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Land use changes and soil attributes of a Brazilian Cerrado-Amazon Rainforest ecotone landscape

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ABSTRACT: Historically, Amazon rainforest and Cerrado in Maranhão state, Brazil, have been subjected to deforestation. The long-term conversion from natural vegetation to mismanaged pasture may induce soil carbon depletion and compaction. Sustainable land management could be an alternative for recovering degraded land in tropical regions. The objective of this study was to evaluate some soil chemical and physical attributes associated with land use change in a Cerrado-Amazon rainforest ecotone. The study was carried out in Maranhão state, in Northeastern Brazil. Plots were selected from three main land uses in the southwestern part of the state: successional forest (SF), conventional pasture (CP) and agroforestry system (AFS). The experimental design was completely randomized, with three treatments (CP, SF, and AFS) and five replications. To evaluate the chemical attributes, a principal component analysis (PCA) was applied. For the chemical and physical attributes, a factorial scheme (land uses and depths) was used. The PCA separated the AFS land use from the other uses, due to the greater influence of pH, organic matter, available P, Ca, Mg, and K, sum of bases, soil cation exchange capacity and base saturation. The CP was mainly influenced by the acidity components. Long-term conversion from extensive pastures to SF and AFS showed a trend of bulk density reduction and led to lower soil resistance to penetration. The improvement of these two physical indicators in the AFS was associated with soil organic matter and carbon stocks and confirmed the improvement of edaphic conditions after adopting a well-managed system, in this small-scale study, in a tropical region.

Key words: agroecosystem management; integrated production systems; organic carbon stocks; successional forest

Mudanças no uso da terra e atributos do solo em uma paisagem ecótonal brasileira Cerrado-Floresta Amazônica

RESUMO: Historicamente, a Floresta Amazônica e o Cerrado no estado do Maranhão, Brasil, foram sujeitos ao desmatamento. A conversão da vegetação natural em pastagem manejada de forma inadequada pode induzir a depleção de do carbono orgânico do solo e a compactação. O manejo sustentável da terra pode ser uma alternativa para a recuperação de áreas degradadas em regiões tropicais. O objetivo deste estudo foi avaliar alguns atributos químicos e físicos do solo associados à mudança do uso da terra em uma área de ecótono Cerrado-Floresta Amazônica. O estudo foi realizado no Estado do Maranhão, nordeste do Brasil. As parcelas foram selecionadas a partir dos três principais usos da terra na parte sudoeste do estado: floresta sucessional (FS), pastagem convencional (PC) e sistema agroflorestal (SAF). O delineamento experimental foi inteiramente casualizado, com três tratamentos (PC, FS e SAF) e cinco repetições. Para avaliar os atributos químicos, os resultados foram submetidos a uma análise de componentes principais (PCA). Para os atributos químicos e físicos, foi utilizado um esquema fatorial (usos do solo e profundidades). A PCA separou o uso do solo do AFS dos demais usos, devido à maior influência do pH, matéria orgânica, P disponível, Ca, Mg e K, soma de bases, capacidade de troca catiônica do solo e saturação por bases. A PC foi influenciada principalmente pelos componentes da acidez. A conversão de áreas de pastagem extensiva em FS e SAF demonstrou uma tendência de redução da densidade do solo e proporcionou menor resistência do solo à penetração. A melhoria desses dois indicadores físicos na área de SAF foi associada à matéria orgânica do solo e aos estoques de carbono, e confirmou a melhoria das condições edáficas, após a adoção de um sistema bem manejado neste estudo de pequena escala, em uma região tropical.

Palavras-chave: sistema agroflorestal; sistemas integrados de produção; estoque de carbono orgânico; floresta sucessional

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Introduction

The state of Maranhão in the Northeast region of Brazil has three biomes, including Amazon rainforest and Cerrado (i.e., savannah). The Amazon rainforest is in the southwestern region of the state and forms part of a transition zone with the Cerrado, known as the Cerrado-Amazon rainforest ecotone. The biome biodiversity is threatened, as Maranhão is part of ''Matopiba", a Federal Government creation, where are the last agricultural commodity frontiers in the Brazil (Bezerra & Gonzaga, 2019).

Historically, the region has been subjected to deforestation, the introduction of poorly managed pastures and cultivation of monocultures (grains and eucalyptus) (INPE, 2020; Lopes et al., 2021). Lopes et al. (2021) analyzed the soy expansion in the Matopiba region, through data collection in 18 municipalities, including in the Maranhão. Their findings exposed a brutal process of environmental degradation. The main reason is because land use changes, especially due the transformation of diversified landscapes into monocultures, have intensified without considering the fragility of the biomes (Campos et al., 2011; Bastos Lima & Persson, 2020).

In tropical regions, the soils are weathered, naturally acidic and have high aluminum saturation and poor fertility, especially low phosphorus availability (Mantovanelli et al., 2016), due of high amounts of Fe and Al oxides in the clay-mineral fraction (Quesada et al., 2011; Abrahão et al., 2019). This edaphic condition, allied to weather with two well-defined seasons, one rainy and one dry, make the effects of land use changes in the southwest of Maranhão different compared to others in the Matopiba (Abrahão & Costa, 2018). In this scenario, the long-term conversion from natural vegetation to mismanaged pasture may induce significant soil carbon depletion and acidity gradients (Fujisaki et al., 2015; Durigan et al., 2017), increasing bulk density and soil resistance to penetration (Cherubin et al., 2016; Souza et al., 2018).

The adoption of sustainable land management could be a viable alternative for recovering degraded land in tropical regions. The conservationist practices must maintain continuous soil cover, minimum soil disturbance, periodic corrections to soil acidity, fertilization and adequate animal stocks (Tavanti et al., 2020). However, the time needed for soil chemical and physical properties to recover after anthropogenic changes depends on the severity of the degradation, soil type and climatic conditions (Greenwood & McKenzie, 2001).

The adoption of integrated production systems is an alternative to improve the sustainability of management practices (Schwab et al., 2015; Couto et al., 2016). These well-established systems play a crucial role in restoring ecosystem services and can, partially, offset the negative impacts of the long-term use of extensive pastures. In agroforestry systems, trees are cultivated with agricultural crops or livestock, which has been shown to enhance nutrient cycling, carbon sequestration, and biodiversity (Nair, 2011; Stefano & Jacobson, 2018). These benefits can stimulate the adoption of the systems in regions where land degradation and rural poverty are correlated, such as the Cerrado-Amazon rainforest ecotone in Maranhão state, Brazil.

Despite extensive research on the impacts of integrated systems on soil properties, limited information is available in the weathered soils of the transition zone between Cerrado and Amazon rainforest. Such studies are important for developing strategies for land management in the region. Thus, the objective of this study was to evaluate some soil chemical and physical attributes, associated with land use changes, in the Cerrado-Amazon rainforest ecotone in Northeastern Brazil. The study was based on the hypothesis that the introduction of agroforestry systems can be an alternative to restore soil organic matter and carbon stocks, attenuating the depletion of soil nutrients and compaction induced by changing from native forest to extensive pasture.

Materials and Methods

Study area

The study was carried out on Monalisa Farm, in São Francisco do Brejão (5° 14' 03" S 47° 22' 57" W), Maranhão state, in Northeastern Brazil. The farm is part of the Brazilian Legal Amazon, in the transition zone between the Cerrado and Amazon rainforest biomes, called the Cerrado-Amazon rainforest ecotone (Figure 1).

The regional climate is classified as Aw (humid tropical), according to the Köppen climate classification. It is characterized by two well-defined seasons, a dry winter and wet summer. The rainy season occurs from December to May, with a monthly average of 250 mm precipitation, and the dry season occurs from June to November, with a monthly average of 17 mm precipitation. The mean annual temperature is 26 °C.

The soil in the experimental areas was classified as a "Latossolo Vermelho distrofico" (Brazilian classification of soil, like Oxisoil in the Soil Taxonomy and Ferralsols in the WRB) (Santos et al., 2018). The soil have 185 g dm^{-3} of clay, 135 g dm^{-3} of silt, and 680 g dm^{-3} of sand, characterized as loamy sandy soil, determined according to the methodology described in Teixeira et al. (2017). It is characterized by highly weathered minerals (Ki and Kr weathering indexes have values < 2.0). The clay fractions were predominantly 1:1 mineral (kaolinite), iron, and aluminum oxide (hematite and gibbsite), deep, and exhibit diffuse boundaries between horizons.

The plots were selected based on three mainland uses in southwestern Maranhão state. The land use systems are adjacent to each other, in the same landscape, and separated by fences. The primary forest was completely cleared around 1970, using fire, and converted into unimproved pasture with brachiaria grass (*Urochloa brizantha* cv. Marandu, Syn. *Brachiaria brizantha*). The history of land use was provided by the landowners.

Since 2000, part of the area, that was previously occupied by unimproved pasture, has been left fallow under natural succession to restore the forest. This part was named successional

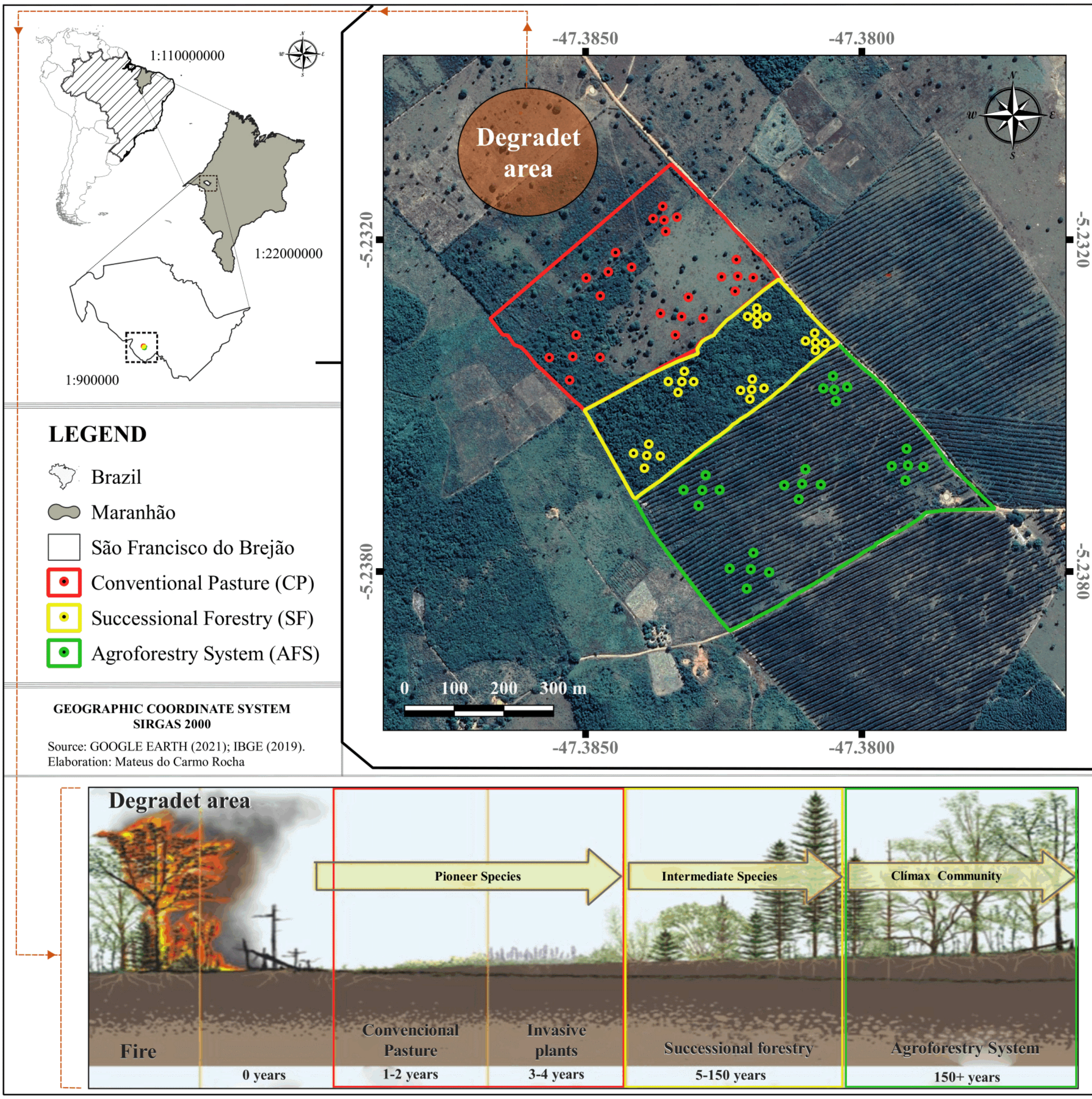

Figure 1. Maps of the Cerrado and Amazon rainforest in Maranhão state, and the location of conventional pasture area (CP), successional forestry area (SF) and agroforestry system area (AFS), and their location within Brazilian territory.

forest (SF). The other part of the area, named conventional pasture (CP), is still managed as unimproved pasture, and predominantly covered by brachiaria grass and weeds. The CP area is characterized by extensive management and absence of animal rotation, lime or fertilization. The stocking rate was above than 1.0 animal units per hectare, and there were few trees to provide shade and no nearby water source.

Near the SF is an integrated system area, named agroforestry system (AFS), which was implemented in 2016, with single rows of *Eucalyptus grandis* intercropped with brachiaria grass. In this area, long-term pasture was converted to AFS. The area was plowed and harrowed and the chopped vegetation (shrubs and small trees) was left on the land.

Before planting, 300 kg ha^{-1} of reactive natural phosphate was applied throughout the area. Three months after, 800 kg ha^{-1} of lime was applied, followed by plowing and harrowing. The spacing adopted for the eucalyptus seedlings was 10 × 2 m (400 trees per hectare). Between the lines of eucalyptus, 12 kg of seeds per ha of brachiaria grass (cv. Marandu) was sown and managed for animal feed. The introduction of animals (1.0 animal unit per hectare) to the AFS occurred 18 months after the system was implemented. We also observed water and salt sources in the AFS area.

Soil sampling and data collection

The experimental design was completely randomized, with three treatments (CP, SF and AFS) and five replications. The experiment was evaluated during the rainy and dry seasons in the region, February and August 2019, respectively. Within each land use area, five representative sampling points were semi-randomly selected, spaced 15 m apart, to take soil samples.

At each sampling point, a small trench (30 × 30 × 30 cm) was opened to collect undisturbed and disturbed soil samples. The undisturbed samples were collected in the center of the 0-5 and 5-10 cm layers, using 100 cm^{-3} metallic cylinders. The disturbed samples were collected at depths of 0-5, 5-10, and 10-20 cm with a shovel. Soil resistance to penetration (SRP) was obtained using a handheld electronic penetrometer (SondaTerra®), with a 30º angle and 4 mm^2 surface area of the cone. The rate of penetration was 6 cm min^{-1}.

The disturbed soil samples were dried, ground and sieved (2 mm) to determine the chemical attributes. The following was determined: soil pH, using a glass electrode in a soil: water ratio 1:2.5; soil organic matter, by the dichromate oxidation method; exchangeable aluminum (Al), calcium (Ca) and magnesium (Mg), extracted with KCl 1 mol L^{-1}; potential acidity (H + Al), available phosphorus (P) and potassium (K), by double acid (0.0125 mol L^{-1} H_2SO_4 + 0.05 mol L^{-1} HCl), and cation exchange capacity (T and t), sum of bases (SB), base saturation (V), and aluminum saturation (m), according to the methodology described by Teixeira et al. (2017).

The undisturbed samples were dried at 105 °C for 48 hours and weighed. Bulk density (BD) was calculated by the sample soil dry mass (g)/cylinder volume (cm^3). The soil organic carbon stock (SOC) at the depths 0-5 and 5-10 cm was a product of three variables, percentage of organic carbon (g dm^{-3}), bulk density (kg dm^{-3}) and layer thickness (cm) (Veldkamp, 1994).

Statistical analysis

To verify ANOVA assumptions, the data were first tested for: a) normality with the Shapiro-Wilk test ($p < 0.05$) and b) homoscedasticity with Bartlett test ($p < 0.05$). Since they complied with these assumptions, the data were analyzed with an ANOVA using the software R version 3.5.2 and, when there were significant differences, the means were compared using a post-hoc Tukey test ($p < 0.05$).

To evaluate the chemical soil attributes in the 0-5, 5-10, and 10-20 cm layers, in February (rainy season) and August (dry season) 2019, to reveal similarities and differences between the AFS, SF and CP areas, multivariate statistics were applied using a principal component analysis (PCA). To run the PCA, highly correlated variables were withdrawn to avoid multicollinearity issues in the correlation matrix used in the analysis. Through the principal component scores, it was possible to group the chemical soil attributes with a higher contribution in each area. For the chemical and physical attributes, a factorial scheme (land uses and depths) was used and, in the case of significant differences, the means were compared with Tukey test ($p < 0.05$).

Results

The results demonstrate a similar grouping pattern for the three depths (0-5, 5-10, and 10-20 cm) and the two seasons evaluated, which formed three very distinct groups of AFS, SF and CP (Figure 2). For the dry season, the PCA explained 88.5% of the variance in the first principal component and 8.4% in the second principal component. The total variance of the data set at the 0-5 cm depth was 96.9% (Figure 2A).

For the rainy season, the PCA explained 84.8% of the variance in the first component and 10.4% in the second component, with 95.2% of the total variance of the data set (Figure 2D). For the 5-10 cm depth, the components explained 97.2 and 92.1% of the total variance of the data set for the dry and rainy seasons, respectively (Figure 2B and 2E). For the 10-20 cm layer, the PCA explained 95.9 and 91.0% in both seasons for the dry and rainy seasons, respectively (Figure 2C and 2F).

The PCA was validated by a 3 × 3 factorial analysis, three land uses and three depths. The analysis of variance revealed the interaction of the factors was significant for all the soil fertility indicators (Tables 1 and 2). The CP area had the lowest values for the soil fertility indicators and the introduction of AFS promoted improvements for the loamy sandy soil in the Cerrado-Amazon rainforest ecotone in Maranhão state.

The SOM contents in the 0-5 cm surface layer were statistically similar for the AFS and SF areas. The average values were 20.20 g dm^{-3} for the AFS and 20.06 g dm^{-3} for the SF in the rainy season. In the dry season, the AFS and SF areas had values of 21.64 and 20.78 g dm^{-3}, respectively. These two land uses had higher SOM contents than the CP area, 11.84 and 12.50 g dm^{-3} (Table 1). In the AFS and SF, the SOM values decreased significantly with depth. However, for the CP area this pattern was not repeated. In the layer below 10 cm, the CP area had an increase in SOM content (Table 1).

The variables related to soil acidity indicated significantly less acidification in the AFS. The lime, which was incorporated into the 20 cm layer, increased the pH values to 5.00 and 4.90 in the rainy and dry seasons (average of the three depths evaluated), reflecting the high values of exchangeable Ca and Mg, and reduced potential acidity, exchangeable aluminum, and aluminum saturation. For the SF area, the values were 4.41 and 4.32, and for the CP system the values were 4.19 and 4.16, in the rainy and dry seasons (Table 1).

We found a noticeable improvement in P and K in the AFS in all soil layers for both seasons. The P values were 13.74 and 13.24 mg dm^{-3} in the 0-5 cm layer, for the rainy and dry seasons, respectively. Meanwhile, in the CP and SF, P did not exceed 3.12 mg dm^{-3} in the three depths evaluated (Table 1). The K values were 50.87 and 42.73% higher in the AFS compared to the CP for the two seasons. For the SF, the values were 31.6 and 29.9% lower than the AFS (Table 1).

We found significant different for the sum of bases, cation exchange capacity and saturation of bases between land uses and soil layers. These values were higher in top layers of the AFS, which reaffirmed the improvement in edaphic conditions of this land use system (Table 2). For almost all variables, the variation between depths had a similar pattern between all land uses; higher values were found in the superficial layers and the values decreased with depth (Tables 1 and 2).

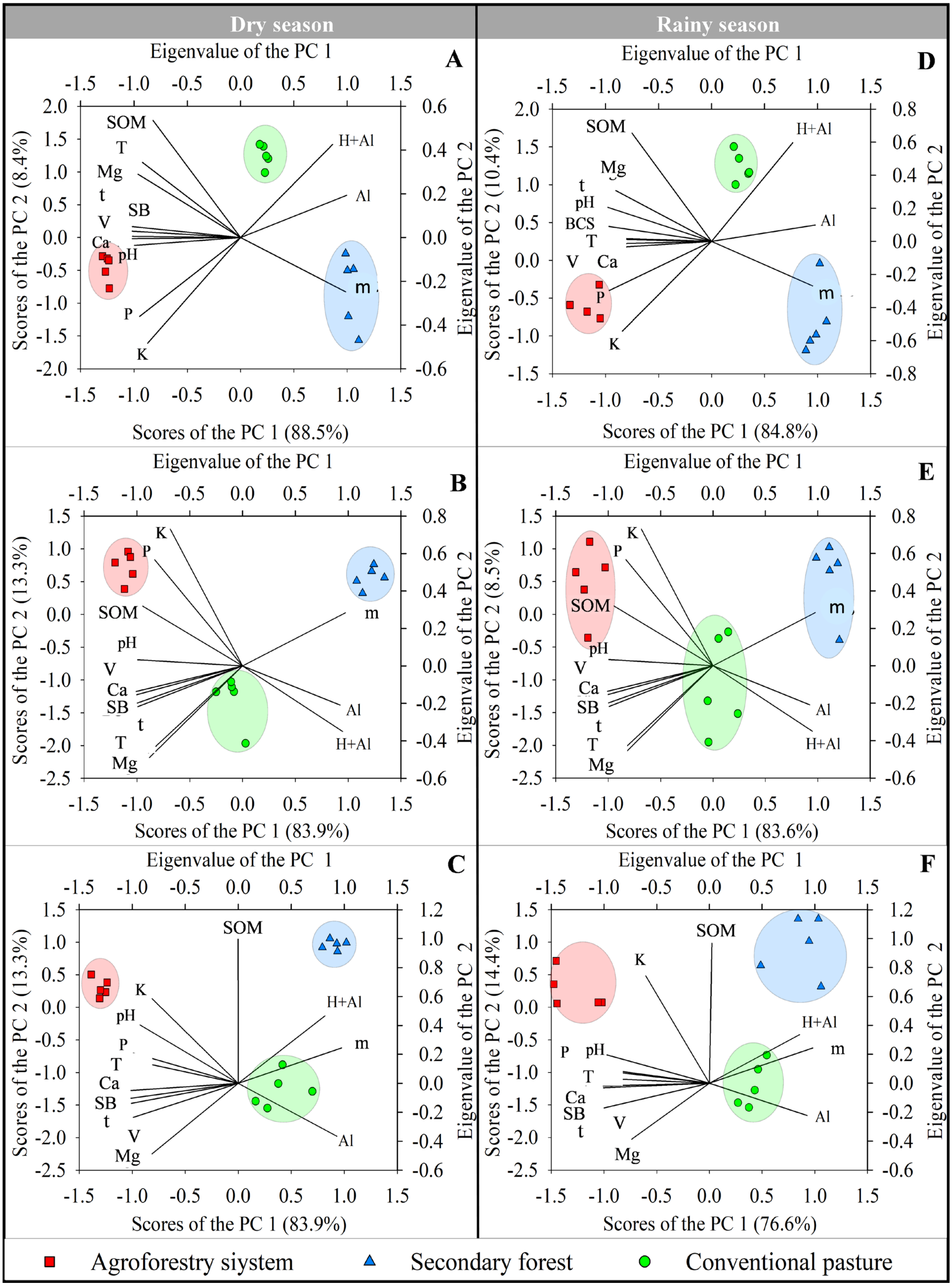

Figure 2. Principal component analysis (PCA) of soil chemical attributes in the 0-5 cm (A, D), 5-10 cm (B, E), and 10-20 cm (C, F) layers, in February 2019 (rainy season) and August 2019 (dry season), in areas with different land uses in Maranhão state, Brazil. Conventional pasture (CP), successional forest (SF) and agroforestry system (AFS). Soil organic matter (SOM), hydrogen potential (pH), calcium (Ca), magnesium (Mg), potassium (K), aluminum (Al), phosphorus (P), saturation by aluminum (m), potential acidity (H + Al), sum of bases (SB), base saturation (V), cation exchange capacity pH7.0 (T) and effective cation exchange capacity. (t).

Table 1. Mean values of the chemical indicators, organic matter (SOM), hydrogen potential (pH), extractable phosphorus (P), calcium (Ca), magnesium (Mg), aluminum (Al) and aluminum saturation (m), in conventional pasture (CP), agroforestry system (AFS) and successional forest (SF) areas, for soil samples collected at depths of 0-5, 5-10, and 10-20 cm, in the rainy season and dry season in 2019.

Rainy season									
Depth (cm)	Land use								
	CP	AFS	FS	CP	AFS	SF	CP	AFS	SF
	SOM (g dm^{-3})			pH (H_2O)			P (mg dm^{-3})		
0-5	11.84 bC	20.20 aA	20.06 aB	4.34 aC	5.10 aA	4.66 aB	2.92 aB	13.74 aA	3.12 aB
5-10	12.92 abC	17.54 bA	14.54 bB	4.16 bC	5.02 aA	4.50 bB	2.36 bB	6.16 bA	2.68 abB
10-20	13.70 aA	12.50 cB	10.00 cC	4.08 bB	4.88 bA	4.08 cB	2.12 bB	4.96 cA	2.48 bB
CV (%)	5.1			1.97			6.93		
	K (cmol$_c$ dm^{-3})			Ca (cmol$_c$ dm^{-3})			Mg (cmol$_c$ dm^{-3})		
0-5	0.14 aB	0.30 aA	0.09 aC	0.51 aC	3.32 aA	1.22 aB	0.41 aC	1.28 aA	0.90 aB
5-10	0.09 bB	0.19 bA	0.06 bC	0.40 aC	1.94 bA	1.18 aB	0.34 aB	0.87 bA	0.75 aA
10-20	0.06 cA	0.08 cA	0.03 cB	0.29 aC	1.67 bA	0.57 bB	0.22 aB	0.47 cA	0.37 bAB
CV (%)	14.24			21.08			24.82		
	Al (cmol$_c$ dm^{-3})			H+Al (cmol$_c$ dm^{-3})			m (%)		
0-5	0.22 aA	0.00 bC	0.17 bB	2.01 abA	1.33 bB	2.25 aA	19.93 cA	0.00 cC	8.89 bB
5-10	0.22 aA	0.15 aC	0.19 bB	2.29 aA	1.68 aB	2.09 aA	27.40 bA	6.94 bC	10.38 bB
10-20	0.22 aA	0.14 aB	0.22 aA	1.91 bA	1.47 abB	1.68 bAB	35.92 aA	9.89 aC	23.95 aB
CV (%)	10.03			11.44			10.08		
Dry season									
Depth (cm)	Land use								
	CP	AFS	SF	CP	AFS	SF	CP	AFS	SF
	SOM (g dm^{-3})			pH (H_2O)			P (mg dm^{-3})		
0-5	12.50 bB	21.64 aA	20.78 aA	4.28 aC	5.06 aA	4.54 aB	2.64 aB	13.24 aA	2.50 aB
5-10	14.44 aC	18.14 bA	15.43 bB	4.10 bC	4.80 bA	4.50 aB	2.30 abB	5.48 bA	2.30 abB
10-20	14.42 aA	13.40 cB	11.00 cC	4.10 bB	4.80 bA	3.94 bC	1.98 bB	4.52 cA	2.06 bB
CV (%)	3.7			1.69			5.56		
	K (cmol$_c$ dm^{-3})			Ca (cmol$_c$ dm^{-3})			Mg (cmol$_c$ dm^{-3})		
0-5	0.10 aB	0.25 aA	0.07 aC	0.48 aC	2.61 aA	1.21 aB	0.39 aC	1.00 aA	0.76 aB
5-10	0.06 bB	0.13 bA	0.05 bC	0.31 bC	1.54 bA	1.16 aB	0.29 bB	0.64 bA	0.65 bA
10-20	0.04 cB	0.09 cA	0.02 cC	0.23 cC	1.16 cA	0.49 bB	0.16 cB	0.35 cA	0.29 cA
CV (%)	11.23			4.46			10.34		
	Al (cmol$_c$ dm^{-3})			H+Al (cmol$_c$ dm^{-3})			M (%)		
0-5	0.24 aA	0.00 bC	0.20 bB	2.45 aA	1.37 aB	2.43 aA	17.05 cA	0.00 bC	7.21 bB
5-10	0.25 aA	0.17 aC	0.22 bB	2.25 bA	1.63 bB	2.08 bA	21.11 bA	4.86 aC	8.86 bB
10-20	0.24 aA	0.17 aB	0.25 aA	2.43 bA	1.55 abB	1.70 cB	28.48 aA	6.21 aC	18.88 aB
CV (%)	6.93			8.43			14.56		

* Significant differences between land uses are represented by uppercase letters in the row and between depths by lowercase letters in the column at a 5% significance level.

The sum of bases in the AFS ranged from 4.9 to 2.23 cmol$_c$ dm^{-3} and 3.87 to 1.59 cmol$_c$ dm^{-3} and decreased with depth, for the rainy and dry seasons, respectively. For all depths, these values were higher than those of the CP, which did not have values above 1.06 and 0.97 cmol$_c$ dm^{-3} for both seasons. The values for the sum of bases in the CP were also lower than those in the SF. The same trends were verified for the saturation of bases. The values for V at the 0-5 cm depth were high in the AFS, 78.33 and 73.82%, for the rainy and dry seasons. For the SF, the values were 49.52 and 45.70%, while for the CP the values did not exceed 34.89%.

The values for cation exchange capacity did not exceed 6.23 and 4.90 cmol$_c$ dm^{-3} (T and t). Even with high SOM, the values for T and t were not greater, due the highly weathered soil. The mineralogy of the clay fraction is dominated by kaolinite, aluminum, and iron oxides, with Kr and Ki levels less than 2.

The integrated system promoted higher SOC stocks, reaching 16.1 and 13.7 Mg C ha^{-1} for the 0-5 cm layer and 13.7 and 11.6 Mg C ha^{-1} for the 5-10 cm layer, in the dry and rainy seasons, respectively (Table 3). For the SF area, these values reached 13.7 and 13.2 Mg C ha^{-1} in the 0-5 cm layer and 10.8 and 9.4 Mg C ha^{-1} in the 5-10 cm layer, which are statistically similar to those observed in the AFS, in the dry and rainy seasons. The CP had 9.8 and 8.2 Mg C ha^{-1} in the 0-5 cm layer and 11.5 and 9.4 Mg C ha^{-1} in the 5-10 cm layer. In the first layer, the CP had the lowest SOC values compared to the other land uses, but these values increased in the 5-10 cm layer (Table 3).

There were statistical differences in bulk density between land uses, but no interaction between land uses and soil depths. The bulk density values were lower in the SF area (1.36 and 1.31 g cm^{-3}) than in the CP area (1.58 and 1.42 g cm^{-3}). The values in the AFS did not differ from the CP and SF (Table 4).

Table 2. Mean values for the sum of bases (SB), cation exchange capacity at pH 7.0 (T), effective cation exchange capacity (t) and base saturation (V) in conventional pasture (CP), agroforestry system (AFS) and successional forest (SF) areas, in soil samples collected at depths of 0-5, 5-10, and 10-20 cm, in the rainy and dry seasons in 2019.

Depth (cm)	Rainy season					
	Land use					
	CP	AFS	SF	CP	AFS	SF
	SB ($mmol_c$ dm^{-3})			V (%)		
0-5	1.06 aC	4.90 aA	2.22 aB	34.89 aC	78.33 aA	49.52 aB
5-10	0.83 aC	3.00 bA	1.99 aB	26.77 bC	64.17 bA	48.87 aB
10-20	0.57 aB	2.23 cA	0.97 bB	22.96 bC	59.99 bA	36.55 bB
CV (%)	16.94			7.56		
	T ($mmol_c$ dm^{-3})			t ($mmol_c$ dm^{-3})		
0-5	3.07 abC	6.23 aA	4.47 aB	1.28 aC	4.90 aA	2.39 aB
5-10	3.12 aB	4.68 bA	4.08 aA	1.05 aC	3.15 bA	2.19 aB
10-20	2.48 bB	3.70 cA	2.64 bB	0.79 aB	2.37 Ca	1.19 bB
CV (%)	10.52			15.7		
	Dry season					
Depth (cm)	Land use					
	CP	AFS	SF	CP	AFS	SF
	SB ($cmol_c$ dm^{-3})			V (%)		
0-5	0.97 aC	3.87 aA	2.05 aB	28.55 aC	73.82 aA	45.70 aB
5-10	0.66 bC	2.31 bA	1.86 bB	22.64 bC	58.60 bA	47.20 aB
10-20	0.43 cC	1.59 cA	0.81 cB	17.44 cC	50.52 cA	32.14 bB
CV (%)	4.39			3.25		
	T ($cmol_c$ dm^{-3})			t ($cmol_c$ dm^{-3})		
0-5	3.44 aC	5.24 aA	4.48 aB	1.21 aC	3.87 aA	2.25 aB
5-10	2.91 bB	3.94 bA	3.94 bA	0.91 bC	2.48 bA	2.09 bB
10-20	2.46 cB	3.14 cA	2.51 cB	0.67 cC	1.76 cA	1.06 cB
CV (%)	5.99			4.05		

* Significant differences between land uses are represented by uppercase letters in the row and between depths by lowercase letters in the column at a 5% significance level.

Table 3. Soil organic carbon stock (SOC) in the conventional pasture (CP), agroforestry system (AFS) and successional forest (SF) areas, in soil samples collected at depths of 0-5 and 5-10 cm, in the rainy and dry seasons in 2019.

Depth (cm)	Rainy season			Dry season		
	Land use					
	CP	AFS	SF	CP	AFS	SF
	SOC (Mg C ha^{-1})			SOC (Mg C ha^{-1})		
0-5	9.8 cB	16.1 aA	13.7 aB	8.2 bB	13.7 aA	13.2 aA
5-10	11.5 aB	13.7 bA	10.8 bB	9.4 aB	11.6 bA	9.4 bB
Total	21.3	29.8	24.5	17.6	25.3	22.6
CV (%)	7.17			8.31		

* Significant differences between land uses are represented by uppercase letters in the row and between depths by lowercase letters in the column at a 5% significance level.

The SRP was significantly higher in the CP compared to the AFS and SF for all evaluated depths and in both seasons. For the dry season, the AFS and SF had similar values for soil resistance to penetration. For the rainy season, the SF area had the lowest SRP (Table 5).

Discussion

For all evaluated layers, in both seasons, the first component separated the AFS land use from the others, due to the greater pH, SOM, P, Ca, Mg, and K, which is reflected in the increased sum of bases, soil cation exchange capacity (T and t) and base saturation (V). The second component separated the CP land use and was mainly influenced by the acidity components. The SF area, despite SOM values like the AFS area, was separated from this land use due to the greater influence of Al and H + Al levels.

Table 4. Soil bulk density (BD) in the conventional pasture (CP), agroforestry system (AFS) and successional forest (SF) areas, in soil samples collected at depths of 0-5 and 5-10 cm, in the rainy and dry seasons in 2019.

Factor		Rainy season	Dry season
Land uses	CP	1.58 ± 0.14 a	1.42 ± 0.10 a
	AFS	1.50 ± 0.13 ab	1.34 ± 0.10 ab
	SF	1.36 ± 0.14 b	1.31 ± 0.09 b
Depth (cm)	0-5	1.46 ± 0.18 a	1.36 ± 0.08 a
	5-10	1.50 ± 0.10 a	1.37 ± 0.11 a
CV (%)		8.09	10.31

* Significant differences are represented by lowercase letters in the column at a 5% significance level.

Table 5. Soil resistance to penetration (SRP) in the conventional pasture (CP), agroforestry system (AFS) and successional forest (SF) areas, in soil samples collected at depths of 0-5 and 5-10 cm, in the rainy and dry seasons in 2019.

Depth (cm)	Rainy season			Dry season		
	Land uses					
	CP	AFS	SF	CP	AFS	SF
	SRP (MPa)			SRP (MPa)		
0-6	0.48 abA	0.42 aB	0.13 aC	0.46 bA	0.15 cB	0.13 bB
6-10	0.52 abA	0.36 abB	0.13 aC	1.14 aA	0.34 bcB	0.22 abB
10-14	0.53 Aa	0.33 bcB	0.16 aC	1.23 aA	0.52 abB	0.32 abC
14-20	0.46 Ba	0.29 cB	0.19 aC	1.16 aA	0.59 aB	0.41 aB
CV (%)	37.49			18.92		

* Significant differences between land uses are represented by uppercase letters in the row and between depths by lowercase letters in the column at a 5% significance level.

According to our hypothesis, we expected that adopting an integrated production system could restore soil organic matter and carbon stocks. Indeed, due to the presence of the tree component and tropical grass with a C4 metabolism between the rows of eucalyptus, we found higher SOM and SOC values for the AFS in the loamy sandy soil in this region. These results were similar, and even greater, than those found for the SF. These assertions are supported by Schwab et al. (2015), who reported that AFS are more efficient at carbon storage compared to other cultivation systems. Couto et al. (2016) also found more carbon in soils in several AFS areas than in areas of secondary forest and pasture.

In the AFS, the C sinks in soil and in biomass could offset cattle production greenhouse gas emissions, and mitigate climate change. According Figueiredo et al. (2017), the conversion of degraded pasture to well-managed pasture and the integrated system can reduce their associated greenhouse gas emissions in terms of kg CO_2eq. The authors concluded that this reduction was due to pasture improvement and the provision of technical potential for C sinks in soil and biomas.

The SOM and SOC decreased with depth in both the AFS and SF, which had higher values in the topsoil layers in the rainy and dry seasons due to the constant deposition of plant leaves, roots and their exudates, stems, flowers, and seeds. This finding corroborates that by Laganiere et al. (2010), who explained that forest land uses, in general, have more SOM in the upper soil layers due to permanent surface cover and continuous inputs of SOC by litter.

Although the SOM and SOC values decreased with depth in the AFS and SF, the CP area had the highest SOM content in the layer below 10 cm. Some studies have shown that conversion from Amazon rainforest to deep-rooted pasture species, such as brachiaria grass, does not promote changes in soil carbon stocks (Fujisaki et al., 2015; Durigan et al., 2017), which corroborates the results of this study.

The long-term pasture of brachiaria, which is a perennial tropical grass with a deep and large root system that inputs C to offset native mineralization (Fujisaki et al., 2015), coupled to the absence of soil tillage management that promotes less organic matter oxidation and loss, may have contributed to the volume of underground biomass (Cherubin et al., 2016). Moreover, the faster turnover of grass roots than tree roots (Fujisaka et al., 1998) could be another reason for the increased SOM in the deepest layer in the long-term pasture system.

Forest soils of Amazonian regions are naturally acidic, with high aluminum saturation and poor fertility (Mantovanelli et al., 2016). This condition could be due to the release of organic acids from the mineralization of organic matter, which promotes a decrease in soil pH, coupled to constant leaching (Barreto et al., 2006) and high amounts of Fe and Al oxides (Quesada et al., 2011). In the AFS, the pH values increased because of the use of limestone, which is reflected in the high sum of bases and influenced the soil base saturation. These results reveal the importance of acidity correction to allow nutrient availability, Ca and Mg supply and favorable conditions for the establishment of the tree component and productive pasture. Natale et al. (2012) highlighted the importance of liming, especially in naturally acidic soils, to enhance soil fertility.

In this sense, the availability P in Brazilian *Latossolos* (i.e., Oxisols) is naturally low. This is due to the presence of Fe and Al oxides and phosphorus that precipitates with Al ions, which are both conditions present in high levels in these highly weathered soils in the Amazon region (Quesada et al., 2011). The adoption of the AFS promoted high P values, due the acidity correction and reactive natural phosphate applied. This also occurred for the available K in the soil, which was higher in this system compared to the CP and SF, due to mineral fertilization carried out in 2016.

The soil management in the AFS promoted effects for the sum of bases, cation exchange capacity (T and t) and base saturation. All these variables were significantly higher compared to those for the CP and SF. The lime was the main factor responsible for increasing T and t since the clay mineralogy is dominated by oxyhydroxides with low nutrient reserves. The deprotonation of the aluminol and ferrol groups present in oxyhydroxides and kaolinite and the ionization of functional groups of organic matter caused by the adsorption of hydroxyls are effects of liming.

Almost all the chemical attributes were greater in the SF area compared to the CP. As described above, forest soils in Amazonian regions are naturally acidic, with high aluminum saturation and poor fertility, and our results indicated that the lack of management in grazing areas may lead to chemical degradation. The CP area had the lowest values for nutrients and fertility indicators. This led us to conclude that, in this scenario, the increased SB, T, t, and V in the AFS implies the system has the potential to remediate unmanaged weathered loamy sandy soils in the climatic zone studied.

The difference in the macronutrients and the other attributes related to soil fertility, in the soil profile, can be explained by the continuous deposition of organic material on the surface, which acts in nutrient cycling. According to findings in the literature, the decomposition of litter promotes nutrient cycling, which is reflected in the soil fertility in forests (Didham, 1998; Caldeira et al., 2008; Hoosbeek et al., 2018).

The SF had the lowest values for bulk density, which was expected due to absence of cattle trampling coupled to frequent additions of SOM from litter fall. The values of BD in the AFS did not differ from those of the CP and SF. The forces applied by continuous cattle trampling could have exceeded the support capacity of the soil in the CP, leading to intense soil compaction, as confirmed by the higher values for bulk density and soil resistance to penetration found in this area. These results could also be attributed to the lower SOM and SOC in the top layer (0-5 cm) compared to the other two land uses.

This assertation is supported by the literature, since greater values of BD and SRP verified in grazing areas are primarily caused by low organic matter on the soil surface, allied to compressive forces from continuous cattle trampling (Cherubin et al., 2016). The BD is strongly dependent on organic matter content and management, which have been used as soil quality indicators. The physical degradation of some soils is commonly related to organic matter reduction and increased density (Li & Shao, 2006; Grosbellet et al., 2011).

A BD higher than 1.6 g cm^{-3} in soils with great amounts of sandy could promote a limiting condition for optimum plant growth in tropical soils (Reichert et al., 2003, 2009; Cherubin et al., 2016). In the dry season, the CP had a value of 1.58 ± 0.14 g cm^{-3}, suggesting that the soil compaction was close to the upper limit and affected root development by limiting access to water and nutrients in the soil strata. The means for the SF and AFS are below this critical value, indicating that the BD did not affect root growth under these two lands uses in this soil. Agroforestry systems tend to have a physical quality like that of forest soils over time (Cherubin et al., 2019).

The treading effect of grazing animals is a function of the mass of the animals, foot size and kinetic energy (Greenwood & McKenzie, 2001). Geissen et al. (2009) concluded that permanent pasture in Mexico led to higher SRP and soil compaction. Costa et al. (2012) also found that an increased SRP associated with high-intensity grazing promoted lower root growth of *Panicum maximum*.

In the CP area, there are few trees that provide shade for animals and there is no nearby water source. More animal movement was observed during the day between water and feeding or shaded places. Greater pressures occur when the animal is moving (Greenwood & McKenzie, 2001). It has been found that livestock trampling, especially under wet soil conditions, induces widespread degradation of the soil surface structure in pastures (Ball et al., 2017; Emmet-Booth et al., 2018).

The higher SRP values for the CP area demonstrate the need to change this management practice to avoid soil compaction. We assumed that high organic deposit on the topsoil in the AFS, originating from aboveground and belowground sources, could reduce soil compaction. In fact, lower SRP values were found in the AFS compared to the CP with depths for both seasons. Cherubin et al. (2019) compared resistance to soil penetration in an agroforestry system and pasture area and observed the lowest values in the AFS. The authors attributed this factor to the constant supply of organic residues in the soil.

The AFS was managed over the last four years with adult animals (but low stocking rates), resowing of the brachiaria grass, shade promoted by the trees and presence of a nearby water source. These factors may have reduced the amount of trampling per unit of soil surface that, in turn, could have reduce the impact of animal movement on the soil. The organic matter, especially in the surface layers, also contributed to increasing soil resilience in the AFS in order to reverse the soil degradation processes (Silva et al., 2011; Arévalo-Gardini et al., 2015). Soil organic matter has important functions that maintain physical and chemical qualities; thus, it is considered the main indicator of soil quality (Cherubin et al., 2016; Bünemann et al., 2018; Cherubin et al., 2019).

In this context, according to Greenwood & McKenzie (2001), many years are generally required for natural recovery of soil physical conditions in drier climates. However, according to these authors, faster responses may be possible under some conditions, such as frequent wetting and drying and when pasture growth is vigorous. Similar climatic conditions occur in the land use areas evaluated in this study, including the integrated production system. The region is characterized by two well-defined seasons, a dry winter and wet summer. For the AFS, this climate and the well-managed tropical C4 grass reaffirmed the improvement in edaphic conditions in this land use system located in Cerrado-Amazon rainforest ecotone.

Therefore, such research, like this one and others carried out in integrated systems, has shown improvement in soil quality and the reduction on the C footprint of cattle production (Figueiredo et al., 2017). The integrated systems can contribute to avoiding further deforestation. Meantime, additional efforts must happen to achieve the comprehension about the management associated to greenhouse gas emissions, and their potential for C sinks in soil and biomass.

However, the implementation of integrated systems need incentive policies. The impact that credit provision will have on integrated system adoption by different stakeholders must be studied (Gil et al., 2015). The authors also suggested to design small-scale business models, which can be used on small-scale farms. Gil et al. (2016) affirm that the access to information, supply chain infrastructure and historical land use patterns are the most important factors influencing the system diffusion. These considerations are especially important for the Maranhão state, where is one of the lowest human development indices in Brazil.

Conclusions

The lack of management in grazing areas lead to soil chemical and physical degradation in the loamy sand soil in this tropical region.

The introduction of an integrated production system promoted improvements in the loamy sandy soil in the Cerrado-Amazon rainforest ecotone in Maranhão state. For all evaluated layers, in both seasons, the agroforestry system land use had the higher values for all soil fertility indicators.

Long-term conversion (20 years) from extensive pasture to the natural recovery of the area (SF) and a sustainable managed system (AFS) showed a trend towards bulk density reduction and led to significantly lower soil resistance to penetration. The improvement of these two physical indicators in the agroforest system was strongly associated with the soil organic matter and carbon stocks. In this small-scale study, well-managed integrated systems have the potential to remediate unmanaged weathered loamy sandy soils in this climatic zone of Brazil.

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Compliance with Ethical Standards

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