2015). In this study, the agroforestry system comprises 33 species; this results in ecological interactions between plant species (MARTINS; RANIERI, 2014) and their contribution to a heterogenous litterfall, which probable functioned as a conditioning agent for the higher values for the sum of bases, cation exchange capacity, and available P, pointing to the greater ecological sustainability of the present agroforestry system compared to the managed areas (cassava cultivation and pasture). As a result, the farmers consider that the main advantages of agroforestry systems are better soil protection, less damage to the environment, quality food, and food security, which helps increase the monthly family income (LUCENA; LIMA; BAKKE, 2023).

The process of improving the chemical quality of the soil increases with the time of the agroforestry systems, as the availability of soil organic matter becomes greater (IWATA *et al*., 2012) and is more marked when their composition includes an abundance of native species (MARTINS; RANIERI, 2014), compared to those systems with less species richness (SANTIAGO *et al*., 2013) and to other types of land use (FREITAS *et al*., 2018). This set of characteristics, together with the increasing value of land in districts where these systems are used (SCHEMBERGUE *et al*., 2017), and the guarantee of food security for producers, justifies the installation of agroforestry systems (FREITAS *et al*., 2018), including as a strategic alternative to the recovery of protected rural areas for small producers who are not yet in compliance with the Law (MARTINS; RANIERI, 2014). Therefore, cassava cultivation can be inserted in multistrata agroforestry systems to allow family farmers to have an income from different species and products throughout the year (VIEIRA *et al*., 2007).

CONCLUSIONS

The type of land use affected the chemical attributes of the soil. Principal component analysis revealed that neither total organic carbon nor the total nitrogen content helped differentiate between land use systems, whereas the chemical attributes CEC, pH, K^+, Na^+, and available P were the most relevant in indicating the effect of land use systems on the soil (down to 40 cm) in the study area. Despite the native forest presenting greater soil fertility (SB, CEC, available P) to a depth of 0.40 m, hierarchical cluster analysis indicated that this land use system presented lower dissimilarity in relation to the agroforestry system when compared to the areas of cassava and pasture, in the mesoregion of the Juruá Valley, in the state of Acre.

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