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Original Article

Fertility and carbon stock in pasture and forest environments in the Southern Amazon[1]

Fertilidade e estoque de carbono em ambientes de pastagem e floresta no sul da Amazônia

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HIGHLIGHTS:

Phosphorus, pH, organic carbon, and bulk density were the attributes most sensitive to soil management.
Pasture soils had carbon stock levels 0.8 to 12.4 Mg ha^{-1} lower than forest soils.
Lack of conservation management has led these pastures to degradation.

ABSTRACT: Inadequate management of pasture soils in the Amazon has resulted in a predominance of degraded pastures. Considering the natural characteristics of this region can favor more appropriate strategies for sustainability, the objective of this study was to evaluate the differences in the chemical and physical attributes of pasture and forest soils in the Southern Amazon and to identify the most sensitive attributes of their fertility. Additionally, this study suggests appropriate management practices for sustainable pastures. Soil samples from the 0 to 0.20 m layer were analyzed to determine pH, exchangeable bases (calcium, magnesium, and potassium), exchangeable aluminum, potential acidity, phosphorus, organic carbon, bulk density, and texture. Pasture soils had a higher pH, calcium content, and bulk density than forest soils. However, the pasture soils had lower phosphorus and organic matter content. The soil organic carbon stocks were also lower in pasture soils, with levels 0.8 to 12 Mg ha^{-1} lower than in forest soils. The fertility attributes most sensitive to soil management in these pastures were phosphorus, pH, organic carbon, and bulk density. The lack of nutrients and soil and water conservation practices have contributed to the degradation of these pastures. Therefore, the recommended management for these pastures should aim to improve the organic matter content, reduce compaction, and replenish and cycle nutrients.

Key words: climate changes, conservation management, livestock, soil degradation, sustainability

RESUMO: O manejo inadequado de solos de pastagens na Amazônia resulta em predomínio de pastagens degradadas. Considerando as características naturais dessa região pode favorecer estratégias mais adequadas para sua sustentabilidade, o objetivo desse estudo foi avaliar as diferenças de atributos químicos e físicos de solos de pastagens e florestas no sul da Amazônia e identificar os atributos mais sensíveis de sua fertilidade. Além disso, sugerir práticas de manejo mais adequadas para essas pastagens em direção à sustentabilidade. Amostras de solo da camada de 0 a 0,20 m foram analisadas para determinação de pH, bases trocáveis (cálcio, magnésio e potássio), alumínio trocável, acidez potencial, fósforo, carbono orgânico, densidade aparente e textura. Os solos de pastagem tiveram maior pH, cálcio e densidade aparente do que os solos de floresta. No entanto, os solos de pastagem apresentaram menores teores de fósforo e matéria orgânica. Os estoques de carbono orgânico do solo também foram menores nas pastagens, com teores de 0,8 a 12 Mg ha^{-1} inferiores aos solos da floresta. Os atributos de fertilidade mais sensíveis ao manejo do solo nessas pastagens foram fósforo, pH, carbono orgânico e densidade aparente. A carência de nutrientes e de práticas de conservação do solo e da água têm contribuído para o estado de degradação dessas pastagens. Portanto, o manejo recomendado para essas pastagens deve visar a melhoria da matéria orgânica, redução da compactação, além da reposição e ciclagem de nutrientes.

Palavras-chave: mudanças climáticas, manejo conservacionista, pecuária, degradação do solo, sustentabilidade

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Introduction

In Brazil, the Amazon biome comprises 55 million hectares of pastures used for livestock, of which 57% are moderately or severely degraded (MapBiomas, 2022). Currently, deforestation, greenhouse gas emissions, and soil degradation are the major impacts of livestock production in the Amazon. Therefore, the sustainability of this activity in the Amazon, which continues to advance over native forests, is of considerable concern (Bueno et al., 2021).

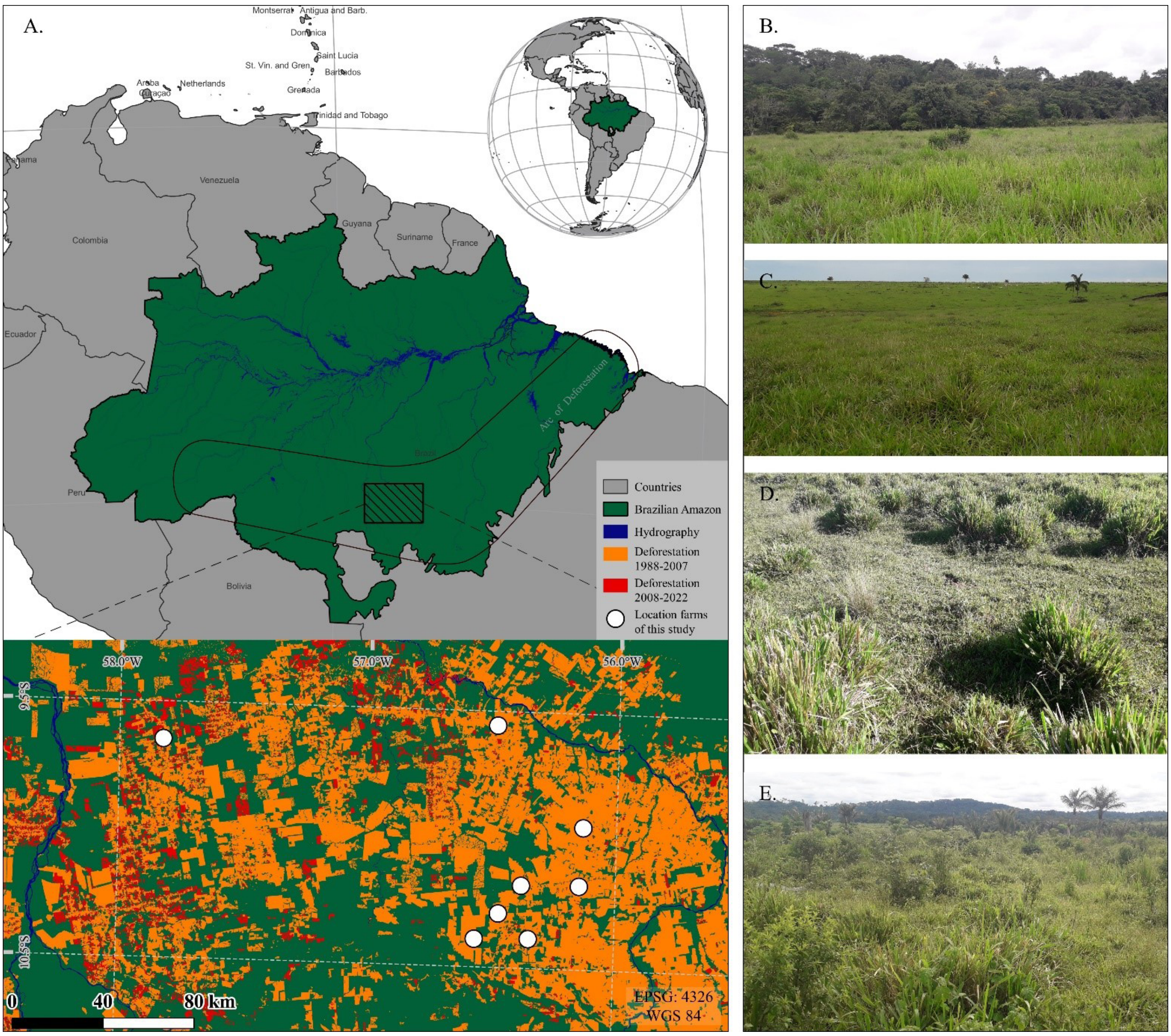
In the Amazon, there has been rapid process of modification of the natural landscape, giving way to pastures, followed by agriculture. Efforts to intensify these production systems have been adopted with the justification of productivity potential and contribution to sustainable development; however, livestock still predominates with low production rates (Ermgassen et al., 2018).

The conversion of native areas into pastures modifies soil conditions, exposing them to degradation when preceded by inadequate management, for example, by increasing the susceptibility to erosion and loss of organic matter and nutrients (Bronick & Lal, 2005; Rueda et al., 2020; Silva et al., 2022; Rocha et al. 2023). As a result, productivity is reduced, and environmental impacts are aggravated. However, few studies have compared agricultural practices in the Amazon with the conditions of natural vegetation (Bueno et al., 2021).

Evaluating the chemical and physical attributes of soil is important for identifying the impact of soil management and allowing management that guarantees its functionality (Cardoso, 2013). Therefore, the objective of this study was to evaluate the differences in the chemical and physical attributes of pasture and forest soils in the Southern Amazon and to identify the most sensitive attributes of their fertility. Additionally, to suggests more appropriate management practices for sustainable pastures.

Material and Methods

This study was conducted on eight farms that practice extensive beef cattle farming in the southern Brazilian Amazon (Figure 1). According to Köppen's classification, the climate in the region is Am, with average temperatures between 20 and



Source: INPE (2022)

Figure 1. Location map of the study area and sampling sites (A). Photographs of studied environments: Pasture and adjacent forest (B); Amazon typical extensive pasture (C); Pasture degradation by land cover failures (D); and Pasture degradation by weeds (E)

35 °C and rainfall between 2,000 and 3,000 mm $year^{-1}$. The predominant slope was between 5 and 15% and, the elevation was between 260 and 375 m. The study region is located in the Amazon arc of deforestation and is considered one of the most important agricultural frontiers of this biome.

Soil samples were collected from the pastures and forest environments adjacent to the pastures of each farm during the rainy season (2021/2022). Soil samples were collected at 0-0.20 m depth in each environment from three points at least 50 m apart. At each sampling point, one composite sample was obtained from three individual samples, with a minimum distance of 10 m between them, for total of 48 samples (three samples from each pasture environment and three samples from each forest environment for each studied farm). Additionally, a semi-structured questionnaire was used to obtain technical, productive, and historical land use information (Universidade do Estado de Mato Grosso, Brazil, Research Ethics Committee: 44321521.5.0000.5166). General information for each farm is presented in Table 1.

The following chemical and physical soil analyses were performed: potential of hydrogen (pH) was determined in water (1:2.5); soil organic carbon (SOC) was determined by colorimetry after wet digestion; soil organic matter (OM) was obtained by multiplying the SOC by 1.724 (assuming that organic matter has 58% carbon); phosphorus (P) was determined using colorimetry at a wavelength of 660 nm after extraction with Mehlich-1 solution; exchangeable potassium (K^+) was determined using flame spectrophotometry after extraction with Mehlich-1 solution; exchangeable calcium (Ca^{2+}), exchangeable magnesium (Mg^{2+}), and exchangeable aluminum (Al^{3+}) were extracted with 1 mol L^{-1} KCl and determined using titrimetry; potential acidity (H + Al) was determined using titrimetry following extraction with 0.5 mol L^{-1} calcium acetate; bulk density of soil (Bd) was determined using the volumetric cylinder method; and texture (sand, silt, and clay) was determined using the densimeter method.

After conducting the chemical and physical soil analyses, the variables of the soil assortment complex and SOC stock were determined using the following equations:

$$EB\left(cmol_c\ dm^{-3}\right)=\sum\left(Ca^{2+},Mg^{2+},K^{+}\right) \qquad (1)$$

$$CEC\left(cmol_c\ dm^{-3}\right)=\sum\left[EB,\left(H+Al\right)\right] \qquad (2)$$

$$m\left(\%\right)=\frac{Al^{3+}}{\sum\left(EB,Al^{3+}\right)}\times 100 \qquad (3)$$

$$BS\left(\%\right)=\frac{EB}{CEC}\times 100 \qquad (4)$$

$$SOC\ Stock\left(Mg\ ha^{-1}\right)=\frac{\left(SOC\times Bd\times E\times A\right)}{F} \qquad (5)$$

where:

EB - sum of exchangeable bases;

CEC - cation exchange capacity;

m - percentage of aluminum saturation;

BS - percentage of base saturation;

SOC - soil organic carbon (g dm^{-3});

Bd - bulk density of the soil (Mg m^{-3}) (for pasture environments, the average Bd of the forest environment adjacent to the pasture was used);

E - thickness of the soil layer (0.20 m);

A - area unit (10,000 m^2); and,

F - conversion factor from kg to Mg (1,000).

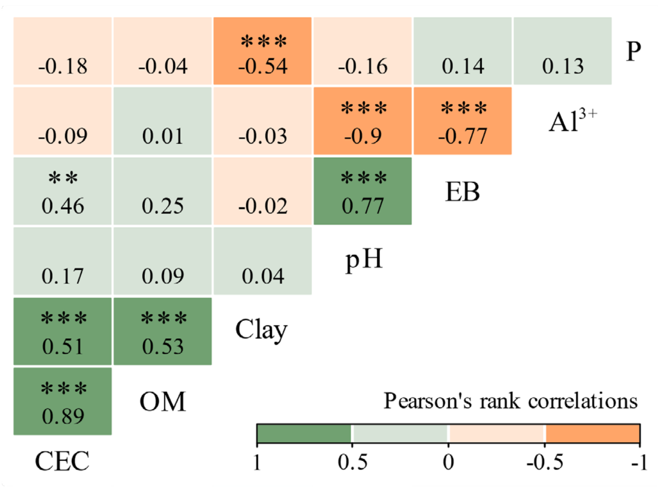
The data obtained were analyzed for normality using the Shapiro-Wilk test and, when necessary, were adjusted using the Box-Cox transformation method. A Pearson correlation matrix was constructed between the main physical and chemical quantitative soil variables, followed by a linear regression analysis between highly correlated variables. Student's t-test (parametric distribution) or Mann-Whitney U test (non-parametric distribution) was applied to compare the results between pastures (Farms I to VIII) and forest environments (adjacent to each pasture) as two naturally distinct groups (pasture × forest). The significance level was set at 5% ($p \leq 0.05$).

Results and Discussion

The results of the correlation analysis between the main chemical and physical soil variables are shown in Figure 2.

Table 1. General information on farms included in this study

Farm	Farm size category (hectare)	Pastures size (hectare)	Soil class	Forest-to-pasture conversion	Current grass	Soil fertility management
I	> 1,000	13	Ultisol and Oxisol	1991	*Urochloa brizantha*	Sporadic use of limestone and mineral fertilizer
II	200 to 1,000	11	Ultisol and Oxisol	1995	*Panicum maximum*	Use of limestone and mineral fertilizer in 2016
III	200 to 1,000	8	Ultisol and Oxisol	1994	*Panicum maximum*; *Urochloa brizantha*	Use of limestone in 2016
IV	> 1,000	53	Oxisol	1985	*Urochloa brizantha*	Sporadic use of limestone and mineral fertilizer
V	200 to 1,000	6	Ultisol and Oxisol	1999	*Urochloa brizantha*	No correction of soil fertility
VI	> 1,000	34	Ultisol	2007	*Urochloa brizantha*	Use of limestone and mineral phosphate in 2015
VII	200 to 1,000	15	Ultisol and Oxisol	1995	*Urochloa brizantha*	Sporadic use of limestone.
VIII	> 1,000	20	Ultisol and Oxisol	1984	*Panicum maximum*	Sporadic use of limestone and mineral fertilizer



Correlation significance test: ** $p \leq 0.01$; *** $p \leq 0.001$

Figure 2. Pearson correlation matrix between soil chemical and physical variables. EB: sum of exchangeable bases; OM: organic matter; CEC: cation exchange capacity

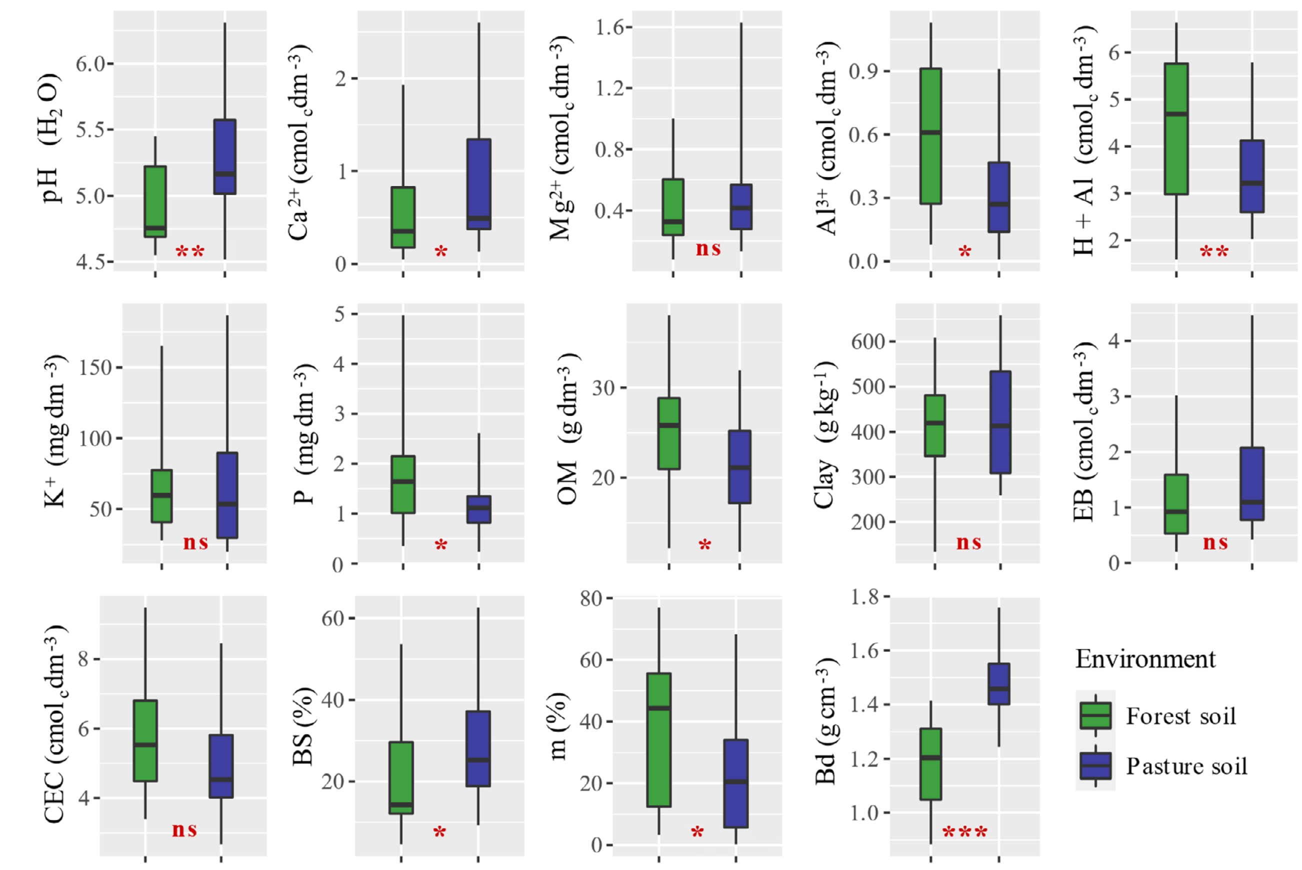
Positive correlations were observed between pH and EB and between clay, CEC, and OM. Although there was a positive correlation between the EB and CEC, they were collinear, as the CEC was derived from the EB (Eq. 2). Furthermore, negative correlations were observed between Al^{3+} with pH and EB, and between P and clay.

The pH is one of the main indicators of soil fertility and is responsible for the adsorption and desorption reactions of chemical elements in the soil solution (Raij, 1983). Low pH conditions indicate a low availability of Ca^{2+}, Mg^{2+}, and K^+ that make up EB, which explains the positive correlation between pH and EB. This also explains the negative correlation between Al^{3+} with pH and EB, considering that Al^{3+}, which is inversely related to exchangeable bases, becomes more soluble as the soil pH is reduced (Havlin, 2005).

The positive correlation between clay, OM, and CEC reflect a typical soil dynamic in which clay and OM interact to form aggregates. In the aggregate structure, clay and OM are less exposed to water erosion (Zhu et al., 2022), and OM is less susceptible to rapid mineralization (Liu et al., 2022). This is particularly relevant in the Amazon, which experiences intense rainfall and high temperatures. The CEC is directly influenced by clay and OM, as they form negative electrical charges in the soil and provide higher CEC values (Umasankareswari et al., 2022). This intricate correlation is of great importance for the sustainability of production systems, as inadequate management of these soils invariably results in their degradation.

The P results showed a behavior typical of tropical soils in which this nutrient is complexed with clay, making it less available to plants in clayey soils. In clayey soils, P is strongly adsorbed to Fe and Al oxides (Barbosa et al., 2022), which typically occur in the main soil classes of the Amazon Biome; for example, Ultisols and Oxisols represent 72% of this territory (BDIA, 2022).

A comparison of the chemical and physical soil variables between the pasture and forest environments is shown in Figure 3. The pasture soils had higher pH, Ca^{2+}, and BS, whereas the forest soils had higher potential acidity, Al^{3+}, m, P, and OM. These results indicate differences that can be



Significance level by Student's t-test or Mann-Whitney U test: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; ns - Not significant; OM - Organic matter; EB - Sum of exchangeable bases; CEC - Cation exchange capacity; BS - Percentage of base saturation; m - Percentage of aluminum saturation; Bd - Bulk density

Figure 3. Chemical and physical attributes of soils of pasture and forest environments

attributed to pasture management, as in some farms, limestone was occasionally applied to correct soil acidity, increase exchangeable bases (Ca^{2+} and Mg^{2+}), and neutralize Al^{3+}.

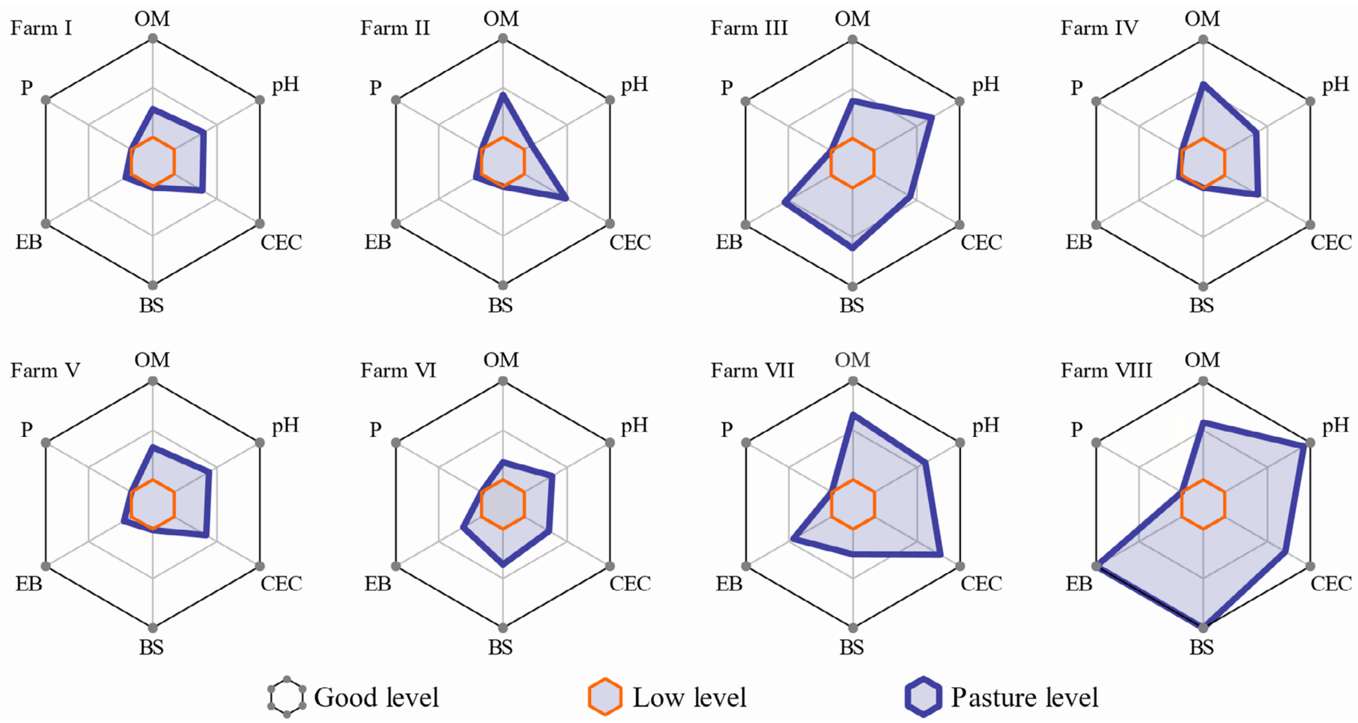
Lower P and OM values in pasture soils than in forest soils indicate losses of these soil attributes due to the management adopted. Additionally, using information obtained through interviews and *in loco* observations, it was possible to verify that no regular mineral replacement or soil conservation practices were adopted for these pastures. Improving animal productivity in pasture systems requires monitoring soil nutrient stocks, fluxes, and fertilization to ensure the replacement of extracted nutrients, without which there will be inevitable nutrient depletion and pasture degradation (Rueda et al., 2020). Furthermore, adopting soil protection and conservation practices is essential for the sustainability of production systems (Silva et al., 2022).

The pasture soils had higher Bd values than the forest soils. This difference can also be attributed to the management of the production system, considering that animal trampling and occasional machinery traffic affect the soil surface, causing compaction and reducing the physical space available for air and water. For plants, there is a critical limit of soil density, beyond which it becomes a significant impediment to root growth. This limit can be estimated by considering Bd and clay content according to the equation proposed by Reichert et al. (2009). Thus, the Bd critical limit of pasture environments was predominantly above or close to this limit, which was estimated between 1.32 and 1.64 g cm^{-3}. These results indicate the need for practices to correct or prevent excessive compaction of these soils and maintain them at an adequate level for root growth.

Regarding the interpretation of the natural fertility conditions of these soils (forest soils, Figure 3) based on the interpretation tables by Ribeiro et al. (1999), these soils had medium and high acidity, low and medium Al^{3+}, Ca^{2+}, and Mg^{2+}, medium K^{+}, and very low P levels. This implies that using these soils for pastures also requires practices to correct the acidity and fertility of the main macronutrients required to establish and maintain forage in addition to replenishing nutrients to maintain production.

The CEC of forest soils was considered predominantly medium, with their 25th to 75th percentiles between 4.5 and 6.8 $cmol_c$ dm^{-3}. However, it is important to note the high correlation of this attribute with OM (0.89; $p \leq 0.001$; Figure 2), mainly because there was a reduction of OM in the pasture environment, which contributed to reducing the CEC by approximately 0.7 $cmol_c$ dm^{-3} to levels considered low and medium, between 4.0 and 5.8 $cmol_c$ dm^{-3}. The CEC is an indicator of the potential of the soil to serve agricultural use and normally has values dependent on soil mineralogy and mainly on the OM in tropical soils (Raij, 1983). Low CEC values indicate that the soil retains few exchangeable bases, increasing the need for fertilization (Umasankareswari et al., 2022). Thus, we highlight the importance of preserving or improving OM to allow sufficient conditions for CEC, favoring soil fertility, and minimizing the need for agricultural inputs.

Land use change affects soil fertility; therefore, natural or anthropogenic differences in each environment can result in different responses (Silva et al., 2022; Rocha et al., 2023). However, we observed some common characteristics in interpreting of pasture soil fertility at each farm (Figure 4). These pastures had soil fertility conditions predominantly below the good level, mainly with regard to P, which was below the minimum level on all farms. This highlights the need to implement better soil fertility management practices, such as improving OM and nutrient cycling and regular replenishment of nutrients to cultivate pastures.



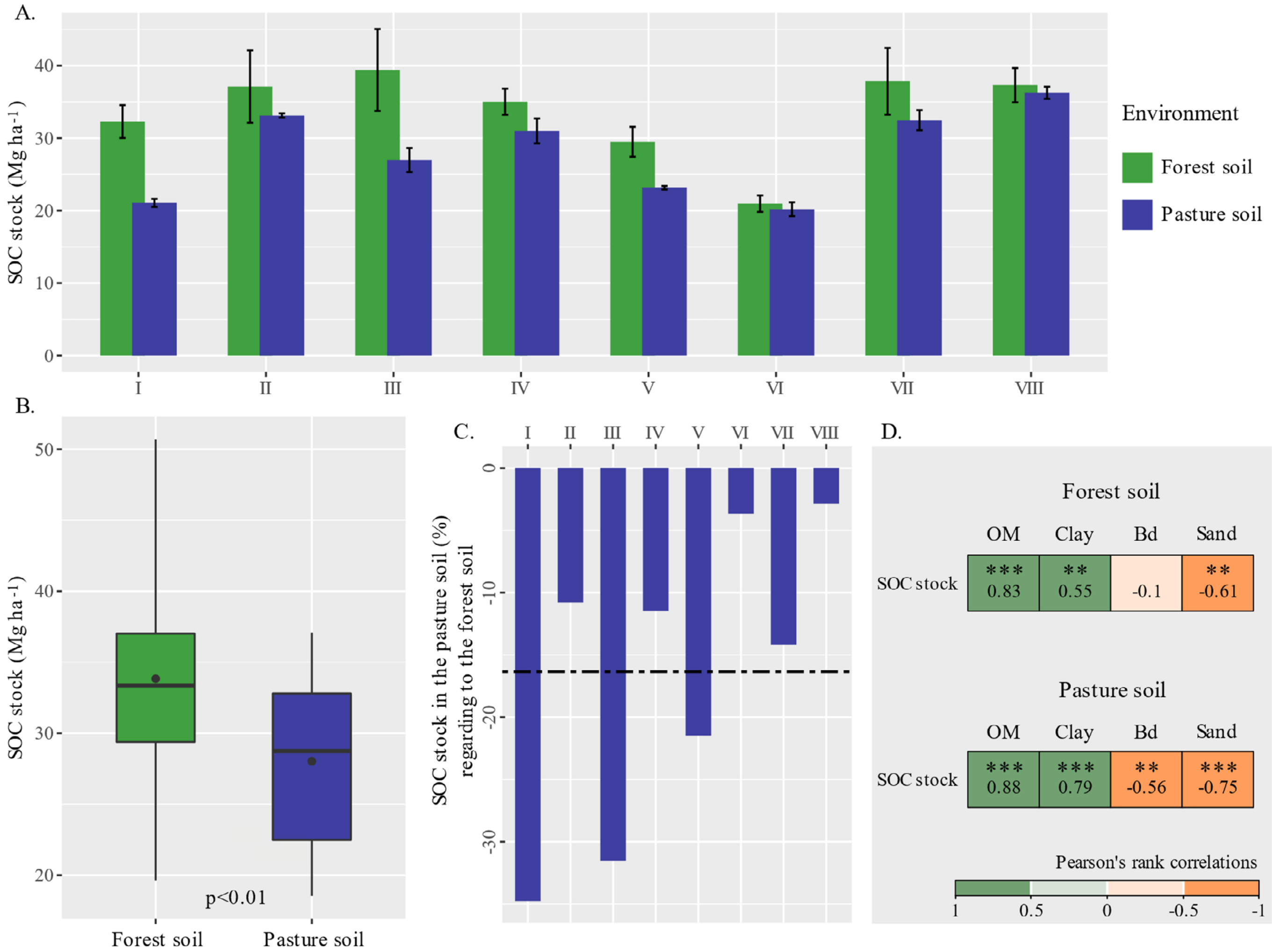
Low and good levels suggested by Ribeiro et al. (1999): OM (7.0; 40.1 g dm^{-3}), pH (4.5; 6.1), CEC (1.6; 6.56 $cmol_c$ dm^{-3}), BS (20.0; 60.1%), EB (0.6; 3.61 $cmol_c$ dm^{-3}), and P (4.0; 12.1 mg dm^{-3}). The values of the pasture soil attributes were interpreted from the median of the samples from each pasture. OM - Organic matter; CEC - Cation exchange capacity; BS - Percentage of base saturation; EB - Sum of exchangeable bases

Figure 4. Interpretation of pasture soil fertility in each farm (I-VIII)

The SOC stock results for the pasture and forest environments are shown in Figure 5. Despite the variability between the studied sites (Figure 5A), the pasture environment had the lowest SOC stocks ($\bar{x}$ = 28 Mg ha^{-1}) compared to the forest environment ($\bar{x}$ = 33.7 Mg ha^{-1}) (Figure 5B). The magnitude of this difference in each location studied ranged from 2.8 to 34.8% ($\bar{x}$ = 16.3) of SOC loss from the pasture environment in relation to the respective forest environment locations (Figure 5C). This means that the conversion of forest areas into pasture represented SOC losses of approximately 0.8 to 12.4 Mg ha^{-1} ($\bar{x}$ = 5.7), even when considering only the surface soil layer (0 to 0.20 m).

The correlation results for SOC stock with soil physical attributes suggested differences between the forest and pasture environments (Figure 5D). Clay and sand showed stronger correlations with SOC stock in pasture than in forest environments. These results reinforce the importance of considering the natural characteristics of these soils, which may be more fragile depending on the management conditions to which they are exposed. For example, low-clay soils (sandy soils) are more likely to suffer the greatest losses of soil carbon because of the absence of conservationist practices because the soil texture is related to the formation of aggregates, which directly influences its ability to retain OM (Zhu et al., 2022).

In the pastures, the reduction in SOC stock was correlated with an increase in Bd, which did not occur in the forest environment (Figure 5D). This difference was associated with pasture soil management, which is more exposed to surface impacts, as discussed in relation to Bd (Figure 3). Additionally, in soils with a higher SOC stock, higher OM also contributes to a reduction in Bd because of its lower density in relation to the soil and its role in dampening the surface impact, which is particularly more relevant in managed soils. This explains the different correlations between SOC stock and Bd in the pasture and forest environments. Although, it is important to highlight that in compacted soils, there is less root development, difficulty in plant growth, and increased laminar erosion, among other aspects, contributing to the general degradation of the pasture and increased CO_2 emissions (Bronick & Lal, 2005). That is, soil compaction indirectly implies a reduction in SOC stock.



Correlation significance test: ** p ≤ 0.01; *** p ≤ 0.001

Figure 5. Soil organic carbon (SOC) stocks in the forest and pasture environments (layer 0 to 0.20 m). Average and standard error of SOC stock in each studied farm (I-VIII) and environment (A), Boxplot with average of SOC stock data and statistical significance by Student's t-test for environments studied (B), SOC stock in the pasture in relation to the respective adjacent forest environment (C), and Pearson correlation analysis for SOC stock with organic matter (OM), clay, sand, and bulk density (Bd) in the forest and pasture environments (D)

Achieving a level of sustainable livestock development in the Amazon is a great challenge; however, seeking solutions to achieve this target is necessary. Many pathways have been suggested to reduce deforestation (Skidmore et al., 2021), reduce environmental impacts (Dick et al., 2021), enhance productivity (Ermgassen et al., 2018), and protect biodiversity (Neate-Clegg & Şekercioğlu, 2020). However, it remains unclear how and when cattle ranching in the Amazon will become sustainable (Bueno et al., 2021).

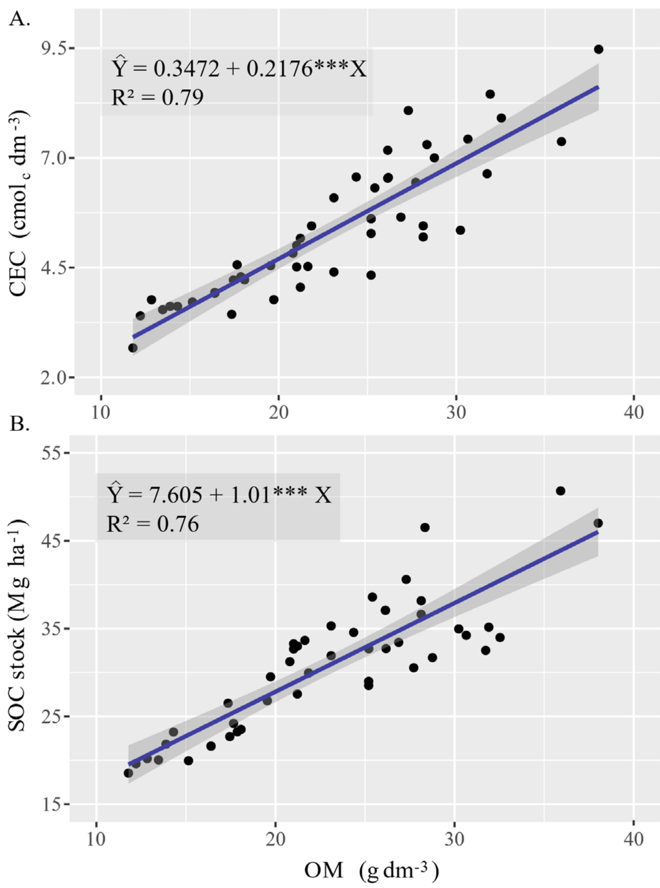
Considering the multifunctionality of soil, which provides several essential ecosystem services for life (Adhikari & Hartemink, 2016), guaranteeing soil health is necessary for the sustainability of livestock production systems. Therefore, pasture management in the Amazon is a basic prerequisite for guaranteeing soil health through production practices.

In the regression analysis, we found indications that an increment of only 5 g dm^{-3} of OM would result in improvements of approximately 1.1 cmol$_c$ dm^{-3} of CEC (Figure 6A) and 5 Mg ha^{-1} in SOC stock in the topsoil layer (Figure 6B). This would represent a significant improvement in the fertility of these soils, increasing their capacity to retain and make available nutrients, favoring the efficiency of fertilizers, or even reducing their dependence on them. Furthermore, considering 55 million hectares of pastures in the Amazon (MapBiomas, 2022), this would represent the sequestration of one petagram of atmospheric CO_2 (5×10^{-9} Pg C ha^{-1} × 5.5×10^{7} ha × 3.66 CO_2), which reinforces the potential of soil as a carbon sink to mitigate climate change (Lal, 2020). However, adopting certain agricultural practices should be carefully considered, as they may eventually result in adverse effects on soil quality, such as environmental contamination from fertilization with organic waste (Scheid et al., 2020).

To improve OM and promote soil health, several production techniques that are already widely recognized by conservationists and ecological pasture managers can contribute. Among these, some options may require low economic investment, such as improving grazing control, avoiding overgrazing, and excessive animal stocking load (McTavish et al., 2021), such as the adaptive multipaddock technique (Teague & Kreuter, 2020). Among other techniques, there are integrated production systems, such as crop-livestock-forestry integration, which have achieved promising results despite requiring high investments and payback time between 2.5 and 8.5 years (Ermgassen et al., 2018).

To overcome the constant challenges related to the costs associated with the adoption of better agricultural practices, the implementation of incentives through rural extension programs (Rocha-Júnior et al., 2020), payments for environmental services (Biggs et al., 2021), and credit subsidies for sustainable projects (Costa-Júnior et al., 2019) are considered important options. Additionally, the evaluation of ecosystem services through indicators, such as OM, Bd, and soil sorption complexes, can be adopted in these areas of the Amazon to monitor changes toward sustainability. Additionally, these indicators are relatively simple, accessible, and inexpensive.

Finally, it is necessary to consider the existence of several aspects to be overcome or understood in the context of farms in the Amazon for the sustainable intensification of livestock production, such as precarious infrastructure, lack of qualified labor, an unfavorable regulatory environment, and the cultural value of the traditional method of livestock production (Cortner et al., 2019). This highlights the importance of promoting the strengthening of actions of an educational nature, technological dissemination, and the development of scientific research with multidisciplinary approaches to support all dimensions of the concept of social, economic, and environmental sustainability, and to overcome multiple established challenges.



***: significant at p ≤ 0.001 by F test

Figure 6. Linear regression of cation exchange capacity (CEC) (A) and soil organic carbon (SOC) stock (B) in response to organic matter (OM) in the forest and pasture environments in the Southern Amazon

Conclusions

1. Pasture environments in the Southern Amazon show changes in the chemical and physical attributes of the soil compared to forest environments. The attributes most sensitive to soil management were phosphorus, pH, organic carbon, and bulk density.

2. The current conditions of these soils indicate that the conversion of forest to pasture represents losses in the organic carbon stock between 0.8 and 12.4 Mg ha^{-1} in the surface layer of the soil.

3. The lack of nutrients and soil and water conservation practices have contributed to the degradation of these pastures.

4. The recommended management for these pastures should aim to improve the organic matter content, reduce compaction, and replenish and cycle nutrients.

Acknowledgments

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