

Soil organic carbon dynamics in the Cerrado–Amazon ecotone: Effects of land-use change on organic carbon sequestration and losses

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ABSTRACT

Transition zones between major biomes, such as the Cerrado–Amazon ecotone, are critical for studying soil organic carbon (SOC) dynamics. These ecotonal areas are shaped by shifts in vegetation, climate, and soil properties, influencing carbon cycling on broader ecological scales. However, they are also highly vulnerable to land-use changes, particularly the conversion of native forests into agricultural systems, which can disrupt ecosystem functions and reduce the soil's carbon storage capacity. This study evaluated carbon sequestration across native forests, croplands, and pastures in the Cerrado, Amazon, and Cerrado–Amazon ecotone biomes. Soil samples were collected at six depths (0–1.0 m) from four random points in each land use. The highest concentrations of carbon (C) and nitrogen (N) were found in the surface layer (0–0.05 m). Managed soils, especially croplands, showed significant reductions in C stocks, 30 % in the Cerrado, 33 % in the Amazon, and 43 % in the ecotone, down to 1.0 m. Croplands in the ecotone also had the greatest decrease in cation exchange capacity (CEC), with a ~38 % reduction up to 0.20 m. In the Amazon, croplands showed higher levels of humic acid (HA) and humin (HU) fractions compared to native forests (32.5 g kg⁻¹ vs. 8.7 g kg⁻¹). Meanwhile, the conversion of native vegetation reduced the fulvic acid fraction (FAF) in deeper layers and led to SOC losses, resulting in carbon losses of 4.9, 2.5, and 9.0 Mg ha⁻¹ year⁻¹ in the Cerrado, ecotone, and Amazon, respectively. These findings emphasize the urgent need for sustainable land management practices in the Cerrado–Amazon ecotone to mitigate carbon losses, preserve ecosystem functions, and reduce greenhouse gas emissions in the face of ongoing land use and climate change.

1. Introduction

Climate change, largely driven by global warming since the industrial revolution, has become one of the most pressing environmental issues globally. The primary cause of this phenomenon is the rising concentration of greenhouse gases (GHGs) in the atmosphere, with CO₂ as the main contributor (Barbera et al., 2020; Sugihara et al., 2012). Brazil is one of the largest GHG emitters, and most of its emissions are linked to land-use change and agricultural activities, which account for 72 % of the national total (U.S. Agency for International Development, 2023). Among these, inadequate soil use and management are

responsible for a substantial share, 22 % of gross and 28 % of net emissions (IPCC, 2020).

Soils are central to the global carbon cycle, storing more carbon than the atmosphere and vegetation combined (Lal and Cerri, 2006; Machado, 2005). When well-managed, soil serves as a significant carbon sink. However, land-use changes, especially the conversion of native vegetation into pasture and croplands, have increased the risk of soil organic carbon (SOC) depletion and associated CO₂ emissions (FAO, 2017; Gougoulas et al., 2014). Such changes alter the balance between carbon inputs (e.g., litter deposition, root exudation) and outputs (e.g., microbial decomposition, leaching, erosion), directly affecting SOC

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dynamics. The removal of natural vegetation disrupts physical protection mechanisms of SOC, such as aggregation and occlusion within soil microstructures, and weakens chemical stabilization through the breakdown of organo-mineral associations (dos Santos et al., 2019; Iwata et al., 2021). These conversions often involve biomass burning, soil disturbance, and inadequate management, reducing organic inputs and accelerating the decomposition of soil organic matter. Over time, this leads to reduced microbial efficiency in carbon stabilization, faster mineralization of labile C fractions, and lower persistence of stable pools.

The preservation or restoration of SOC stocks thus depends on how these landscapes are managed post-conversion, with direct consequences for both climate regulation and long-term soil fertility. In tropical regions such as the Amazon and Cerrado biomes, the situation is particularly critical due to the predominance of highly weathered soils with low natural fertility (Soares et al., 2020). These soils are rich in iron and aluminum oxides and contain low-activity clays, which influence SOC stabilization by forming organo-mineral complexes (Locatelli et al., 2025). Although these interactions can promote long-term carbon retention, they are highly sensitive to disturbances caused by intensive land-use practices (Rittl et al., 2017). Moreover, the turnover rate of SOC in tropical soils is typically higher due to elevated temperatures and moisture regimes, further amplifying the impacts of disturbance on carbon losses.

The Cerrado-Amazon ecotone, a transitional region between forest and savanna systems, presents unique challenges and opportunities in this context. This zone is ecologically diverse and functionally complex, integrating structural and biogeochemical traits from both biomes. Because of its intermediate characteristics, particularly regarding vegetation cover, organic matter input, and decomposition dynamics, the ecotone is more sensitive to environmental change (Popin et al., 2025). Land-use change in this region can destabilize the fragile equilibrium of SOC input–output processes. For example, reductions in deep-root biomass and litter quality may diminish the formation of stable organo-mineral complexes, while soil exposure and compaction can limit infiltration and aeration, accelerating SOC oxidation. Land-use conversion in this region may result in disproportionately higher losses of SOC compared to core areas of the Amazon and Cerrado, especially given the fragile balance of soil processes and the lack of tailored management strategies.

Despite this vulnerability, the ecotone may also play a critical role in regional carbon retention and atmospheric CO₂ sequestration, acting as a buffer or transitional sink in the broader landscape. However, its potential to fulfill this role is increasingly threatened by agricultural expansion and deforestation, which can undermine its capacity to store carbon effectively and contribute to climate mitigation.

Based on this context, we hypothesize that SOC loss is more pronounced in the Cerrado-Amazon ecotone due to its heightened sensitivity to land-use change and disturbance. The objective of this study is to quantify and compare soil carbon stocks in native forest, pasture, and agricultural systems across the Amazon, Cerrado, and ecotonal regions, and to evaluate how changes in land use influence SOC retention and stabilization under different ecological conditions.

2. Materials and methods

2.1. Description of the study area

The soil samples were collected at the Estação Ecológica do Rio Ronuro (ESEC) located in the central region of the state of Mato Grosso, municipality of Nova Ubiratã, between the geographic coordinates 12° 46' 00", 14° 07' 00" S and 55° 15' 00", 54° 19' 00" W (EA – Fig. A1). ESEC Rio Ronuro was created by Brazilian State Decree No. 2207/98 (amended by State Law 8325/05) and covers an area of 102,000 ha (ISA, 2015).

The reserve is located within an equatorial climate, characterized by

transitional forests between the Cerrado and Amazon biomes. It has a short dry season in winter, average temperatures of above 25 °C, and annual rainfall of approximately 2000 mm. The predominant climate is type Am by the Köppen climate classification system (Kottek et al., 2006). The Conservation Unit lies within the Amazon basin, draining into the Santo Cristo, Hinternam, Von Den Steinen, and Ronuro rivers (CEPEMAR, 1998).

Rock types in the region originate from the Cenozoic, Mesozoic, and Proterozoic that form lithologies composed of sands, silts, gravels, claystones, and intercalations of arkoses and siltstones, among others. The geomorphological features are associated with the Brazilian Highlands, represented by the Parecis Plateau and the Paranatinga Depression, where there are significant variations in height and large plateaus. Regarding pedology, Oxisols, Quartz sands (Quartzarenic Neosols), Inceptisol, and Spodosol are predominant within the ESEC region (CEPEMAR, 1998).

Areas selected for this study are located within two biomes (Amazon and Cerrado) and a region between the two biomes called the Amazon-Cerrado transition (ecotone). Details on the history and management of the areas are available in Table 1.

All study areas, regardless of vegetation type, are classified as Latossolo Vermelho-Amarelo according to the Brazilian Soil Classification System (Embrapa, 2013), or Oxisol Typic Hapludox according to U. S. Soil taxonomy (Soil Survey Staff, 2014), which are deeply weathered tropical soils common in the Amazon-Cerrado transition. Although the soil classification is consistent across sites, textural variability is evident: clay content ranged from 153 to 258 g kg⁻¹, silt from 13 to 46 g kg⁻¹, and sand from 717 to 817 g kg⁻¹. These differences reflect the influence of parent material, topography, and land use history, and they directly impact physical protection mechanisms and carbon stabilization potential. Texture details are available in Table 1.

To evaluate the degree of weathering and mineral reactivity, we calculated the *Ki* (silica-to-alumina molecular ratio) and *Kr* (silica-to-alumina plus iron molecular ratio) indices following the methodology described by Embrapa (2017). The procedure involves solubilizing soil using a 1:1 diluted sulfuric acid solution, followed by quantification of SiO₂, Al₂O₃, and Fe₂O₃ in the extract. Theoretical values for Latossolo Vermelho-Amarelo typically range from 1.0 to 2.5 for *Ki*, indicating moderate to intense weathering, and from <0.5 to 1.0 for *Kr*, reflecting low to moderate contents of primary minerals. In this study, the values obtained for both indices fell within these expected ranges, with similar results observed across all vegetation types and regions. This consistency suggests a comparable degree of weathering and mineral reactivity among the sites, which may imply a similar potential for soil carbon retention. When combined with texture data and vegetation cover, these indices offer valuable insights into the mechanisms controlling soil carbon stabilization across the Amazon-Cerrado gradient.

2.2. Sample collection

Soil samples were collected during November 2019 in the area described in electronic annexes (EA – Fig. A1), located within two biomes: Cerrado and Amazon, and one ecotone: Cerrado-Amazon transition. Three plots were randomly delineated within each area, with each plot representing a different land use and considered as a specific soil sampling area. The land used included Native vegetation (Forest), characterized by an area unmodified by human activity; Croplands, characterized by cropping systems of soybean, corn, and cotton; and Pasture, characterized by livestock and forage grasses.

Within each plot (study zone) four points were randomly along a plot line arranged perpendicular to the study area/zone. In each study area, we determined four more plot lines within the collection points described above, thus representing the repetitions. Soil samples were collected at 36 points in each of the nine plots at depths of 0.0–0.05 m; 0.05–0.10 m; 0.10–0.20 m; 0.20–0.40 m; 0.40–0.60 m and 0.60–1.0 m. In each of the nine plots, at the same depths, undisturbed samples were

Table 1
History of land use within the study areas.

Biome	Land use	Clay* g kg ⁻¹	Silt	Sand	Land use and management
Amazon	Native Vegetation	215 (±13.1)	13	772	Native vegetation is characterized by Submontane Seasonal Semideciduous Forests with palms and Submontane Open Ombrophiles Forest with palms, and eventually vines. The conservation unit (CU) is within an ecological transition area, which has high species and habitat richness and has been primarily shaped by the climate, relief and soils (CEPEMAR, 1998).
	Cropland	153 (±11.4)	30	817	Conversion of native vegetation occurred in 2002. The current main cultivars are soybeans in the summer with a secondary corn crop. Average amounts of fertilizer used are 80–100 kg ha ⁻¹ of K ₂ O, 80–100 kg ha ⁻¹ of P ₂ O ₅ for soybean, and 20 kg ha ⁻¹ of P ₂ O ₅ for corn. Liming performed on average every 4 to 5 years with ~ 4 Mg ha ⁻¹ .
	Pasture	168 (±10.7)	32	800	Conversion of native vegetation occurred in 2001. Cultivation of <i>Urochloa decumbens</i> over an extensive area with no supplementary fertilization.
Cerrado	Native Vegetation	160 (±8.7)	25	815	Characterized by gallery forests and savanna forests of short stature and flat tabletop shape. The UC is located within an area that is home to several ecosystems and plant species and has been primarily shaped by the seasonal tropical climate (CEPEMAR, 1998).
	Cropland	258 (±15.9)	25	717	Conversion of native vegetation occurred in 1998. The current main cultivars are soybeans in the summer with a secondary corn crop. Average amounts of fertilizer used are 80–100 kg ha ⁻¹ of

Table 1 (continued)

Biome	Land use	Clay* g kg ⁻¹	Silt	Sand	Land use and management
Ecotone (Transition)					K ₂ O, 80–100 kg ha ⁻¹ of P ₂ O ₅ for soybean, and 20 kg ha ⁻¹ of K ₂ O, 20 kg ha ⁻¹ of P ₂ O ₅ for corn. Liming performed on average every 4 to 5 years with ~ 4 Mg ha ⁻¹ .
	Pasture	235 (±16.0)	45	720	Conversion of native vegetation occurred in 2002. Cultivation of <i>Urochloa decumbens</i> over an extensive area with no supplementary fertilization.
	Native Vegetation	171 (±19.0)	23	806	Characterized by the presence of a band of vegetation formed between the Cerrado and the Amazon, it presents both Submontane Open Semideciduous Ombrophiles Forest and Savanna Forest (CEPEMAR, 1998).
	Cropland	180 (±11.8)	24	796	Conversion of native vegetation occurred in 1983. Cultivation of <i>Urochloa decumbens</i> over an extensive area with no supplementary fertilization until 2002. Post-2002 primary cultivars are soybeans in the summer with a secondary corn crop. Average amounts of fertilizer used are 80–100 kg ha ⁻¹ of K ₂ O, 80–100 kg ha ⁻¹ of P ₂ O ₅ for soybean, and 20 kg ha ⁻¹ of K ₂ O, 20 kg ha ⁻¹ of P ₂ O ₅ for corn. Liming performed on average every 4 to 5 years with ~ 4 Mg ha ⁻¹ .
	Pasture	191 (±19.5)	46	763	Conversion of native vegetation occurred in 1992. Cultivation of <i>Urochloa decumbens</i> over an extensive area with no supplementary fertilization.

* Average from 0 to 0.60 m.

collected with volumetric rings (100 cm³). To account for vegetation differences within the Amazon-Cerrado transition, nine plots were established, three in typical savanna (Cerrado *stricto sensu*), three in Amazon rainforest, and three in semi-deciduous forest areas (Ecotone). In each plot, 36 sampling points were distributed across six soil depths (0.0–1.0 m) using a systematic transect layout with random point

selection. This design ensured representativeness across contrasting vegetation types with distinct carbon cycling dynamics.

At each of these points, six pseudo-replicates were collected, resulting in a total of 216 samples. Additionally, 54 undisturbed samples were obtained from nine selected points using volumetric rings. All samples were properly labeled, stored, and subsequently analyzed.

2.3. Determination of total organic carbon (TOC) and total nitrogen (TN)

The stock TOC and TN were determined via elemental analysis of TOC at the EMBRAPA soil laboratory, using a TOC analyzer (vario TOC Cube) calculated according to the following Eq. (1):

$$TOC/TN = TOC/TN \times \rho \times (\rho_{\text{reference}}/\rho) \times P \quad (1)$$

where: TOC / TN = carbon pool / total nitrogen (%); TOC / TN = total organic carbon content / total nitrogen (Mg ha^{-1}); ρ = bulk density (g cm^{-3}); $\rho_{\text{reference}}$ = bulk density of native vegetation (g cm^{-3}); P = depth of soil profile (cm).

2.4. Oxidizable fraction labile carbon

The fraction was performed following Chan et al. (2001), adapted by Rangel et al. (2008), where C was oxidized by potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) in an acid medium with 3 mol L^{-1} of H_2SO_4 (Sulfuric acid).

This was done by transferring 0.3 g of soil (dried and ground) into a 125 mL conical flask. Then, 10 mL of potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) was added to the concentrations of 3 mol L^{-1} with 1 vol (5 mL) of concentrated sulfuric acid (H_2SO_4), respectively, for each sample. After this procedure, they were manually shaken and left to rest for 30 min. After resting a reading was performed in an automatic burette by adding 5 drops of phenanthroline indicator ($\text{C}_{12}\text{H}_8\text{N}_2\text{H}_2\text{O}$). The titration was performed with a 0.4 mol L^{-1} ferrous ammonium sulfate solution [$\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$]. Non-labile C (NCL) was estimated by the difference between SOC and labile C (LC).

2.5. Chemical fractionation of organic matter

The determination of SOM fractionation was performed by the differential solubility technique with the adaptation of Benites et al. (2003), obtaining the organic carbon in the fractions of Fulvic acid (FA), Humic acid (HA), and Humin (HU).

The following procedures were carried out: 1.4 g of soil (dried and ground) was transferred to 50 mL centrifuge tubes and an extraction mixture of 20 mL of NaOH 0.1 mol L^{-1} was added. After manual shaking, they were left to rest for 24 h. Following this they were centrifuged for 30 min, then the supernatant was removed to add NaOH followed by standing for 1 h. After centrifuging for the second time, the supernatant was collected and added to the previously reserved one. The supernatant obtained in the previous step was acidified with drops of 20 % H_2SO_4 , stirred simultaneously until a pH of 1.0 was obtained, and was again kept at rest for a period of 18 h to decant the fulvic and humic acids.

The acidified material was subsequently filtered through a $0.45 \mu\text{m}$ membrane filter under vacuum, collecting each fraction of fulvic and humic acids to the measured volume and making up with distilled water to 50 mL. The remaining soil in the centrifuge tubes was considered as a humin fraction, and this remaining soil was transferred to test tubes where they were dried in an oven at a temperature of 65°C .

The determination of the fulvic and humic acid fractions was carried out as follows: 5 mL of the solution (fulvic and humic acid) was pipetted into test tubes, followed by the addition of 3 mL of potassium dichromate and 5 mL of concentrated sulfuric acid, using a vortex mixer to mix the reagents (Bagherifam et al., 2023). After mixing, the extracts were taken to the digester block, preheated to 150°C for 30 min, and titrated with ammonium ferrous sulfate at 0.4 mol L^{-1} . Then, 10 mL of sulfuric acid followed by 10 mL of potassium dichromate were pipetted into the

test tubes with dried residues (Humin), followed by vortex mixing of the reagents, then taken to the digester block, preheated at a temperature of 150°C for 30 min, then titrated with 0.4 mol L^{-1} ferrous ammonium sulfate.

2.6. Determination of bulk density

To determine bulk density (BD), undisturbed soil samples were collected using volumetric rings 0.05 m in height and diameter. The samples were dried in the laboratory at $\pm 105^\circ\text{C}$ for 24 h and the apparent density was calculated by the dry soil mass/annular volume ratio (Blake and Hartge, 1996).

2.7. Cation exchange capacity (CEC)

The soil CEC was estimated based on the determination of the contents of calcium (Ca), magnesium (Mg), aluminum (Al), potassium (K), and potential acidity ($\text{H} + \text{Al}$). To extract the exchangeable levels of Ca, Mg, and Al, the KCl extraction solution was used at 1 mol L^{-1} , while K extraction was performed using Mehlich-1 solution (0.05 mol L^{-1} of HCl and $0.0125 \text{ mol L}^{-1}$ of H_2SO_4). The potential acidity was extracted by the 1 mol L^{-1} solution of calcium acetate buffered to pH 7. The levels of Ca, Mg, and K were determined by atomic absorption spectrophotometry, while Al and $\text{H} + \text{Al}$'s levels were determined by titrating the extract with 0.025 mol L^{-1} NaOH solution. Subsequently, the values of cation exchange capacity at pH 7.0 (CEC) were estimated:

$$\text{CEC} = \text{Ca} + \text{Mg} + \text{K} + \text{H} + \text{Al} \quad (2)$$

2.8. Carbon management index

The carbon management index (CMI) was estimated according to Blair et al. (1995), using the following Equation (3):

$$\text{CMI} = \text{CCI} \times \text{LI} \times 100 \quad (3)$$

where CCI is the stock TOC content ($\text{CCI} = \text{C stock cultivated area} / \text{C stock reference area}$) and LI is the lability index ($\text{LI} = \text{L cultivated area} / \text{L reference area}$);

$\text{L} = \text{LC} / \text{NLC}$, where NLC (non-labile C) is the difference between C stock and LC (labile C). The degree of polymerization (DP) was determined by the proportion of carbon in the humic and fulvic acid fraction, using the following Eq. (4):

$$\text{DP} = \text{HA} / \text{FA} \quad (4)$$

2.9. Statistical analysis

The study consisted of the analysis of soil attributes from the two biomes and the ecotone (Amazon, Cerrado, and Transition) and three land use systems (native vegetation, pasture, and cropland), with all attributes determined at six soil depths ($0.0\text{--}0.05 \text{ m}$; $0.05\text{--}0.10 \text{ m}$; $0.10\text{--}0.20 \text{ m}$; $0.20\text{--}0.40 \text{ m}$; $0.40\text{--}0.60 \text{ m}$; and $0.60\text{--}1.0 \text{ m}$), with three repetitions. Given the high number of attributes and the relatively large original data matrix, we chose to perform a multivariate analysis, with analyses conducted separately for each soil depth studied.

We first performed a descriptive analysis of the data in order to estimate the mean, median, minimum, and maximum values, coefficient of variation, kurtosis, and skewness of the data. The normality of the data was then verified using the Shapiro-Wilk test (Shapiro and Wilk, 1965). Several outliers were removed from the data set, respecting, however, the limit of 5 % of the total observations. To define outliers, values of three times the interquartile range in the Box Plot chart were used (dos Santos et al., 2020).

To avoid the influence of the unit factor (scale differences) of the parameters evaluated and its possible effect on the final decision of the study, the data set was standardized, allowing the variables to present

the same contribution to the calculation of the coefficient of similarity between sampling units (plots) or accesses (Wilks, 2005). The standardization used was carried out using the following Eq. (5):

$$Z_{ij} = \frac{X_{ij} - \bar{X}_j}{S_j} \quad (5)$$

where: X_{ij} is the value of the i -th access of the variable j ; $\bar{X}_j$ is the original mean of the j -th variable, S_j is the standard deviation and Z_{ij} is the value of the standardized variable.

Multivariate analysis allows us to obtain a broader view of the behavior of variables in a given set of data, aiming to reduce its dimensionality with minimal loss of information. With principal component analysis (PCA) it is possible to transform a set of original variables, correlated with each other, into another set of uncorrelated (orthogonal) variables called principal components. However, to verify the presence of basic assumptions for the correct application of PCA for the data set under analysis, we submitted our data to the Kaiser-Meyer-Olkin test (greater than 0.50) and the Bartlett sphericity test (less than 0.05). We also verified the commonality of variables, whose values below 0.5 were removed, and only the principal components with eigenvalues >1.0 were selected.

To enable the classification and recognition of homogeneous data groups, hierarchical cluster analyses were conducted. This analysis used Euclidean distance between accessions and was performed using Ward's algorithm (Sneath and Sokal, 1973). The results were presented in a dendrogram to visually identify the clusters of accessions. The groups identified through hierarchical analysis were also represented in the principal component graphs. We used the one-way PERMANOVA to confirm the clusters established by the hierarchical analyses, followed by pairwise statistical comparisons using the Pairwise Permutation Test.

For the calculations of TOC and C losses (C balance in the system) along the 1.0 m soil profile, the sum of the original, non-standardized averages of the clusters corresponding to each land use system within each biome was used, while still respecting the clusters formed at each sampled depth. The mean of the soil attributes was compared using the *Bootstrap* test ($p < 0.05$). Bootstrapping involves repeatedly drawing random samples, with replacements, from the original dataset. For each of these samples, the mean (or another statistic of interest) is calculated.

By repeating this process thousands of times, an empirical distribution of the statistic is formed. This distribution is then used to assess the accuracy of the estimates and to conduct hypothesis tests, like comparing means, without relying on strict parametric assumptions.

3. Results

3.1. Effects of land use on SOC and TN dynamics

SOC and TN concentrations exhibited a marked vertical stratification, with significantly higher values in the surface layer (0–0.05 m) across all biomes and land-use types (Fig. 1). Native vegetation areas consistently showed the highest SOC and TN values at the surface ($C = 22.5$ and $N = 1.8 \text{ g kg}^{-1}$), while the lowest concentrations were observed in cropland soils ($C = 6.8$ and $N = 0.5 \text{ g kg}^{-1}$). These trends were consistent across the Amazon, Cerrado, and Cerrado-Amazon ecotone regions, indicating a strong influence of land use regardless of biome (Fig. 1). From 0.05 to 0.20 m, the same pattern was maintained, with forested sites in the Amazon and Cerrado maintaining higher C and N concentrations ($C = 14.1$ and $N = 1.0 \text{ g kg}^{-1}$), whereas croplands, particularly in the Ecotone and Cerrado, exhibited significant depletion of both elements ($C = 5.8$ and $N = 0.5 \text{ g kg}^{-1}$) (Fig. 1).

Below 0.20 m, the effects of land use on SOC and TN became less pronounced, with differences diminishing along the profile (Fig. 1). However, native forests in the Amazon biome still retained higher carbon and nitrogen concentrations down to 1 m, highlighting their role in deep organic matter accumulation and nutrient retention. In contrast, cropland areas in the Ecotone showed the lowest values in subsurface layers, reflecting reduced organic inputs and possible degradation of soil structure. Although pasture systems often maintained intermediate values between native vegetation and cropland, they did not fully restore SOC and TN, especially in deeper layers (Fig. 1).

3.2. SOM composition across land uses

The distribution of organic carbon fractions in the soil varied notably according to land use and region (Fig. 2). The HU was the most abundant fraction throughout the profiles, especially at greater depths, while HA

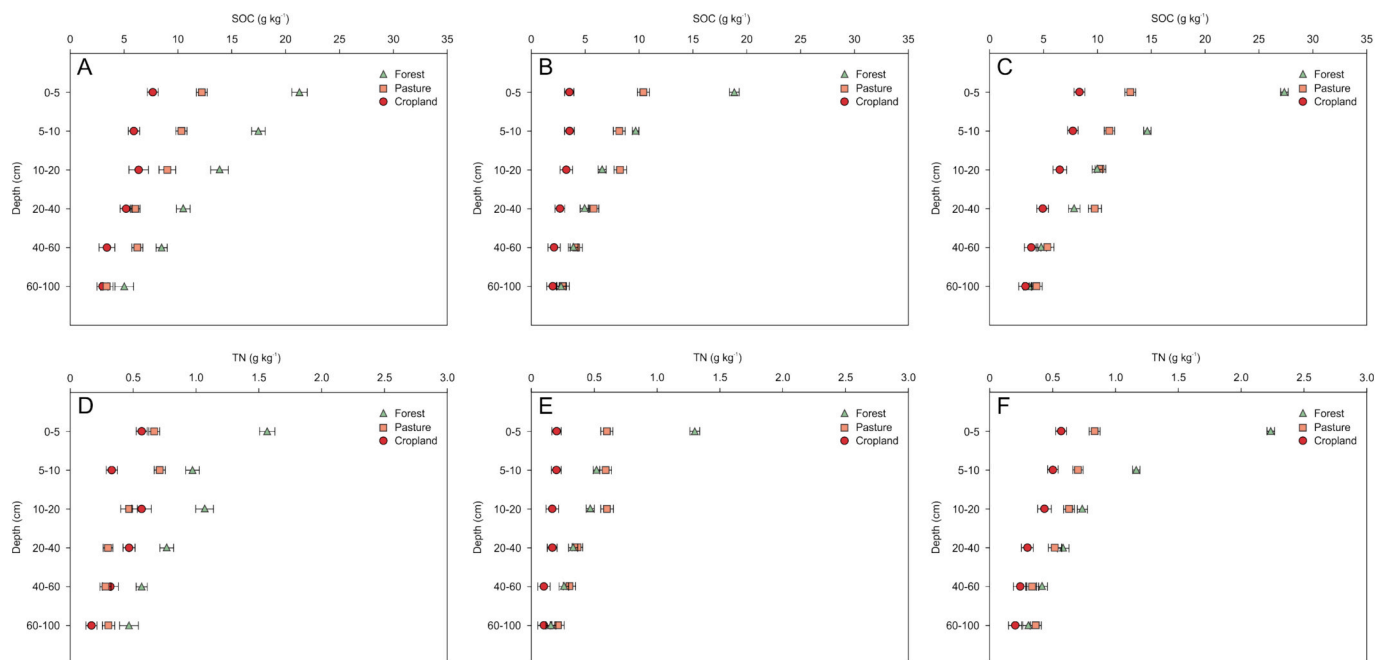


Fig. 1. Soil organic carbon (SOC) and total nitrogen (TN) along the soil profile (1 m depth) in areas under native vegetation, pasture and agriculture in the three study regions [Amazon (A and D)], [Cerrado-Amazon Ecotone (B and E)] and [Cerrado (C and F)]. Horizontal bars denote the standard error of the mean ($n = 3$).

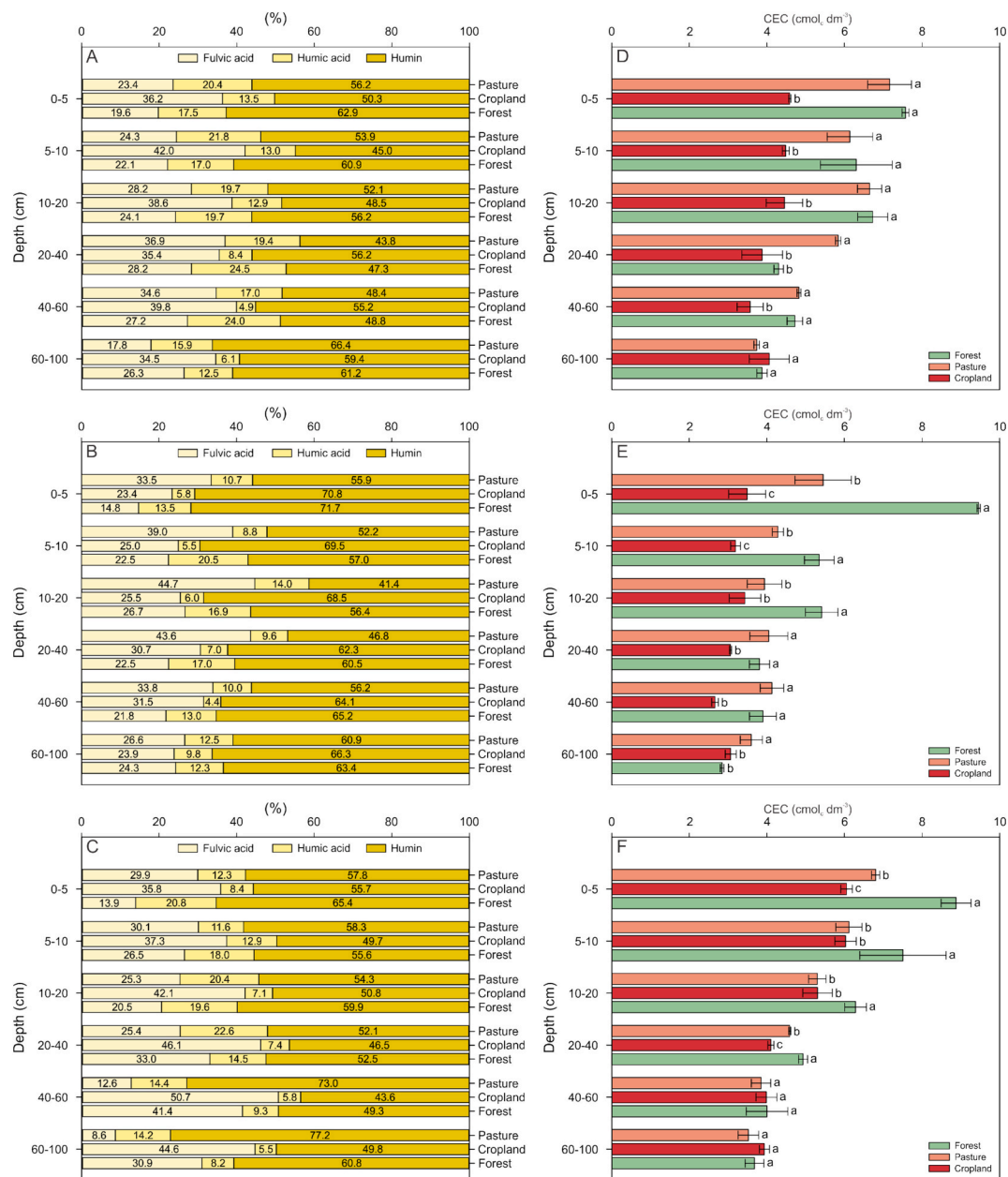


Fig. 2. Chemical fractionation of organic carbon and cation exchange capacity (CEC) along the soil profile (1 m depth) in areas under native vegetation, pasture and agriculture in the three study regions [Amazon (A and D)], [Cerrado-Amazon Ecotone (B and E)] and [Cerrado (C and F)]. Horizontal bars denote the standard error of the mean (*n* = 3). Means followed by the same letter do not differ from each other by the *Bootstrap* test (*p* < 0.05).

was more concentrated in the surface layers of soils under native vegetation. FA made up the smallest portion in all cases. Forested areas, particularly in the Amazon, showed a higher proportion of HA in the top 0.20 m, suggesting greater input and cycling of organic residues. In contrast, soils under pasture and cropland showed a relative increase in HU dominance below 0.20 m, indicating organic matter with a higher degree of humification and greater stability, but reduced biological reactivity.

These patterns were supported by quantitative data, the highest accumulated concentrations of HU and HA were found in native vegetation areas, with 13.3 and 8.7 g kg⁻¹, respectively (Fig. 2). In the Amazon forest, both fractions were consistently higher throughout the entire soil profile (0–1.0 m), whereas in the Cerrado and Ecotone, elevated levels were mostly confined to the surface layers. Agricultural areas in all three regions showed the lowest concentrations of these fractions, especially below 0.40 m in Ecotone croplands, where HA was

markedly reduced. These results highlight how land-use changes, particularly conversion to cropland, lead to a decline in the most reactive and functional components of soil OM.

CEC followed a similar trend, with significant differences among land uses observed only in the upper 0.20 m (*p* < 0.05) (Fig. 2). The surface layer (0–0.05 m), which responds most rapidly to changes in land use, showed the highest CEC values in forested soils across all biomes. Between 5 and 20 cm, elevated CEC values were found only in native areas within the Amazon and Cerrado, reaching up to 7.4 cmol_e dm⁻³. Croplands, especially in the Ecotone, showed an average 38 % reduction in CEC compared to native systems at this depth (Fig. 2E). On average, total organic carbon (TOC) down to 0.10 m was 8.52 Mg ha⁻¹, with about 60 % of the CEC attributed to the organic component. A linear relationship was observed: the greater the TOC, the more it contributed to CEC. In contrast, the mineral fraction accounted for a smaller and more stable portion of exchange capacity, estimated at

around $2.64 \text{ cmol}_c \text{ dm}^{-3}$ (Fig. 3).

3.3. Linking SOM composition to the carbon management index

The degree of polymerization (DP) of soil organic carbon was significantly affected by land use across all evaluated depths and biomes (Tables A1–A3). Croplands consistently showed the highest average DP values ($\bar{x} = 4.8$), with peaks at intermediate depths, such as 5.8 at 0.10–0.20 m in the Amazon and 5.6 in the Cerrado, indicating a predominance of more complex and recalcitrant organic compounds. In contrast, native vegetation areas had the lowest DP values ($\bar{x} = 1.1$), regardless of biome or depth, suggesting a greater presence of labile and recently deposited organic matter. Pasture areas exhibited intermediate DP values, reflecting partial stabilization of organic material, likely resulting from moderate inputs of organic residues and changes in microbial dynamics after land-use conversion.

Land use also influenced the Carbon Compartment Index (CCI) and Carbon Management Index (CMI), particularly in the upper 0.40 m of the soil profile. CCI values were generally lower in native vegetation, where the baseline is defined as 1.0, and increased in response to land-use change. In croplands, especially in the Cerrado and Amazon biomes, average CCI values reached $\bar{x} = 0.9$ at 0.20–0.40 m depth. Pasture areas presented even higher CCI values, particularly in the Cerrado (1.4) and Ecotone (1.1), indicating an increase in the proportion of non-labile carbon in these systems. While these values suggest a shift in carbon composition toward more stable forms, they remain close to the forest baseline and do not necessarily reflect carbon accumulation.

The CMI results further differentiate the carbon management potential among land uses. Pasture areas showed the highest average CMI values ($\bar{x} = 116$) across biomes, with notably high values in the Cerrado (405.4 at 0.05–0.10 m) and Ecotone (85.2 at 0.10–0.20 m), indicating a partial recovery of soil carbon quality and turnover. In comparison, native vegetation was set as the baseline (CMI = 100), while croplands presented the lowest average values ($\bar{x} = 44$), reflecting a reduction in the quality and functionality of the soil organic matter pool. These results demonstrate that, although both land-use changes reduce labile carbon fractions, pastures may favor better carbon stabilization and management outcomes than intensive agriculture, particularly in surface and intermediate soil layers.

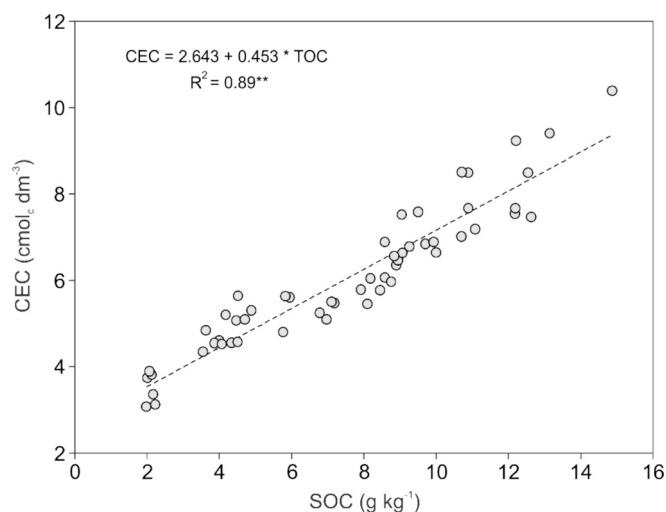


Fig. 3. Cation exchange capacity (CEC) as a function of soil organic carbon (SOC) in Oxisols under native vegetation, cropland and pasture in the Amazon, Cerrado and Ecotone at a depth of 0.0–0.10 m. ** Significant at 1 % probability by the *F*-test.

3.4. Variation in C stocks across biomes and land uses

The highest C stocks in the 0–1.0 m soil profile were found under native forest in the Amazon biome (123.5 Mg ha^{-1}), while the lowest was found in croplands of the Ecotone region (39.2 Mg ha^{-1}) (Fig. 4A). Across all biomes, the conversion of native vegetation to cropland resulted in significant declines in C stock ($p < 0.05$), with the most substantial reductions observed in the Amazon (–43 %), followed by the Ecotone (–33 %) and the Cerrado (–30 %) (Fig. 4B). Interestingly, pasture in the Cerrado maintained C stocks statistically similar to native vegetation, suggesting a potential for partial preservation or recovery of soil organic carbon under this land use.

These reductions in soil carbon stocks represent substantial losses of C from the soil system (Fig. 5). Estimated losses since land-use conversion over 20 years were $9.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in the Amazon, $2.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in the Ecotone, and $4.9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in the Cerrado croplands. These values reflect the cumulative depletion of C from the soil profile and are consistent with the magnitude of stock reductions observed. The proportional loss of TOC in Amazon croplands was nearly 43 % greater than that observed in the Cerrado, reinforcing the greater vulnerability of Amazonian soils to C depletion after deforestation and agricultural expansion.

PCA further supports these patterns by revealing distinct clustering of soil chemical attributes by land use (Fig. 6). At surface depths (0–0.10 m), native forest soils across biomes clustered separately from croplands, primarily due to higher values of humic substances (HA, HU), TOC, and indicators of carbon quality (LC, NLC, CMI). In contrast, cropland soils were associated with greater BD, higher degrees of polymerization (DP), reduced CMI and CEC values, traits that align with degraded soil conditions, and reduced carbon functionality. Pastures formed transitional clusters, especially in intermediate layers (e.g., 0.20–0.60 m), indicating partial retention of forest-like chemical attributes. These multivariate results emphasize that while forest conversion leads to predictable and widespread losses in soil carbon quantity and quality, the extent of degradation varies by biome and land-use type.

4. Discussion

4.1. Influence of land use and biome on SOC and TN stocks

The higher values of C and N stored in native vegetation areas are due to the greater contribution of litter, associated with reduced mineralization rates in non-anthropogenic environments, mainly due to the absence of soil disturbance (Petter et al., 2017; Soares et al., 2020). However, litter inputs in native vegetation areas have a different impact on the levels of SOC and TN stored along the 1.0 m soil profile between the Amazon, Cerrado, and Ecotone (Fig. 1). Below 0.20 m, native vegetation in the Cerrado and Ecotone regions stores noticeably lower amounts of SOC and TN than native vegetation in the Amazon (Fig. 1). Hence the importance of determining SOC and TN at depths of up to 1.0 m, otherwise the results may lead to erroneous interpretations of these levels in surface layers, especially when the objective is to verify the contribution of forests to the carbon and nitrogen pool in terrestrial ecosystems.

Studies indicate an annual deposition of litter within areas of native vegetation in the Amazon in the order of $\sim 13.0 \text{ Mg ha}^{-1}$, in the Cerrado $\sim 5.0 \text{ Mg ha}^{-1}$ (Matos et al., 2017; Valadão et al., 2016), and in the Amazon-Cerrado Ecotone $\sim 8.0 \text{ Mg ha}^{-1}$ (Almeida et al., 2015). This would explain the higher content of stored C and N within the soil profile of Amazon compared to the Cerrado and Ecotone (Fig. 1). Therefore, the reduction in SOC recorded in the surface soil layer (0.0–0.10 m) in agricultural areas compared to native vegetation is due to the lower contribution of plant litter on the surface, resulting from the cultivation system adopted in these areas (characterized by the cultivation of soybeans in the summer with a secondary corn crop), and the respective management techniques implemented. Our results demonstrate that the

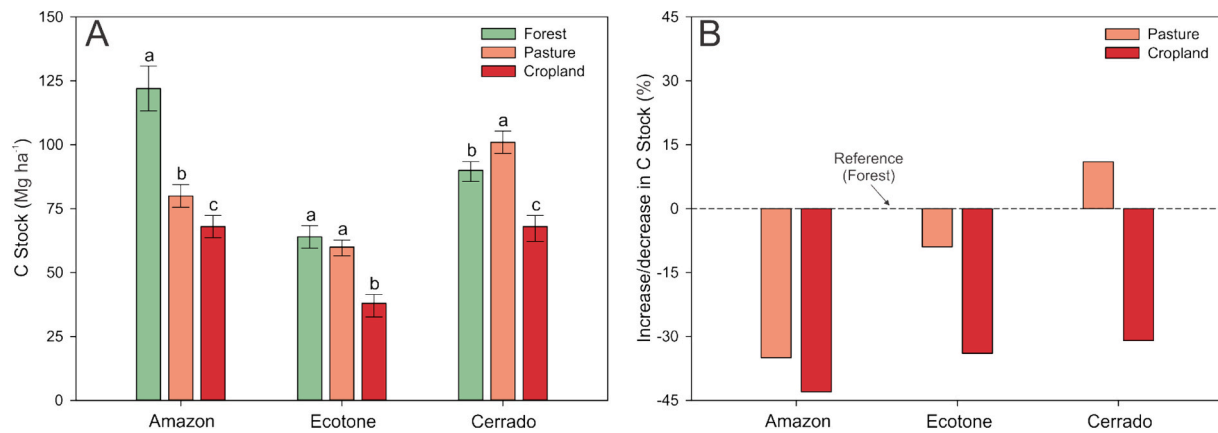


Fig. 4. Carbon stock (A) and percentage increase/reduction of carbon stocks (B) at depths of 0.0–1.0 m in Oxisol under native vegetation (Forest), agricultural and pastures lands in the Amazon, Cerrado and Ecotone. Vertical bars denote the standard error of the mean ($n = 3$). Means followed by the same letter do not differ from each other by the *Bootstrap* test ($p < 0.05$).

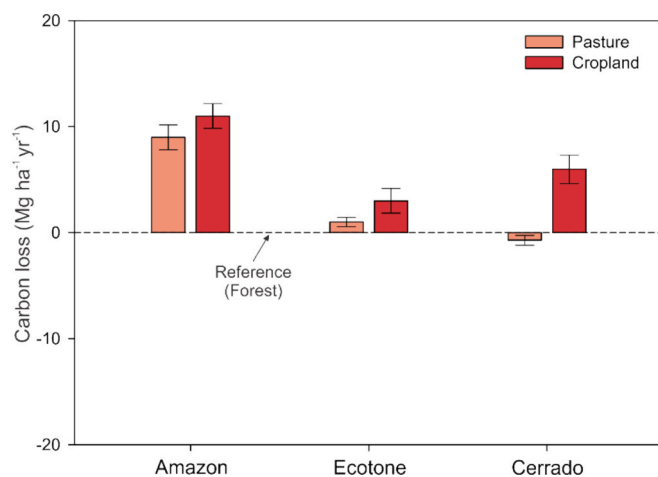


Fig. 5. Carbon loss along the 1.0 m profile in Oxisol under cropland and pasture in the Amazon, Ecotone and Cerrado.

surface layer (up to 0.10 m) is more sensitive to changes in land use and soil management techniques, in agreement with other studies (Poeplau et al., 2015), in which it was also found that significant changes in TOC occur more intensely at depths of up to 0.20 m.

The conversion of native forest to cropland, regardless of the biome, results in significant loss of C and N when not managed properly, corroborating previous studies (Bonini et al., 2018; Petter et al., 2017). However, some long-established pasture areas demonstrated a carbon retention potential comparable to native forests, particularly in the Cerrado, highlighting their role in mitigating C losses when managed under stable conditions (Strey et al., 2016). The magnitude of these losses was strongly influenced by the management practices adopted, reinforcing the idea that the sustainability of agroecosystems must be based on maintaining a continuous supply of organic residues to the soil, ideally at levels comparable to those of native vegetation in each biome. Furthermore, soil management in croplands should aim to preserve and enhance the carbon reservoir, minimizing disturbance and improving organic matter stability.

In agricultural areas, particularly those under conventional soybean–corn succession systems, poor management practices often accelerate SOM depletion and nutrient losses (Locatelli et al., 2022). A common example is the use of a leveling harrow after the corn harvest to incorporate or eliminate crop residues. While intended to prepare the soil for the next planting cycle, this practice disrupts soil structure, reduces aggregate stability, and exposes SOM to microbial decomposition

by increasing aeration and oxidation (Soares et al., 2021). Such physical disturbance not only leads to the rapid mineralization of carbon and nitrogen but also reduces the long-term fertility of the soil. As a consequence, farmers often become increasingly reliant on synthetic fertilizers to maintain productivity, driving up production costs and potentially decreasing yields when compared to systems that promote SOM accumulation, such as minimum tillage, cover cropping, and crop-livestock integration.

4.2. SOM stability and cation exchange

The higher C values in the HA and HU fractions of organic matter along the 1.0 m soil profile in the native vegetation of the Amazon are a result of the greater contribution of organic matter to the soil surface. The higher C–HU values were expected since this fraction is composed of highly complex molecules and is closely linked to the mineral fraction of the soil, especially oxides (Sparks, 2001). Such characteristics confer high molecular stability, making it less susceptible to polymerization (Andreux and Becerra, 1975; Chen et al., 2018). In addition, oxides play a key role in aggregate formation and carbon stabilization by providing physical protection to organic matter within microaggregates, thus enhancing the persistence of C–HU in the soil matrix (Grandy and Robertson, 2006). However, the high levels of C–HU, particularly in native Amazonian vegetation, seem to demonstrate the colloidal properties of the soil organic matrix, such as low apparent density and high CEC.

It was expected that the greater contribution of litter in native vegetation areas would provide higher levels of C–FA, since this is a more favorable condition for C accumulation compared to areas of agricultural land and pasture, as this fraction is the most influenced by the deposition of litter with greater lability (Lázaro-Lobo et al., 2023). Although in theory, greater litter deposition would lead to higher levels of C–FA, this has not been confirmed. A possible explanation for the lack of significant difference between C–FA levels for native vegetation areas and agricultural land/pasture areas up to a depth of 0–0.20 m is greater vertical movement in the soil profile in native vegetation areas (Amorim et al., 2022). This could be explained by the lower apparent density in areas of native vegetation, favoring water infiltration into the soil associated with the low molecular weight of this fraction and the high presence of polar functional groups, giving it high solvating power (Alves et al., 2024).

Our studies strongly demonstrated a drastic reduction in the contribution of native vegetation to the formation of humic substances (HA and HU) in the Cerrado biome and the Ecotone zone at depths below 0.20 m. This characteristic is further reinforced by the presence of agriculture and livestock farming under traditional management. When

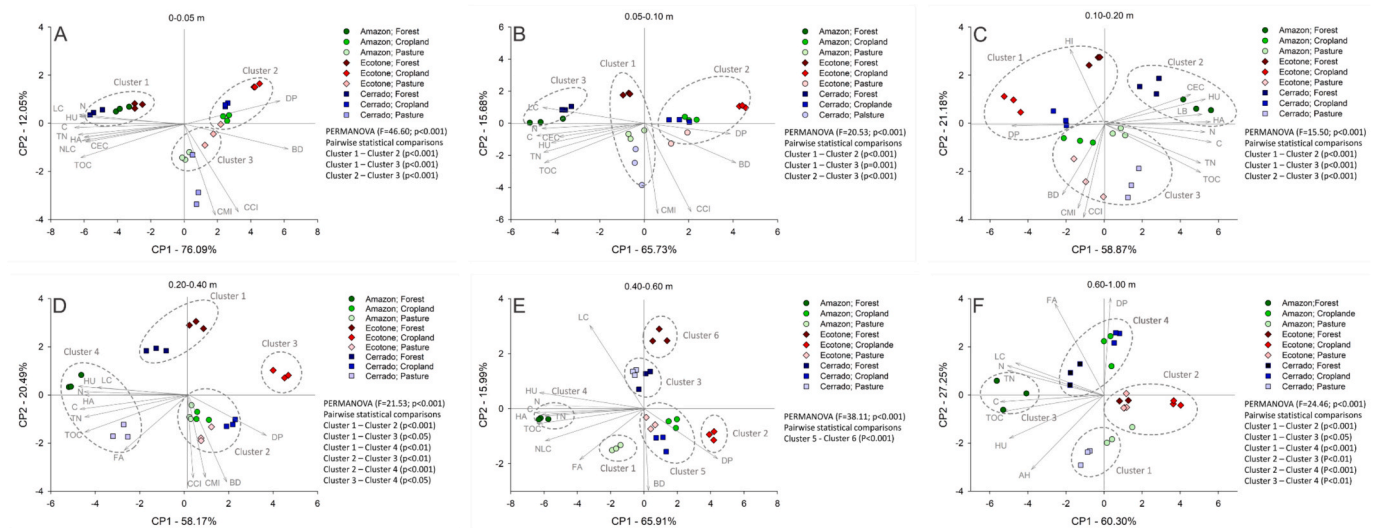


Fig. 6. Principal component analysis of soil chemical attributes under different land uses in the Cerrado, Amazon and Ecotone. Carbon stock (C), nitrogen (N), soil organic carbon (TOC), bulk density (BD), total stored nitrogen (TN), cation exchange capacity (CEC), humic acid (HA), humin (HU), fulvic acid (FA), degree of polymerization (DP), labile carbon (LC), non-labile carbon (NLC), carbon compartment index (CCI) and carbon management index (CMI) in the Cerrado, Ecotone and Amazon under three land use systems: native vegetation, cropland and pasture. Depths of 0–0.05 m (A); 0.05–0.10 m (B) and 0.10–0.20 m (C), 0.20–0.40 m (D), 0.40–0.60 m (E) and 0.60–1.0 m (F). The dashed lines indicate significant clusters by permutation analysis (PERMANOVA, $p \leq 0.05$). Details on cluster averages can be found in the electronic annex – Table A4.

considering the contribution of native vegetation along the 1.0 m soil profile in the Amazon biome, the management of agricultural systems within this biome cannot be similar to that adopted for the Cerrado and the Ecotone. The positive correlation of CEC with TOC proves that the CEC of Oxisols in the Amazon/Cerrado transition region is highly dependent on TOC and that the loss of stored carbon in the medium and long term can seriously compromise production capacity in these areas.

The high dependence of CEC on the organic matrix of the soil is justified by the low contribution of the mineral matrix to the cation exchange in Cerrado Oxisols. This is due to the composition of the mineral matrix of these soils, mainly characterized by the presence of gibbsite, goethite, hematite, and kaolinite. Regarding the pH conditions of arable soils (5.5 to 6.5), gibbsite, goethite, and hematite contribute little to the CEC of soils, as the point of zero charge (PZC) of these minerals is higher than 7.0 (dos Santos et al., 2009; Soares and Alleoni, 2008; Sparks, 2001). There remains, therefore, the contribution of kaolinite, whose PZC is close to ~3.5–4.0 (da Silva et al., 2008). The increase in TOC provides a greater number of negative charges in the soil and, consequently, increases the sorption of cations, thus reflecting an increase in CEC. This phenomenon can be explained by the fact that SOM contributes to the increase of negative variable charge through the dissociation of acidic functional groups, reducing the PZC of the soil (Sposito, 1994; Yeasmin et al., 2017).

These findings highlight the importance of preserving SOC not only as a strategy for climate mitigation but also for maintaining soil fertility in tropical regions dominated by low-activity clays. As organic matter is depleted, whether due to land use change, erosion, or inadequate agricultural practices, the soil's ability to retain essential cations such as Ca^{2+} , Mg^{2+} , and K^+ is drastically reduced (de Lima et al., 2025). This compromises nutrient availability and may lead to increased reliance on external inputs such as fertilizers, raising production costs and reducing long-term sustainability.

4.3. Indicators of carbon management

The high DP values observed in croplands are likely due to the incorporation of plant residues through mechanical practices that increase particle disaggregation and accelerate organic matter mineralization. Although DP is often used to assess the degree of residue

humification, high values can also reflect a limited and inconsistent input of organic material, insufficient to sustain or increase TOC stocks (Petter et al., 2017). This pattern aligns with the low TOC levels observed in croplands. Similarly, lower CCI values in croplands and pastures highlight the poor contribution of these systems to organic C retention, underscoring the inefficiency of regional management practices based on monocultures or simplified crop rotations.

CMI values above 100 typically suggest favorable management, indicating effective contributions of organic matter to the system (Petter et al., 2017). However, when CMI is interpreted in isolation, it can lead to misinterpretation. For example, pastures displayed relatively high CMI values despite low TOC levels. This apparent contradiction is explained by the similar C lability (L) between pastures and native vegetation, pointing to a dominance of easily decomposable organic inputs. In these systems, plant residues are mostly grass leaves with low C:N ratios and high degradability, while recalcitrant materials like stems and branches are absent (Campos et al., 2013; Müller et al., 2012). Consequently, C input is more labile and quickly mineralized, limiting long-term C sequestration.

This behavior also helps explain the higher HU contents in pastures below 0.20 m, particularly in the Cerrado biome. The presence of labile surface material facilitates the vertical translocation of partially decomposed organic matter to deeper layers, where reduced microbial activity and lower oxygen availability allow for its accumulation (Carvalho et al., 2023). In contrast, croplands tend to lose both labile and stable fractions, reflecting deeper structural degradation. In the Cerrado–Amazon ecotone, intermediate levels of labile and humified fractions were recorded, possibly due to more recent and less intensive land-use changes that have preserved elements of the native vegetation structure (Passos et al., 2018).

These findings are further supported by PCA results (Fig. 6), which clearly differentiate land-use systems and biomes, especially in surface layers. In the 0–0.05 m layer, clusters corresponding to forest, pasture, and cropland are clearly delineated, reflecting variations in SOM quality and associated soil properties. However, PCA also revealed that separation is not solely driven by TOC or HA/HU contents. In the ecotone, for example, distinct clusters emerged even when TOC was low, suggesting that factors such as C lability, pH, and bulk density also contribute significantly to the variance. The analysis illustrates that PCA can

effectively capture multivariate soil dynamics but must be interpreted alongside direct indicators of soil quality and C functionality.

The integrated use of DP, L, CCI, and CMI adds depth to this interpretation, enabling a more complete understanding of soil degradation processes. These indicators reflect changes not only in C quantity but also in stability and turnover, offering insight into how soil functions are affected by land-use change.

Finally, the impact of land-use change on C stock and quality is evident when considering the overall patterns of loss associated with the transition from native vegetation to agricultural and pasture systems, particularly in relation to the decline of stable C fractions such as HA and HU, the increase in lability, and the reduction of TOC. These trends, as previously illustrated, indicate a loss not only in C quantity but also in C functionality. Such findings reinforce the importance of using multiple indicators to fully capture the extent of soil degradation and guide the development of strategies aimed at restoring both the stability and capacity of soils to retain organic C over the long term.

4.4. Main limitations and future perspectives

Although this study provided a broad assessment of SOC and TN dynamics across major land-use types, it did not explore in detail the influence of specific agricultural practices or the vertical movement and stabilization processes of organic matter within the soil profile. Important mechanisms such as the interaction between dissolved organic matter and mineral surfaces, particularly at greater depths, remain unaddressed. Likewise, microbial processes, the stability of soil aggregates, and the composition of carbon fractions were not part of the current scope, limiting a deeper interpretation of SOC stabilization pathways.

The pronounced carbon losses observed in the Cerrado-Amazon ecotone highlight the urgent need to direct future research towards these transitional zones. These areas are particularly vulnerable to land-use change, yet still poorly understood. There is a clear opportunity to

assess the effectiveness of land management practices tailored to ecotone conditions and to investigate how ongoing climate shifts may intensify carbon depletion and disrupt ecosystem stability.

In addition, aspects such as the contribution of humic substances (e.g., amino and fulvic acids) to vertical carbon transformation, and the potential of SOC stabilization in pasture systems, especially in the 0.10–0.30 m layer, should be further investigated. The role of deep-rooting Cerrado species in enhancing subsoil carbon storage also remains unclear and deserves attention Fig. 7.

Addressing these knowledge gaps will require integrated approaches that combine biogeochemical analyses, long-term field data, and site-specific experimentation. Such efforts are essential to guide the development of more effective land-use strategies that promote carbon retention and support the resilience of tropical soils.

5. Final remarks

The conversion of native vegetation to agriculture in the Amazon, Cerrado, and their ecotone resulted in substantial reductions in SOC and TN, especially in surface layers. Carbon losses reached 9.8, 4.9, and 2.5 $\text{Mg ha}^{-1} \text{ year}^{-1}$ in the Amazon, Cerrado, and ecotone, respectively, reflecting declines of 30–43 % in SOC stocks within the top 1.0 m.

These reductions were accompanied by a loss of functional organic matter, particularly FA and HA, and a relative increase in HU, suggesting decreased C reactivity. The observed decline in CEC further highlights the central role of organic matter in maintaining soil fertility in low-activity clay systems.

Our findings underscore the vulnerability of tropical soils to C depletion and functional degradation under conventional land-use systems. Although specific practices were not assessed, the patterns observed suggest that traditional agricultural management is insufficient to preserve long-term soil health.

Sustainable land-use strategies that enhance organic inputs and

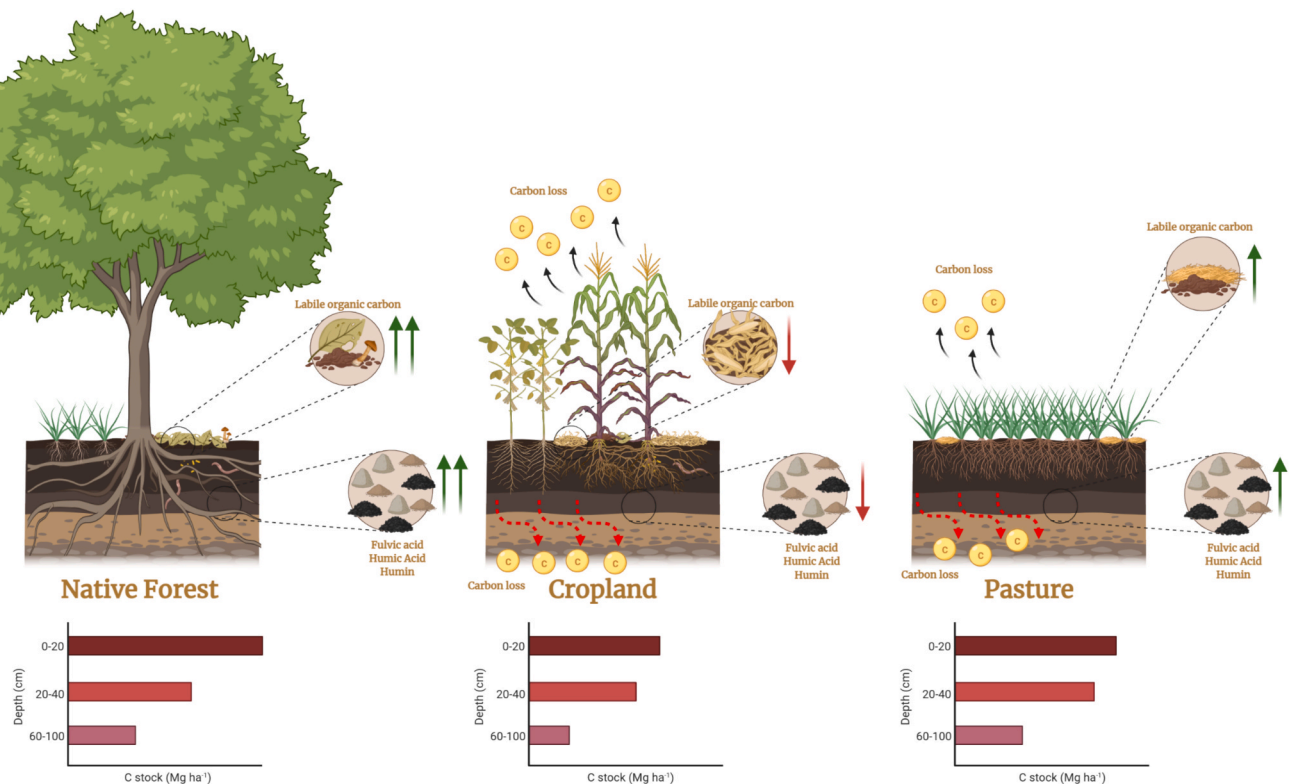


Fig. 7. The impact of land use changes on soil organic carbon pools in the Cerrado-Amazon ecotone, comparing land use changes from native forest to agriculture and pasture. The scheme demonstrates the loss of organic carbon after land use change, in addition to associating these changes with the labile organic carbon content and chemical fractions of organic matter.

stabilize SOC are essential for maintaining productivity and ecosystem resilience, particularly in transitional zones like the Cerrado–Amazon ecotone.

CRediT authorship contribution statement

Ruthcatia Bernadin: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Onã da Silva Freddi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Matheus Bortolanza Soares:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Domingos de Jesus Rodrigues:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Investigation. **Ben Hur Marimon Junior:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation. **Larissa Borges de Lima:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Fabiano André Petter:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.catena.2025.109366>.

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