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Evaluation of physicochemical attributes of a yellow latosol under agroforestry system as compared to secondary forest in the Eastern Amazon

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Abstract In Brazil, the productive and sustainable use of Amazonian soils under agroforestry systems (AFS) has been considered a research challenge. This study aimed to evaluate the physicochemical attributes of a soil under AFS, comparing it with the soil under an adjacent secondary forest (SF). The study was carried out in an AFS area cultivated with passion fruit (*Passiflora edulis*), cupuaçu (*Theobroma grandiflorum*) and Brazilian mahogany (*Swietenia macrophylla*), between 2005 and 2019. Both study areas (AFS and SF) were divided into five blocks. Sampling was carried out in two soil depths (0–20 cm and 20–40 cm), which was subjected to chemical analysis to determine the pH in water, contents of macro- and micronutrients, exchangeable bases, exchangeable aluminum, base saturation, cation exchange capacity and organic matter contents. As for the physical attributes, penetration resistance (PR) up to 40 cm deep in the soil was evaluated, using 50 randomized measurement per study area. The contents of macronutrients were higher in AFS, and the content of organic matter was higher in SF. The contents of micronutrients did not follow a specific pattern, and presented a similar distribution in both environments. The PR was higher in SF, showing a linear behavior that increases with increasing depths, while in AFS, there was a stabilization tendency within soil depth. Soil fertility was better in AFS, mainly due to the residual contents of periodic fertilization, in addition to presenting better conditions for root establishment.

Keywords Land use · Fertility · Penetration resistance · Secondary forest

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Introduction

In the Amazon territory, there is great soil spatial variability, which is attributed to climate, source material, biotic interactions and topography, among other factors. However, high levels of acidity, leaching, weathering, low fertility and high contents of exchangeable aluminum are common characteristics in more than 60% of the soils, in which Latosol and Argisols are the predominant soil types (Junqueira et al. 2016). Overall, unaltered soils are highly dependent on nutrient recycling to maintain fertility and biodiversity, which depends on organic matter from vegetation. This shows the close relationship between soil and vegetation of the Amazon biome (Moline and Coutinho 2015).

Agricultural models that aim only at high levels of short-term profitability have intensified soil degradation, which is characterized by changes in the soil quality status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries. Thus, there is no concern for maintaining ecological systems that can guarantee sustainable production in the present and in the future (Ponisio et al. 2015).

In the Amazon region, soil degradation is influenced by a range of processes, whether agricultural or not, with emphasis on the slash and burn system, also known as itinerant agriculture. The burning of vegetation and organic material on the soil surface promotes rapid fertilization due to the ash material, with a decrease in acidity and an improvement in the ability to exchange cations (Navarrete et al. 2015). However, the advantages of the system last only in the early years, and then there are several harms to the edaphic complex. Souza et al. (2018) reported increased compaction and drastic decreases in fertility and the carbon stock of the soil. Béliveau et al. (2017) observed a significant increase in soil surface density and, consequently, in erosion rates.

For this reason, it is essential to search for alternative land use systems that provide conditions for improving carbon sequestration, with increased biomass production, avoiding accelerated soil degradation.

In this context, agroforestry systems (AFS) are important for improving the chemical, physical and biological attributes of the soil due to the conservation and interaction between the participating plant species (Verma et al. 2013). The action of the tree component constantly deposits organic residues on the soil surface, contributing to the maintenance and stability of the local microclimate. Several studies demonstrate the positive effects of AFS on the soil, i.e., the maintenance of microbiological biodiversity (Ferreira et al. 2006), the increase of nutrient contents (Rosenstock et al. 2014), less acidity and saturation by aluminum (Schwab et al. 2015) and low records of erosion and compaction (Liu et al. 2016).

This demonstrates that it is necessary to evaluate these benefits in the Amazon context. Therefore, this study aimed to evaluate the physical and chemical attributes of the soil cultivated with *Theobroma grandiflorum* and *Swietenia macrophylla* under an agroforestry system, comparing it with the soil of an adjacent secondary forest.

Material and methods

Study area

The experiment was conducted in a rural producer area located in Tomé Açu, state of Para, Brazil (02°26′03.0″ S, 48°18′37.6″ W) for 15 years (2005–2019). The agroforestry system is composed of cupuaçu (*Theobroma grandiflorum*), Brazilian mahogany (*Swietenia macrophylla*) and passion fruit (*Passiflora edulis*). The latter was removed from the area after the third year of implantation.

According to the Köppen classification, the climate of the region is classified as Ami, with average annual precipitation of 2,716 mm, average relative humidity of 85% and average temperature of 26.4 °C. Climatic data were collected at a meteorological station located at the physical base of Embrapa Amazônia Oriental, in Tomé Açu. The soil of the area was classified as Yellow Latosol (Embrapa 2016), which is characterized as deep, with high acidity and low natural fertility.

Experimental conditions

No liming was performed in AFS area at the beginning of the experiment. Nevertheless, 1 kg of dolomitic limestone was annually applied per cupuaçu tree, distributed in the canopy projection as a source of calcium and magnesium. No organic fertilization was carried out. Only on cupuaçu trees, there was the application of 400 g per plant of the formulation NPK 18-18-18 until the 3rd year and, subsequently, 800 g per plant of the formulation NPK 10-28-20, annually, until the 15th year. In the first five years of the experiment, fertilization was carried out in the projection of the cupuaçu plants. However, in the most advanced stages of the experiment, aerial fertilization was carried out in the total area.

Semiannually, machinery was used in the experimental area for mowing the weeds between the lines, with the residues being kept in place to compose the litter.

In order to carry out a homogeneous sampling of both physical and chemical attributes, the AFS area was divided into five segments (blocks) of approximately 1,800 m^2 each.

As a comparative reference, an area of secondary forest (SF) of approximately 2 hectares adjacent to the AFS area was used. The SF area remained fallow for more than 20 years, and it was previously an area of pepper cultivation. Currently, it is in an advanced ecological succession status, with considerable accumulation of biomass, perceived by the litter thickness, great variety of species and plants in full growth. The SF area was also divided into five blocks with the same dimensions as those established for AFS.

For the evaluation of the chemical attributes of the areas, 15 samples were collected per block at each depth (0–0.2 m and 0.2–0.4 m) to form two composite samples and then five samples per depth were used. At the end of the entire process, 20 composite samples were obtained, being 10 from each system.

Studied variables

Chemical analyses were performed to determine the pH in water, contents of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al) and sodium (Na), potential acidity (H + Al), organic matter (OM) and micronutrients (Zn, Cu, Fe and Mn). With these values, it was possible to estimate potential CEC (T), effective CEC (t), sum of bases (SB), base saturation (V%) and aluminum saturation (m%). Laboratory analysis and determinations followed the procedures of Embrapa (2009).

The physical analysis of the soil to determine the proportions of sand, silt and clay (Table 1) was performed by the pipette method, following the granulometric analysis methodology proposed by Embrapa (2009). It demonstrated that both areas present similar characteristics, with medium texture and a predominance of the sand fraction.

The soil penetration resistance (PR) was evaluated considering the first 40 cm of the edaphic profile. The collection of these data occurred in the same blocks used in the sample collection for chemical and physical analysis of the soil. However, it was considered the collection of ten PR measurements per block of each system, with an approximate distance of 15 m between measurements, totaling 50 measurements.

The equipment used to measure the vertical PR was the PNT-2000 model geo-referenced electronic penetrometer, with a 30° conical tip and a conical area of 129 mm^2. In the sampled locations, measurements were taken at every five centimeters, up to a soil depth of 40 cm.

Statistical analysis

The results of the soil analyses were first submitted to the Kolmogorov–Smirnov test to verify the normality of the data, and then subjected to analysis of variance, considering a completely randomized experimental design. The factors were arranged in subplots (two environments and two depths), with five replications. SAS (Statistical Analysis System) University Edition statistical software was used. The variables that data did not show normality were evaluated by non-parametric Mann–Whitney analysis, using the Excel software.

The penetration resistance data were also submitted to the normality test, analysis of variance and regression analysis, aiming at observing the variable pattern, according to the studied soil depths.

Table 1 Soil granulometry under secondary forest and agroforestry system, in Tomé Açu—Pará, 2019

Secondary forest			
Soil depth	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
0–20	763	65	172
20–40	661.4	54.6	284
Agroforestry system			
Soil depth	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
0–20	743.8	68.2	188
20–40	651.2	60.8	288

Results

The analysis of variance revealed an interaction of the factors "Management areas" and "Depths" was significant for the variables K, Fe and Zn. As for the other variables, comparisons were carried out individually.

The variables related to soil acidity (Table 2) demonstrated significantly less acidification in the area under AFS. The contents of exchangeable aluminum and potential acidity in the soil of SF were four times higher than in the soil under AFS, reflecting

Table 2 Average levels of soil pH, aluminum (Al), sum of bases (SB), potential acidity (H + Al), potential CEC (T), effective CEC (t), calcium (Ca), magnesium (Mg), base saturation (V), aluminum saturation (m), phosphorus (P) and organic matter (OM) in secondary forest (SF) and agroforestry (AFS) management systems, evaluated in Tomé Açu, PA, 2019

Management system	pH*	Al*	SB**	H + Al*	T*	t**	Ca**	Mg**	V**	m**	P*	OM*
	H_2O	cmolc dm^{-3}							%		mg dm^{-3}	g kg^{-1}
SF	4.4b	0.8a	1.1b	4.6a	5.6a	1.9b	0.6b	0.4b	18b	46a	4.9b	14.8a
AFS	5.1a	0.2b	1.9a	2.2b	4.1b	2.1a	1.3a	0.6a	47a	9b	33.1a	9.7b

* and ** means followed by the same letter in the column do not differ from each other at 5% significance level by the Mann–Whitney and t tests, respectively

the difference between values of aluminum saturation. On the other hand, the sum of bases and the effective CEC were higher in AFS. These results are related to soil pH, which is comparatively lower in SF, probably due to the annual use of limestone carried out in the AFS area.

Considering that there was no management in SF, the importance of liming in the implantation of any cultivation system under the studied conditions is evident. The results of pH, Al and sum of bases (SB) influenced the behavior of soil base saturation (Table 2), which was significantly lower in SF. As for AFS, the soil base saturation reached a value of 47%, which is important regarding nutrient availability.

The active acidity (pH) did not vary between soil depths in both management systems (Table 3). The values of changeable acidity (Al) and aluminum saturation (m) were significantly lower in the AFS area. Regarding the potential acidity (H + Al), it was significantly higher in the superficial layer of SF. These results conditioned the differences observed in the values of SB, CEC, V and m (Table 3).

The contents of most macronutrients in the agroforestry system were higher than the levels found in the secondary forest (Table 2). The only macronutrient with higher levels in the soil under SF was K in the superficial layer of the soil (Table 4). Regarding the levels of organic matter, superiority was observed in the secondary forest in relation to the agroforestry system (Table 2).

The comparison of the contents of macronutrients and organic matter (OM) between the evaluated soil layers (Table 3) revealed that the values are higher and significantly different in the superficial layer (0–20), except for Ca in SF and Mg and OM in AFS. These results also demonstrated that these variables were higher in the AFS area. As for K, the content in superficial layers was significantly higher, following the tendency of the other macronutrients (Table 4).

As for the contents of Cu and Mn (Table 5), higher levels were observed in the agroforestry system.

Table 3 Average pH, aluminum (Al), sum of bases (SB), potential acidity (H + Al), potential CEC (T), effective CEC (t), calcium (Ca), magnesium (Mg), saturation by bases (V), saturation by aluminum (m), phosphorus (P) and organic matter (OM) as a function of soil depth in both management systems, in Tomé Açu, PA, 2019

Soil depth	pH*	Al*	SB**	H + Al*	T*	t**	Ca**	Mg**	V**	m**	P*	OM*
cm	H_2O	cmolc dm^{-3}							%		mg dm^{-3}	g kg^{-1}
Secondary forest												
0–20	4.4a	0.8a	1.3a	5.4a	6.8a	2.1a	0.8a	0.5a	19.3a	39.2a	6.7a	18.4a
20–40	4.4a	0.8a	0.8b	3.7b	4.5b	1.6b	0.5a	0.2b	17.0a	53.0a	3.1b	11.1b
Agroforestry system												
0–20	5.1a	0.1b	2.2a	2.2a	4.4a	2.4a	1.5a	0.7a	50.6a	5.2a	40.3a	9.9a
20–40	5.1a	0.3a	1.6b	2.2a	3.8b	1.9b	1.1b	0.5a	42.8b	13.6b	25.9b	9.6a

* and ** means followed by the same letter in the column do not differ from each other at 5% significance level by the Mann–Whitney and t tests, respectively

Table 4 Mean contents of potassium (K), in cmolc dm^{-3}, as a function of soil depth and management system, in Tomé Açu, PA, 2019

	Management system	
Soil depth (cm)	Secondary forest	Agroforestry system
0–20	0.05aA	0.03aB
20–40	0.02bA	0.02bA

* Significant differences between management systems are represented by uppercase letters and between depths by lowercase letters by the t test at 5% significance level

Table 5 Mean micronutrient contents of copper (Cu) and manganese (Mn) in secondary forest (SF) and agroforestry system (AFS), in Tomé Açu, PA, 2019

Management system	Cu* (mg kg^{-1})	Mn** (mg kg^{-1})
SF	0.4b	4.5a
AFS	0.7a	5.8a

* and ** means followed by the same letter in the column do not differ from each other at 5% significance level by the Mann–Whitney and t tests, respectively

Although there was no direct fertilization with the elements in the area, in addition to a variation between depths with a similar pattern between both studied areas, higher values were found in the superficial layers (0–20 cm) (Table 7). The same behavior can be observed for Zn (Table 6). The high levels of Fe (Table 6) found in both managed systems are considered a typical characteristic of soils in some regions of the Amazon.

The penetration resistance (PR) varied significantly within soil depth in both studied areas, with a difference in the data adjustment model between PR and depth (Fig. 1). By the regression analysis, PR in the secondary forest was adjusted to the linear model, showing increasing values with soil depth and indicating that for each centimeter penetration in the soil, the resistance increased up to 0.0983 MPa.

The response curve of the resistance to penetration in the agroforestry system demonstrated a more complex behavior when compared with the curve for the secondary forest. The distribution pattern of the points can be explained by a second-degree polynomial model, with a tendency to stabilize the PR in the deepest layers of the soil, when considering the studied range. According to the adjusted model, the highest penetration resistance value (2.16 MPa) is 42 cm deep.

Table 6 Mean contents of zinc (Zn) and iron (Fe) as a function of soil depth in both management systems, in Tomé Açu, PA, 2019

Zn (mg kg^{-1})		
	Management system*	
Soil depth (cm)*	SF	AFS
0–20	0.64aB	2.39aA
20–40	0.3aB	1.11bA
Fe (mg kg^{-1})		
	Management system*	
Soil depth (cm)*	SF	AFS
0–20	204.9aA	145.5aB
20–40	220.8aA	122.9bB

* Significant differences between management systems are represented by uppercase letters and by lowercase letters between soil depths by the t test at 5% significance level

Table 7 Mean contents of copper (Cu) and manganese (Mn) at both soil depths in secondary forest (SF) and agroforestry system (AFS), in Tomé Açu, PA, 2019

Soil depth	Cu*	Mn**
cm	mg kg^{-1}	
	Secondary forest	
0–20	0.4a	6.4a
20–40	0.3a	2.6b
	Agroforestry system	
0–20	0.9a	7.3a
20–40	0.5b	4.2b

* and ** means followed by the same letter in the column do not differ from each other at 5% significance level by the Mann–Whitney and t tests, respectively

Discussion

The results observed in the secondary forest soil are in agreement with Mantovanelli et al. (2016), who considered Amazonian soils to be naturally acidic and with high aluminum saturation, in addition to

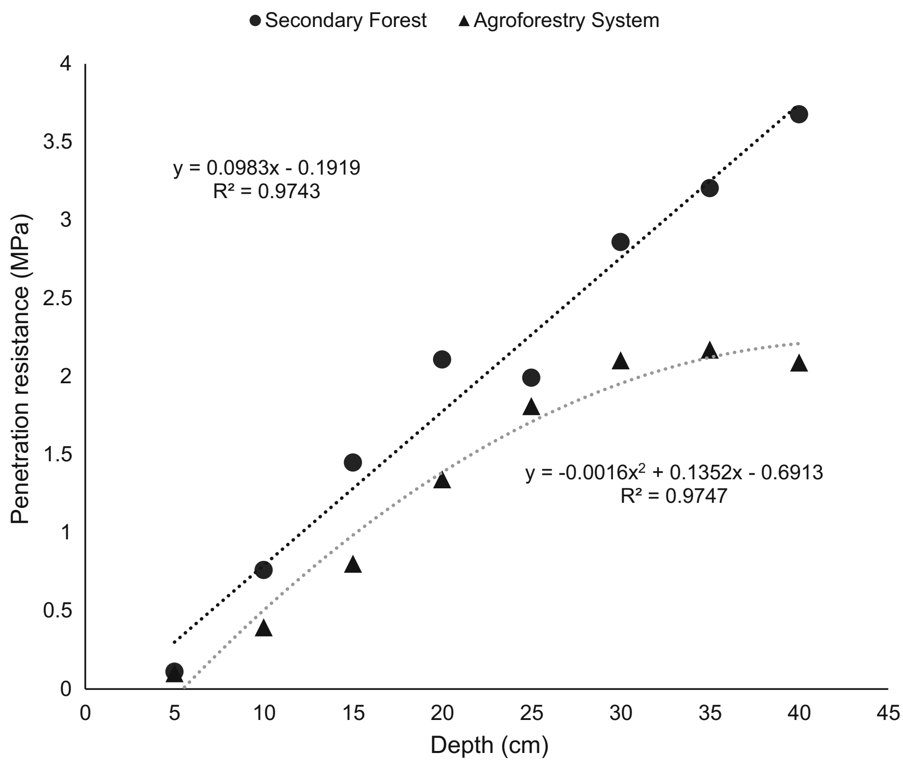

Fig. 1 Penetration resistance at different soil depths under secondary forest and agroforestry system, in Tomé Açu, PA, 2019

being poorly fertile, mainly due to leaching. Barreto et al. (2006) explained that in the forest areas, there is a more accentuated action of organic acids from the mineralization of organic matter and release by the roots, which promotes a decrease in soil pH. Ebeling et al. (2008) directly related the carbon content in the soil with its acidity. Natale et al. (2012) highlighted the importance of liming, especially in naturally acidic soils, to increase pH, decrease acidity levels and supply Ca and Mg, which are important bases for plant nutrition.

On the other hand, Collier and Araújo (2010) found higher values of potential acidity and exchangeable acidity in soil of an agroforestry system, located in the state of Tocantins, southeast of the Legal Amazon, when compared with the levels of the present study. However, the authors did not perform any type of fertility management, such as liming and fertilization in AFS of the study. Barreto et al. (2006) and Silva et al. (2011) used acidity correction methods, using phosphate rock and liming and mineral fertilizer application, respectively.

Iwata et al. (2012) highlighted the direct relation between age of AFS versus soil quality, depending on the species used and the management used. The authors found higher values of macronutrients in AFS when compared with the native forest, a result similar to that found in the present study.

According to Quesada et al. (2011), latosols present in the Amazon basin are naturally low in exchangeable phosphorus. Gama-Rodrigues et al. (2014) pointed out that one of the main factors for this unavailability is that phosphorus precipitates with the ions Al and Fe, which are present in high levels in soil of Amazon region. This relationship was also observed in the present study (Tables 2 and 6). It justifies the need for the use of acidity correction and phosphate fertilizers as a practice, which allows the increase in phosphorus in the soil and, consequently, greater availability to plants. According to Lima et al. (2011), agroforestry systems allow the movement of phosphorus through the interaction between roots at different depths. Silva Junior et al. (2012) also found high values of P in AFS. The action of agroforestry combined with soil management can also be observed in the behavior of other elements, such as Ca and Mg. Pérez-Flores et al. (2018) and Chauhan et al (2018) highlighted the action of litter produced by the accumulation of branches, leaves, flowers and fruits of the species, which contributes significantly in the increments of the elements.

Nevertheless, the particularities should be highlighted that involve the choice of species that will compose the AFS and the edaphic management that should be employed. In the present study, the relationship between cupuaçu and K is emphasized, in which the plant presents great demand for the nutrient for fruit formation. Alfaia et al. (2004) when working with an agroforestry system involving cupuaçu and peach palm observed similar results. It is worth noting that the study sought to follow certain coherence with the reality of the region's producers, reflecting on the recurrence of the use of the formulation NPK 10-28-20. In this way, very high levels of phosphorus (higher value in the proportion of the formulation) were identified in detriment to potassium, which is the main macronutrient required by the plant in the productive period. This result makes it possible to base recommendations for formulations different from those currently in use, adapting to the needs of the plant.

Latosols from the Amazon region present a tendency towards low natural fertility. For this reason, the biodiversity of the Amazonian flora is highly dependent on the recycling of nutrients and organic matter produced in the ecosystem itself (Junqueira et al. 2016). In the present study, this relationship was recorded (Table 2). Although AFS promotes soil conservation, either by direct protection exercised by the crowns of perennial plants, or by the deposition of organic material on the soil, which improves conditions for the soil microbiota (Monroe et al. 2016), the carbon content and organic matter were lower than those found in the secondary forest. The great diversity of species present in this environment, in addition to the greater density of plants per area, allows greater input of organic material on the soil and, consequently, greater production of organic matter and carbon fixation.

Studies demonstrated that soils under forest present great potential to store carbon, but also showed that changes in the landscape reduce this potential (Marques et al. 2016; Singh et al. 2016; Durigan et al. 2017). The difference between the values of carbon and organic matter in both evaluated systems in the present study proves these theories. When compared with other cultivation systems, AFS are more efficient in carbon storage (Schwab et al. 2015). It is worth mentioning that the age of AFS can influence the stored carbon content. Couto et al. (2016) found higher values of stored carbon when comparing several AFS areas of approximately 20 years old with areas of secondary forest and pasture.

The difference in the content of macronutrients in the soil profile can be explained by the effect of organic material on the surface, which acts as a natural fertilizer, in addition to preserving and stimulating the microbiota. The results are consistent with those found by Silva et al. (2011). The levels of organic matter and carbon in the secondary forest followed the trend of the other treatments. According to Cotrufo et al. (2015), the influence of litter on carbon deposition is more intense in the first 20 cm of the soil, under natural conditions.

Regarding micronutrients, the values found in the present study for Cu, Mn and Zn can be considered high, when comparing with the levels found by Moreira and Fageria (2008) in Latosols of the Amazon region. It is inferred that a large part of the contribution of micronutrients comes from organic matter, since the metallic micronutrients evaluated here are normally complex with organic compounds, thus having a direct relationship with the contents of organic matter in the soil (Carmo et al. 2012). Imtiaz et al. (2010) highlighted the influence of pH on the availability of these nutrients, showing an inverse relationship. Following these two premises, the micronutrient contents should be higher in the secondary forest, since in this area the content of organic matter is higher and the pH is lower (Table 2). However, there is a direct relationship between the amount of micronutrients in the soil and the addition of chemical fertilizers (NPK). Rutkowska et al. (2014) confirmed this behavior, in which the exclusive treatment with NPK provided the highest levels of Cu, Fe, Mn and Zn due to the greater acidification in this condition. However, in the present study, AFS areas have lower levels of acidity. Thus, it could justify higher levels of micronutrients in the areas of AFS could be related to the presence of micronutrients, such as impurities, in the fertilizers used, both in NPK and in limestone. For example, Carvalho et al. (2012) studied the amount of impurities (micronutrients) in some NPK formulations and in the limestone and found the presence, sometimes significant, sometimes diminished, of the four micronutrients studied here.

Oliveira et al. (2015) highlighted the compression of the soil caused by the growth of the roots as one of the primary factors for the high values of PR in areas of native forest. Couto et al. (2016), when evaluating the penetration resistance in agroforestry systems, considered three classes: the first class, with PR values less than 2 MPa, which represents soils without restrictions to root penetration; the second class, with PR values between 2 and 3.5 MPa, which represents soils with restrictive action to root penetration; and the third class, representing soils with an impeding action to root penetration, presenting values higher than 3.5 MPa. Taking this classification into account, there is little restriction on the penetration of roots in the agroforestry system of the present study. On the other hand, there is a greater restriction in the secondary forest, reaching the impediment level in the deeper layers.

Freitas et al. (2012), when comparing the resistance to soil penetration of an agroforestry system with three other environments (native forest, pasture and stump gardens), also observed the lowest values in AFS. The authors attributed this factor to the constant supply of organic residues in the soil. The use of irrigation in the agroforestry system of the present study is emphasized, which, according to Silva et al. (2011), increases the friability of the soil.

Comparing the agroforestry system analyzed in the present study with other cultivation systems found in the literature, lower values of resistance to penetration in the AFS were found. Ralisch et al. (2008) observed more compacted soils in no-tillage, conventional tillage and native forest systems. Wendling et al. (2012) also reported higher PR values for the natural landscape and pasture. Nevertheless, the authors observed a similar behavior to that of the present study, when measuring the variable in a *Pinus* forest. The low frequency of the passage of machines in AFS of the present study may have contributed to the lower compaction rate in this environment.

Conclusions

The soil of the agroforestry system had superior chemical characteristics to the soil of the adjacent secondary forest, which is mainly attributed to the management of fertilization employed, providing better conditions for the development of the species. The low use of machinery in AFS allowed the maintenance of the physical characteristics of the soil, especially soil friability. The fertilizers normally used by the producers for cupuaçu trees are unbalanced, since there were an excess of phosphorus and a lack of potassium in the soil of the studied AFS.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by SFdaSC, RMA, MAPG, RPdeO, JLPN and VMNL. SFdaSC wrote the first draft of the manuscript, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest There are no conflicts of interests in this article.

Availability of data and material The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

References

Alfaia SS, Ribeiro GA, Nobre AD, Luizão RC, Luizão FG (2004) Evaluation of soil fertility in smallholder agroforestry systems and pastures in western Amazonia. Agr Ecosyst Environ. https://doi.org/10.1016/j.agee.2003.08.011

Barreto AC, Lima FHS, Freire MBG, Freire FJ (2006) Características químicas e físicas de um solo sob floresta, sistema agroflorestal e pastagem no sul da Bahia. Rev Caatinga 19:415–425. https://periodicos.ufersa.edu.br/index.php/caatinga/article/view/66

Béliveau A, Lucotte M, Davidson R, Paquet S, Mertens F, Passos CJ, Romana CA (2017) Reduction of soil erosion and mercury losses in agroforestry systems compared to forests and cultivated fields in the Brazilian Amazon. J Environ Manage. https://doi.org/10.1016/j.jenvman.2017.07.037

Carmo DL, Nanetti DC, Lacerda TM, Nanetti NA, Santo DJE (2012) Micronutrientes em solo e folha de cafeeiro sob sistema agroflorestal no sul de minas gerais. Coffee Sci

7:76–83. https://www.sbicafe.ufv.br:80/handle/123456789/7903

Carvalho VGB, Nascimento CWA, Biondi CM (2012) Potencial de fertilizantes e corretivos no aporte de micronutrientes ao solo. Rev Bras Ciência Solo. https://doi.org/10.1590/S0100-06832012000300023

Chauhan SK, Singh S, Sharma S, Vashist BB, Sharma R, Saralch HS (2018) Soil health (physical, chemical and biological) status under short rotation tree plantations on riverain soils. J Pharmacogn Phytochem 7:1599–1605. https://www.phytojournal.com/archives/2018/vol7issue5/PartAB/7-4-730-360.pdf

Collier LS, Araújo GP (2010) Fertilidade do solo sob sistemas de produção de subsistência, agrofloresta e vegetação remanescente em Esperantina, Tocantins. Floresta Ambiente. https://doi.org/10.4322/floram.2011.005

Cotrufo MF, Soong JL, Horton AJ, Campbell EE, Haddix ML, Wall DH, Parton WJ (2015) Formation of soil organic matter via biochemical and physical pathways of litter mass loss. Nat Geosci. https://doi.org/10.1038/ngeo2520

Couto WH, Anjos LHC, Wadt PGS, Pereira MG (2016) Atributos edáficos e resistência a penetração em áreas de sistemas agroflorestais no sudoeste amazônico. Ciência Florest. https://doi.org/10.5902/1980509824210

Durigan M, Cherubin MR, Camargo PB, Ferreira JN, Berenguer E, Gardner TA, Barlow J, Dias CTS, Signor D, Oliveira Júnior RC, Cerri CEP (2017) Soil organic matter responses to anthropogenic forest disturbance and land use change in the Eastern Brazilian Amazon. Sustainability. https://doi.org/10.3390/su9030379

Ebeling AG, Anjos LHC, Perez DV, Pereira MG, Valladares GS (2008) Relação entre acidez e outros atributos químicos em solos com teores elevados de matéria orgânica. Bragantia. https://doi.org/10.1590/S0006-87052008000200019

Embrapa (2009) Manual de análises químicas de solos, plantas e fertilizantes. Embrapa Informação Tecnológica, Brasília

Embrapa (2016) Mapas de solos e de aptidão agrícola de áreas alteradas do Pará. Embrapa Amazônia Oriental, Belém

Ferreira SJF, Luizão FJ, Miranda SAF, Silva MSR, Vital ART (2006) Nutrientes na solução do solo em floresta de terra firme na Amazônia Central submetida à extração seletiva de madeira. Acta Amazon. https://doi.org/10.1590/S0044-59672006000100008

Fonte SJ, Barrios E, Six J (2010) Earthworms, soil fertility and aggregate-associated soil organic matter dynamics in the Quesungual agroforestry system. Geoderma. https://doi.org/10.1016/j.geoderma.2009.12.016

Freitas IC, Santos FCV, Custódio Filho RO, Silva NRA, Correchel V (2012) Resistência à penetração em Neossolo Quartzarênico submetido a diferentes formas de manejo. Rev Bras Eng Agr Ambient. https://doi.org/10.1590/S1415-43662012001200003

Gama-Rodrigues AC, Sales MVS, Silva PSD, Comenford NB, Cropper WP, Gama-Rodrigues EF (2014) An exploratory analysis of phosphorus transformations in tropical soils using structural equation modelling. Biogeochemistry. https://doi.org/10.1007/s10533-013-9946-x

Imtiaz M, Rashid A, Khan P, Memon MY, Aslam M (2010) The role of micronutrients in crop production and human health. Pak J Bot 42:2565–2578. https://www.researchgate.net/profile/Muhammad_Imtiaz6/publication/228502279_The_role_of_micronutrients_in_crop_production_and_human_health/links/09e41511dd9aca5861000000.pdf

Iwata BF, Leite LFC, Araújo ASF, Nunes LAPL, Gehring C, Campos LP (2012) Sistemas agroflorestais e seus efeitos sobre os atributos químicos em Argissolo Vermelho-Amarelo do Cerrado piauiense. Rev Bras Eng Agr Ambient. https://doi.org/10.1590/S1415-43662012000700005

Junqueira AB, Souza NB, Stomph TJ, Almekinders CJM, Clement CR, Struik PC (2016) Soil fertility gradients shape the agrobiodiversity of Amazonian homegardens. Agr Ecosyst Environ. https://doi.org/10.1016/j.agee.2016.01.002

Lima SS, Leite LFC, Oliveira FC, Costa DB (2011) Atributos químicos e estoques de carbono e nitrogênio em Argissolo Vermelho-Amarelo sob sistemas agroflorestais e agricultura de corte e queima no norte do Piauí. Rev Árvore. https://doi.org/10.1590/S0100-67622011000100006

Liu W, Chunjing Z, Junen W, Chunfeng C (2016) Are rubber-based agroforestry systems effective in controlling rain splash erosion? CATENA. https://doi.org/10.1016/j.catena.2016.06.034

Mantovanelli BC, Campos MCC, Alho LC, Franciscon U, Nascimento MF, Santos LAC (2016) Distribuição espacial dos componentes da acidez do solo em área de campo natural na região de Humaitá, Amazonas. Rev Ciência Agroambiental 14:01–09. https://www.researchgate.net/publication/306888224_Distribuicao_espacial_dos_componentes_da_acidez_do_solo_em_area_de_campo_natural_na_regiao_de_Humaita_Amazonas

Marques JDO, Luizão FJ, Teixeira WG, Vitel CM, Marques EMDA (2016) Soil organic carbon, carbon stock and their relationships to physical attributes under forest soils in central Amazonia. Rev árvore. https://doi.org/10.1590/0100-67622016000200002

Moline EFV, Coutinho ELM (2015) Atributos químicos de solos da Amazônia Ocidental após sucessão da mata nativa em áreas de cultivo. Rev Ciências Agrárias 58:14–20. https://periodicos.ufra.edu.br/index.php/ajaes/article/view/1683

Monroe PHM, Gama-Rodrigues EF, Gama-Rodrigues AC, Marques JRB (2016) Soil carbon stocks and origin under different cacao agroforestry systems in Southern Bahia, Brazil. Agr Ecosyst Environ. https://doi.org/10.1016/j.agee.2016.01.022

Moreira A, Fageria NK (2008) Potential of Brazilian Amazon soils for food and fiber productions. Dyn Soils Dyn Plants 2:82–88. https://www.globalsciencebooks.info/Online/GSBOnline/images/0812/DSDP_2(1&2)/DSDP_2(2)82-88o.pdf

Natale W, Rozane DE, Parent LE, Parent S (2012) Acidez do solo e calagem em pomares de frutíferas tropicais. Rev Bras Frutic. https://doi.org/10.1590/S0100-29452012000400041

Navarrete AA, Tsai SM, Mendes LW, Faust K, Hollander M, Cassman NA, Raes J, Veen JAV, Kuramae EE (2015) Soil microbiome responses to the short-term effects of Amazonian deforestation. Mol Ecol. https://doi.org/10.1111/mec.13172

Oliveira BS, Carvalho MAC, Lange A, Dallacort R, Silva VP (2015) Resistência do solo à penetração em áreas sob o sistema de integração lavoura-pecuária-floresta, na região amazônica. Encicl Biosf 11:3678–3689. https://www.

conhecer.org.br/enciclop/2015c/agrarias/resistencia%2520do%2520solo.pdf

Pérez-Flores J, Pérez AA, Suárez YP, Bolaina VC, Quiroga AL (2018) Leaf litter and its nutrient contribution in the cacao agroforestry system. Agrofor Syst. https://doi.org/10.1007/s10457-017-0096-3

Ponisio LC, M'gonigle LK, Mace KC, Palomino J, Valpine P, Kremen C (2015) Diversification practices reduce organic to conventional yield gap. Proc R Soc B Biol Sci. https://doi.org/10.1098/rspb.2014.1396

Quesada CA, Lloyd J, Anderson LO, Fyllas NM, Schwarz M, Czimczik CI (2011) Soils of Amazonia with particular reference to the RAINFOR sites. Biogeosciences. https://doi.org/10.5194/bg-8-1415-2011

Ralisch R, Miranda TM, Okumura RS, Barbosa GMC, Guimarães MF, Scopel E, Balbino LC (2008) Resistência à penetração de um Latossolo Vermelho Amarelo do Cerrado sob diferentes sistemas de manejo. Rev Bras Eng Agr Ambient. https://doi.org/10.1590/S1415-43662008000400008

Rosenstock TS, Tully KL, Arias-Navarro C, Neufeldt H, Butterbach-Bahl K, Verchot LV (2014) Agroforestry with N_2-fixing trees: sustainable development's friend or foe? Curr Opin Environ Sustain. https://doi.org/10.1016/j.cosust.2013.09.001

Rutkowska B, Szulc W, Sosulski T, Stępień W (2014) Soil micronutrient availability to crops affected by long-term inorganic and organic fertilizer applications. Plant Soil Environ. https://doi.org/10.17221/914/2013-PSE

Schwab N, Schickhoff U, Fischer E (2015) Transition to agroforestry significantly improves soil quality: A case study in the central mid-hills of Nepal. Agr Ecosyst Environ. https://doi.org/10.1016/j.agee.2015.03.004

Silva Junior CA, Boechat CL, Carvalho LA (2012) Atributos químicos do solo sob conversão de floresta amazônica para diferentes sistemas na região norte do Pará, Brasil. Biosci J 28:566–572. https://www.seer.ufu.br/index.php/biosciencejournal/article/view/13640

Silva DC, Silva MLN, Curi N, Oliveira AH, Souza FS, Martins SG, Macedo RLG (2011) Atributos do solo em sistemas agroflorestais, cultivo convencional e floresta nativa. Rev estud ambient 13:77–86. https://proxy.furb.br/ojs/index.php/rea/article/view/2320

Singh A, Sharma R, Chauhan SK, Sharma S (2016) Effect of different tree species on soil properties under agroforestry system. Indian J Ecol 43:348–351

Souza ES, Fernandes AR, Braz AMS, Oliveira FJ, Alleoni LRF, Campos MCC (2018) Physical, chemical, and mineralogical attributes of a representative group of soils from the eastern Amazon region in Brazil. Soil. https://doi.org/10.5194/soil-4-195-2018

Verma A, Saralch HS, Chauhan SK, Saresh NV, Sankanur M, Srivastva V (2013) Growth behaviour of poplar (*Populus deltoides*) clones under farm forestry. Indian For 139:1079–1083

Wendling B, Vinhal-Freitas IC, Oliveira RC, Babata MM, Borges EM (2012) Densidade, agregação e porosidade do solo em áreas de conversão do cerrado em floresta de pinus, pastagem e plantio direto. Biosci J 28:256–262 https://www.seer.ufu.br/index.php/biosciencejournal/article/view/13277