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Partitioning autochthonous and allochthonous carbon in mangroves of the Brazilian Amazon coast

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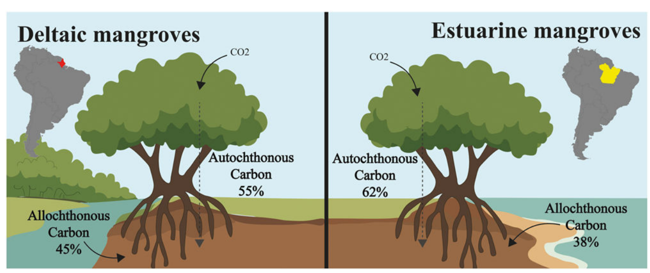
HIGHLIGHTS

- Strong spatial differences in mangrove organic sources due to the Amazon River.
- Autochthonous carbon predominates (>54%) in estuarine mangroves.
- Allochthonous carbon makes up 34–38% of surface soil organic carbon.
- Mangroves in deltaic settings have a 30% lower restoration value.

GRAPHICAL ABSTRACT



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ABSTRACT

Mangrove forests are important coastal carbon sinks, yet the origins of their soil organic carbon can vary among different coastal geomorphic settings. Understanding the relative contributions of autochthonous and allochthonous organic matter in mangroves of the Amazon coast adds important ecological information on the processes driving carbon accumulation and can help guide future restoration efforts in Brazil. Here we applied stable carbon and nitrogen isotope analysis combined with Bayesian mixing models to partition organic matter sources from 496 soil samples in deltaic and estuarine mangrove of the Amazon coast. Autochthonous sources dominated soil organic carbon in deltaic (54 %) and estuarine (67 %) mangroves. The Amazon River contributed to 24 % of the allochthonous inputs to deltaic mangroves (3-fold larger than estuarine settings), highlighting their connection to the health of the freshwater basin. Our models suggest that mangrove carbon contributes substantially the surface soil layer (0−50 cm, >50 % of autochthonous carbon), and suggests a higher value of restoring mangroves in estuarine settings for increased blue carbon credit benefits. This work supports the role of mangroves of the Amazon coast in climate mitigation strategies and guides the valuation of potential restoration projects with region-specific data.

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Introduction

Mangroves are valuable coastal ecosystems that provide essential services, including habitat for diverse organisms, carbon sequestration, pollution reduction, and coastal protection (Owuor et al., 2024; Rico et al., 2024). Their unique soil and hydrodynamic characteristics enhance carbon sequestration and long-term storage, playing a critical role in global climate change mitigation (Kauffman et al., 2020). However, the efficiency of carbon sequestration, and consequently the additionality and permanence of mangrove carbon stocks, varies considerably among regions, influenced not only by soil biogeochemistry and climate, but also by the quality, reactivity, and degradability of organic matter (Ruiz et al., 2024). While geomorphological settings related to tidal amplitude and riverine or marine inputs are often linked to carbon stocks in mangroves soils (Twilley et al., 2018), there are large gaps in our understanding of carbon sources and its preservation in some regions (Arnaud et al., 2025).

Understanding the amount of carbon stored, the carbon sequestration rates and the sources of organic carbon being buried are important to identify the processes related to mangrove carbon capture and its long-term preservation. Although soil carbon stocks are correlated to the coastal geomorphology and hydrodynamics in some areas (Twilley et al., 2018), these patterns do not hold in some regions suggesting that processes related to organic matter sources and their preservation may be additionally relevant to explain mangrove carbon stocks (Kusumaningtyas et al., 2019; Bernardino et al., 2024a,b). Moreover, mangrove soils typically contain a mixture of both autochthonous (e.g., mangrove litter and roots) and allochthonous inputs (e.g., terrestrial and marine carbon) (Qin et al., 2024; Zhang et al., 2024). Quantifying the origin of these sources can inform the biogeochemical reactivity and persistence of the soil carbon, its stabilization mechanisms, and adds critical information to mangrove restoration and carbon crediting planning.

The organic matter naturally delivered by rivers or marine sources, or from mangrove plants, is preserved within mangrove soils through physical burial and mineral association that contribute to its permanence if protected from remineralization under predominantly anoxic conditions (Bernardino et al., 2020; Bernardino et al., 2021; Ruiz et al., 2024; Zhang et al., 2024). In highly dynamic environments such as river deltas, the balance between these processes remains largely uncertain (Suello et al., 2022). Determining the contribution of different carbon sources in mangroves is therefore essential for both carbon market mechanisms in restoration projects and to the understanding of carbon cycling in coastal wetlands (Needelman et al., 2018). This information supports long-term assessments of mangrove productivity and their resilience to global climate change, as the balance between mangrove forest productivity and allochthonous carbon burial may fluctuate over time. While models incorporating these biochemical changes exist for terrestrial soils (Diels et al., 2004), and at global scales for mangroves (Zhang et al., 2024), local-scale models based on empirical data for mangrove soils are lacking, highlighting a critical knowledge gap in carbon dynamics within these ecosystems (Jennerjahn, 2021; Arnaud et al., 2025). The use of generic proxies or global averages can obscure critical regional differences, particularly in deltaic and estuarine settings along the Amazon coast with variable riverine inputs of organic matter (Bernardino et al., 2022).

The Brazilian Amazon coast harbors one of the world's largest preserved mangrove forests (> 700,000 ha) with average total ecosystem carbon stocks of 468 ± 67 Mg C ha^{-1} (Bernardino et al., 2021; Bernardino et al., 2024a). Incorporating these mangroves into Brazil's Nationally Determined Contributions, particularly in the context of REDD + initiatives (Reducing Emissions from Deforestation and forest Degradation), could enhance climate mitigation by preventing the release of large amounts of greenhouse gas (CO_2 and CH_4) to the atmosphere. Although total ecosystem stocks can aid in mitigation plans, they are of limited value for restoration efforts, which require data on the additional benefits of planting mangroves. Therefore, determining sources of organic carbon in these mangroves settings adds a valuable information to Brazil's climate plan to restore over 17,000 ha of forests by 2030 (MMA, 2024). As restoration of mangroves are mostly valued in areas where additional (i.e. autochthonous plant material) carbon can be incorporated (Zhang et al., 2024), identifying these spatial patterns along the Amazon coast can guide restoration plans to coastal sites with higher potential for mangrove-derived sequestration (Lovelock et al., 2022). It also expands access to blue carbon credit financing mechanisms and promotes social co-benefits by involving local communities in conservation and sustainable management efforts (Bernardino et al., 2024a; Owuor et al., 2024). In the Brazilian Amazon nearly 20 % of the mangroves are deltaic and directly under the influence of the Amazon River discharge (Bernardino et al., 2022), while to the east of the Amazon River estuarine mangroves predominate, which potentially increases the contribution of mangrove organic matter sources in those forests (Lana and Bernardino, 2018). These distinct geographical settings likely influence the relative contribution of carbon sources to soil carbon stocks and consequently control the additionality value of potential restoration activities in the Amazon coast.

In this study, we assessed the soil organic carbon contents in multiple mangrove forests of the Amazon coast, contrasting deltaic and estuarine settings. We determined the organic matter isotopic signatures ($\delta^{13}C$ and $\delta^{15}N$) of soil organic carbon and modelled the main sources of organic carbon and nitrogen from over 400 mangrove soil samples. We hypothesized a stronger contribution of allochthonous (riverine) carbon sources in mangroves of the Amazon River delta, whereas estuarine mangroves would exhibit a dominance of autochthonous carbon sources. Our findings provide new insights into the balance between these sources in one of the world's largest pristine mangrove forests.

Material and methods

Study area and sampling

The Amazon coast has an annual temperature between 26.5 °C and 27 °C, and precipitation ranging from 2000 mm to 3300 mm, with a tropical monsoon climate (Lana and Bernardino, 2018). Mangroves were sampled on two expeditions in January 2019 and April 2022, in areas to the west and within the Amazon River delta (Fig. 1; Table S1; Bernardino et al., 2022). Soil samples (n = 469 soil samples) were collected at 17 sites within deltaic (n = 276 soil samples) and estuarine mangroves (n = 193 soil samples; Fig. 1; Table S1). Amazon mangrove forests were typically dominated by mangrove species *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa*, with an occasional contribution of freshwater *varzea* species close to the Amazon river mouth (Bernardino et al., 2022). The deltaic mangrove sites were under the influence of the Amazon River freshwater plume, with lower salinity (2.3 ± 3.4 ppt), acidic soils (pH = 5.6 ± 0.7), suboxic to anoxic redox conditions (Eh ranging from −20 to +194 mV) and higher soil methane effluxes (Bernardino et al., 2022, 2024b). Estuarine mangroves were more influenced by marine water, with higher salinity (17.8 ± 5.2), slightly acidic soils (pH = 6.3 ± 0.7), and anoxic to suboxic redox conditions (Eh ranging from −281 to +240 mV) (Bernardino et al., 2024a,b). In each mangrove forest, soil samples were collected in six sampling plots (20 m apart) using a semi-cylindrical auger (6 cm diameter) and were sectioned in five different depths (0−15 cm, 15−30 cm, 30−50 cm, 50−100 cm, and 100−200 cm). Environmental parameters (soil salinity, pH, and Eh) were measured in situ.

Soil organic carbon content and stable isotopic signatures ($\delta^{13}C$ and $\delta^{15}N$)

Soil samples were initially weighed and dried at 60 °C. For the assessment of total carbon and nitrogen, and organic carbon contents, 0.5 mg of soil samples was weighed in tin and silver foil capsules. The samples used for the determination of organic carbon (silver foil

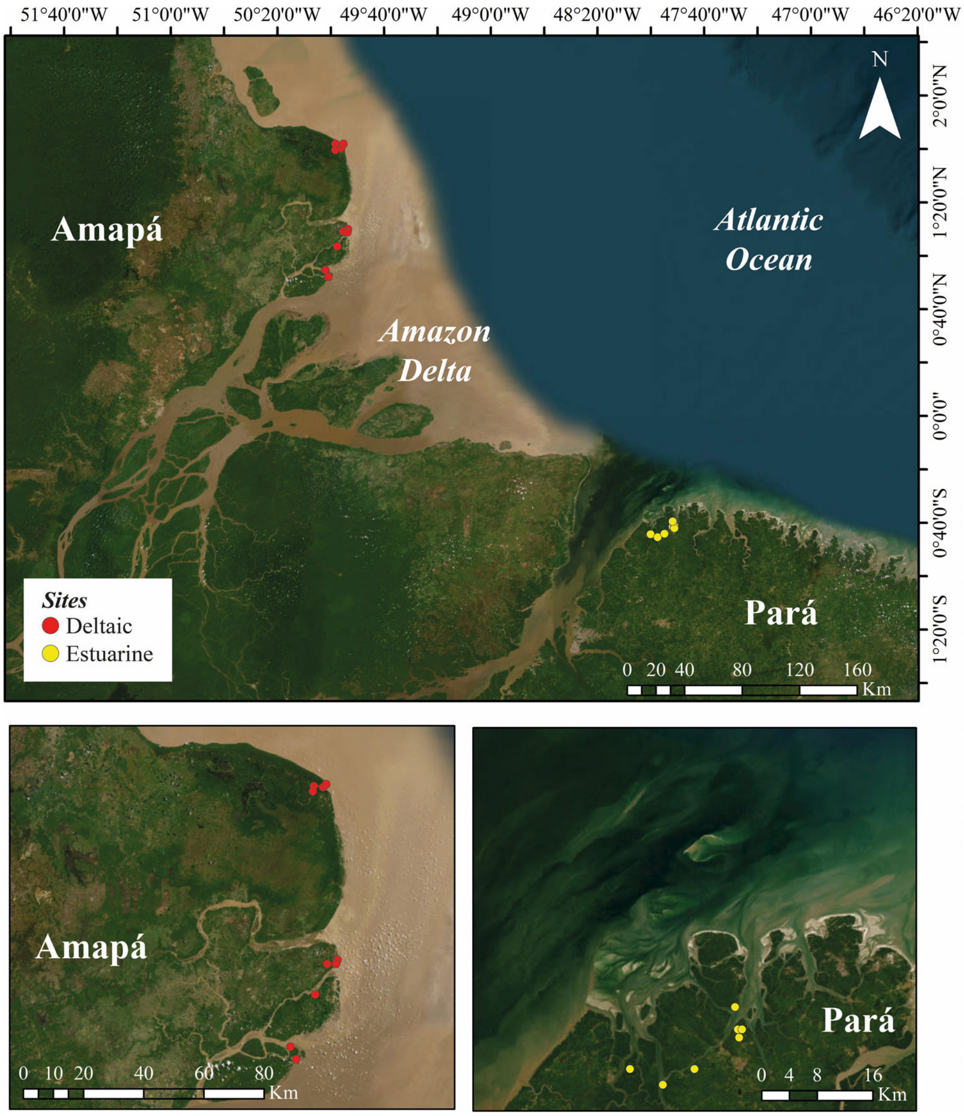

Fig. 1. Location of deltaic and estuarine mangrove forests sampled in the Amazon Delta.

capsules) and ^{13}C isotope signatures (see below) were firstly acidified with 10% HCl to remove inorganic carbon. The acidification was performed by adding small drops of 10% HCl directly onto the samples until visible effervescence ceased, indicating complete carbonate removal. Non-acidified subsamples (tin foil capsules) were used for nitrogen ^{15}N isotopic signatures to avoid isotopic alteration from acids. A Thermo Flash EA 1112 series C-N Soil Analyzer was used to measure total carbon and nitrogen contents. Stable isotope ratios were determined using a Eurovector elemental analyzer to determine the stable isotopic ratios. The CO_2 that was produced was then separated by gas chromatography and fed into an Isotope Ratio Mass Spectrometer (IRMS) for the detection of the $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios. For $\delta^{15}N$ and $\delta^{13}C$, the repeatability was 70.5 % and 70.2 %, respectively. The isotopic ratio is expressed as delta (d) where $dX = [(Rsample/Rstandard) - 1] \times 10^3$ where $R = {}^{15}N/^{14}N$ or $^{13}C/^{12}C$. The standard material for $\delta^{13}C$ determination was Pee Dee Belemnite (PDB), and for $\delta^{15}N$ it was the atmospheric nitrogen.

Bayesian mixing model

To quantify the carbon contribution from different autochthonous (mangrove litter and roots) and allochthonous (marine and riverine input) sources to the mangrove soils, we employed a four-end Bayesian mixing model (MixSIAR package; Stock et al., 2018) with two stable isotope tracers ($\delta^{13}C$ and $\delta^{15}N$). The isotopic data from each individual corer were grouped into two depth intervals (0–50 cm and 50–200 cm) based on the well-established vertical variation of organic matter sources and diagenetic processes within mangrove soils, where surface layers receive more recent inputs, while deeper layers reflect more decomposed and stabilized organic material. To define the sources' isotopic signatures, we used published data selecting studies that collected and analyzed samples of the same plant species and/or as near as possible as our sampling sites. Autochthonous sources were based on isotopic data of mangrove leaves ($\delta^{13}C = -28.06 \pm 1.76$ and $\delta^{15}N = 1.48 \pm 2.39$; Table S2) and roots ($\delta^{13}C = -27.45 \pm 0.73$ and $\delta^{15}N = -0.25 \pm 2.87$; Table S2) from the dominant species found in the sampled sites (*R. mangle*, *A. germinans*, and *L. racemosa*). Allochthonous sources were based on isotopic signatures of riverine ($\delta^{13}C = -28.38 \pm 0.56$ and $\delta^{15}N = 4.53 \pm 0.88$) and marine ($\delta^{13}C = -23.92 \pm 1.46$ and $\delta^{15}N = 7.02 \pm 1.11$) particulate organic carbon (Table S2). We enhanced source fitting by utilizing the data's mean ± standard deviation and by adjusting the source sample size to n = 10,000 to ensure the model's convergence (Stock and Semmens, 2016; Qin et al., 2024; Zhang et al., 2024). We used the results of the Bayesian mixing model and published total ecosystem carbon stock (TECS) data from Amazon mangroves to estimate the contribution of each end-member to the SOC

(Bernardino et al., 2024a,b).

Statistical analysis

We performed Permutational Analysis of Variance (PERMANOVA), based on a Euclidean distance matrix, to compare soil organic carbon contents (SOC), carbon-to-nitrogen ratios (C:N), and stable isotopic signatures ($\delta^{13}C$ and $\delta^{15}N$) among environmental settings (deltaic and estuarine mangroves) and soil depths (0–50 cm and >50 cm). Bonferroni corrections were applied to adjust p-values on pairwise comparisons. A Principal Component Analysis (PCA) was performed on the correlation of the sample units and SOC, C:N ratio, isotopic signatures ($\delta^{13}C$ and $\delta^{15}N$), and environmental variables (soil salinity and pH). To perform the PCA analysis, data were firstly standardized using the *standardize* method of the "decostand" function from the "vegan" package. This method subtracts the mean and divides by the standard deviation of each variable, resulting in centered variables with zero mean and unit variance, allowing all variables to have equal weight in the multivariate analysis. A generalized additive model was fit between SOC (log10 transformed) and carbon isotopic signatures ($\delta^{13}C$). All statistical and graphical procedures were performed in the R environment, using the packages "vegan", "mgcv", and "ggplot2" (Wood, 2011; R Core Team, 2024; Oksanen et al., 2025) and significant differences were considered when $p < 0.05$.

Results

Soil organic carbon contents and isotopic signatures

We observed significant differences in the soil organic carbon (SOC) contents between deltaic and estuarine mangrove forests, as well as across soil depths. Deltaic mangroves showed lower SOC contents (1.84 ± 2.22 %) than estuarine mangroves (2.78 ± 1.77 %; df = 1; Pseudo-F = 27.313; p = 0.001; Table S3). SOC contents also varied with soil depth, with higher concentrations observed in the upper 50 cm of the soil profiles (2.56 ± 2.30 %) when compared to deeper layers (1.68 ± 1.58 %; df = 1; Pseudo-F = 20.092; p = 0.001; Table S3).

Deltaic and estuarine mangrove forests showed significant differences in soil isotopic signatures ($\delta^{13}C$ and $\delta^{15}N$) and C:N ratios (Fig. 2), suggesting a range of organic sources. The $\delta^{13}C$ signature in deltaic mangrove soils was more depleted in ^{13}C (-27.54 ± 1.26) when compared to estuarine mangroves (−26.56 ± 0.80; df = 1; Pseudo-F = 78.155; p = 0.001; Table S4; Fig. 2a). A significant difference was also observed across soil layers, with the upper 50 cm showing depleted $\delta^{13}C$ signatures (−27.47 ± 1.16) when compared to deeper layers (−26.59 ± 1.04; df = 1; Pseudo-F = 65.879; p = 0.001; Table S4; Fig. 2a). Additionally, the $\delta^{13}C$ signature varied significantly across layers across deltaic and estuarine mangroves (df = 1; Pseudo-F = 26.05; p = 0.001; Table S4; Fig. 2a). A significant relationship was observed between higher SOC contents and depleted $\delta^{13}C$ signatures (R^2adj = 0.06; F = 16.17; p < 0.001; Table S5), suggesting that these sources contribute to a higher proportion to the organic carbon in the upper soil layers.

Similarly, $\delta^{15}N$ showed significant differences between deltaic and estuarine mangrove forests (Table S6), with higher values observed in estuarine sites (3.23 ± 1.20) compared to deltaic ones (2.33 ± 3.02; df = 1; Pseudo-F = 16.423; p = 0.001; Table S6; Fig. 2b). However, no significant differences were observed across soil depths (Table S6; Fig. 2b). The C:N ratio was also significantly higher in estuarine mangrove soils (19.30 ± 6.31) than in deltaic sites (10.33 ± 5.69; df = 1; Pseudo-F = 269.13; p = 0.001; Table S7; Fig. 2c).

The separation of deltaic and estuarine sites in the PCA suggests contrasting soil physicochemical conditions and isotopic signatures, and support marked differences in the organic carbon sources between those mangroves (Fig. 3). Higher soil salinities, pH, and SOC contents were primarily associated with estuarine mangrove forests, along with higher C:N ratios and enrichment in ^{13}C and ^{15}N. Soils from upper layers (0–50 cm) were also associated with depleted $\delta^{13}C$ sources (PCA2), especially in deltaic settings.

Bayesian mixing model

The soil organic matter in deltaic and estuarine mangrove forests was

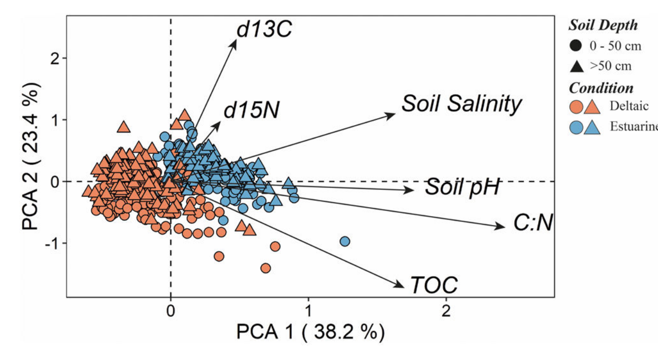

Fig. 3. Principal Component Analysis (PCA) with physicochemical variables (soil salinity and pH), soil organic carbon contents (SOC), carbon-to-nitrogen ratios (C:N), and isotopic signatures (d13C and d15C) from soil samples collected at upper 50 cm and more than 50 cm layers in deltaic and estuarine mangrove forests from the Amazon Delta.

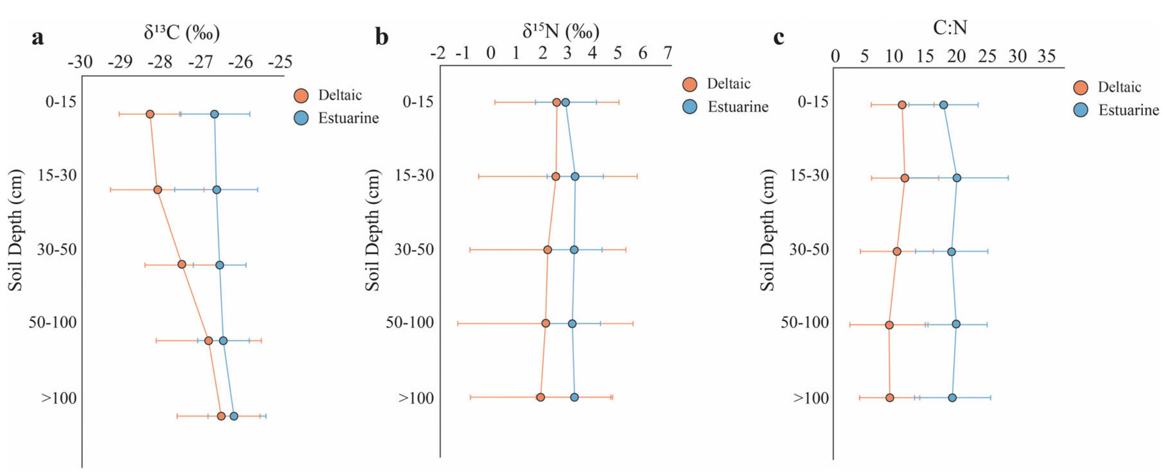

Fig. 2. Soil depth profile of (a) $\delta^{13}C$, (b) $\delta^{15}N$, and (c) C:N ratio from deltaic and estuarine mangrove forests in the Amazon Delta.

primarily derived from autochthonous sources (deltaic = 54.9 % and estuarine = 61.5 %; Table 1). In deltaic mangroves, riverine particulate organic carbon was the main allochthonous source (23.8 ± 19.5%), whereas in estuarine mangroves, it contributed only 6.9 ± 7.1%. Conversely, marine particulate organic carbon accounted for 31.6 ± 10.0 % in estuarine mangroves and 21.3 ± 17.3 in deltaic ones. These results support our hypothesis of the relevance of allochthonous organic sources to mangroves in the Amazon delta; however, it underscores that mangrove organic matter is also relevant to deeper soil carbon stocks. In both deltaic and estuarine mangrove forests, the organic matter in the upper 50 cm of soil was predominantly influenced by mangrove roots (44.6 ± 11.9 % and 41.8 ± 12.0%; respectively). Riverine organic matter was also important to deltaic forests (37.4 ± 2.9 %), when compared to estuarine mangroves (6.9 ± 7.1 %). Marine organic matter inputs to marine and estuarine mangrove forests ranged from 21.3 to 31.6 %. Mangrove leaves were the third end member in both deltaic (21.3 ± 16.7 %) and estuarine (24.2 ± 11.3 %) mangrove forests. In deeper soil layers (>50 cm), mangrove root-derived organic matter was dominant in deltaic (71.0 ± 11.2 %) and estuarine (50.9 ± 12.7 %) mangrove forests.

Converting the variable source contribution to soil carbon stocks in deltaic mangroves, the autochthonous inputs accounted for 298 ± 20 Mg C ha^{-1} (54.9 ± 37.6 %) and allochthonous inputs accounted for 244 ± 19.7 Mg C ha^{-1} (45.1 ± 36.8 %). In estuarine mangroves the autochthonous inputs accounted for 568 ± 20.9 Mg C ha^{-1} (61.5 ± 24.9 %) and allochthonous inputs accounted for 356 ± 14.4 Mg C ha^{-1} (38.5 ± 17.1 %) (Table 1).

Table 1
Contribution (%) of autochthonous (mangrove leaves and roots) and allochthonous (marine and riverine input) to soil organic matter (SOC; Mg C ha^{-1}) during the rainy season in deltaic and estuarine mangrove forests in the Amazon Delta. Contribution to SOC was estimated based on published values for the same sampling sited (Bernardino et al., 2024).

Source	Contribution (%)		Contribution to SOC (Mg C ha^{-1})	
	Deltaic	Estuarine	Deltaic	Estuarine
Overall				
Mangrove leaves	21.3 ± 16.7	24.2 ± 11.3	115.43 ± 8.93	223.50 ± 9.51
Mangrove roots	33.6 ± 20.9	37.3 ± 13.6	182.09 ± 11.17	344.49 ± 11.44
Marine input	21.3 ± 17.3	31.6 ± 10.0	115.43 ± 9.25	291.84 ± 8.41
Riverine input	23.8 ± 19.5	6.9 ± 7.1	128.98 ± 10.42	63.73 ± 5.97
Autochthonous	**54.9 ± 37.6**	**61.5 ± 24.9**	**297.52 ± 20.10**	**567.99 ± 20.95**
Allochthonous	**45.1 ± 36.8**	**38.5 ± 17.1**	**244.41 ± 19.67**	**355.57 ± 14.39**
0–50 cm				
Mangrove leaves	17.6 ± 12.1	24.2 ± 12.5	94.34 ± 8.12	219.20 ± 13.18
Mangrove roots	44.6 ± 11.9	41.8 ± 12.0	239.07 ± 7.99	378.62 ± 12.65
Marine input	0.4 ± 0.6	28.8 ± 1.9	2.14 ± 0.40	260.87 ± 2.00
Riverine input	37.4 ± 2.9	5.2 ± 3.5	200.48 ± 1.95	47.10 ± 3.69
Autochthonous	**62.2 ± 24.0**	**66.0 ± 24.5**	**333.41 ± 16.10**	**597.83 ± 25.83**
Allochthonous	**37.8 ± 3.5**	**34.0 ± 5.4**	**202.62 ± 2.35**	**307.97 ± 5.69**
>50 cm				
Mangrove leaves	7.6 ± 9.8	14.0 ± 12.2	41.55 ± 8.65	130.56 ± 16.45
Mangrove roots	71.0 ± 11.2	50.9 ± 12.7	388.21 ± 9.89	474.67 ± 17.13
Marine input	19.6 ± 3.0	31.1 ± 2.2	107.17 ± 2.65	290.02 ± 2.97
Riverine input	1.8 ± 2.9	4.0 ± 3.1	9.84 ± 2.56	37.30 ± 4.18
Autochthonous	**78.6 ± 21.0**	**64.9 ± 24.9**	**429.76 ± 18.54**	**605.22 ± 33.58**
Allochthonous	**21.4 ± 5.9**	**35.1 ± 5.3**	**117.01 ± 5.21**	**327.32 ± 7.15**

Discussion

This work quantified the contribution of mangrove-derived (autochthonous) and riverine- or marine-derived (allochthonous) organic sources to mangroves in the Brazilian Amazon coast, revealing a greater contribution of allochthonous sources in mangroves of the Amazon River delta. Estuarine mangroves to the east of the Amazon River are primarily sustained by autochthonous organic matter, revealing a marked regional difference in these sources in similar way to other major coastal areas where a range of geomorphic settings are present (Kusumaningtyas et al., 2019; Arnaud et al., 2025). Our results have implications for understanding regional variability in soil mangrove carbon stability, and are consistent with a stronger contribution of autochthonous sources in estuarine mangroves (Zhang et al., 2024). By providing a more spatially resolved dataset from the Amazon coast, our results support an informed spatial planning of current national policy targets for mangrove restoration, which aims to restore over 17,000 ha of mangroves in the country. By using a regional proportion of autochthonous carbon sources to mangroves in the Amazon coast, it is possible to better estimate cost-benefit analysis of the additional carbon that can be obtained in restoration projects in Northern Brazil (Lovelock et al., 2022). These findings emphasize the critical importance of region-specific data for improving accuracy of blue carbon assessments and refining carbon credit models that often rely on spatially aggregated or generalized datasets.

On a global scale, our results align with datasets where autochthonous production has been identified as the dominant contributor to soil organic carbon in estuarine mangrove forests (Qin et al., 2024; Zhang et al., 2024). However, estuarine mangroves in Oceania, East Asia, South Asia, Africa, and North America showed a lower contribution from autochthonous organic carbon (14.7–48.7%) than marine (17.3–41.8%) and terrestrial sources (25.8–43.6%) (Zhang et al., 2024). The lower allochthonous contribution in mangroves has been related to either forest age (Suello et al., 2022), or to dissolution with mineral particles in deltaic regions (Rovai et al., 2018; Bernardino et al., 2024a; Arnaud et al., 2025). The predominance of autochthonous carbon in estuarine mangroves of the Amazon coast aligns with predictions of a higher input of plant biomass in estuarine settings, and supports that the coastal environmental setting has a large influence in the origin of carbon being buried (Rovai et al., 2018).

By constraining the mean proportions of autochthonous sources, our mixing model indicates that mangrove-derived organic matter contributed on average to 297 ± 20.1 Mg C ha^{-1} and 568 ± 21 Mg C ha^{-1} in deltaic and estuarine forests, respectively, while allochthonous sources accounted for 244 ± 20 Mg C ha^{-1} and 356 ± 14 Mg C ha^{-1}, respectively. Considering the mean total ecosystem carbon stock (TECS) of estuarine forests (486 ± 21 Mg C ha^{-1}; Bernardino et al., 2024a), this suggests a greater benefit per area (>30%) of mangrove restoration in estuarine settings given the additional input of plant carbon. Recognizing these distinctions can add value to Brazil's target for mangrove restoration and the development of effective management plans that ensure the permanence and integrity of carbon stocks (UNFCC, 1998).

Salinity is a key driver shaping the biogeochemical processes that influence SOC content and stability. Elevated salinity generally slows soil organic matter decomposition, promoting SOC accumulation (Rath and Rousk, 2015). Salinity also modulates iron (Fe) geochemistry, which is known to play a crucial role in SOC stabilization in mangrove soils. Although Fe phases were not directly analyzed in this study, previous research in Amazon mangroves has shown that reactive Fe oxides can form organo-mineral complexes that protect organic carbon from microbial degradation (Ruiz et al., 2024). Therefore, the greater SOC accumulation observed under more saline conditions may be partly associated with Fe-mediated mechanisms that enhance carbon protection through adsorption and complexation reactions. Similarly, soil pH and redox potential (Eh) are key regulators of organic matter transformation in mangrove soils, and these processes also favor the persistence of soil carbon in estuarine settings (Wang et al., 2019).

Isotopic signatures ($\delta^{13}C$ and $\delta^{15}N$) and C:N ratios can vary among mangrove species and between different plant parts. For instance, comparisons between leaves and roots of *Laguncularia racemosa* reveal differences of up to 3 ‰ in $\delta^{13}C$ and 30 units in the C:N ratio (Vane et al., 2013). These ranges are important when assessing the relative contributions of above- and belowground biomass to litter inputs in mangrove soils (Adame et al., 2024). Furthermore, isotopic signatures and the C:N ratio undergo substantial changes during decomposition. In terrestrial soils, organic matter can become enriched in ^{13}C by up to 4 ‰ compared to its original plant material (Lichtfouse et al., 1995), although similar studies for mangrove soil are scarce. Moreover, we observed higher $\delta^{13}C$ isotopic signatures in deeper soil layers, along with a decrease in organic carbon content, which suggest microbially-derived organic matter at depth. Microbial communities tend to preferentially respire more depleted in ^{13}C molecules, leaving behind organic matter enriched in ^{13}C that are associated with biomass production and metabolic products (Gleixner et al., 1993). These depleted ^{13}C sources likely originate from mangrove litter and terrestrial C3 plants (typically −24 to −34 ‰; Kelleway et al., 2018). Our results suggest slight differences in nitrogen sources between estuarine and deltaic mangroves, which are likely related to dilution of plant organic sources by large mineral inputs in Amazon delta mangroves and higher proportion of lignin-rich material in estuarine settings (Kaal et al., 2022). The lignin-rich material in estuarine mangroves is more resistant to microbial decomposition in the short-term (Weiss et al., 2016). This is the first report of the contrasting dominance of C and N sources in deltaic and estuarine mangroves of the Amazon coast, which support how hydrodynamic processes related to coastal environmental settings have an influence on the deposition and preservation of mangrove carbon sources (Kusumaningtyas et al., 2019).

Our study provides the first in situ-based quantification of organic carbon sources along the Amazon coast and their contribution to belowground SOC, providing key insights for mangrove conservation and restoration projects. Our findings reinforce the importance of mangrove forests in storing vast carbon stocks and reveal a predominant contribution of autochthonous organic matter to mangrove soils (>54%), contrasting with previous studies that reported higher allochthonous contribution (51–80%; Suello et al., 2022; Zhang et al., 2024; Qin et al., 2024). We also found that the proportion of allochthonous inputs varies significantly with environmental settings (e.g., distance from hinterland and ocean), soil depth, and rates of allochthonous input and accretion rate, all of which are controlled by local-scale factors (Jennerjahn, 2021). Nevertheless, our results also highlight the increased importance of allochthonous organic matter in the Amazon delta, supporting the strong links of these coastal wetlands to the river dynamics (Bernardino et al., 2024a). Since deltaic mangroves exhibit a greater proportion of riverine-derived organic matter (nearly 25%), they may be particularly vulnerable to anthropogenic influences on the freshwater outflow of the Amazon River Basin, upriver human influences such as damming of Amazonian tributaries could significantly impact their long-term carbon sequestration potential (Beveridge et al., 2024).

We found that allochthonous sources are more important for building carbon stocks in the 0−50 cm layer (range 34–38%) compared to deeper layers (range 21–35%). These values emphasize the importance of recognizing both autochthonous and allochthonous contributions when evaluating mangrove carbon budgets, particularly for applications in carbon accounting and crediting mechanisms. Although both organic matter sources contribute to carbon accumulation and storage, their inclusion in carbon market assessments remain debated. Current frameworks differ on whether total soil organic carbon should be considered or only the portion derived from in situ (autochthonous) fixation (Houston et al., 2024). This inconsistency may lead to overestimating mitigation benefits in regions with high allochthonous inputs, such as deltaic mangroves influenced by large river systems. Our results support that accurate source attribution is important for ensuring that blue carbon credits represent genuine and verifiable greenhouse gas reductions (Michaelowa et al., 2019; Wang et al., 2024). Conversely, excluding allochthonous carbon may undervalue the climate regulation potential of these areas, since this allochthonous carbon often contains greater proportions of refractory carbon, with longer residence time due to its chemical composition and resistance to remineralization (e.g., association with metals and fine-grained minerals) (Ruiz et al., 2024). Therefore, we do not interpret allochthonous carbon as "additional" in the strict sense of carbon market definitions, but rather as an integral component of the natural carbon sequestration processes maintained by mangrove ecosystems. Protecting these ecosystems ensures the retention and stabilization of both locally produced and externally supplied organic matter, contributing to long-term carbon permanence.

Our assessment, by applying a Bayesian mixing model based on in situ stable carbon isotope data, provides the first robust quantification of the relative contributions of autochthonous and allochthonous carbon in mangrove forests of the Amazon River delta. This represents a significant methodological advance and provides a more scientifically rigorous basis for evaluating carbon partitioning and storage potential in mangrove restoration projects in Brazil. Beyond its regional significance, within one of the world's largest and most dynamic mangrove provinces, this framework contributes globally to blue carbon science by demonstrating how isotopic-based Bayesian models can refine estimates of carbon origin. These findings highlight the importance of incorporating locally derived data into carbon accounting frameworks. While the preservation of the standing vegetation is essential to ensure the long-term storage of autochthonous carbon in above- and belowground biomass, protecting the geomorphological and hydrological conditions that facilitate allochthonous carbon deposition may help maintain soil organic carbon stocks. Therefore, the restoration of degraded mangroves and the establishment of buffer zones through adaptative management strategies may help mitigate disturbances in the long term. Incorporating mangrove ecosystems into carbon credit markets, with sequestration potential quantified using locally calibrated models that consider organic matter composition and carbon stability, may provide financial incentives for conservation and reforestation initiatives. Future research should explore the influence of extreme weather events on carbon fluxes, and predictive modeling of climate change effects to mangrove carbon burial and preservation. These aspects are crucial for integrating mangrove conservation into international frameworks, enhancing our understanding of the economic value of mangrove carbon stocks, and strengthening blue carbon policies.

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Declaration of interest statement

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 data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2026.02.007.

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