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Chemical attributes and soil carbon and nitrogen stocks in pastures in the Maranhão Amazon

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ABSTRACT

In the eastern Amazon region, converting forests into pastureland is a common practice that quickly leads to the degradation of these areas. This study aimed to evaluate the influence of different land uses in different evaluation periods on the chemical attributes, total contents, and carbon and nitrogen stocks of the soil in the Maranhão Amazon. The land use systems analyzed were: perennial pasture (PP), recovered pasture (RP), and secondary forest (SF). Trenches were opened in 2013 and 2019 in each use system in the 0.0-0.20 m and 0.20-0.40 m soil layers. The soil chemical attributes (pH, P, K, Ca, and Mg) and C and N contents and stocks were assessed. PP in the surface layer showed superior results compared to RP and SF, while the opposite behavior occurred in the subsurface. The chemical attributes of the soil decreased over the years evaluated, regardless of the layer and area. The chemical attributes of the soil, as well as the C and N contents and stocks, changed depending on the land use, layer, and year of sampling.

Keywords: Agrosystems, Soil fertility, Soil management.

Atributos químicos e estoque de Carbono e Nitrogênio do solo em pastagens na Amazônia Maranhense

RESUMO

Na região leste amazônica, a conversão das florestas em áreas de pastagem é uma prática comum que rapidamente leva à degradação dessas áreas. O objetivo deste estudo foi avaliar a influência dos diferentes usos do solo em diferentes períodos de avaliação sobre os atributos químicos, teores totais e estoque de carbono e nitrogênio do solo na Amazônia Maranhense. Os sistemas de uso do solo analisados foram: pastagem perene (PP), pastagem recuperada (PR) e floresta secundária (FS). Em cada sistema de uso, foram abertas trincheiras nos anos de 2013 e 2019, nas camadas de 0,0-0,20 m e 0,20-0,40 m. Foram avaliados os atributos químicos do solo (pH, P, K, Ca e Mg) e os teores e estoques de C e N. A PP na camada superficial apresentou resultados superiores quando comparada com a PR e a FS, enquanto na subsuperfície ocorreu o comportamento inverso. Os atributos químicos do solo apresentaram redução ao longo dos anos avaliados, independentemente da camada e área. Os atributos químicos do solo, assim como os teores e estoques de C e N, sofreram alterações em função do uso do solo, camada e ano de amostragem.

Palavras-chave: Agrossistemas, Fertilidade do solo, Manejo do solo.

1. Introduction

The Amazon region provides countless environmental services for the survival of life on the planet. As well as playing an important role in conserving the genetic diversity of countless biological species, it contributes to climate regulation and biogeochemical cycles (Paolino et al., 2021).

The Legal Amazon, established by Law nº 1.806/1953 and updated by Law nº. 5.173/1966, is made up of nine Brazilian states: Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins, Mato Grosso, and Maranhão. The latter includes only 181 municipalities in Maranhão (IBGE, 2021). The area of the Legal Amazon is equivalent to 61% of the entire national territory (IBGE, 2021).

However, the Maranhão Legal Amazon region has been widely affected by deforestation, illegal logging, mining, charcoal production, and other environmentally damaging activities (INPE, 2023). The rate of deforested areas in 2023 increased by around 5.17% compared to the previous year, when it was 271 km^2 in the state of Maranhão alone (INPE, 2023).

The conversion of forests into pasture areas for cattle breeding or agricultural activities is a common practice in the Western Mesoregion of Maranhão, resulting in significant changes in soil attributes (Rego et al., 2023). The practices of cutting and burning vegetation have led to the degradation of these areas (Viana et al., 2016), resulting in an expansion of around 27% in the areas destined for managed pastures between 2000 and 2018 (IBGE, 2021).

Inadequate soil use and management have contributed to the emission of greenhouse gases (GHGs), damaging the environment and the sustainability of the region. This is due to soil organic matter (SOM) degradation, negatively affecting its physical and chemical attributes and biodiversity (Costa et al., 2015). According to Rosa et al. (2014) and Oliveira et al. (2020), cultivated pastures, ecosystems altered by anthropogenic action, can modify carbon and nitrogen flow, resulting in higher GHG emissions when poorly managed.

Soil chemical attributes, such as cation exchange capacity (CEC), available macro and micronutrients, acidity, and soil organic carbon, are essential indicators for assessing soil quality and the environmental sustainability of natural and anthropogenic ecosystems (Cherubin et al., 2015).

Knowledge of the soil chemical attributes and the carbon (C) and nitrogen (N) levels caused by different use systems is essential for improving soil quality. Once the soil chemical characteristics have been identified, it is possible to develop strategies to manage the soil appropriately for agricultural use.

Based on this principle, the replacement of natural ecosystems by agricultural systems causes changes in fertility and the content and stock of carbon (StockC) and (StockN) in the soil. In this context, this study aimed to evaluate the influence of different land uses in different evaluation periods on the chemical attributes, total content, and soil stock of C and N in the Maranhão Amazon.

2. Material and Methods

The soil samples were collected at the Technological Reference Unit (TRU) of Embrapa Cocais in partnership with the Maranhão State University (UEMA) in Pindaré Mirim/MA, at 03°46'13.91” S, 45°20'46.65” W, and altitude of 23 meters. According to the Köppen classification, the climate of the region is tropical (AW-type), with a dry winter, average annual temperature of 26 °C, and average annual rainfall of 2000 mm (Alvares et al., 2014; Araújo, 2013).

The soil of the TRU is classified as Plintossolo Argilúvico (Santos et al., 2018), with a medium texture (Table 1), originating from sediments of the Itapecuru formation and characterized by fine sandstones (Araújo, 2013). The relief varies from gentle to undulating and is covered by an Ombrophilous Forest associated with secondary forest vegetation, with a predominance of babassu palm (*Attalea speciosa* Mart.) (Mata dos Cocais), dominant in the Mid North region of the state of Maranhão (Araújo, 2013).

The experimental design was entirely randomized in a 3x2x2 factorial scheme. The first factor covered the study areas: Perennial Pasture (PP) and recovered Pasture through the intercropping of corn + *Urochloa brizantha* (cultivar Marandu) (RP) and Secondary Forest (SF). The second factor refers to the soil layers sampled (0.00-0.20 m and 0.20-0.40 m). The third factor corresponds to the collection years (2013 and 2019). The sampling units were trenches, collected randomly, and considered independent, functioning as replicates or plots (Ferreira et al., 2012). The experiment had a total of 48 plots. The history and characteristics of the management used are detailed in Table 2 and Figure 1.

In 2013 and 2019, three and five trenches were dug, respectively. All the trenches had 1x1x1 meter dimensions and were randomly arranged in the areas for sampling.

On opposite sides of the trenches, undisturbed samples were collected in the 0.0-0.20 and 0.20-0.40 m layers, using a collector and 100 cm^3 stainless steel volumetric rings to determine soil density (Sd) (Teixeira et al., 2017), which is used in the C and N stocks calculations.

Table 1. Soil particle size characterization in the different areas and layers in the Pindaré-Mirim region, Maranhão, Brazil.

Areas	Layer (m)	Sand	Silt	Clay	Textural class
		----------------g kg^{-1}----------------			
PP	0.00-0.20	579.30	343.00	77.80	Sandy loam
	0.20-0.40	616.05	260.40	123.65	
RP	0.00-0.20	741.90	120.75	137.30	
	0.20-0.40	723.05	97.30	179.70	
SF	0.00-0.20	746.65	135.25	118.10	
	0.20-0.40	707.20	124.25	168.60	

Perennial pasture (PP), Recovered pasture (RP), and Secondary forest (SF).

Table 2. History and characteristics of the areas studied in the TRU in Pindaré Mirim, Maranhão, Brazil.

Areas	History of the area
Perennial pasture (PP)	The pasture with Jaraguá grass (*Hyparrhenia rufa*) was established in 1970 and renewed in 1999 with *Urochloa brizantha*, cultivar Marandu, without soil correction or fertilization. The process included mowing, burning the residues, and sowing by hand. Intended for continuous grazing by beef cattle on an extensive basis, with a stocking rate of 0.7 AU/ha/year, the pasture undergoes periodic mechanical mowing to control natural regeneration.
Recovered pasture with the intercropping of corn + *Urochloa brizantha* (cultivar Marandu) (RP)	In 2012, the pasture was recovered with crop-livestock integration, involving intensive soil preparation with a loader and harrowing, followed by the mechanized sowing of the intercropping of corn (Hybrid DKB 175) + *Urochloa brizantha* (cultivar Marandu). The forage seeds were mixed with the fertilizer, with a dose of 200 kg ha^{-1} of the 08 20 20 + Zn formulation and 100 kg ha^{-1} of urea as a topdressing fertilization for the corn. The pasture is used for rotational grazing by beef cattle, with a stocking rate of 1.0 AU/ha/year.
Secondary forest (SF)	The area is an Open Ombrophilous Forest, predominated by babassu palms (*Attalea speciosa*) in the Mata dos Cocais, Maranhão (MARANHÃO, 2013). Other palm trees are also present, according to Rios (2001). This area, which has been preserved for over 50 years, serves as a reference for the natural conditions of the soil.

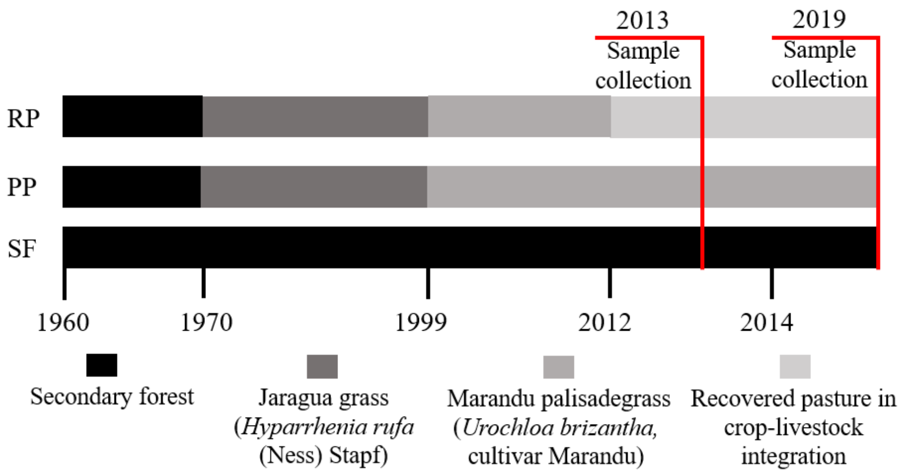

Figure 1. History of use of the areas evaluated, with their respective implementation and sampling. Perennial pasture (PP), Recovered pasture (RP), and Secondary forest (SF).

The disturbed samples were collected at three points ten meters apart from the trench walls, using a Dutch auger, making twelve single samples to make up a representative composite sample in the same layers mentioned above. The samples were then stored in the Federal University of Maranhão plant nutrition laboratory for subsequent air drying and sieving through a 2 mm mesh. After this treatment, the soil samples were chemically determined.

The disturbed soil samples were air dried and chemically characterized according to the methodology described by Teixeira et al. (2017). The pH in water was determined using a combined electrode immersed in a suspension of soil and distilled water in a 1:2.5 ratio. Calcium (Ca) and magnesium (Mg) were extracted using a 1 mol L^{-1} KCl solution and determined using an atomic absorption spectrophotometer. Available phosphorus (P) and potassium (K) were extracted using the Mehlich-1 solution (HCl 0.5 N + H_2SO_4 0.025 N). P was then determined using a UV-VIS spectrophotometer and K^+ by flame photometry (Teixeira et al., 2017).

The total carbon (TC) and total nitrogen (N) contents were determined by dry combustion using the Elemental Analyzer (Flash EA 1112, Thermo Electron Corporation, Milan, Italy). The air-dried soil samples were ground in a mill until they passed through a 100 mesh sieve (0.150 µm). The C and N stocks (Mg ha^{-1}) were calculated from the TC and TN contents in the soil samples, according to equation (1).

$$Stock = \frac{(content\ x\ Sd\ x\ thickness)}{10} \quad (1)$$

The content of the element (C or N) is given in %, the Sd in Mg cm^{-3}, and the “thickness” of the layer for which the stock is being calculated is measured in cm.

Comparisons were made between equal soil masses to compare the stocks calculated between the areas properly. This is because soils subjected to different management may have different densities, which implies comparisons of different soil masses when considering layers with the same thickness, such as those used in the sampling in this study. Therefore, to correctly compare the C and N stocks between the areas, it is necessary to adjust the values of the depths used in the calculations. To do this, adjustments were made to the values of the layers used in the calculations, according to equation (2) (Rego et al., 2023).

$$Corrected\ depth\ (cm) = \frac{WADref}{WADcor}\ x\ DEPcor \quad (2)$$

WADref represents the weighted average density of the reference area (Mg cm^{-3}), WADcor is the weighted average density of the area being corrected (g cm^{-3}), and DEPcor is the original depth of the layer being corrected (cm).

The data obtained was subjected to the normality (Shapiro Wilk) and homogeneity of variances (Barlett) tests at 5% significance, and when these assumptions were met, it was subjected to analysis of variance (ANOVA) and the F test ($P<0.05$). The means were compared using the Tukey test. Statistical analyses were conducted using R software version 4.1 (R Core Team, 2021).

3. Results and Discussion

Interactions were observed between land uses and soil layers (Factors A and C) for the C and N contents and their respective stocks, between land uses and years of evaluation (Factors A and C) for the Ca, Mg, and N contents, and between years of evaluation and soil layers (Factors C and B) for pH and Mg. For P and K contents, only effects of isolated factors were observed (Table 3).

The PP and SF areas had the highest C contents in the surface layer (0.0-0.20 m), 13.2% and 13.5%, respectively, higher than those found in RP, while the highest StockC value was found in PP (Figures 2a and 2c). The opposite behavior occurred in the subsurface soil layer (0.20-0.40 cm), in which RP had 14.1% and 12% more C than PP and SF, respectively, and the highest StockC values (Figures 2a and 2c). The highest levels of N and StockN were found in the surface layer PP, 22.4% and 38.2% higher than in the RP and SF, respectively. In the subsurface layer, the highest levels were found in the RP, a behavior similar to that observed in the C and StockC levels (Figures 2b and 2d).

The surface layer (0.0-0.20 m) stands out for having the highest levels of C and N. This is due to the constant input of SOM resulting from the decomposition of plant and animal waste and the intense biological activity and high concentration of roots in this region (Sales et al., 2018; Ribeiro et al., 2019). On the other hand, in subsurface layers, the contributions to StockC and StockN are less expressive, deriving mainly from the deposition of roots and the transport of material within the soil (Sales et al., 2018; Ribeiro et al., 2019).

The highest levels of C and N, as well as StockC and StockN, were found in the PP, which is related to the deposition of plant residues and animal waste over several years, as well as the root system of the grasses and the longer time for the establishment and balance of soil organisms (Araújo et al., 2011; Campos et al., 2016). Concerning RP, the results may reflect the short recovery time needed to restore the values in the surface layer. However, it is possible to see in the subsurface layers that the contributions of the roots are already having an effect, showing results that are superior to those of PP and SF.

According to Castilho et al. (2016), grasses have a distribution pattern of thin and thick roots that occur in greater concentration in the surface layers of the soil, which leads to an accumulation of SOM on the surface, regardless of the type of land use. It can, therefore, be inferred that the PP had the highest C and N contents, as well as StockC and StockN, due to its greater permanence in the area and the fibrous roots of the grasses, compared to the pivoting system of the areas in the forest environment.

Table 3. Chemical attributes, soil density, nitrogen, and soil carbon according to the land uses, soil layers, and years of evaluations in a Plintossolo Argilúvico in Pindaré Mirim, Maranhão, Brazil.

Factors	pH	P	K	Ca	Mg	C	N	Sd	StockC	StockN
	(H_2O)	mg dm^{-3}	-----$cmol_c$ dm^{-3}-----			---g kg^{-1}---		Mg cm^{-3}	---Mg ha^{-1}---	
Land uses (A)										
RP	4.88 a	1.06 a	0.25 b	1.49 b	3.17 a	6.24 a	0.63 b	1.41 a	8.16 a	1.03 a
PP	4.82 a	1.34 a	0.35 a	2.72 a	4.22 a	6.29 a	0.80 a	1.37 ab	8.65 a	1.11 a
SF	4.75 a	1.56 a	0.20 b	1.50 b	2.31 a	6.64 a	0.74 ab	1.34 b	8.36 a	0.84 b
Standard error	0.065	0.161	0.021	0.277	0.566	0.218	0.026	0.015	0.308	0.038
P-value	0.380	0.167	0.006	0.032	0.135	0.607	0.011	0.038	0.565	0.006
Soil layers (B)										
0.0-0.20 m	4.92 a	1.45 a	0.27 a	2.09 a	3.32 a	7.89 a	0.84 a	1.36 a	10.62a	1.14 a
0.20-0.40 m	4.72 b	1.19 b	0.26 a	1.72 b	3.13 a	4.46 b	0.61 b	1.38 a	6.15 b	0.85 b
Standard error	0.025	0.068	0.019	0.065	0.178	0.071	0.018	0.013	0.094	0.023
P-value	0.380	0.035	0.678	0.006	0.481	0.000	0.000	0.200	0.000	0.000
Years of cultivation (C)										
2013	4.83 a	1.69 a	0.32 a	2.16 a	3.83 a	6.89 a	0.74 a	1.34 b	9.08 a	0.98 a
2019	4.80 a	1.47 a	0.22 b	1.65 b	2.64 b	5.46 b	0.71 a	1.41 a	7.70 b	1.01 a
Standard error	0.042	0.112	0.020	0.085	0.224	0.265	0.028	0.017	0.308	0.039
P-value	0.615	0.080	0.004	0.001	0.003	0.002	0.509	0.013	0.008	0.624
A × B										
Standard error	0.072	0.117	0.032	0.112	0.309	0.123	0.031	0.023	0.162	0.039
P-value	0.656	0.487	0.555	0.112	0.587	0.001	0.018	0.144	0.003	0.011
A × C										
Standard error	0.0721	0.1577	0.0345	0.1475	0.3877	0.4583	0.0484	0.0301	0.5325	0.0670
P-value	0.4309	0.2221	0.7111	0.0053	0.0094	0.1294	0.0321	0.6672	0.2219	0.0581
C × B										
Standard error	0.059	0.193	0.028	0.121	0.317	0.374	0.040	0.025	0.435	0.055
P-value	0.008	0.107	0.784	0.639	0.046	0.104	0.396	0.256	0.085	0.438

Equal lowercase letters in the column for each factor and variable do not differ significantly ($p<0.05$) by the Tukey test. Interactions between factors A × B × C showed no differences ($p<0.05$) by the Tukey test. Captions: RP: Recovered pasture; PP: Perennial pasture; SF: Secondary forest. pH: Hydrogen potential, P: Phosphorus, K: Potassium, Ca: Calcium, Mg: Magnesium, C: Carbon, N: Nitrogen, Sd: Soil density, StockC: Total carbon stock, StockN: Total nitrogen stock.

However, it is important to note that the RP is a recovered area and that this difference could be eliminated over time, as the plants are younger and more vigorous than in the PP, which was installed 20 years ago. The lower levels of C and N found in the surface layer of the RP area (0.0-0.20 cm) can be explained by the fact that the soil was prepared during its establishment, which reduced these levels and stocks. However, in the subsurface (0.20-0.40 m), an increase in C and N content can be observed, as well as in StockC and StockN, due to the renewal of the pasture and the ability of forage plants of the *Urochloa* genus to exploit it. Even with the initial reduction in the surface layer, the RP area has the potential to recover these nutrients, provided there is adequate management and sufficient time for recovery (Bieluczyk et al., 2020).

There was an influence of the interaction ($p<0.05$) between land uses and years of evaluation on the Ca, Mg, and NT contents (Figure 3 and Table 3). The Ca contents ranged among the areas, with the highest values occurring in PP in the first year of evaluation (2013), 51% higher in 2013 and 36% higher in 2019 than SF (Figure 3a).

According to Rodrigues et al. (2017), it is common to find higher Ca contents in anthropized environments and lower levels in environments with native vegetation since, in natural environments, there is no correction or fertilization of the soil, which is originally dystrophic. The initial increase in Ca contents can be explained by the presence of this nutrient in the ash resulting from biomass burning during the traditional preparation of the area for grazing, but these values tend to decrease over time. The return of chemical conditions close to the soil's original levels, in many cases lower, after burning the pasture can be attributed to the absorption of nutrients by the roots, their loss through leaching in the soil profile due to the action of rainwater, and also the removal of part of the ash deposited on the soil surface by the wind action of the wind (Proner Júnior et al., 2022; Dias Filho, 2022).

There was variation between the years of evaluation in PP, with a decrease in Ca content over time (Figure 3a) due to its fixation in plant biomass, pasture consumption, and the non-replenishment of nutrients. Concerning Mg, in the different areas of use and years of evaluation, the highest values (5.45 $cmol_c$ dm^{-3}) were found in the perennial pasture and the evaluation conducted in 2013 (Figure 3b). Similar results were found by Braz et al. (2013), who confirmed that the highest calcium and magnesium contents were found in areas cultivated with pasture, contributing to an increase in the sum of bases compared to areas of native forest.

Concerning NT content, within the same land use, there was a significant difference only in SF, which differed from the other uses only in the second year of evaluation, with 30% lower NT content than PP (Figure 3c). These results can be explained by nutrient cycling in pasture environments occurring more quickly than in forest environments (Vieira, 2017). According to Iwata et al. (2012), the low C:N ratio of organic substrates provides rapid decomposition, as they tend to have higher N contents than those that decompose more slowly, which are responsible for conserving C in the soil.

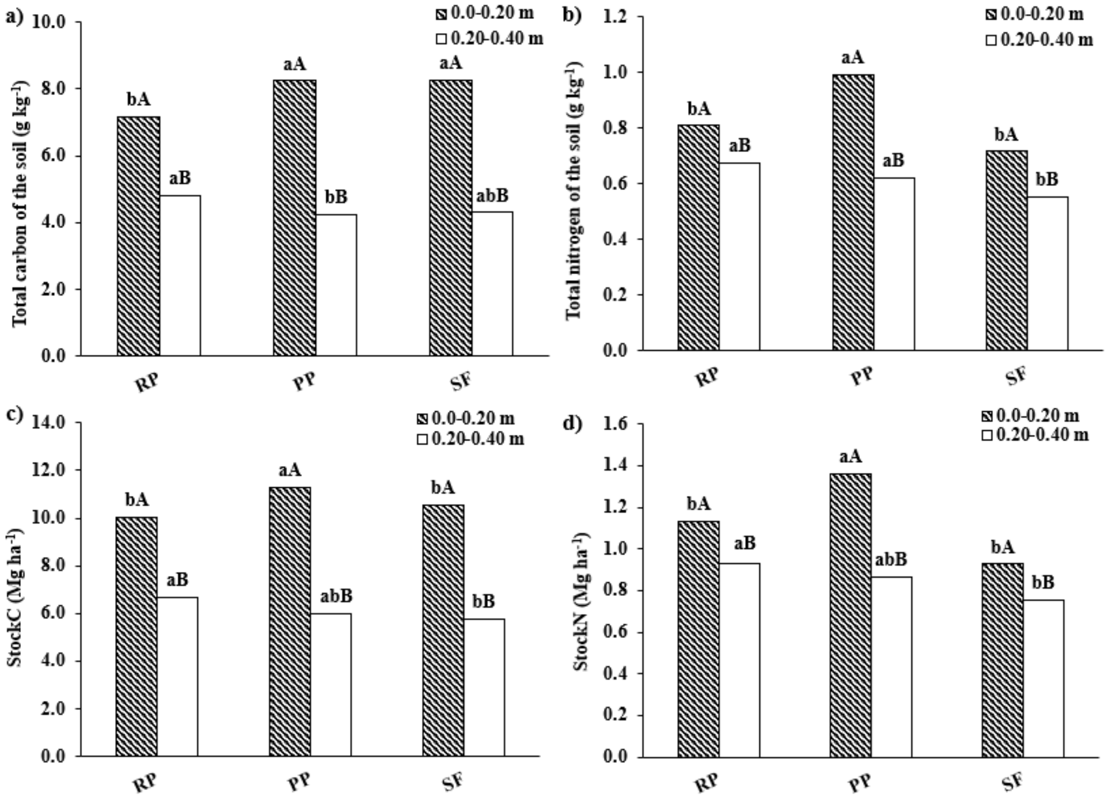

Figure 2. Total carbon content (a), total nitrogen content (b), StockC (c), and StockN (d) of soil according to the land use (recovered pasture – RP, perennial pasture – PP, and secondary forest – SF) and soil layers (0.0-0.20 m, 0.20-0.40 m). Bars followed by the same lowercase letters for land uses and uppercase letters for soil layers do not differ by the Tukey test ($p < 0.05$).

No significant differences were found in soil pH between the years of evaluation in the surface layer (0.0-0.20 cm), while in the subsurface layer (0.20-0.40 m), the lowest values were observed in 2019 (Figure 4a). Using fire and incorporating ash from the original vegetation when preparing the soil for planting may have raised the pH and increased the levels of exchangeable bases (Alves e Modesto Júnior, 2020). This is probably due to the rapid mineralization of nutrients and the high concentrations in the ash. However, as pointed out by

Lorenzon et al. (2014), the pH of the soil after burning does not always increase, as this depends on the composition and quantity of ash generated and the characteristics of the soil. Low pH values are common in the Amazon region, as observed by Mantovanelli et al. (2015) and Aquino et al. (2016), who recorded pH values below 5, indicating the soil acidity in the region.

Magnesium contents did not differ between soil layers, but there was a significant difference ($p<0.05$) in the 0.0-0.20 m soil layer between the years of evaluation, with a 44% reduction from 2013 to 2019 (Figure 4b).

This decrease in the Mg content in the soil over the years of evaluation may have occurred due to the absorption of this nutrient through the pasture and its removal through animal grazing, as well as the absence of soil fertility management (Oliveira et al., 2017) since there was no application of correctives in the areas of perennial pasture and secondary forest. The analysis of the P and K contents and soil density revealed significant values ($p<0.05$) only for the simple effects (Table 3). The P content differed according to the soil layer, while the K and Sd contents showed significant differences between the different areas and in the different years of evaluation.

There was a significant difference in K content among land uses; PP had the highest value, 0.35 cmolc dm^{-3}. The K content also varied significantly between the years of evaluation, with the highest values (0.32 cmolc dm^{-3}) found in 2013. This result can be explained by the residual effect of the burning used to prepare the area in the short term.

Fire can potentially increase the availability of nutrients for plant growth due to the high concentration of P, K, and Ca in the ash (Salomão e Hirle, 2019), which may have consequently increased the K content in the first year of evaluation. Braz et al. (2013), in a study analyzing soil attributes after converting forest to pasture in the Amazon, found an increase in pH values, P, Ca, and K availability in the soil, and a decrease in exchangeable Al levels. The action of fire causes changes in all the chemical attributes evaluated (Silva Neto et al., 2019). RP had the highest soil density values, with an average value of 5% higher than SF. Soil density increased over the years of evaluation, with the average value ranging from 1.34 Mg m^{-3} in 2013 to 1.41 Mg m^{-3} in 2019.

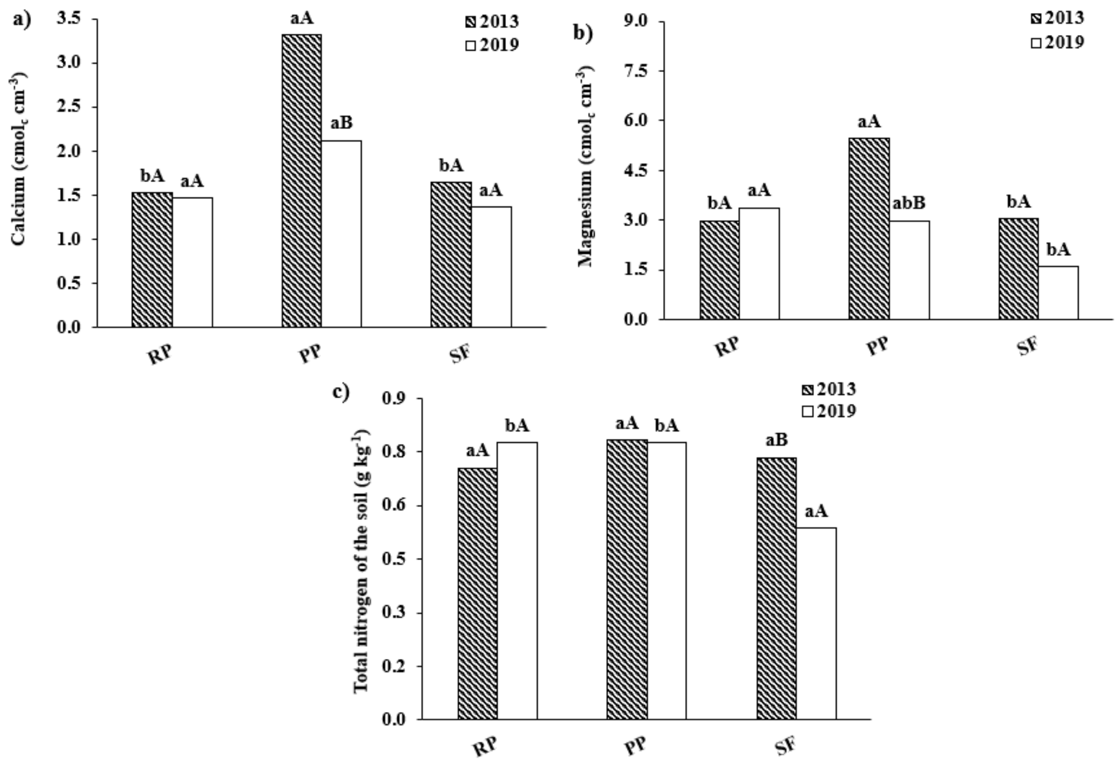

Figure 3. Calcium content (a), magnesium content (b), and total nitrogen content (c) of soil according to the land use (recovered pasture – RP, perennial pasture – PP, and secondary forest – SF) and years of evaluations (2013 and 2019). Bars followed by the same lowercase letters for land uses and uppercase letters for years of evaluation do not differ by the Tukey test ($p< 0.05$).

Similar results were found by Martins et al. (2020), who observed lower Sd values in native forest areas. These results can be attributed to the management and preparation of the soil for the establishment of the pasture, with the use of machinery and through the trampling of the animals during grazing. In pastures, higher Sd values are associated with the degradation of the structure due to animal trampling and the soil texture itself (Sattler et al., 2017). The physical vulnerability of pasture makes the soil more susceptible to compaction and more exposed to erosion processes (Carmo et al., 2018).

The P content was higher in the surface layer (0.0-0.20 m) in all the areas evaluated, 17.9% higher than in the subsurface layer (0.20-0.40 m). This is because P is a nutrient with low mobility in the soil. Furthermore, burning biomass may favor the increase of this nutrient in the surface layer, as reported by Kauffman et al. (1994), in which the increase in P content is related to the formation and deposition of ash in the soil layers.

Magnesium contents did not differ between soil layers, but there was a significant difference ($p<0.05$) in the 0.0-0.20 m soil layer between the years of evaluation, with a 44% reduction from 2013 to 2019 (Figure 4b). This decrease in the Mg content in the soil over the years of evaluation may have occurred due to the absorption of this nutrient through the pasture and its removal through animal grazing, as well as the absence of soil fertility management (Oliveira et al., 2017) since there was no application of correctives in the areas of perennial pasture and secondary forest.

The analysis of the P and K contents and soil density revealed significant values ($p<0.05$) only for the simple effects (Table 3). The P content differed according to the soil layer, while the K and Sd contents showed significant differences between the different areas and in the different years of evaluation. There was a significant difference in K content among land uses; PP had the highest value, 0.35 $cmol_c$ dm^{-3}.

The K content also varied significantly between the years of evaluation, with the highest values (0.32 $cmol_c$ dm^{-3}) found in 2013. This result can be explained by the residual effect of the burning used to prepare the area in the short term. Fire can potentially increase the availability of nutrients for plant growth due to the high concentration of P, K, and Ca in the ash (Salomão e Hirle, 2019), which may have consequently increased the K content in the first year of evaluation. Braz et al. (2013), in a study analyzing soil attributes after converting forest to pasture in the Amazon, found an increase in pH values, P, Ca, and K availability in the soil, and a decrease in exchangeable Al levels.

The action of fire causes changes in all the chemical attributes evaluated (Silva Neto et al., 2019).RP had the highest soil density values, with an average value of 5% higher than SF. Soil density increased over the years of evaluation, with the average value ranging from 1.34 Mg m^{-3} in 2013 to 1.41 Mg m^{-3} in 2019. Similar results were found by Martins et al. (2020), who observed lower Sd values in native forest areas. These results can be attributed to the management and preparation of the soil for the establishment of the pasture, with the use of machinery and through the trampling of the animals during grazing. In pastures, higher Sd values are associated with the degradation of the structure due to animal trampling and the soil texture itself (Sattler et al., 2017).

The physical vulnerability of pasture makes the soil more susceptible to compaction and more exposed to erosion processes (Carmo et al., 2018). The P content was higher in the surface layer (0.0-0.20 m) in all the areas evaluated, 17.9% higher than in the subsurface layer (0.20-0.40 m). This is because P is a nutrient with low mobility in the soil. Furthermore, burning biomass may favor the increase of this nutrient in the surface layer, as reported by Kauffman et al. (1994), in which the increase in P content is related to the formation and deposition of ash in the soil layers.

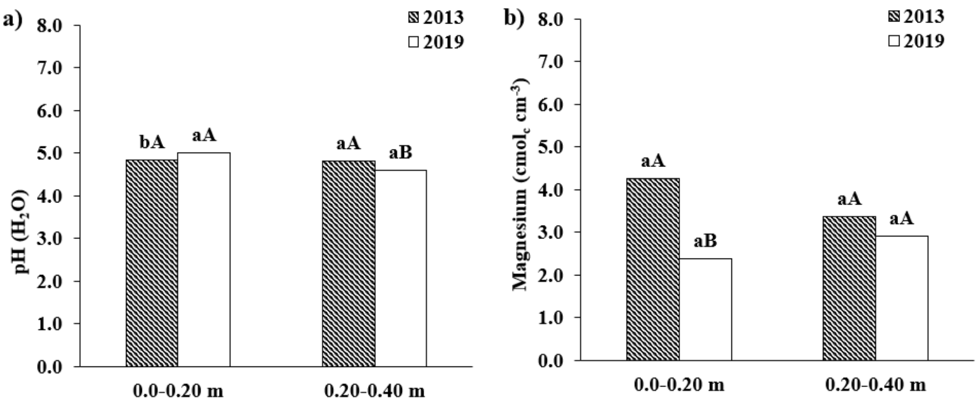

Figure 4. pH (a) and magnesium content (b) of soil according to the layers (0.0-20 and 0.20-0.40 m) and years of evaluations (2013 and 2019). Bars followed by the same lowercase letters for soil layers and uppercase letters for years of evaluation do not differ by the Tukey test ($p< 0.05$).

4. Conclusions

Perennial pasture had superior results in the surface layer compared to recovered pasture and secondary forest, while the opposite behavior occurred in the subsurface layer. The chemical attributes of the soil decreased over the years, regardless of the layer and area. The chemical attributes of the soil and the C and N contents and stocks changed depending on the land use, soil layer, and year of evaluation.

Authors' Contribution

Maycon Pedrosa Cardoso, Rodrigo Barbosa Silva, and Carlos Augusto Rocha de Moraes Rego were responsible for developing the experimental design, choosing the methodologies, and analyzing the data statistically. Maycon Pedrosa Cardoso, Carlos Augusto Rocha de Moraes Rego, and Victor Roberto Ribeiro Reis conducted the data collection and actively participated in reviewing and editing the manuscript. Luciano Cavalcante Muniz coordinated the project, managed the resources, and supervised all the work. Victor Roberto Ribeiro Reis conducted additional experiments and created the figures and tables. Caio Vinicius Sales Pereira da Macena provided the necessary materials and resources and organized the database. Maycon Pedrosa Cardoso and Carlos Augusto Rocha de Moraes Rego drafted the original version of the manuscript and contributed to obtaining funding. Luciano Cavalcante Muniz and Pedro Augusto de Oliveira Morais validated the results and approved the final version of the text before submission.

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