Journal of Sustainable Development; Vol. 16, No. 4; 2023
ISSN 1913-9063 E-ISSN 1913-9071
Published by Canadian Center of Science and Education

Impacts of Forest-Agriculture Conversion on Soil Physical-Water Attributes in Amazon Basin, Southeastern Brazil

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Received: April 7, 2023 Accepted: May 30, 2023 Online Published: June 1, 2023

doi:10.5539/jsd.v16n4p66 URL: https://doi.org/10.5539/jsd.v16n4p66

Abstract

Several studies have shown that negative changes in physical attributes affect root growth and plant development. Thus, the objective of this work was to evaluate the impacts of forest-agricultural conversion on the physical-water attributes of the soil in the Amazon basin, southeastern Brazil. The study was carried out in Canutama - AM, in which areas of annatto, cupuaçu and guarana cultivation and a forest area were selected. Meshes of 90 m x 70 m, 90 m x 56 m and 54 m x 42 m were established, comprising 80 sampling points per layer. The points were georeferenced and the undisturbed soil samples were collected in volumetric rings to determine the physical and hydric attributes. data were submitted to descriptive statistics and multivariate analysis. It was observed that aspects such as the implementation time of the different use and occupation systems can be controlling factors for the restoration of these physical properties.

Keywords: Amazon rain forest, use and management, physical attributes

1. Introduction

The changes promoted by anthropic actions have caused serious environmental problems, such as the reduction of biodiversity and the degradation of the soil and water. The Amazon region is located in the northern part of South America with about 6 million km². In this region, the Amazon Biome is characterized by being a very extensive region, with high geological, geomorphological, edaphic, climatic and vegetation diversity (Fonseca et al, 2021).

Studies have shown the importance of the soil physical attributes in the growth of the root system of the most varied crops, affecting the plant development (Lima et al., 2022). This fact is mainly due to physical variables related to the pore space of the soil and the presence of moisture, as processes such as infiltration and storage of water in the soil are essential for the supply of water throughout the crop cycle. On the other hand, the increase in soil density, resistance to root penetration and relative microporosity (Lima et al, 2021) limit the plant root growth and, at the same time, decrease the availability of water and oxygen in the soil, resulting in the reduction of the crop productivity, especially under conditions of excess or water deficit (Reichert et al, 2009; Tavares Filho et al, 2010).

Different management practices can result in the compaction of deep soil layers, changing the behavior of infiltration and the water runoff, which can cause soil erosion (Pantoja et al, 2019; Souza et al, 2023). In compacted soils, there is a change in the structure and, consequently, an increase in the soil resistance to penetration and soil density and, in turn, a decrease in porosity, macroporosity, availability of water and nutrients and diffusion of gases in the soil (Frozzi et al, 2020), which relationships with root development are fundamental.

On the other hand, it is essential to use tools capable of explaining the intercorrelations between the variables and discovering which of them contribute more to the characterization and/or alteration of the soil attributes. Thus, the use of multivariate analysis allows for a simultaneous analysis of several parameters, helping to interpret the results and to make decisions about the proper use and the management of the soil (Souza et al., 2020). In this context, several works, such as those developed by Souza et al. (2020), Enck et al. (2022), Aquino et al. (2016), Brito et al.

(2022) and Oliveira et al. (2017), relate the soil attributes to factors related to the agricultural production. Thus, the objective of this work was to evaluate the impacts of forest agricultural use conversion on the physical-water attributes in southeastern Amazonas state, Brazil.

2. Method

2.1 Location and Characterization of the Study Area

The study was carried out in rural properties that are part of the São Francisco settlement located in the municipality of Canutama, Amazonas, Brazil under geographic coordinates (8º 11’ 22’’ S; 64º 00’ 83’’ W). Four areas were selected, three areas under different uses with cultivation of urucum (*Bixa orellana* L.), cupuaçu (*Theobroma grandiflorum* (Willd. ex. Spreng) Schum) and guaraná (*Paullinia cupana* (Mart.) Ducke) and more areas under forest (Figure 1).

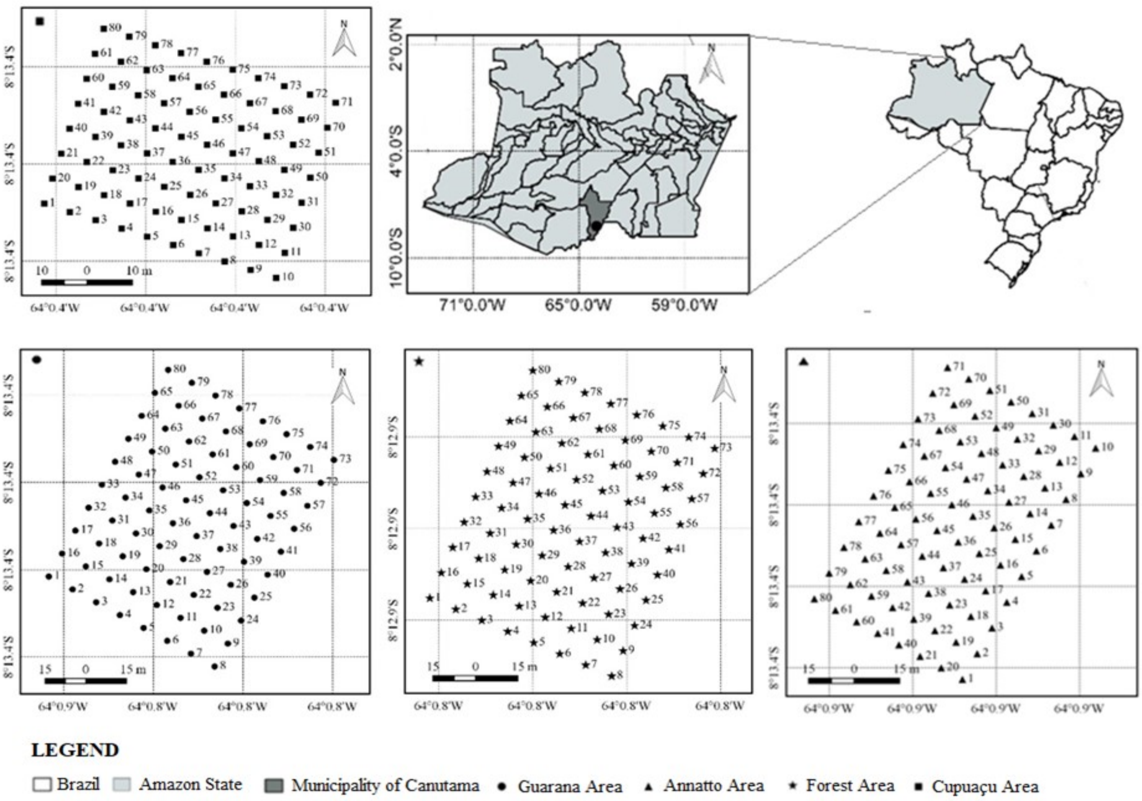

Figure 1. Location and digital elevation model of areas with guaraná, cupuaçu, urucum and forest, in the municipality of Canutama, southern Amazonas state

Source: Author (2023)

The region's climate is Tropical Rainy, with a dry period of short duration. The average partial rainfall varies between 2250 and 2750 mm per year, with a rainy period between October and June. The annual average temperatures vary between 25 and 27ºC and the relative humidity is between 85 and 90% (Brasil, 1978). Soil classification followed the criteria as Argissolo Vermelho Amarelo established by the Brazilian Soil Classification System (Santos et al. 2018) and Ultisols the World Reference Base of Soils (IUSS Working Group WRB 2015). Located on the Amazon Plain between the Purus and Madeira rivers, it is associated with alluvial sediments from the Quaternary period. Regarding to the chemical characteristics present in the Amazonian Ultisols, according to Teixeira et al. (2017) are highly variable, for the most part, presenting an extremely to moderately acidic reaction.

Regarding the history of the areas under study, the following information is verified:

a) Guaraná area: it has been cultivated for seven (07) years, coming from the felling and burning of the forest, with consequent manual logging to clear the area in the first year of cultivation, with no type of fertilization and liming in the area, weed control is only carried out using a motorized mower, in addition to spraying with glyphosate herbicides to control the thatch (*Imperata brasiliensis*).

b) Cupuaçu area: for seven (07) years under cupuaçu cultivation, the forest was initially cut down and burned, with subsequent manual logging to clean the area in the first year of cultivation, no fertilization and liming was carried out, weed control is carried out with a motorized mower, in addition to spraying with glyphosate herbicides to control the thatch (*Imperata brasiliensis*).

c) Annatto area: area cultivated with Annatto in the last three (03) years, after felling, forest burning, manual logging and cleaning in the first year of cultivation. There is no fertilization and liming, only weed control with a motorized mower and spraying with glyphosate herbicides to control the thatch (*Imperata brasiliensis*).

d) Forest area: for comparison purposes, a forest area was selected as a tropical rainforest. Its vegetation is evergreen, characterized by the presence of phanerophytes (plants which the renewal buds are more than 25 cm from the ground), in addition to being composed of dense and multi-layered trees between 20 and 50 meters in height.

2.2 Field Methodology

The sample collection was carried out during the period of low rainfall, so that for each area, grids of 90 mx 70 m were established with regular spacing of 10 m for guaraná and forest, 90 mx 56 m with regular spacing of 10 x 8 m for Annatto and 54 mx 42 m with regular spacing of 6 m between the sampling points for cupuaçu. The soils were sampled at the grid crossing points, under layers of 0.00-0.05; 0.05-0.10; and 0.10-0.20 m in depth, comprising 80 sampling points per layer and totaling 240 samples per area. The points were georeferenced with a Garmin GPS equipment model Etrex (Datum South American´69).

2.3 Laboratory Determinations and Analysis

At each sampling point, the soil samples were collected. Afterwards, they were dried in the shade and crushed manually, passing them through a sieve with a diameter of 2.00 mm. Then, the particle size analysis was carried out using the pipette method, with a 1 mol L^{-1} NaOH solution as chemical dispersant and mechanical agitation in a high-speed stirrer for 15 minutes. The sand was separated by sieving and the clay and silt were separated by sedimentation (Teixeira et al, 2017).

In addition, undisturbed samples were collected in volumetric rings measuring 4.0 cm in height and 5.1 cm in internal diameter, specifically in the three layers evaluated, so the respective samples were used for the determination of soil density (Ds), macroporosity (MaP) and microporosity (MiP) and total pore volume (VTP). Undisturbed samples were saturated by gradually raising, up to two-thirds of the height of the ring, a sheet of water in a plastic container. After the saturation, the samples were weighed and taken to the tension table to determine the soil MiP, being subjected to a tension of -0.006 Mpa.

Afterwards, the samples were taken to an oven at 105ºC to determine the volumetric humidity, Ds and VTP, using the volumetric ring method. The MaP, on the other hand, was determined by the difference between VTP and MiP (Teixeira et al, 2017).

Along with the criterion of establishing critical limits of Ds, the Equation defined in Jones (1983) was used, thus fixing the critical range of Ds associated with the clay content (Equation 1).

$$Dsc = 1,77 - 0,00063 * Argila \tag{1}$$

Where: Dsc = Critical soil density.

2.4 Statistical Analysis

After obtaining the data of physical-water attributes, the descriptive statistical analyzes were performed, calculating the mean, median, standard deviation, coefficient of variation, coefficient of asymmetry and coefficient of kurtosis. The hypothesis of data normality was tested using the Kolmogorov-Smirnov test, using the Minitab 17 statistical software.

Subsequently, the univariate analysis of variance was performed to verify whether 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% probability, using the software SPSS 21 (SPSS, 2001).

The multivariate analyzes were carried out by the factor analysis of the principal components (PCA), which were carried out in order to find the statistical significance of the sets of soil attributes that most discriminate the environments, in relation to the different areas under study, obtaining the answer which they are the environments which attributes are more influenced by the anthropic action.

The suitability of the factor analysis was performed by the Kaiser-Meyer-Olkin (KMO) measure, which assesses the simple and partial correlations of the variables, and by the Bartlett sphericity test, which is intended to reject the equality between the correlation matrix with the identity. The extraction of factors will be performed by the principal component analysis, incorporating variables that have commonalities equal to or greater than five (5.0). The choice of the number of factors to be used was made using the Kaiser criterion (factors with eigenvalues greater than 1.0). In order to simplify the factor analysis, the orthogonal rotation (varimax) was performed and represented in a factorial plane of the variables and scores for the main components.

In PCA scatter plots after varimax rotation, scores were constructed with standardized values, such that the mean is zero and the distance between scores is measured in terms of standard deviation. Thus, the variables in the same quadrant (1st, 2nd, 3rd and 4th) and closer together in the PCA scatter plot are better correlated. Likewise, scores assigned to samples that are close together and in the same quadrant are related to the variables in that quadrant (Jordão et al., 2021).

3. Results and Discussion

The texture was sufficiently homogeneous between the conditions of use, ranging from loam to silty loam, assuming that the areas developed in the same source material and under the same pedogenetic conditions. This allowed the comparison between soils in terms of their physical-hydric properties, while attributing the differences to changes in land use and management. The subsurface clay contents varied significantly between the studied conditions of use.

The removal of natural vegetation for the establishment and implementation of new agricultural activities in the Amazon context is something very common and a destabilizing factor for the physical properties of the soil. By the values of soil density, it is possible to observe such variations that result from these changes, mainly comparing the two extremes forest (Ds = 0.87 g cm-3) and guaraná (Ds = 1.10 g cm-3) in the layer of 0.0-0.05 m (Table 1). Also considering the Ds in the surface layer, the forest area is similar to the cupuaçu cultivation system (Ds = 0.91 g cm-3), an evident factor due to the high input of organic residues that favor the maintenance of cover to the soil, and consequently, alteration in the physicochemical structure of the soil. The other areas, guaraná and urucum, show similarities around the distribution ranges, an evident factor due to the low soil coverage by these crops.

In the 0.05-0.10 m and 0.10-0.20 m layers, the effect of Ds as a function of the reduction in MOS levels leads to a minimal decrease in variations, thus showing that in the Amazonian environments, the effect of MOS reduction, does not tend to be so evident in depth as to have severe impacts on DS. Thus, soil disturbance, right after the native vegetation removal phase, can increase this physical property and, therefore, the soil compaction (Afzalinia; Zabihi, 2014; Salem et al, 2015).

According to the variations in Ds, the reflection in macroporosity (MaP) is clear once it is a highly correlated physical attribute. Thus, in the cultivation system with guaraná, the MaP ranged from 0.09 $m^{-3}m^{-3}$ (0.0-0.05 m) and 0.10 m^{-3} m^{-3} (0.0-0.10 m) 0.10-0.20 m) (Tables 1, 2 and 3). On the surface, the variation was the same for forest, cupuaçu and urucum (0.15 m^{-3} m^{-3}). However, the variation in MaP is evidenced at a depth of 0.05-0.10 m, with values ranging between 0.10 $m^{-3}m^{-3}$ for guaraná and urucum, and 0.13 m^{-3} m^{-3} and 0 .17 $m^{-3}m^{-3}$, respectively for cupuaçu and forest (Table 2). For the 0.10-0.20 m layer (Table 3), the values conflict, being the forest area with the greatest variations around this physical attribute. Therefore, the loss of macroporosity in converted agricultural soils is probably more influenced by the lack of vegetation cover and crop root systems or by the time or effect of resilience (Fraiser et al, 2017).

Table 1. Descriptive statistics and mean test of forest-agriculture conversion on soil physical attributes in 0.00-0.05 m layers in Canutama, Amazonas state, Brazil

Parameters	**Ds**	**MaP**	**MiP**	**Pt**	**Θv**	**Silt**	**Clay**	**Sand**
	g cm^{-3}	------------------- m^{-3} m^{-3}			------------------	--------------- g.kg^{-1}		--------------------
				Guaraná				
Me	1,10**a**	0,09**b**	0,37**a**	0,46**a**	0,36**a**	392,0**a**	215,4a	392,6**a**
Md	1,10	0,09	0,37	0,46	0,37	392	216	390
DP	0,10	0,02	0,04	0,04	0,04	40,6	32,04	48,0
CV%	9,5	26,9	12,2	8,6	12,4	10,4	14,9	12,30
Assim	-0,19	0,72	0,05	0,54	-0,08	0,22	-0,45	0,08
Curt.	-0,22	1,42	-0,19	0,42	-0,75	-0,30	-0,05	-0,53
K-S	0,05*	0,05*	0,07*	0,07*	0,08*	0,09*	0,13*	0,06*
				Urucum				
Me	0,99**b**	0,15**a**	0,35**b**	0,50**a**	0,35**a**	445,3**a**	177,6b	377,1**b**
Md	1,00	0,14	0,35	0,47	0,35	442,3	175,6	375,1
DP	0,14	0,05	0,03	0,05	0,04	56,1	40,3	51,9
CV%	14,4	35,1	9,75	10,9	12,7	12,7	22,9	13,9
Assim	0,03	0,85	0,19	-1,05	0,75	0,25	-0,11	0,57
Curt.	0,81	0,17	1,03	4,56	2,89	0,04	-1,04	-0,43
K-S	0,06*	0,12*	0,09*	0,07*	0,08*	0,10*	0,12*	0,10*
				Cupuaçu				
Me	0,91**c**	0,15**a**	0,27**c**	0,42**b**	0,28**b**	520,5**a**	215,7a	263,8**b**
Md	0,92	0,16	0,27	0,40	0,28	519,6	209,2	265,5
DP	0,10	0,04	0,04	0,04	0,05	43,0	33,4	34,2
CV%	10,8	26,5	15,6	11,0	18,8	8,28	15,5	13,0
Assim	-0,25	0,08	-0,07	0,32	0,48	0,13	-0,01	0,24
Curt.	-0,11	-0,33	-0,54	-0,16	0,85	-0,38	-0,33	-0,83
K-S	0,06*	0,06*	0,05*	0,08*	0,06*	0,04*	0,14*	0,09*
				Forest				
Me	0,87**c**	0,15**a**	0,34**b**	0,49**a**	0,36**a**	526,0**a**	215,0a	259,0**b**
Md	0,87	0,15	0,35	0,48	0,36	529	215,4	252
DP	0,13	0,05	0,05	0,07	0,06	37,5	32,0	26,1
CV%	15,4	35,7	13,7	14,8	16,0	7,09	14,8	10,5
Assim	0,14	0,25	-0,19	-0,93	-0,12	-0,02	-0,59	0,03
Curt.	0,16	-0,55	-0,69	1,27	-0,15	0,83	0,98	0,13
K-S	0,07*	0,07*	0,08*	0,09*	0,07*	0,07*	0,15*	0,07*

Ds: Soil density; MaP: Macroporosity; MiP: Microporosity; Pt: total porosity; Θv: Volumetric Humidity; Me.: average; Md.: median; SD: standard deviation; CV: coefficient of variation; Thus.: asymmetry; Curt. Kurtosis; K-S: Kolmogorov-Smirnov normality test, *significant at 5% probability; means followed by the same letter in the column do not differ statistically (Tukey $p < 0.05$).

Table 2. Descriptive statistics and mean test of forest-agriculture conversion on soil physical attributes in 0.05-0.10 m layers in Canutama, Amazonas state, Brazil

Parameters	Ds	MaP	MiP	Pt	Θv	Silt	Clay	Sand
	g cm^{-3}	------------------- m^{-3} m^{-3} ------------------				------------- $g.kg^{-1}$ --------------------		
Guaraná								
Me	1,12**a**	0,10**c**	0,36**a**	0,46**b**	0,36**a**	412,3**a**	224,1**c**	363,6**b**
Md	1,11	0,09	0,36	0,45	0,36	407,2	228,7	357,3
DP	0,07	0,03	0,03	0,04	0,05	39,9	52,1	41,5
CV%	5,9	34,3	9,66	8,85	13,6	9,68	23,09	11,42
Assim	0,60	0,76	-0,39	0,16	-0,80	0,05	-0,20	0,47
Curt.	-0,17	0,51	0,13	-0,24	1,81	1,53	0,48	-0,33
K-S	0,13*	0,08*	0,08*	0,06*	0,11*	0,10*	0,10*	0,08*
Urucum								
Me	1,05**b**	0,10**c**	0,34**b**	0,44**c**	0,34**b**	320,0**a**	296,0**ab**	384,0**a**
Md	1,06	0,09	0,34	0,43	0,34	320,7	296	385,9
DP	0,09	0,03	0,03	0,04	0,02	34,4	48,6	51,6
CV%	8,14	34,3	8,04	10,0	7,09	10,7	16,4	13,32
Assim	-0,70	0,76	-0,39	0,37	-0,05	0,01	-0,15	0,45
Curt.	0,53	0,52	1,01	0,21	-0,42	-0,34	-0,83	-0,51
K-S	0,07*	0,08*	0,04*	0,08*	0,04*	0,09*	0,11*	0,12*
Cupuaçu								
Me	1,13**a**	0,13**b**	0,23**c**	0,36**d**	0,23**c**	418,1**b**	297,3**a**	284,6**c**
Md	1,14	0,13	0,23	0,36	0,23	415,2	303,2	286,7
DP	0,10	0,02	0,03	0,03	0,04	59,4	43,5	30,0
CV%	8,97	18,1	14,6	8,9	16,6	14,2	14,6	10,5
Assim	-0,12	0,62	0,20	0,49	0,35	0,98	-0,74	-0,20
Curt.	-0,60	0,18	-0,16	-0,35	-0,06	1,29	0,22	0,31
K-S	0,08*	0,12*	0,06*	0,09*	0,07*	0,09*	0,10*	0,06*
Forest								
Me	0,96**c**	0,17**a**	0,35**ab**	0,52**a**	0,35**ab**	482,2**a**	278,9**b**	238,9**c**
Md	0,97	0,17	0,35	0,52	0,35	483,4	276,9	238,0
DP	0,09	0,04	0,03	0,04	0,04	45,9	39,8	24,1
CV%	9,60	23,3	10,0	8,18	11,7	9,54	14,3	10,1
Assim	0,01	-0,11	-0,01	-0,72	0,17	-0,17	0,21	0,21
Curt.	0,19	1,38	-0,41	4,07	0,33	-0,35	0,00	0,13
K-S	0,07*	0,09*	0,08*	0,13*	0,07*	0,08*	0,10*	0,06*

Ds: Soil density; MaP: Macroporosity; MiP: Microporosity; Pt: total porosity; Θv: Volumetric Humidity; Me.: average; Md.: median; SD: standard deviation; CV: coefficient of variation; Thus.: asymmetry; Curt. Kurtosis; K-S: Kolmogorov-Smirnov normality test, *significant at 5% probability; means followed by the same letter in the column do not differ statistically (Tukey $p < 0.05$).

Table 3. Descriptive statistics and mean test of forest-agriculture conversion on soil physical attributes in layers 0.10-0.20 m in Canutama, Amazonas state, Brazil

Parameters	Ds	MaP	MiP	Pt	Ɵv	Silt	Clay	Sand
	g cm^{-3}	------------------ m^{-3} m^{-3} ------------------				--------------- g.kg^{-1} --------------------		
Guaraná								
Me	1,13**a**	0,11b**c**	0,37**a**	0,48**a**	0,37**a**	434,9**a**	201,6**c**	363,5**b**
Md	1,12	0,11	0,37	0,49	0,37	435,4	204	360,1
DP	0,06	0,04	0,04	0,06	0,06	23,6	39,1	40,7
CV%	5,7	34,0	10,8	11,8	16,9	5,43	19,2	11,2
Assim	0,28	0,18	-0,62	-0,68	-0,43	0,19	-0,36	0,76
Curt.	-0,33	0,24	0,95	1,75	1,84	0,56	-0,65	0,03
K-S	0,09*	0,06*	0,10*	0,06*	0,11*	0,08*	0,10*	0,10*
Urucum								
Me	1,06**b**	0,10**c**	0,33**b**	0,43**b**	0,33**b**	401,3**a**	220,4**c**	378,3**b**
Md	1,06	0,10	0,33	0,43	0,33	409,1	211,2	380,3
DP	0,09	0,03	0,02	0,03	0,03	54,3	48,1	53,6
CV%	8,90	28,5	7,22	6,89	8,11	13,4	21,8	14,1
Assim	0,01	0,15	-0,09	-0,04	0,42	-0,01	0,03	0,29
Curt.	0,00	-0,54	-0,21	0,07	0,06	-0,42	-0,43	-0,43
K-S	0,05*	0,06*	0,04*	0,06*	0,06*	0,08*	0,12*	0,07*
Cupuaçu								
Me	1,16**a**	0,12**b**	0,11**c**	0,23**c**	0,36**a**	418,4b**a**	302,3**b**	279,3**c**
Md	1,18	0,12	0,11	0,23	0,36	419,5	295,2	278,4
DP	0,10	0,03	0,03	0,06	0,04	44,5	35,7	26,6
CV%	8,63	25,5	29,7	27,3	10,9	10,6	11,8	9,53
Assim	-0,22	0,48	0,57	0,57	-0,20	0,06	0,31	0,40
Curt.	1,11	-0,20	-0,17	-0,20	0,16	0,50	-0,05	-0,10
K-S	0,12*	0,12*	0,14*	0,13*	0,07*	0,07*	0,10*	0,06*
Forest								
Me	1,02**c**	0,16**a**	0,33**b**	0,49**a**	0,33**b**	469,5**a**	289,3**b**	241,2**b**
Md	1,03	0,16	0,33	0,50	0,33	466,2	292	241
DP	0,09	0,04	0,03	0,04	0,02	39,4	32,5	27,2
CV%	9,26	26,0	8,21	8,59	8,99	8,44	11,2	11,3
Assim	-0,09	0,67	-0,33	-0,11	-0,25	0,25	-0,80	0,42
Curt.	0,83	0,69	1,48	1,55	1,54	0,53	1,24	0,15
K-S	0,06*	0,12*	0,08*	0,08*	0,06*	0,06*	0,15*	0,09*

Ds: Soil density; MaP: Macroporosity; MiP: Microporosity; Pt: total porosity; Ɵv: Volumetric Humidity; Me.: average; Md.: median; SD: standard deviation; CV: coefficient of variation; Thus.: asymmetry; Curt. Kurtosis; K-S: Kolmogorov-Smirnov normality test, *significant at 5% probability; means followed by the same letter in the column do not differ statistically (Tukey $p < 0.05$).

The total porosity (Pt) varied complete ($p < 0.05$) between the different use conditions (Tables 1, 2 and 3). The cultivation system with guarana had 14.8% less total porosity compared to the area of forest in the surface layer (0.0-0.05 m). In the intermediate layer, the difference between the same areas was also important, with differences of 28.85% in Pt. In the lower depth, the differences between uses was even higher with 53.06% less total porosity between cupuaçu and guarana.

The loss of porosity due to the conversion of natural systems into cultivated ones did not affect the macropores, despite the cupuaçu system showing a marked reduction in Pt, and these results are inverse to the results reported in the literature (Rabot et al, 2018). In the lower layer, the differences were considerably greater, which would indicate a compaction induced by the use and occupation of the soil. However, this condition was not evidenced, largely due to the possible input of organic material evident in these areas. Thus, the effect of agricultural use resulted in a change in the total porosity which, in turn, was accompanied by changes in the pore size distribution.

The soil water retention characteristics from volumetric moisture balanced at 6 KPa (Tables 1, 2 and 3) were different only for the cupuaçu cultivation system, a condition evident due to the marked reduction in the volume of Pt. in the pore system, it results in lower retained water content, which implied a decrease in the volume of macropores and in total porosity, and a correspondingly lower index of water content in the soil.

Due to the variability in the different conditions of land use and occupation, from Table 4, it is possible to identify the attributes that exert the greatest influence on the soil cultivation systems based on the multivariate analysis. Most of the variability of the data is explained by the attributes that correlated with Factor 1, thus, they could be interpreted as the most sensitive in demonstrating the heterogeneity in the conversion environments, and such variations may be associated with the active formation processes, but it can also be related to the anthropic actions that took place in the environment. In this way, the monitoring of such attributes is essential for the knowledge of the most problematic areas in terms of soil degradation, with the possibility of establishing specific management zones.

Table 4. Contribution of physical-water attributes in factors 1 and 2 in forest-agriculture conversion on soil physical attributes in Southeast Amazonas state, Brazil

Guaraná			**Urucum**		
Attribute	**F1 (%)**	**F2 (%)**	**Attribute**	**F1 (%)**	**F2 (%)**
Ds (g cm^{-3})	2.26	18.44	Ds (g cm^{-3})	7.90	20.39
Macro (m^3 m^{-3})	0.15	10.63	Macro (m^3 m^{-3})	9.30	2.66
Micro (m^3 m^{-3})	4.97	8.09	Micro (m^3 m^{-3})	0.12	15.19
Pt (m^3 m^{-3})	2.44	21.78	Pt (m^3 m^{-3})	4.21	0.11
Θv (m^3 m^{-3})	4.42	4.67	Θv (m^3 m^{-3})	0.98	27.55
Silt (g kg^{-1})	1.17	4.71	Silt (g kg^{-1})	10.99	3.63
Clay (g kg^{-1})	24.09	2.94	Clay (g kg^{-1})	17.75	5.77
Sand (g kg^{-1})	12.20	0.55	Sand(g kg^{-1})	0.38	0.07
Cupuaçu			**Forest**		
Attribute	**F1 (%)**	**F2 (%)**	**Attribute**	**F1 (%)**	**F2 (%)**
Ds (g cm^{-3})	11.08	0.52	Ds (g cm^{-3})	8.98	13.63
Macro (m^3 m^{-3})	3.13	13.70	Macro (m^3 m^{-3})	0.03	18.52
Micro (m^3 m^{-3})	7.79	12.13	Micro (m^3 m^{-3})	0.02	21.33
Pt (m^3 m^{-3})	7.94	21.48	Pt (m^3 m^{-3})	0.40	1.27
Θv (m^3 m^{-3})	1.75	23.07	Θv (m^3 m^{-3})	0.06	28.11
Silt (g kg^{-1})	12.92	7.48	Silt (g kg^{-1})	15.58	0.57
Clay (g kg^{-1})	13.37	5.50	Clay (g kg^{-1})	20.90	1.75
Sand(g kg^{-1})	2.67	5.00	Sand (g kg^{-1})	0.42	0.51

In all conditions of use, the clay fraction is considered dominant in the contribution, mainly to Factor 1 with 24.09%, 17.75%, 13.37% and 20.90% respectively in the areas of guaraná, urucum, cupuaçu and forest. This result is due to the clay factor, which is of fundamental importance in explaining most of the existing variability and influences the management systems. The clay fraction of tropical and subtropical soils is dominated by minerals such as kaolinite, Fe and Al sesquioxides, 2:1 expansive clay minerals, illite (Fonseca et al, 2021). Thus, due to the domain of kaolinite, in quantitative terms, it is the main component of the clay fraction of most tropical and subtropical soils, thus being an important component to act in the processes of alteration of the soil structure.

Considering the other physical-water attributes, it is observed that the system with guaraná cultivation presents microporosity as being its most influential attribute (F1 = 4.97%), while the system with urucum has a domain of macroporosity as a physical property of greater influence (F1 = 9.30%) and the cupuaçu area has the soil density as being its most influential attribute (F1 = 11.08%). These results show that for each of these systems, the Forest-Agricultural Use conversion caused impacts even on small scales, and these were practically unexposed, but that, from the multivariate analysis, it is possible to observe that those attributes related to soil structure, are the most impacted. Together with these attributes, there is possibly a greater impact or change in the others, when submitted to some form of management.

As highlighted in Fernández et al. (2021), the agricultural use of land leads to degradation of the soil structure, which, in turn, aggravates and impacts the natural characteristics. To reverse this process, significant indicators that reflect the degree of damage to the soil system. In the forest area, it is observed that the greatest contribution in the change of physical-water attributes refers to the density of the soil (F1 = 8.98%), thus favoring an effect of densification of the soil. Priori et al. (2021) highlight that the soil tends to a condition of densification, as a consequence of its textural composition, moisture regime and genesis, noting that, in the subsurface layers, densification may be due to the packing of granular sediments, partially cemented, which soils with block-type structures or similar tend to be the most dense.

The principal components graph (ACP) is presented in figure 2. The first and second principal components were necessary to explain the total variance, justifying the use of CP1 and CP2. According to Oliveira et al. (2017), the CPs that present eigenvalues greater than one can be used for a two-dimensional ordering of accesses and variables, which allowed the construction of a biplot graph. In the cultivation system with guaraná, it is observed that there was a contribution of 57.92% in explaining the variability of the data, for urucum these values were in the order of 61.18%, cupuaçu with 71.77% and forest with 57 .88%, these values correspond to an isolated analysis of each environment. When the joint assessment is made, encompassing all areas, the contribution of F1 and F2 is in the range of 62.27%.

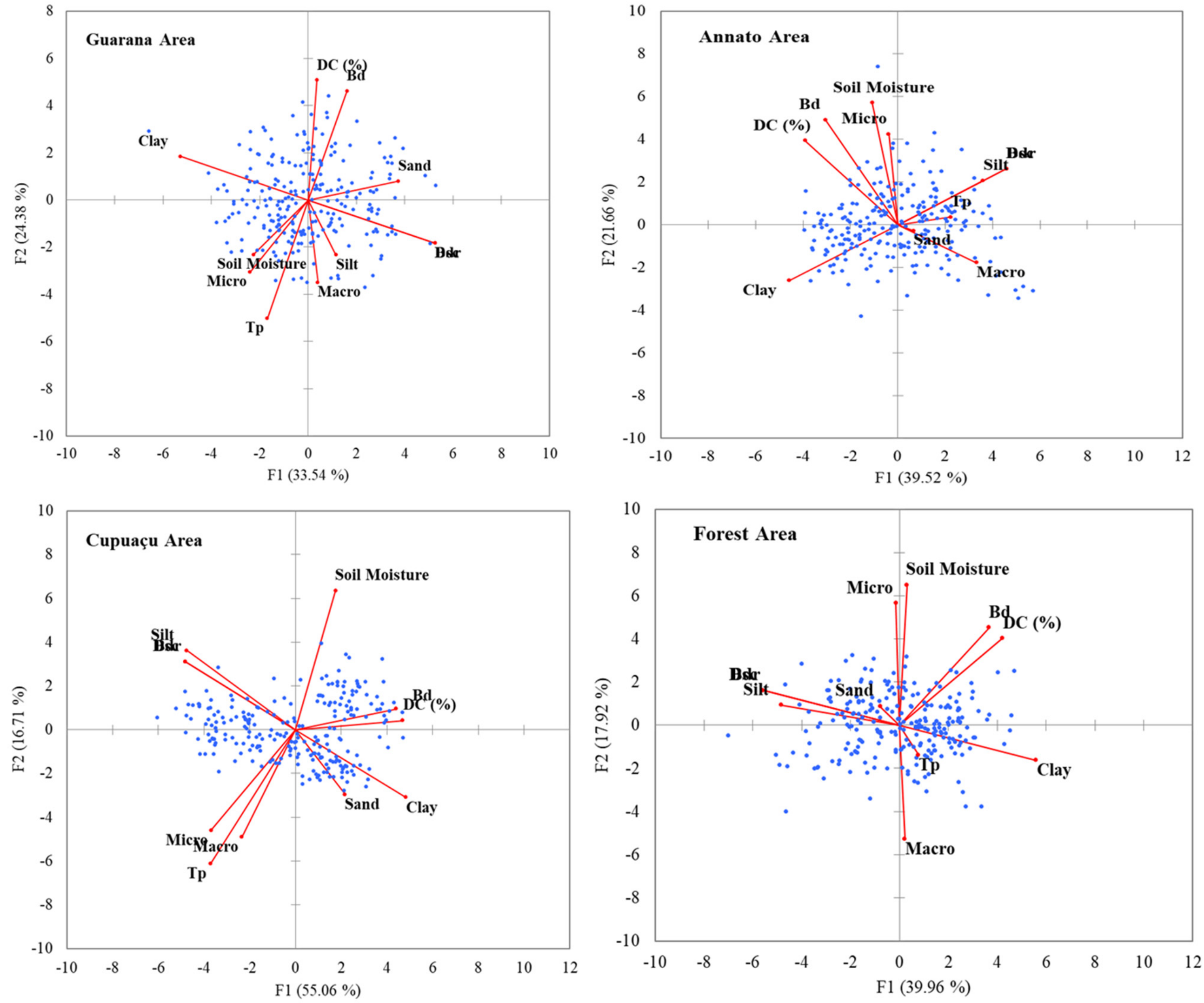

Figure 2. Principal components graph of forest-agriculture conversion on soil physical-water attributes in southeastern Amazonas state, Brazil

Source: Author (2023).

Analyzed separately or together by PCA (Figure 2), the results corroborate what was already presented in Table 4, on the evidence of the clay fraction acting on the other physical-hydric attributes, making evident its participation in modifying the entire composition of the system, especially by the proportionality condition as presented in all areas, by the inverse effect with the critical soil density and macroporosity and microporosity. When analyzing all the systems together, it is clear that there is also a greater relationship with the soil moisture. These results demonstrate that the physical attributes can be the most important and the ones that most contribute to the separation of the areas, emphasizing the physical attributes of the soil, since these – macro, micro and soil density – were the attributes that are most related to the areas.

Figure 3 presents the critical values and degrees of compaction regarding the studied land use and occupation systems. First, it is observed that for all conversion systems, the values are below the limits which are considered critical, with variations of approximately 0.8 g cm-3. The optimal and critical limits of the soil density for crop growth depend on the soil texture, mineralogy, particle shape and organic matter, which affect the soil structure and therefore water, air and the soil mechanical strength (Moraes et al, 2020). Due to the fact that the study areas present homogeneous textures, the critical density variation range was around 1.60 g cm-3 to 1.64 g cm-3.

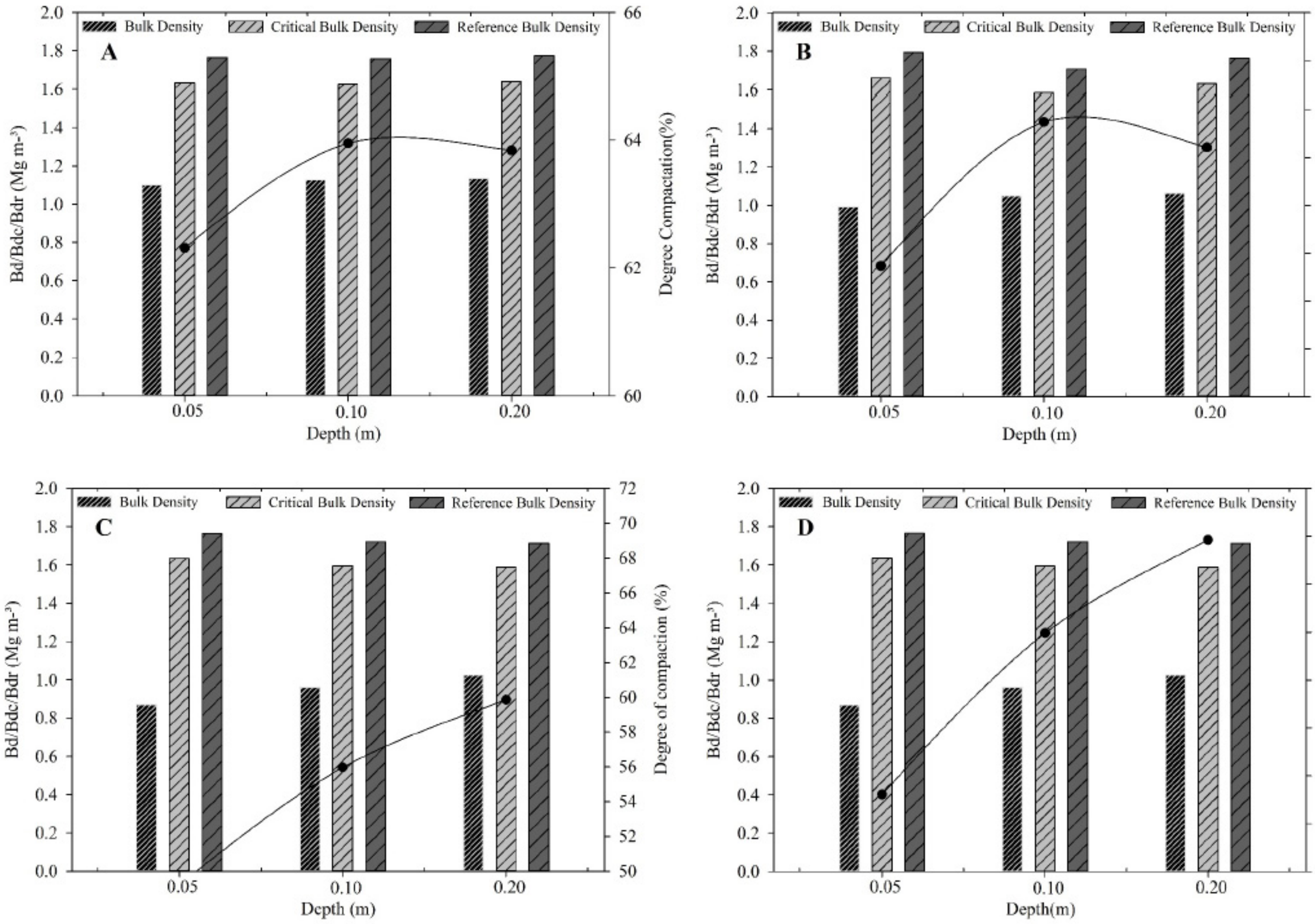

Figure 3. Relationship between soil density, critical density, reference density and degree of compaction in areas of Guaraná (A), Urucum (B), Cupuaçu (C) and Forest (D)

Source: Author (2023).

In an inverse condition, considering a large impact on the current density of the soils in this study, and if they presented an adverse condition, restrictions on root growth would not necessarily translate into reduced crop growth or yield, and the root system of crops may show variable tolerance to soil compaction. Wang et al. (2022) state that roots with elongated length can provide an adequate supply of water and nutrients, as in the case of the species cultivated in this study, which have a very aggressive root system that exploits the soil.

A low degree of compaction reduces root-soil contact, while a high degree of compaction reduces the soil aeration and increases the penetration resistance with a negative effect on the root growth and development (Gomes junior et al, 2023). Thus, the crop growth is negatively affected by the soil compaction, but the highest yields are not obtained in a very loose soil (Suzuki et al, 2022). In this work, the values corresponding to the degree of compaction were in a range of 52-64%, considering the cultivated species, and the current physical quality index of these soils would be an adequate value, since there are no impediments to root growth.

4. Final Considerations

Intense changes in physical attributes were not observed according to forest-to-agricultural conversions in physical-water attributes. Aspects such as the implementation time of the different use and occupation systems can be controlling factors for the reestablishment of these physical properties.

From the critical values established for soil density, it is verified that the current values are well below the critical limits, with the organic matter factor being a contributor to such evidenced conditions. In this sense, the values of degree of compaction are associated in the range of 52-64%, being these, for the implanted cultures, of excellent conditions for the development and production.

The use of multivariate analysis techniques is efficient to verify the similarities or differences, based on the physical attributes of the soil in each studied area once it made possible to identify the attributes of greater influence.

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