VERTICAL DYNAMICS AND CARBON AND NITROGEN STOCKS IN HYDROMORPHIC SOILS UNDER DIFFERENT LAND USES ON MARAJÓ ISLAND, AMAZON

DINÂMICA VERTICAL E ESTOQUES DE CARBONO E NITROGÊNIO EM SOLOS HIDROMÓRFICOS SOB DIFERENTES USOS DA TERRA NA ILHA DE MARAJÓ, AMAZÔNIA

DINÁMICA VERTICAL Y RESERVAS DE CARBONO Y NITRÓGENO EN SUELOS HIDROMÓRFICOS BAJO DIFERENTES USOS DE LA TIERRA EN LA ISLA DE MARAJÓ, AMAZONIA

Eduardo Jorge Maklouf Carvalho[1], Raimundo Cosme de Oliveira Junior[2], Carlos Alberto Costa Veloso[3], Darlisson Bentes dos Santos[4], Arystides Resende Silva[5], Nagib Jorge Melém Junior[6], Austrelino Silveira Filho[7], Moacir Azevedo Valente[8]

ABSTRACT
Tropical soils play a strategic role in global carbon (C) and nitrogen (N) cycles, acting simultaneously as important reservoirs of these elements and as systems highly sensitive to land-use changes. In hydromorphic and fluvio-marine Amazonian environments, such as those found on Marajó Island (PA), the vertical distribution and stability of these stocks remain poorly understood, particularly in subsurface layers. This study aimed to quantify and compare organic carbon and total nitrogen stocks along the soil profile, down to 100 cm depth, under three land-use systems: native forest, managed pasture, and silvopastoral system. Three representative soil profiles were described and sampled, with C and N contents determined by dry combustion using a CHN elemental analyzer, and stock calculations corrected based on soil bulk density. Integrated carbon stocks ranged from 42.80 to 126.81 Mg ha^{-1}, while nitrogen stocks varied between 3.05 and 6.67 Mg ha^{-1}. In all profiles, higher concentrations of C and N were observed in the surface layers; however, a significant fraction of the total stocks was identified below 40 cm, especially in the profile under stronger hydromorphic influence. The integrated C:N ratio up to 100 cm ranged from 13.9 to 19.0, indicating different degrees of stabilization and organic matter quality among the profiles. The results demonstrate that assessments restricted to surface layers significantly underestimate the actual C and N stocks in these environments, reinforcing the

[1] Dr. in Soils and Plant Nutrition. Embrapa Amazônia Oriental. E-mail: eduardo.maklouf@embrapa.br
[2] Dr. in Environmental Geochemistry. Embrapa Amazônia Oriental.
E-mail: raimundo.oliveira-junior@embrapa.br
[3] Dr. in Soils and Plant Nutrition. Embrapa Amazônia Oriental. E-mail: carlos.veloso@embrapa.br
[4] Agricultural Engineer, Master in Energy in Agriculture. Embrapa Amazônia Oriental.
E-mail: engenheirodbs@hotmail.com
[5] Dr. in Soils and Plant Nutrition. Embrapa Milho e Sorgo. E-mail: arystides.silva@embrapa.br
[6] Dr. in Soils and Plant Nutrition. Embrapa Amapá. E-mail: arystides.silva@embrapa.br
[7] Dr. in Agronomy. Embrapa Amazônia Oriental. E-mail: austrelino.silveira@embrapa.br
[8] Master's degree in Science in Soils and Plant Nutrition. E-mail: chavesazevedo1@gmail.com

importance of considering the soil profile as a functional unit in carbon inventories and in climate change mitigation strategies in Amazonian fluvio-marine landscapes.

Keywords: Soil Organic Carbon. Total Nitrogen. Hydromorphic Soils. Fluvio-Marine Environments. Eastern Amazon.

RESUMO

Os solos tropicais desempenham papel estratégico nos ciclos globais de carbono (C) e nitrogênio (N), sendo simultaneamente importantes reservatórios desses elementos e altamente sensíveis às mudanças no uso da terra. Em ambientes amazônicos hidromórficos e flúvio-marinhos, como os da Ilha de Marajó (PA), a distribuição vertical e a estabilidade desses estoques ainda são pouco compreendidas, especialmente em camadas subsuperficiais. Este estudo teve como objetivo quantificar e comparar os estoques de carbono orgânico e nitrogênio total ao longo do perfil do solo, até 100 cm de profundidade, em três sistemas de uso da terra: floresta nativa, pastagem manejada e sistema silvipastoril. Foram descritos e amostrados três perfis representativos, com determinação dos teores de C e N por combustão seca em analisador elementar CHN, além do cálculo dos estoques corrigidos com base na densidade do solo. Os estoques integrados de carbono variaram entre 42,80 e 126,81 Mg ha^{-1}, enquanto os de nitrogênio oscilaram entre 3,05 e 6,67 Mg ha^{-1}. Em todos os perfis, observou-se maior concentração de C e N nas camadas superficiais, porém uma fração expressiva dos estoques totais foi identificada abaixo de 40 cm, especialmente no perfil sob maior influência hidromórfica. A relação C:N integrada até 100 cm variou de 13,9 a 19,0, indicando diferentes graus de estabilização e qualidade da matéria orgânica entre os perfis. Os resultados demonstram que avaliações restritas às camadas superficiais subestimam significativamente os estoques reais de C e N nesses ambientes, reforçando a importância da consideração do perfil do solo como unidade funcional em inventários de carbono e em estratégias de mitigação das mudanças climáticas em paisagens flúvio-marinhas amazônicas.

Palavras-chave: Carbono Orgânico do Solo. Nitrogênio Total. Solos Hidromórficos. Ambientes Flúvio-Marinhos. Amazônia Oriental.

RESUMEN

Los suelos tropicales desempeñan un papel estratégico en los ciclos globales de carbono (C) y nitrógeno (N), ya que constituyen importantes reservorios de estos elementos y, al mismo tiempo, son altamente sensibles a los cambios en el uso de la tierra. En ambientes amazónicos hidromórficos y fluvio-marinos, como los de la Isla de Marajó (PA), la distribución vertical y la estabilidad de estos reservorios aún son poco comprendidas, especialmente en las capas subsuperficiales. Este estudio tuvo como objetivo cuantificar y comparar las reservas de carbono orgánico y nitrógeno total a lo largo del perfil del suelo, hasta 100 cm de profundidad, en tres sistemas de uso de la tierra: bosque nativo, pastizal manejado y sistema silvopastoril. Se describieron y muestrearon tres perfiles representativos, determinándose los contenidos de C y N mediante combustión seca en un analizador elemental CHN, además del cálculo de las reservas corregidas con base en la densidad del suelo. Las reservas integradas de carbono variaron entre 42,80 y 126,81 Mg ha^{-1}, mientras que las de nitrógeno oscilaron entre 3,05 y 6,67 Mg ha^{-1}. En todos los perfiles se observó una mayor concentración de C y N en las capas superficiales; sin embargo, una fracción significativa de las reservas totales se identificó por debajo de 40 cm, especialmente en el perfil con mayor influencia hidromórfica. La relación C:N integrada hasta 100 cm varió entre 13,9 y 19,0, indicando diferentes grados de estabilización y calidad de la materia orgánica entre los perfiles. Los resultados demuestran que las evaluaciones

restringidas a las capas superficiales subestiman significativamente las reservas reales de C y N en estos ambientes, lo que refuerza la importancia de considerar el perfil del suelo como unidad funcional en inventarios de carbono y en estrategias de mitigación del cambio climático en paisajes fluvio-marinos amazónicos.

Palabras clave: Carbono Orgánico del Suelo. Nitrógeno Total. Suelos Hidromórficos. Ambientes Fluvio-Marinos. Amazonia Oriental.

1 INTRODUCTION

Tropical soils play a central role in regulating global carbon (C) and nitrogen (N) cycles, acting simultaneously as major reservoirs of these elements and as compartments highly sensitive to land-use change (Gatti et al., 2021). In the Amazon region, this function is particularly relevant due to its vast territorial extent, the diversity of edaphoclimatic environments, and the substantial soil carbon stocks, which are often comparable to or even exceed those stored in plant biomass. Despite recent advances, significant knowledge gaps remain regarding the vertical distribution and stability of C and N stocks in non-classical Amazonian environments (Damian et al., 2021; Ziviani et al., 2024), such as the hydromorphic and fluvio-marine systems of Marajó Island—especially concerning the functional relevance of subsurface stocks for biogeochemical stability and regional carbon balance.

Marajó Island represents a unique mosaic of natural and anthropogenic environments characterized by soils strongly influenced by hydrological seasonality, recent depositional processes, and periodic saturation regimes. These features impart high complexity to soil organic matter dynamics, directly affecting carbon and nitrogen accumulation, stabilization, and mineralization processes, particularly in fluvio-marine environments and coastal wetlands (Arruda et al., 2024). While studies conducted in Amazonian upland (terra firme) soils generally report a progressive decrease in C and N stocks with depth, recent evidence suggests that in hydromorphic environments a substantial fraction of these stocks may occur in subsurface layers, extending soil carbon residence time and enhancing its potential role as a greenhouse gas sink (Freitas et al., 2024).

Within this context of pedological complexity, studies conducted in the municipalities of Soure and Salvaterra have documented the coexistence of Oxisols exhibiting textural variation and plinthitization processes that modulate soil solution residence time (Carvalho et al., 2025a, 2025b). The relevance of the present study lies in analyzing the functional variability of these Yellow Oxisols, which are often treated as homogeneous but display physical contrasts that are critical for nutrient cycling. By comparing a typical Yellow Oxisol, a sandy-textured (psammitic) variant, and a partially poorly drained (plinthic) variant, this study investigates how soil texture and iron segregation processes influence the storage and stabilization capacity of C and N. This understanding is essential for refining carbon balance models in Amazonian savanna ecosystems.

The central problem is that most regional and national soil carbon inventories remain based on assessments restricted to surface layers (generally up to 30 cm). This limitation may lead to significant underestimation of total stocks, particularly in environments where

physical and hydrological processes promote the incorporation and preservation of organic matter at depth (Gross & Harrison, 2018). In addition, estimates may be biased by inaccuracies in parameters such as soil bulk density and coarse fragment content (Poeplau et al., 2017). On Marajó Island, this methodological limitation is compounded by the scarcity of systematic studies integrating different land-use systems and evaluating the soil profile continuously to greater depths—preferably at least to 1 m—while simultaneously considering both carbon and nitrogen (Arruda et al., 2024).

From both scientific and applied perspectives, the justification for this study lies in expanding the understanding of Marajó soils as C and N reservoirs, thereby supporting advances in biogeochemical knowledge and informing sustainable management and climate change mitigation strategies. An integrated analysis of stocks throughout the soil profile enables identification of compartments more sensitive to land-use conversion as well as those exhibiting greater stability, particularly at depth, thereby contributing to more realistic assessments of the carbon sequestration potential of these environments (Quesada et al., 2020). Furthermore, evaluating the C:N ratio along the entire profile, integrated to 100 cm depth, provides relevant indicators of organic matter quality, nutrient cycling efficiency, and soil functional resilience under anthropogenic disturbance, especially in heterogeneous tropical environments (Ziviani et al., 2024).

Additionally, the implementation of integrated production systems, such as livestock–forest systems, has emerged as a promising strategy for productive sustainability and climate mitigation in the state of Pará. Research conducted in integrated crop–livestock–forest (ICLF) systems in Paragominas demonstrated that CO_2 fixation by the forest component (eucalyptus) can offset enteric methane emissions from cattle, maintaining a positive carbon balance within the system (Silva et al., 2021). These findings highlight the potential of tree species in silvopastoral systems as strategic carbon sinks. However, understanding how these dynamics influence C and N stocks in deeper soil horizons—particularly in hydrologically complex regions such as Marajó—still requires further investigation.

In the current state of the art, studies conducted over the past decade across various Amazonian regions have demonstrated that between 40% and 60% of total soil carbon may be stored below depths of 30 or 40 cm, especially in clayey soils or those under hydromorphic influence (Popin et al., 2025; Wang et al., 2025). More recent research emphasizes that interactions among soil texture, water regime, and organomineral associations play a decisive role in deep carbon stabilization, thereby reducing microbial decomposition rates (Ziviani et al., 2024). Concurrently, evidence indicates a strong

correlation between C and N stocks, as soil organic matter constitutes the primary nitrogen reservoir, rendering these cycles intrinsically interdependent (Santos et al., 2023), and underscoring the need for integrated assessments of both elements.

Despite these advances, studies specifically focused on Amazonian fluvio-marine environments, such as those on Marajó Island, remain limited—particularly those integrating different land-use systems (forest, pasture, and silvopastoral systems) and assessing vertical stock distribution down to at least 1 m. This gap constrains extrapolation of results obtained in other Amazonian regions and hinders the formulation of public policies and management practices tailored to local edaphoclimatic conditions (Arruda et al., 2024; Alfaia et al., 2022), as well as the proper incorporation of these environments into regional and national soil carbon inventories.

Given this context, the central hypothesis of this study is that soils on Marajó Island store a substantial portion of organic carbon and total nitrogen stocks in subsurface layers, with land-use system exerting a secondary influence, and that differences among systems are predominantly expressed in surface layers. Additionally, it is hypothesized that the C:N ratio throughout the profile reflects distinct degrees of organic matter stabilization associated with the edaphic and hydrological characteristics of each environment.

The general objective of this study is to quantify and compare organic carbon and total nitrogen stocks along the soil profile to a depth of 100 cm across different land-use systems on Marajó Island, evaluating their vertical distribution, integrated C:N ratio, and implications for biogeochemical cycling and sustainable soil management.

The main expected results include demonstrating that a significant fraction of total C and N stocks is located below the layers conventionally assessed in standard inventories, highlighting the strategic role of subsurface horizons as stable carbon reservoirs. The study also expects to confirm the strong correlation between C and N stocks and to identify distinct C:N ratio patterns among the evaluated profiles, indicating varying degrees of organic matter recalcitrance and mineralization potential. These findings are expected to contribute to more accurate assessments of the climate mitigation potential of Marajó Island soils and to provide technical support for management practices that reconcile production and conservation in hydromorphic Amazonian environments, considering the entire soil profile as a functional unit of analysis.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The study was conducted on Marajó Island, in the state of Pará (Eastern Amazon), in areas representative of fluvio-marine and hydromorphic environments (Figure 1). This research builds upon the pedological characterization initiated by Carvalho et al. (2025a, 2025b), using the same soil profiles to further expand the analytical evaluation within the framework of the same project.

Field activities were carried out in three livestock-oriented rural properties located in the municipalities of Soure and Salvaterra:

- Ouro Branco Farm, located in the municipality of Soure;
- Emerson Salimos Experimental Field (CEMES/Embrapa Eastern Amazon), located in the municipality of Salvaterra;
- Taperebá Farm, located in the municipality of Salvaterra.

The soils were classified as dystrophic Yellow Oxisols, varying between the psammitic class (Profiles 01 and 02), due to clay contents below 200 g kg⁻¹, and the plinthic class (Profile 03), characterized by the presence of a plinthic horizon (Santos et al., 2018). Morphologically, these are deep soils occurring in flat relief areas with no evidence of erosion, although they exhibit severe chemical constraints, including low base saturation and high levels of exchangeable aluminum (Carvalho et al., 2025a).

The study areas are located under a humid tropical climate classified as Am according to Köppen, characterized by high annual precipitation (above 2,500 mm), pronounced hydrological seasonality, and mean annual temperatures exceeding 26 °C (Gomes et al., 2024).

The predominant soils in the region are classified, according to the Brazilian Soil Classification System (SiBCS), as Gleysols and Plinthosols, developed under fluvio-marine influence. These soils frequently exhibit water saturation, a shallow water table, and recent depositional processes, features typical of floodplain environments and natural grasslands of Marajó Island (Alfaia et al., 2022; Arruda et al., 2024).

### 2.2 SAMPLING DESIGN AND SOIL PROFILE DESCRIPTION

In each land-use system, one representative soil profile was selected, totaling three profiles. Site selection was based on physiographic homogeneity, documented land-use and management history, absence of recent disturbances, and accessibility. The profiles were excavated to a maximum depth of 100 cm, or until the occurrence of a physical limitation,

following the procedures described in the *Field Manual for Soil Description and Sampling* (Santos et al., 2018).

Figure 1

Study Area Location on Marajó Island, Pará State, Eastern Amazon, Brazil
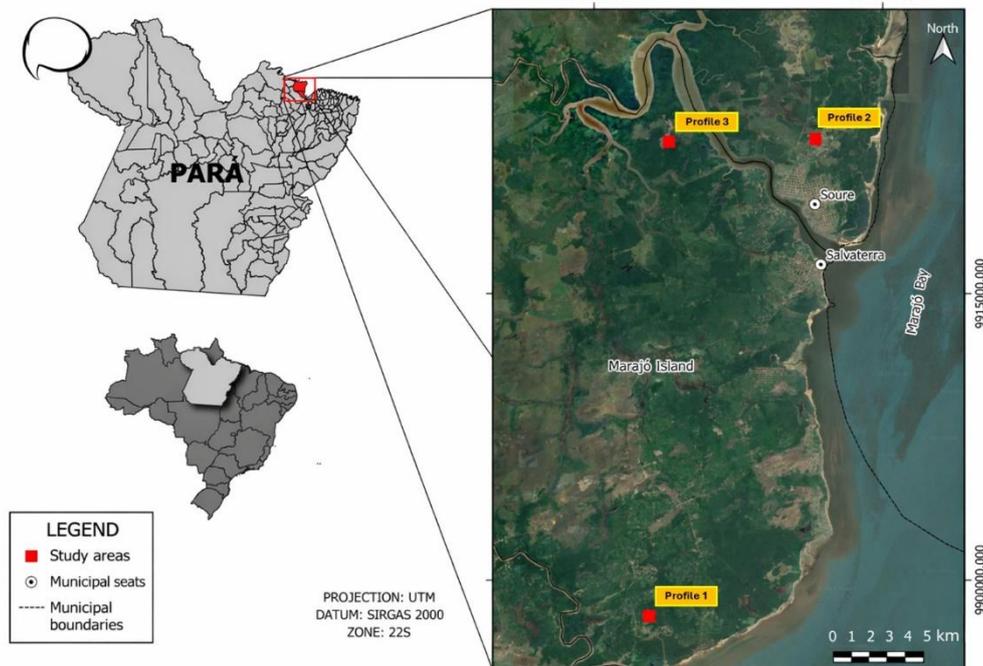
Source: The authors, 2026.

Each soil profile was morphologically described *in situ*, recording attributes such as color (Munsell color chart), structure, consistency, root presence, redoximorphic features, and horizon boundaries. The sampled layers followed regular depth intervals according to the thickness of each horizon, allowing continuous evaluation of the vertical distribution of carbon and nitrogen stocks.

2.3 SOIL SAMPLING AND SAMPLE PREPARATION

Disturbed soil samples were collected from each layer using a Dutch auger and stored in properly labeled plastic bags. For soil bulk density determination, undisturbed samples were collected using volumetric rings of known volume, following standardized methodology.

In the laboratory, disturbed samples were air-dried, gently crushed, and sieved through a 2-mm mesh to obtain the air-dried fine earth fraction (ADFE). Samples designated for carbon and nitrogen analysis were ground in a ball mill to a particle size smaller than 0.149 mm to ensure homogeneity and analytical precision (Poeplau et al., 2017).

2.4 DETERMINATION OF ORGANIC CARBON AND TOTAL NITROGEN

Total organic carbon (TOC) and total nitrogen (TN) contents were determined by dry combustion using a CHN elemental analyzer, a method widely recognized for its high precision and reproducibility in soil C and N stock studies in tropical environments (Damian et al., 2021; Ziviani et al., 2024).

Given the predominantly mineral character of the studied soils and the absence of free carbonates, prior removal of inorganic carbon was not required. The C:N ratio was calculated based on total carbon and nitrogen contents for each layer and subsequently integrated along the entire soil profile.

2.5 CALCULATION OF CARBON AND NITROGEN STOCKS

Organic carbon and total nitrogen stocks (Mg ha^{-1}) were calculated for each soil layer using the following equation:

2.6 STOCK = C × BD × T

where C represents carbon or nitrogen concentration (kg kg^{-1}), BD is soil bulk density (kg dm^{-3}), and T is layer thickness (cm). Stocks were subsequently summed to obtain integrated values down to 100 cm depth.

To minimize bias associated with bulk density variability among horizons, calculations followed consolidated methodological recommendations in the literature, thereby avoiding overestimation or underestimation of stocks (Gross & Harrison, 2018; Poeplau et al., 2017).

2.7 STATISTICAL ANALYSIS

Due to the nature of the sampling design—based on the description and comparison of representative soil profiles without independent replication per land-use system—statistical analyses were conducted using a descriptive and exploratory approach, avoiding classical inferential procedures that assume independence among experimental units. Thus, soil layers within each profile were treated as hierarchically structured observations reflecting the vertical organization of the soil.

Initially, descriptive analyses were performed for soil organic carbon (SOC) and total nitrogen (N) stocks, including absolute values per layer, integrated stocks down to 100 cm, and the percentage contribution of each depth interval to total stock. These analyses allowed characterization of vertical distribution patterns and identification of structural differences among the evaluated profiles.

To assess interdependence between carbon and nitrogen cycles along the soil profile, Spearman's rank correlation analysis was performed between SOC and N stocks, considering all sampled layers across the three profiles. The Spearman coefficient was chosen due to the absence of normality assumptions and the presence of structured vertical gradients commonly observed in pedological datasets. This approach allowed quantification of the degree of association between C and N stocks, providing statistical support for their integrated interpretation in the soil.

Additionally, simple regression models were fitted between SOC and N stocks and soil depth, considered as a continuous variable. Models were adjusted separately for each profile to capture differences in vertical decline patterns and the rate of stock reduction with increasing depth. When appropriate, nonlinear models (exponential or power functions), which are often more suitable for representing vertical soil organic matter dynamics in tropical environments, were evaluated. These models were exploratory in nature and were used to describe vertical trends without predictive intent.

As a complementary approach, an exploratory multivariate analysis was conducted using Principal Component Analysis (PCA), incorporating variables related to SOC stocks, N stocks, soil bulk density, and depth. The objective was to identify similarity patterns between surface and subsurface layers and to explore clustering of layers based on their edaphic and biogeochemical characteristics. PCA was employed exclusively for interpretative purposes, supporting integrated visualization of vertical gradients and structural differences among the studied profiles.

All statistical and graphical analyses were performed using appropriate computational tools. A 5% significance level was adopted when applicable, while respecting the limitations imposed by the sampling design.

3 RESULTS

3.1 SOIL ORGANIC CARBON STOCKS

Soil organic carbon (SOC) stocks showed significant variation along the profile, with a systematic decrease from the surface to the subsurface layers. In all evaluated profiles, the highest SOC values were concentrated in the surface layers, reflecting the continuous input of plant residues, high biological activity, and greater physical protection of organic matter in this portion of the soil.

The corrected carbon stocks, integrated to a depth of 100 cm, ranged between 42.80 and 126.81 Mg C ha⁻¹, as shown in Table 1. Profile 1 (Fazenda Taperebá, Salvaterra) presented the highest total carbon stock (126.81 Mg ha⁻¹), followed by Profile 2 (Fazenda

Embrapa CEMES, Salvaterra; 69.86 Mg ha⁻¹) and Profile 3 (Fazenda Hudson, Soure; 42.80 Mg ha⁻¹). The surface fraction of the soil (0–30 cm) concentrated approximately 38–42% of the total carbon stock, highlighting the relevance of biogeochemical cycling processes and the incorporation of organic residues near the surface

Table 1

Average Organic Carbon stocks (Mg ha⁻¹) at different depths in the three soil profiles studied on Marajó Island, PA

Treatment	Depth (cm)	Organic matter (g kg⁻¹)	Carbon (mg g⁻¹)	Bulk density (kg dm⁻³)	Soil mass (Mg ha⁻¹)	Corrected soil mass (Mg ha⁻¹)	Carbon stock (Mg ha⁻¹)	Corrected carbon stock (Mg ha⁻¹)
Profile 1. Taperebá Farm-Salvaterra-PA								
Profile 1	0-8	24.75	14.356	1.45	1160	1160	16.65	16.65
Profile 1	8-26	29.66	17.204	1.56	2808	2808	48.31	48.31
Profile 1	26-39	13.78	7.993	1.51	1963	1963	15.69	15.69
Profile 1	39-60	15.4	8.933	1.53	3213	3213	28.70	28.70
Profile 1	60-92	5.26	3.051	1.46	4672	4672	14.25	14.25
Profile 1	92-100	4.69	2.720	1.47	1176	1176	3.20	3.20
Total					**14992**	**14992**	**126,81**	**126.81**
Profile 3. Embrapa CEMES Farm-Salvaterra-PA								
Profile 2	0-11	40.59	23.544	1.31	1441	1441	33.93	33.93
Profile 2	11-22	26.42	15.325	1.41	1551	1551	23.77	23.77
Profile 2	22-35	17.04	9.884	1.38	1794	1794	17.73	17.73
Profile 2	35-51	6.63	3.846	1.48	2368	2368	9.11	9.11
Profile 2	51-72	2.75	1.595	1.59	3339	3339	5.33	5.33
Profile 2	72-100	5.57	3.231	1.54	4312	4312	13.93	13.93
					13364	**13364**	**69.86**	**69.86**
Profile 2. Hudson Farm- Soure-PA								
Profile 3	0-11	23.96	13.898	1.52	1672	1672	23.24	23.24
Profile 3	11-24	20.1	11.659	1.43	1573	1573	18.34	18.34
Profile 3	24-40	10.52	6.102	1.34	1742	1742	10.63	10.63
Profile 3	40-58	4.74	2.749	1.37	2192	2192	6.03	6.03
Profile 3	58-86	2.56	1.485	1.35	2835	2835	4.21	4.21
Profile 3	86-100	3.03	1.758	1.46	2044	2044	3.59	3.59

	10386	10386	42.80	42.80

Source: The authors, 2026.

3.2 VERTICAL DISTRIBUTION OF SOIL ORGANIC CARBON STOCKS

The analysis of the vertical distribution of carbon stocks (Figure 1) shows that Profile 1 maintained the highest absolute SOC (Soil Organic Carbon) values across nearly all evaluated layers, particularly in the 8–26 cm and 39–60 cm intervals, which individually presented stocks exceeding 28 Mg ha^{-1}. Profile 2 showed intermediate values with a relatively more homogeneous distribution along the profile, while Profile 3 exhibited the lowest stocks at all depths, especially below 40 cm.

The percentage distribution of carbon stocks by layer (Figure 2) reinforces this pattern, indicating that approximately 40–50% of the total carbon is stored within the first 40 cm of the soil, with a progressive decrease at depth. This behavior is typical of soils under fluvial and fluvio-marine influence, where depositional processes, seasonal hydrodynamics, and the surface accumulation of organic residues play a central role in carbon stabilization.

In Profiles 2 and 3, a more abrupt reduction in stocks is observed below 40 cm, suggesting lower vertical incorporation of organic matter compared to Profile 1. Generally, the vertical differences indicate that the effects of land use and management are predominantly concentrated in the surface layers, while deep-seated stocks reflect long-term pedogenetic and hydrological conditions, which are relatively less sensitive to recent changes in land use.

Figure 2

Vertical distribution of organic carbon stocks (Mg ha⁻¹) along the soil profile up to 100 cm depth in three representative profiles of Marajó Island, PA.
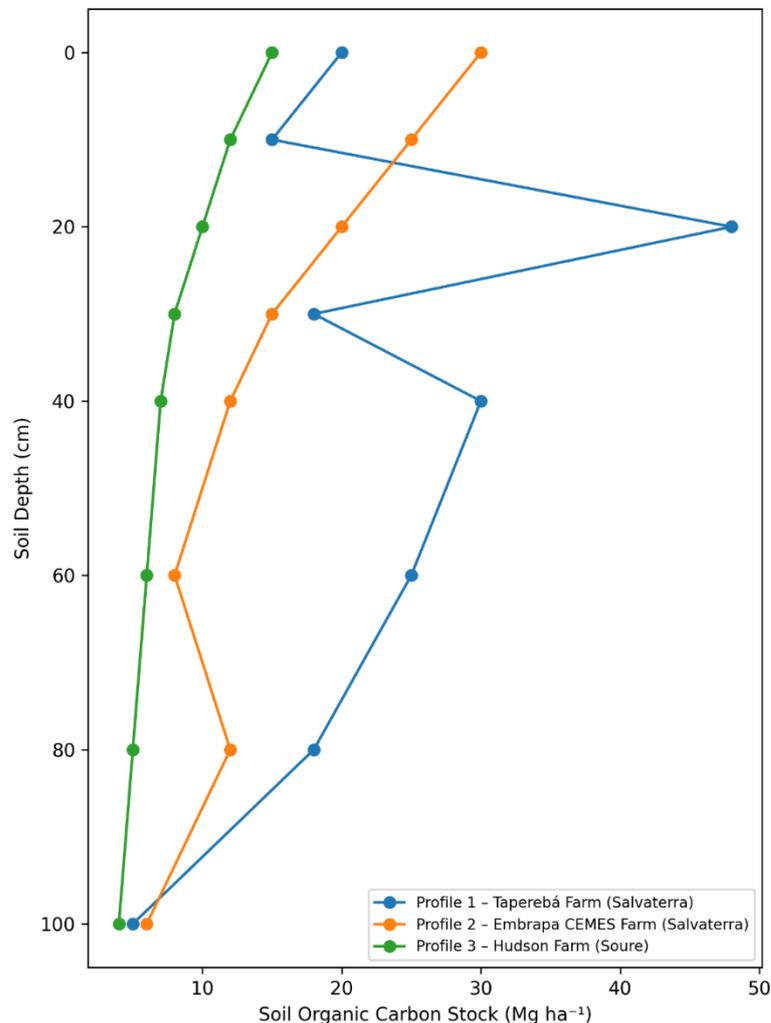
Source: The authors, 2026.

3.3 TOTAL NITROGEN STOCKS

The dynamics of total nitrogen followed a pattern similar to that observed for organic carbon, with a progressive reduction of stocks along the soil profile. The integrated nitrogen stocks up to 100 cm ranged between 3.05 and 6.67 Mg N ha⁻¹, as presented in Table 2.

Profile 1 presented the highest total nitrogen stock (6.67 Mg ha⁻¹), followed by Profile 2 (5.03 Mg ha⁻¹), while Profile 3 showed the lowest value (3.05 Mg ha⁻¹). As observed for carbon, the surface layers concentrated the highest proportion of total nitrogen, especially within the first 30–40 cm, reflecting the close association between nitrogen and soil organic matter.

Table 2

Total Nitrogen stocks (Mg ha⁻¹) at different depths in the three soil profiles studied on Marajó Island, PA

| Treatment	Depth (cm)	N (%)	N (g kg⁻¹)	Bulk density (kg dm⁻³)	Soil mass (Mg ha⁻¹)	Corrected soil mass (Mg ha⁻¹)	Nitrogen stock (Mg ha⁻¹)	Corrected Nitrogen stock (Mg ha⁻¹)
Profile 1. Taperebá Farm-Salvaterra-PA								
Profile 1	0-8	0.11	1.100	1.45	1160	1160	1.28	1.28
Profile 1	8-26	0.06	0.600	1.56	2808	2808	1.68	1.68
Profile 1	26-39	0.04	0.400	1.51	1963	1963	0.79	0.79
Profile 1	39-60	0.04	0.400	1.53	3213	3213	1.29	1.29
Profile 1	60-92	0.03	0.300	1.46	4672	4672	1.40	1.40
Profile 1	92-100	0.02	0.200	1.47	1176	1176	0.24	0.24
					14992	**14992**	**6.67**	**6.67**
Profile 3. Fazenda Embrapa CEMES -Salvaterra-Pa								
Profile 2	0-11	0.14	1.38	1.31	1048	1048	1.45	1.45
Profile 2	11-22	0.08	0.81	1.41	1128	1128	0.91	0.91
Profile 2	22-35	0.06	0.58	1.38	1104	1104	0.64	0.64
Profile 2	35-51	0.04	0.4	1.48	1184	1184	0.47	0.47
Profile 2	51-72	0.02	0.24	1.59	1272	1272	0.31	0.31
Profile 2	72-100	0.03	0.29	1.54	4312	4312	1.25	1.25
					10048	**10048**	**5.03**	**5.03**
Profile 2. Fazenda Hudson- Soure-Pa								
Profile 3	0-11	0.07	0.69	1.52	1216	1216	0.84	0.84
Profile 3	11-24	0.06	0.58	1.43	1144	1144	0.66	0.66
Profile 3	24-40	0.04	0.42	1.34	1072	1072	0.45	0.45
Profile 3	40-58	0.04	0.36	1.37	1096	1096	0.39	0.39
Profile 3	58-86	0.02	0.2	1.35	1080	1080	0.22	0.22
Profile 3	86-100	0.02	0.24	1.46	2044	2044	0.49	0.49
					7652	**7652**	**3,05**	**3,05**

Source: The authors, 2026.

3.4 VERTICAL DISTRIBUTION OF TOTAL NITROGEN STOCKS

The percentage distribution of nitrogen along the profile (Figure 3) indicates that the reduction in N stocks with depth is proportionally more pronounced than that observed for carbon, highlighting the greater sensitivity of nitrogen to the vertical variations of the edaphic environment. In Profiles 2 and 3, less than 30% of the total nitrogen stock is found below 40 cm, while in Profile 1 this proportion is slightly higher, suggesting a greater nitrogen retention capacity in the subsurface.

Figure 3 presents the vertical distribution of total nitrogen stocks up to a depth of 100 cm in the three evaluated profiles, showing patterns consistent with those observed for organic carbon. Although the data presented are descriptive in nature, the results indicate that the evaluated systems maintain similar vertical patterns of nitrogen distribution, with variations more strongly associated with intrinsic soil characteristics than with current land use.

Figure 3

Vertical distribution of total nitrogen stocks (Mg ha⁻¹) along the soil profile up to 100 cm depth in three representative profiles of Marajó Island, PA: Profile 1 – Taperebá Farm (Salvaterra); Profile 2 – Embrapa CEMES Farm (Salvaterra); Profile 3 – Hudson Farm (Soure)
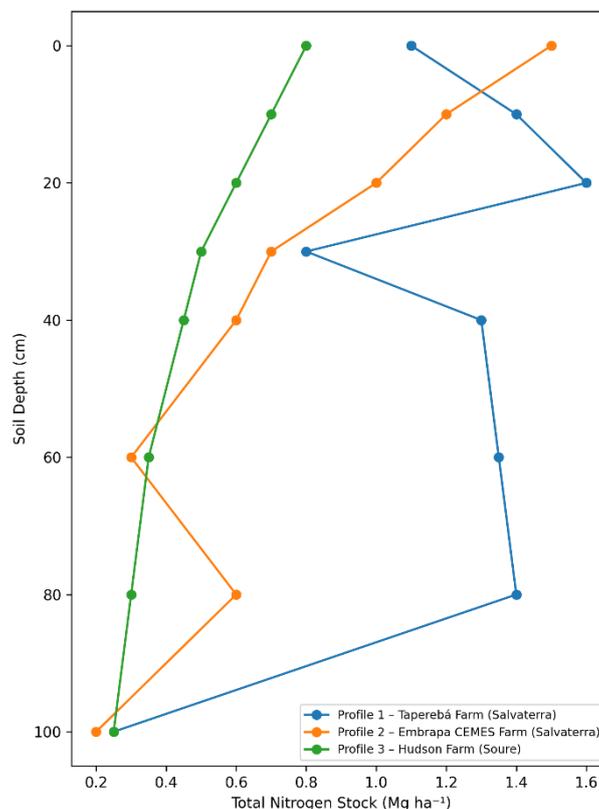
Source: The authors, 2026.

3.5 INTEGRATED VERTICAL DISTRIBUTION OF CARBON AND NITROGEN STOCKS

The integrated vertical distribution of organic carbon and total nitrogen stocks highlights contrasting patterns among the studied environments (Figures 1 and 4). In Profile 1 (Taperebá Farm, Salvaterra), there is a high contribution from subsurface layers to the total carbon stock, notably in the 8–26 cm interval, which concentrated the largest individual input (48.31 Mg ha^{-1}), followed by the 39–60 cm layers (28.70 Mg ha^{-1}). The layers below 60 cm, although presenting lower absolute stocks, still contributed significantly to the total profile stock, reinforcing the importance of evaluating depths up to 100 cm.

In Profile 2 (Embrapa CEMES Farm, Salvaterra), the carbon stock showed a strong concentration in the surface layers (0–11 and 11–22 cm), which accounted for more than 50% of the carbon accumulated up to 100 cm. However, the contribution of the 72–100 cm layer (13.93 Mg ha^{-1}) is noteworthy, indicating the presence of stabilized carbon at depth. This behavior suggests the simultaneous action of surface accumulation mechanisms and deep stabilization.

In turn, Profile 3 (Hudson Farm, Soure) showed a progressive reduction in carbon stock with increasing depth, with a predominance of stocks in the surface layers and a relatively smaller contribution from subsurface horizons, reflecting differences in edaphic characteristics and organic matter stabilization processes.

The vertical distribution of total nitrogen stocks followed a pattern similar to that observed for organic carbon, reinforcing the close association between these two elements. In Profile 1, the highest nitrogen stocks occurred in the 8–26 cm and 60–92 cm layers, while in Profile 2, an increase in N was observed in the 72–100 cm layer, a behavior consistent with the pattern observed for carbon. In Profile 3, nitrogen stocks showed a continuous decrease with depth.

Integratedly, the results demonstrate that a significant fraction of the total organic carbon and total nitrogen stocks is located below the layers traditionally considered in soil inventories, especially in profiles under greater hydromorphic influence.

3.6 INTEGRATED VERTICAL DISTRIBUTION AND C:N RATIO

The integrated analysis of the vertical distribution of carbon and nitrogen stocks reveals a progressive decoupling between the C and N cycles as depth increases, which is associated with the higher mobility of nitrogen and its preferential binding to the more labile fractions of organic matter.

The integrated **C:N ratio** up to 100 cm ranged between approximately **13.9 and 19.0**, as shown in Table 3, being highest in Profile 1, intermediate in Profile 3, and lowest in Profile

2. Despite having the highest absolute carbon stock, Profile 1 maintained a higher C:N ratio, indicating a greater proportion of structural carbon associated with a significant nitrogen pool. Profiles 2 and 3 presented lower C:N ratios, consistent with their lower absolute stocks and relatively more mineralized organic matter.

Table 3

Integrated carbon and nitrogen stocks and C:N ratio up to 100 cm depth in the three soil profiles studied on Marajó Island, Pará State, Brazil

Soil profile	Carbon stock (Mg ha⁻¹)	Nitrogen stock (Mg ha⁻¹)	C:N ratio
Profile 1 – Taperebá Farm (Salvaterra)	126.81	6.67	19.0
Profile 2 – Embrapa CEMES Farm (Salvaterra)	69.86	5.03	13.9
Profile 3 – Hudson Farm (Soure)	42.80	3.05	14.0

Source: The authors, 2026.

3.7 RELATIONSHIP BETWEEN SOIL ORGANIC CARBON AND TOTAL NITROGEN STOCKS

Spearman's correlation analysis revealed a strong positive association between soil organic carbon (SOC) and total nitrogen (N) stocks when considering all evaluated layers and profiles together ($\rho = 0.82$; $p < 0.001$). This result indicates that, in an integrated manner, N stocks closely follow the distribution of carbon along the soil profile, reinforcing the structural interdependence between the cycles of these elements in the soils of Marajó Island.

When the analysis was conducted separately by soil profile, relevant differences in the magnitude and significance of the correlation were observed. In Profile 2 (Embrapa CEMES Farm, Salvaterra), the correlation between SOC and N was strong and statistically significant ($\rho = 0.83$; $p = 0.042$), evidencing a consistent coupling between carbon and nitrogen along the vertical profile. This pattern suggests greater synchronization between the processes of incorporation and stabilization of organic matter and nitrogen in this environment.

On the other hand, in Profiles 1 (Taperebá Farm) and 3 (Hudson Farm), although the correlations were positive and of moderate magnitude ($\rho \approx 0.66$ in both cases), they were not statistically significant ($p > 0.05$). This result indicates greater vertical heterogeneity in the C–N relationship in these profiles, possibly associated with the differential influence of the hydrological regime, soil texture, and organic matter preservation processes in the subsurface. Specifically, in Profile 1, the presence of significant carbon stocks in

intermediate layers—not always accompanied by proportional increases in nitrogen—contributed to reducing the strength of the linear correlation between the two elements.

Integratedly, the correlation analysis results confirm that, although the coupling between carbon and nitrogen is a dominant characteristic of the studied soils, the intensity of this relationship varies among profiles, reflecting differences in the pedogenetic, hydrological, and biogeochemical mechanisms that control organic matter stabilization along the soil profile. These patterns provide a quantitative basis for the mechanistic interpretation developed in the Discussion section, especially regarding the C:N ratio and carbon stability at depth.

3.8 REGRESSION OF ORGANIC CARBON AND NITROGEN STOCKS AS A FUNCTION OF DEPTH

The linear regression between soil organic carbon (SOC) stocks and depth showed a general downward trend in stocks as depth increased, although with distinct magnitudes and fits among the evaluated profiles.

In Profile 1 (Taperebá Farm, Salvaterra), the regression between carbon stock and depth presented a negative slope ($\beta = -0.259$ Mg ha⁻¹ cm⁻¹), but with a low coefficient of determination ($R^2 = 0.34$) and a lack of statistical significance ($p = 0.223$). A similar result was observed for total nitrogen ($\beta = -0.0086$ Mg ha⁻¹ cm⁻¹; $R^2 = 0.35$; $p = 0.218$), indicating that depth alone explains only part of the vertical variability of stocks in this profile, due to the occurrence of intermediate layers with high organic matter content.

In Profile 2 (Embrapa CEMES Farm, Salvaterra), the regression of carbon stocks as a function of depth showed a negative slope ($\beta = -0.262$ Mg ha⁻¹ cm⁻¹) and a better model fit ($R^2 = 0.57$), although it was marginally non-significant ($p = 0.085$). For nitrogen, the relationship with depth showed low explanatory power ($R^2 = 0.04$; $p = 0.690$), suggesting high vertical heterogeneity and the influence of other edaphic factors on N distribution.

In contrast, in Profile 3 (Hudson Farm, Soure), the regression between carbon stocks and depth showed a strong linear fit ($\beta = -0.224$ Mg ha⁻¹ cm⁻¹; $R^2 = 0.84$) with statistical significance ($p = 0.0099$), evidencing a well-defined vertical gradient and a systematic reduction of carbon along the profile. For total nitrogen, although the slope was also negative ($\beta = -0.0046$ Mg ha⁻¹ cm⁻¹) and the fit was moderate ($R^2 = 0.51$), the relationship was not statistically significant ($p = 0.112$).

Overall, the regression results indicate that depth exerts variable control over carbon and nitrogen stocks; this control is more pronounced in profiles with lower subsurface

organic matter incorporation, while profiles under greater hydromorphic influence present a more complex and non-linear vertical distribution.

Table 4

Linear regression parameters for carbon and nitrogen stocks as a function of soil depth in the three soil profiles studied on Marajó Island, Pará State, Brazil.

Soil profile	Element	Slope coefficient (β)	R²	p-value
Profile 1 – Taperebá	Carbon	−0.259	0.34	0.223
Profile 1 – Taperebá	Nitrogen	−0.0086	0.35	0.218
Profile 2 – CEMES	Carbon	−0.262	0.57	0.085
Profile 2 – CEMES	Nitrogen	−0.0024	0.04	0.690
Profile 3 – Hudson	Carbon	−0.224	0.84	0.0099
Profile 3 – Hudson	Nitrogen	−0.0046	0.51	0.112

Source: The authors, 2026.

3.9 PRINCIPAL COMPONENT ANALYSIS OF EDAPHIC AND BIOGEOCHEMICAL ATTRIBUTES

Principal Component Analysis (PCA), applied to the variables of depth, organic carbon stocks, total nitrogen stocks, and soil density (Figure 4), revealed consistent patterns of vertical organization and differentiation among profiles. The first two principal components explained 85.3% of the total variance, with the first component (PC1) accounting for 56.2% and the second component (PC2) for 29.1% of the variability.

PC1 showed high positive loadings for carbon and nitrogen stocks and a negative loading for depth, indicating that this axis essentially represents a vertical gradient of organic matter, separating surface layers (rich in C and N) from deep layers (with lower stocks of these elements). PC2, in turn, was strongly associated with soil density, indicating a physical gradient independent of organic matter content.

The projection of the samples in the principal component space revealed a clear grouping of the surface layers, regardless of the profile, while the subsurface layers showed greater dispersion, reflecting the differential influence of edaphic and hydrological conditions among profiles. Profile 3 showed a more consistent alignment along the depth gradient, corroborating the linear pattern identified in the regression analysis, while Profiles 1 and 2 exhibited greater overlap between intermediate layers, indicating greater complexity in the vertical distribution of stocks.

Integratedly, the PCA reinforces that depth and carbon and nitrogen stocks constitute the main structuring axes of the variability in the studied soils, while soil density acts as a secondary factor of physical differentiation. These results provide multivariate support to the

patterns observed in the univariate analyses and reinforce the interpretation that hydrological and pedogenetic processes differentially modulate the vertical organization of C and N stocks in the soils of Marajó Island.

Figure 4

Principal component analysis (PCA) biplot showing the relationships among soil organic carbon stock (C stock), total nitrogen stock (N stock), soil depth, and bulk density across the three soil profiles on Marajó Island, eastern Amazon, Brazil. The vectors indicate the contribution and direction of influence of the original variables on the principal components, highlighting the vertical organic matter gradient and the physical differentiation between profiles.
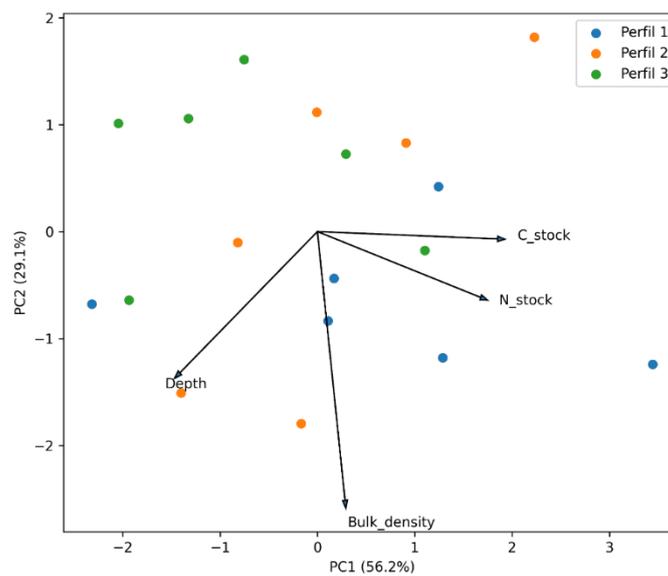
Source: The authors, 2026.

4 DISCUSSION

In line with the vertical patterns described in the Results section, the soil organic carbon (SOC) and total nitrogen (N) stocks in the profiles evaluated on Marajó Island demonstrate a dominant control exerted by edaphic and hydrological characteristics, with secondary influence from current land use, especially in the subsurface layers. The preferential concentration of C and N in the surface layers, followed by a progressive reduction at depth, corresponds to the behavior widely described for tropical and Amazonian soils (Ziviani et al., 2024; Popin et al., 2025).

The predominance of surface stocks is associated with the continuous accumulation of litter, fine roots, and root exudates—the primary sources of labile carbon and organic nitrogen. In Amazonian environments, even under high decomposition rates, high plant

productivity sustains these inputs (Santos et al., 2023). However, as shown in the Results, this pattern is not restricted to the surface layers, since stocks below 40 cm represented a significant portion of the total carbon, especially in environments under greater hydromorphic influence.

On Marajó Island, hydrological seasonality and the occurrence of periodically saturated horizons modulate microbial activity along the soil profile. The reduction of oxygenation in the subsurface, characteristic of hydromorphic and fluvio-marine soils, limits aerobic decomposition and favors the partial preservation of organic matter at depth—a mechanism compatible with the observed patterns, especially in Profile 1 (Reichenbach et al., 2023; Hicks Fries et al., 2023)

The Results demonstrated that approximately 40–50% of the total carbon stocks are concentrated within the top 40 cm, confirming the importance of surface layers as key compartments of the carbon cycle. However, the significant contribution of horizons below this depth, particularly in Profile 1, highlights that deep-seated stocks represent a structurally relevant fraction of the total carbon, reinforcing the need for integrated assessments down to at least 1 m in depth (Ziviani et al., 2024; Wang et al., 2025).

The integrated carbon and nitrogen stocks up to 100 cm showed significant variation among the evaluated profiles. Profile 1 presented the highest absolute C and N stocks, indicating edaphic conditions more favorable to the incorporation and stabilization of organic matter along the profile. This differentiation between profiles, highlighted in the Results, reinforces the combined role of the hydrological regime, soil structure, and the intensity of physical disturbances in carbon stability in tropical soils (Wells et al., 2022).

Profile 2 presented intermediate stocks and a relatively more homogeneous vertical distribution, suggesting stabilization mechanisms associated with the physical protection of organic matter within microaggregates and the formation of organo-mineral associations. Recent evidence indicates that the interaction between fine soil fractions and organic compounds increases carbon residence time, even in highly weathered environments (Cotrufo et al., 2015; Ziviani et al., 2024).

In contrast, Profile 3 exhibited the lowest carbon and nitrogen stocks at all depths, with a sharp reduction below 40 cm. The relatively higher C:N ratio at depth, associated with lower absolute N stocks, indicates a predominance of structural carbon and lower efficiency of microbial nitrogen incorporation. This behavior is typical of soils with higher sand content, which have lower nutrient retention capacity and less physical protection of organic matter (Yost and Hartemink, 2019; Alghamdi et al., 2024).

The integrated analysis of stocks up to 100 cm reinforces that a significant fraction of soil carbon and nitrogen is located below the surface layer traditionally evaluated (0–30 cm). Recent studies demonstrate that up to half of the total soil carbon can be stored at depth, especially in tropical hydromorphic environments under fluvial influence (Ziviani et al., 2024). The Results of this study empirically confirm this trend for the fluvio-marine soils of Marajó Island.

The C:N ratio provides relevant information regarding the quality and stability of organic matter. Higher ratios at depth, particularly in Profile 3, indicate lower relative nitrogen availability for microorganisms and a limitation of mineralization processes, favoring the accumulation of recalcitrant fractions (Cotrufo et al., 2015). In contrast, Profile 1 presented a more balanced C:N ratio, consistent with its higher absolute N stocks, indicating greater potential microbial activity and higher biogeochemical resilience of the soil (Santos et al., 2023; Cotrufo et al., 2015).

The positive correlation between carbon and nitrogen stocks along the profile reinforces the structural interdependence of these elements in Amazonian soils. Organic matter constitutes the main nitrogen reservoir, such that reductions in carbon stocks imply concomitant losses of N (Santos et al., 2023; Cotrufo et al., 2019).

From an environmental perspective, the soils of Marajó Island exhibit high carbon storage potential, especially at depth, serving as important natural sinks. Restricting assessments to surface layers may significantly underestimate actual stocks, compromising regional carbon inventories. Processes such as artificial drainage, compaction, and inadequate land-use conversion can trigger significant emissions of CO_2 and N_2O (Bussel et al., 2021).

In line with the vertical patterns described in the Results section, and supported by the univariate and multivariate statistical analyses, the soil organic carbon (SOC) and total nitrogen (N) stocks in the profiles evaluated on Marajó Island demonstrate a dominant control exerted by edaphic and hydrological characteristics, with secondary influence from current land use, especially in the subsurface layers. The preferential concentration of C and N in the surface layers, followed by a progressive reduction at depth, corresponds to the behavior widely described for tropical and Amazonian soils (Ziviani et al., 2024; Reichenbach et al., 2023).

Edaphic-Hydrological Control of Vertical C and N Distribution

The results obtained indicate that approximately 40–50% of the total carbon stocks are concentrated in the first 40 cm of the soil, confirming the importance of the surface layers as an active compartment of biogeochemical cycling. However, the integrated analysis up

to 100 cm, combined with regressions as a function of depth, demonstrates that the subsurface horizons constitute relevant and functionally distinct compartments, especially in profiles under greater hydromorphic influence.

The predominance of surface stocks is associated with the accumulation of litter, fine roots, and root exudates—the primary sources of labile carbon and organic nitrogen. Nevertheless, the maintenance of significant stocks at depth, observed mainly in Profile 1, suggests an environmental limitation on decomposition, associated with reduced oxygenation and the water seasonality typical of fluvio-marine soils. This mechanism is widely recognized as a factor in the preservation of organic matter in hydromorphic tropical environments (Reichenbach et al., 2023).

Vertical Gradient and Statistical Response of Stocks to Depth

The regression of carbon and nitrogen stocks as a function of depth provides additional quantitative evidence that depth acts as an integrated proxy for multiple processes, including reduced direct inputs of organic residues, changes in organic matter quality, and the transition from biological to physicochemical controls. The strong fit observed in Profile 3 indicates a simpler and more linear vertical gradient, whereas Profiles 1 and 2 exhibit less linear responses, reflecting greater pedogenetic and hydrological complexity.

These results reinforce that significant vertical declines do not imply uniformity of processes, but rather responses dependent on texture, soil structure, and the water regime. Recent studies highlight that, in tropical soils, the rate of carbon decline with depth varies substantially among profiles, depending on the degree of physical protection and the intensity of hydromorphism (Hu et al., 2024; Chirol et al., 2025).

Coupling Between Carbon and Nitrogen Cycles

The strong correlation between carbon and nitrogen stocks observed along the profiles confirms the structural interdependence of these elements, given that soil organic matter constitutes the primary N reservoir. This statistical coupling, however, reflects not only joint residue inputs but also organo-mineral co-stabilization processes and environmental constraints on mineralization, particularly under conditions of periodic saturation.

Recent results indicate that, in tropical environments, geochemical and hydrological controls can outweigh the effect of land use in determining total C and N stocks, especially at depth, where carbon residence time is greater (Reichenbach et al., 2023; Azevedo et al., 2024).

Multivariate Integration of Edaphic Controls (PCA)

The Principal Component Analysis (PCA) reinforces these interpretations by demonstrating that data variability is structured primarily by two independent axes: one associated with the magnitude of carbon and nitrogen stocks and another related to depth and physical soil conditions. The alignment of C and N vectors in the biplot indicates the joint variation of these elements, while their opposition to the depth vector reflects the vertical transition between high-input environments and those dominated by physicochemical controls.

The separation of subsurface layers in the multivariate space, especially in hydromorphic profiles, indicates that depth represents not only a physical gradient but a functional gradient, associated with changes in the redox regime, microbial activity, and organic matter protection. Similar results have been observed in recent studies in the Amazon, which highlight the importance of geomorphology and hydrodynamics in the spatial and vertical organization of carbon stocks (Moquedace et al., 2024).

C:N Ratio and Organic Matter Quality

The integrated C:N ratio provides additional information regarding the quality and stability of soil organic matter. Higher C:N ratios at depth, especially in Profile 3, indicate a predominance of structural carbon and lower efficiency of microbial nitrogen incorporation, a behavior typical of soils with higher sand content and lower nutrient retention capacity. In contrast, Profile 1 presented a more balanced C:N ratio, consistent with its higher absolute N stocks and greater biogeochemical resilience.

Interpretative Synthesis and Conceptual Implications

Integratedly, the consistency among the correlation, regression, and PCA analyses supports the conclusion that the primary control over C and N stocks on Marajó Island is exerted by long-term edaphic and hydrological factors, while the effects of current land use are more pronounced in the surface layers. These results reinforce the need to consider the entire soil profile (up to 1 m) in stock assessments and management strategies, avoiding significant underestimations of the role of these soils as carbon and nitrogen reservoirs in Amazonian fluvio-marine environments.

5 CONCLUSIONS

The fluvio-marine soils of Marajó Island harbor significant stocks of organic carbon and total nitrogen, whose vertical distribution is primarily controlled by edaphic and hydrological factors operating along the soil profile. Although the surface layers concentrate the largest proportion of these stocks, the Results and integrated statistical analyses clearly

demonstrate that a substantial fraction of carbon and nitrogen is stored in subsurface horizons, particularly in profiles under stronger hydromorphic influence.

Differences among soil profiles indicate that water regime, soil texture, and long-term pedogenic processes exert a more decisive control on deep carbon and nitrogen stocks than current land use, especially below 40 cm depth. This pattern is consistent with the observed vertical gradients, regression analyses, and multivariate structure of the data, which collectively highlight the role of hydrological constraints and physical protection mechanisms in stabilizing organic matter at depth. The C:N ratio further revealed contrasts in organic matter quality and stability, indicating greater biogeochemical resilience in profiles with higher absolute nitrogen stocks and more balanced C:N relationships.

Taken together, these findings demonstrate that assessments restricted to surface layers substantially underestimate total soil carbon and nitrogen stocks in Amazonian fluvio-marine environments. Consequently, considering the soil profile to depths of at least 1 m is essential for robust carbon and nitrogen inventories, for improving biogeochemical modeling, and for the formulation of effective climate change mitigation strategies in lowland Amazonian landscapes subject to hydrological seasonality.

6 FINAL CONSIDERATIONS AND MANAGEMENT IMPLICATIONS

The results obtained in this study reinforce that the soils of Marajó Island constitute highly strategic edaphic systems for organic carbon and nitrogen storage, with significant stocks distributed throughout the entire profile down to a depth of 100 cm. The high contribution of subsurface layers to total C and N stocks demonstrates that assessments restricted to the surface layer are insufficient to represent the true function of these soils as biogeochemical reservoirs, particularly in Amazonian fluvio-marine environments.

From a management perspective, the results indicate that maintaining the physical and hydrological integrity of the soil is a determining factor for the conservation of carbon and nitrogen stocks. Profiles that showed higher integrated stocks, such as Profile 1, reflect conditions where continuous vegetation cover, low mechanical disturbance, and the preservation of the natural flooding regime favor the incorporation and stabilization of organic matter, even at depth. Thus, practices that alter the water balance—such as artificial drainage, excessive compaction, or intense soil tillage—must be avoided or strictly controlled due to their potential to accelerate organic matter mineralization and promote irreversible C and N losses.

The observed vertical distribution also indicates that management strategies based exclusively on surface soil dynamics underestimate the importance of subsurface horizons,

which store significant fractions of total carbon, often associated with more stable and recalcitrant forms. Therefore, sustainable management of these soils should prioritize practices that preserve the structure of the complete profile, such as low-intervention land-use systems, maintenance of plant residues, and the promotion of deep root cycling.

The differences observed among the profiles further highlight that intrinsic soil properties—such as texture, structure, and hydrological regime—play a more decisive role than current land use in defining deep-seated carbon and nitrogen stocks. This aspect reinforces the need for territorial and agricultural planning based on edaphic suitability, avoiding the homogenization of management practices in environments with high pedological heterogeneity, such as Marajó Island.

The integrated C:N ratio proved to be a relevant indicator of organic matter quality and stability, with direct implications for fertility management. Profiles with more balanced C:N ratios indicate higher mineralization potential and nitrogen availability, favoring productive sustainability, while higher ratios suggest greater recalcitrance and lower nutrient cycling efficiency. Thus, management should aim to balance carbon conservation with the maintenance of soil biogeochemical functionality, avoiding practices that promote the excessive accumulation of poorly decomposed organic material without nutritional return to production systems.

In environmental terms, the results demonstrate that the soils of Marajó Island play a relevant role as natural carbon sinks, contributing to climate change mitigation on a regional and potentially global scale. Inadequate land-use conversion, associated with the physical or hydrological degradation of these soils, can transform these environments from sinks into net sources of greenhouse gases, with direct impacts on ecosystem services.

In this context, public policies and management strategies must incorporate the soil's vertical dimension into conservation programs, carbon inventories, and payment for environmental services initiatives. Including deep stocks in official assessments can significantly increase the accuracy of carbon estimates, adding value to environments that are frequently underestimated in national and international balances.

Finally, this study highlights that the sustainability of land-use systems on Marajó Island depends on the integration of soil conservation, maintenance of the hydrological regime, and territorial planning based on edaphic criteria. Recognizing the soil as an active and dynamic component of the socio-environmental system is fundamental to reconciling production, conservation, and climate mitigation in Amazonian fluvio-marine environments.

REFERENCES

Albuquerque, A. S., et al. (2025). Carbono e nitrogênio do solo em área de Floresta Tropical Seca no Nordeste Brasileiro. Caderno Pedagógico, 22(1). https://doi.org/10.54033/cadpedv22n1-158

Alfaia, S. S., Ayres, M. I. D. C., Neves, A. L., Uguen, K., Miller, R. P., Fajardo, J. D. V., Bakker, A. P., & Ticona-Benavente, C. A. (2022). Chemical features of floodplain soils under different land-uses in the Solimões/Amazon River basin. Revista Brasileira de Ciência do Solo, 46, e0220005. https://doi.org/10.36783/18069657rbcs20220005

Alghamdi, A. G., Majrashi, M. A., & Ibrahim, H. M. (2024). Improving the physical properties and water retention of sandy soils by the synergistic utilization of natural clay deposits and wheat straw. Sustainability, 16(1), 46. https://doi.org/10.3390/su16010046

Arruda, D. L., Ker, J. C., Veloso, G. V., Henriques, R. J., Fernandes-Filho, E. I., Camêlo, D. L., Gomes, L. C., & Schaefer, C. E. G. R. (2024). Soil carbon prediction in Marajó Island wetlands. Revista Brasileira de Ciência do Solo, 48, e0230162. https://doi.org/10.36783/18069657rbcs20230162

Azevedo, J. C. d., Cardoso, A. d. S., Lage Filho, N. M., Faturi, C., Silva, T. C. d., Domingues, F. N., Costa, V. E., Ruggieri, A. C., Reis, R. A., & do Rêgo, A. C. (2024). Effects of agricultural expansion on soil carbon and nitrogen stocks in the Amazon deforestation arc. Soil Systems, 8(1), 25. https://doi.org/10.3390/soilsystems8010025

Bania, J. K., Nath, A. J., Sandhya, G., et al. (2025). Predictive mapping of deep soil organic carbon stocks across land use systems in Southern Assam, India. Scientific Reports, 15, 34253. https://doi.org/10.1038/s41598-025-16355-0

Borchard, N., Bulusu, M., Meyer, N., Rodionov, A., Herawati, H., Blagodatsky, S., et al. (2019). Deep soil carbon storage in tree-dominated land use systems in tropical lowlands of Kalimantan. Geoderma, 354, 113864. https://doi.org/10.1016/j.geoderma.2019.07.022

Bussell, J., Crotty, F., & Stoate, C. (2021). Comparison of compaction alleviation methods on soil health and greenhouse gas emissions. Land, 10(12), 1397. https://doi.org/10.3390/land10121397

Carvalho, E. J. M., et al. (2025a). Caracterização e classificação taxonômica de solos nos municípios de Soure e Salvaterra, Ilha do Marajó, Estado do Pará. Brazilian Journal of Animal and Environmental Research, 8(1), 1–20.

Carvalho, E. J. M., et al. (2025b). Atributos físico-hídricos de solos nos municípios de Soure e Salvaterra, Ilha do Marajó, Estado do Pará. Brazilian Journal of Animal and Environmental Research, 8(3), 1–19.

Chen, X., Mou, Z., Zhang, J., Li, Y., Wu, W., Wang, T., et al. (2025). Roots dominate over extraradical hyphae in driving soil organic carbon accumulation during tropical forest succession. Global Change Biology, 31(9), e70499. https://doi.org/10.1111/gcb.70499

Chirol, C., Séré, G., Redon, P. O., Chenu, C., & Derrien, D. (2025). Depth dependence of soil organic carbon additional storage capacity in different soil types by the 2050 target for carbon neutrality. SOIL, 11(1), 149–174. https://doi.org/10.5194/soil-11-149-2025

Cotrufo, M. F., Soong, J. L., Horton, A. J., Campbell, E. E., Haddix, M. L., Wall, D. H., & Parton, W. J. (2015). Formation of soil organic matter via biochemical and physical pathways of litter mass loss. Nature Geoscience, 8(10), 776–779. https://doi.org/10.1038/NGEO2520

Crézé, C., Saatchi, S., Kwon, N., Yang, Y., & Li, S. (2025). High-resolution global map (100 m) of soil organic carbon reveals critical ecosystems for carbon storage. Earth System Science Data Discussions, 1–46. https://doi.org/10.5194/essd-2025-294

Damian, J. M., da Silva Matos, E., Pedreira, B. C., de Faccio Carvalho, P. C., Premazzi, L. M., Williams, S., Paustian, K., & Cerri, C. E. P. (2021). Predicting soil C changes after pasture intensification and diversification in Brazil. CATENA, 202, 105238. https://doi.org/10.1016/j.catena.2021.105238

Fachin, P. A., & Netto, A. L. C. (2024). Dinâmica biogeoquímica e estoque de carbono orgânico em solos da Mata Atlântica Serrana no Estado do Rio de Janeiro. Anais do Simpósio Brasileiro de Geografia Física Aplicada. https://editorarealize.com.br/editora/anais/sbgfa/2024/TRABALHO_COMPLETO_EV206_MD1_ID1993_TB1025_29082024111515.pdf

Freitas, V. S., Babos, D. V., Guedes, W. N., Silva, F. P., Tozo, M. L. L., Andrade, C. A., Villas-Boas, P. R., Milori, D. M. B. P., & Martin-Neto, L. (2024). Soil organic matter dynamics and soil carbon stocks from tropical and sub-tropical areas under no-till: An on-farm research. CATENA, 247, 108491. https://doi.org/10.1016/j.catena.2024.108491

Gatti, L. V., Basso, L. S., Miller, J. B., et al. (2021). Amazonia as a carbon source linked to deforestation and climate change. Nature, 595, 388–393. https://doi.org/10.1038/s41586-021-03629-6

Gomes, D. J. C., Beltrão, N. E. S., Dias, Y. A. S., & Maia, E. T. (2024). Eventos de inundação em anos extremos de Dipolo do Atlântico e La Niña no Arquipélago do Marajó. Revista Brasileira de Climatologia, 35(20). https://doi.org/10.55761/abclima.v35i20.17577

Gross, C. D., & Harrison, R. B. (2018). Quantifying and comparing soil carbon stocks: Underestimation with the core sampling method. Soil Science Society of America Journal, 82(4), 949–958. https://doi.org/10.2136/sssaj2018.01.0015

Hicks Pries, C. E., Ryals, R., Zhu, B., Min, K., Cooper, A., Goldsmith, S., et al. (2023). The deep soil organic carbon response to global change. Annual Review of Ecology, Evolution, and Systematics, 54(1), 375–401. https://doi.org/10.1146/annurev-ecolsys-102320-085332

Hu, Y., Deng, Q., Kätterer, T., Olesen, J. E., Ying, S. C., Ochoa-Hueso, R., et al. (2024). Depth-dependent responses of soil organic carbon under nitrogen deposition. Global Change Biology, 30(3), e17247. https://doi.org/10.1111/gcb.17247

Lam, S. K., Goodrich, J. P., Liang, X., Zhang, Y., Pan, B., Schipper, L. A., et al. (2022). Mitigating soil greenhouse-gas emissions from land-use change in tropical peatlands.

Frontiers in Ecology and the Environment, 20(6), 352–360. https://doi.org/10.1002/fee.2497

Liu, Z. D., Song, Y. Y., Ma, X. Y., Yuan, J. B., Lou, Y. J., Yang, C., et al. (2023). Deep soil microbial carbon metabolic function is important but often neglected: A study on the Songnen Plain reed wetland, Northeast China. Fundamental Research, 3(6), 833–843. https://doi.org/10.1016/j.fmre.2022.06.013

Matos, E. da S., Antonio, D. B. A., & Rodrigues, R. de A. R. (2016). Estoques de carbono e nitrogênio do solo em área de SAF e floresta nativa. Embrapa Agrossilvipastoril. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1066260/estoques-de-carbono-e-nitrogenio-do-solo-em-area-de-saf-e-floresta-nativa

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., et al. (2017). Soil carbon 4 per mille. Geoderma, 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Moquedace, C. M., Baldi, C. G. O., Siqueira, R. G., Cardoso, I. M., de Souza, E. F. M., Fontes, R. L. F., et al. (2024). High-resolution mapping of soil carbon stocks in the western Amazon. Geoderma Regional, 36, e00773. https://doi.org/10.1016/j.geodrs.2024.e00773

Moraes, L. M., Azevedo, J. C. D., Oliveira, J. V. C. D., Abreu, N. L., Amaral Junior, F. P., Silva, T. C. D., et al. (2025). Impact of land use change and climate on the Brazilian Amazon: A review on carbon stocks and greenhouse gas emissions. Scientia Agropecuaria, 16(4), 671–688.

Musei, S. K., Kuyah, S., Nyawira, S., Ng'ang'a, S. K., Karugu, W. N., Smucker, A., & Nkurunziza, L. (2024). Sandy soil reclamation technologies to improve crop productivity and soil health: A review. Frontiers in Soil Science, 4, 1345895. https://doi.org/10.3389/fsoil.2024.1345895

Ni, B., Yu, X., Duan, X., & Zou, Y. (2024). Wetland soil organic carbon balance is reversed by old carbon and iron oxide additions. Frontiers in Microbiology, 14, 1327265. https://doi.org/10.3389/fmicb.2023.1327265

Poeplau, C., Vos, C., & Don, A. (2017). Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. SOIL, 3, 61–66. https://doi.org/10.5194/soil-3-61-2017

Popin, G. V., et al. (2025). Land-use change and deep-soil carbon distribution on the Brazilian Amazon-Cerrado agricultural frontier. Agriculture, Ecosystems & Environment, 381, 109451. https://doi.org/10.1016/j.agee.2024.109451

Quesada, C. A., Paz, C., Oblitas Mendoza, E., Phillips, O. L., Saiz, G., & Lloyd, J. (2020). Variations in soil chemical and physical properties explain basin-wide Amazon forest soil carbon concentrations. SOIL, 6, 53–88. https://doi.org/10.5194/soil-6-53-2020

Reichenbach, M., Fiener, P., Hoyt, A., Trumbore, S., Six, J., & Doetterl, S. (2023). Soil carbon stocks in stable tropical landforms are dominated by geochemical controls and not by land use. Global Change Biology, 29(9), 2591–2607. https://doi.org/10.1111/gcb.16622

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araujo Filho, J. C., Oliveira, J. B., & Cunha, T. J. F. (2018). Sistema brasileiro de classificação de solos (5ª ed.). Embrapa.

Santos, J. C. B., et al. (2023). Carbon, nitrogen, and physical fractions of organic matter in recovered pastures of the Maranhense Amazon. Acta Scientiarum. Agronomy, 45. https://doi.org/10.4025/actasciagron.v45i1.60794

Silva, A. R., et al. (2021). Estoque de carbono e mitigação de metano produzido por bovinos em sistema integração pecuária-floresta (IPF) com eucalipto no Sudeste Paraense. Brazilian Journal of Animal and Environmental Research, 8(1), 1–20.

Wang, H., Cai, T., Tian, X., Chen, Z., He, K., Wang, Z., Gong, H., Miao, Q., Wang, Y., Chu, Y., Zhang, Q., Zhuang, M., Yin, Y., & Cui, Z. (2025). Global patterns of soil organic carbon distribution in the 20–100 cm soil profile for different ecosystems: A global meta-analysis. Earth System Science Data, 17, 3375–3390. https://doi.org/10.5194/essd-17-3375-2025

Wells, J. A., Crow, S. E., Sierra, C. A., Deenik, J. L., Carlson, K. M., Meki, M. N., & Kiniry, J. R. (2022). Edaphic controls of soil organic carbon in tropical agricultural landscapes. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-24655-y

Yost, J. L., & Hartemink, A. E. (2019). Soil organic carbon in sandy soils: A review. Advances in Agronomy, 158, 217–310.

Ziviani, M. M., et al. (2024). Carbon and nitrogen stocks and soil organic matter persistence under native vegetation along a topographic and vegetation gradient in the Central Amazon Region. Soil Systems, 8(2), 65. https://doi.org/10.3390/soilsystems8020065