



## How do land use changes affect carbon and nitrogen stocks in Amazon soils under different climatic types?

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### ABSTRACT

The conversion of forests to pastures and croplands has affected soil carbon (C) and nitrogen (N) stocks, particularly in the Amazon. This study aimed to evaluate how different land uses influence soil C and N stocks in two edaphoclimatic contexts in the Amazon Deforestation Arc, Pará, Brazil: São Miguel do Guamá (Af) and Paragominas (Aw). Soil samples were collected from deep soil profiles (0–100 cm) at eight depth intervals across four land use systems (forest, agriculture, intensive pasture, and nominal pasture). In the Af site, intensive pasture presented the highest C (42.36 and 80.21 mg ha<sup>-1</sup>) and N stocks (3.23 and 5.31 mg ha<sup>-1</sup>) at 0–30 and 0–100 cm, respectively. Differences among land uses were observed mainly in the 0–100 cm layer, while variations in the 0–30 cm layer were not statistically significant. In the Aw site, C stocks ranged from 63.86 to 134.48 mg ha<sup>-1</sup> and N stocks from 5.17 to 10.79 mg ha<sup>-1</sup>, with no differences among land uses, a pattern consistent with the buffering capacity typically associated with clay-rich soils. The  $\delta^{13}\text{C}$  analysis indicated replacement of C<sub>3</sub> carbon by C<sub>4</sub> carbon down to 60 cm in the Af site, whereas in the Aw site this substitution was limited to the 0–10 cm layer. The  $\delta^{15}\text{N}$  patterns were consistent with more intense N cycling and organic matter processing in managed systems relative to forest. These results highlight the importance of sustainable land management adapted to edaphoclimatic conditions for conserving C and N stocks in Amazon soils.

### 1. Introduction

Soil plays a crucial role in the global carbon (C) cycle, acting as one of the largest terrestrial reservoirs, with approximately 2500 gigatonnes (Gt) of C stored, which is equivalent to more than three times the C present in the atmosphere and about four times the terrestrial plant biomass (Lal et al., 2021; Minasny et al., 2017). As concerns over climate change intensify, increasing soil C stocks has emerged as a key strategy to mitigate greenhouse gas (GHG) emissions. Global initiatives such as 4

per 1000 suggest that an annual increase of just 0.4% in soil organic C (SOC) could offset a substantial portion of global CO<sub>2</sub> emissions, reinforcing the role of soil organic matter (SOM) restoration in climate regulation (Minasny et al., 2017; Wiesmeier et al., 2020).

In the Amazon biome, the conversion of native forests to agricultural areas and pastures can strongly alter biogeochemical cycles, reducing soil C and nitrogen (N) stocks and contributing to increased GHG emissions (Damian et al., 2021). Global assessments indicate that replacing tropical forests with other land uses may reduce 20–50% of the

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original soil C stock within the first decades after deforestation, depending on crop type and management practices (Lorenz et al., 2019). However, regional studies of Brazilian ecosystems report lower average losses (9–14%), underscoring the strong influence of soil texture, climate, and land management on soil C responses. Under unfavorable edaphoclimatic conditions, inadequate management can further accelerate soil degradation and weaken soil functioning as a carbon sink (Zinn et al., 2018; Medeiros et al., 2025; Lal et al., 2021; Gava et al., 2022).

On the other hand, sustainable soil management strategies can reduce C and N losses and, in some cases, increase soil stocks. Integrated crop–livestock systems and practices such as pasture subdivision, grazing pressure control, and minimum soil disturbance enhance nutrient recycling and have shown significant potential to restore soil C and N stocks, approaching or even surpassing those observed under native vegetation (Cardoso et al., 2020; Freitas et al., 2022). However, the effectiveness of these strategies depends strongly on edaphoclimatic conditions, which directly influence organic matter decomposition, nutrient dynamics, and soil C stability (Vermeulen et al., 2019; Padbhushan et al., 2022).

The Brazilian Amazon includes distinct tropical climate subtypes (Af, Am, and Aw) that influence soil processes (Alvares et al., 2013). These subtypes differ mainly in rainfall seasonality, which can amplify or attenuate the effects of land use change on soil C and N stocks, resulting in spatially heterogeneous responses even within the same macro-region (Nascimento et al., 2022). Despite extensive research on soil C and N dynamics under land use change in the Amazon, most studies have focused on surface soil layers and have often treated the region as climatically homogeneous. Consequently, integrative assessments that jointly consider deep soil profiles (0–100 cm), edaphoclimatic context, and isotopic evidence ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) to infer land use legacy and associated nutrient cycling processes remain limited.

This study addresses these gaps by combining deep soil (0–100 cm) C and N stocks with isotopic tracers to describe how land use systems function within their own edaphoclimatic context, rather than assuming homogeneous soil responses across the Amazon region. By integrating soil stocks, texture, and isotopic signatures, this approach provides a more integrative interpretation of C and N dynamics across contrasting land use systems and climatic settings.

In light of these gaps, we hypothesize that soil C and N stocks, as well as the sources of soil C, vary across land use systems and edaphoclimatic contexts, reflecting differences in soil texture, vegetation cover, and land use history. Thus, this study aimed to: (i) evaluate soil C and N stocks under different land use systems across soil profiles from 0 to 100 cm within two climatic subtypes (Af and Aw) of the Brazilian Amazon; (ii) describe soil C and N patterns across different edaphoclimatic settings, considering soil texture and land use history; and (iii) quantify the relative contribution of  $\text{C}_3$  and  $\text{C}_4$  derived organic matter using  $\delta^{13}\text{C}$ , complemented by  $\delta^{15}\text{N}$  analyses to infer land use legacy and soil nitrogen dynamics.

## 2. Materials and methods

### 2.1. Experimental sites and characterization of the study sites

This study was conducted in September 2021 in two municipalities in the state of Pará, Brazil: São Miguel do Guamá (1°40'27"S, 47°46'16"W) and Paragominas (2°59'42"S, 47°21'10"W), both located in the Amazon Deforestation Arc region (Fig. 1a, b, respectively). According to the Köppen classification, São Miguel do Guamá has a humid tropical climate (Af), with an average annual rainfall of 2538 mm and an average temperature of 26.9 °C (1992–2022). Paragominas has a tropical climate with a dry season (Aw), with a dry period from June to November, average annual rainfall of 1837 mm, and average temperature of 26.9 °C in the same period (Fig. 2) (Alvares et al., 2013; Stackhouse et al., 2015; Andrade et al., 2017; NASA POWER, 2022).

The study areas are located on Latossolo Amarelo, according to the Brazilian Soil Classification System (Santos et al., 2018), corresponding to Oxisols in the USDA Soil Taxonomy (Soil Survey Staff, 2022). In the Af site (São Miguel do Guamá), the soils have a sandy or sandy loam texture, while in the Aw site (Paragominas) clayey soils predominate. The soil chemical and textural characteristics of the 0–20 cm layer are presented in Table 1.

### 2.2. Characterization of treatments

Four land use systems were evaluated at each study site: forest, agriculture, intensive pasture, and nominal pasture (Fig. 1; Table 2). In each land use system, four soil trenches (1.0 × 1.0 × 1.0 m) were opened at different locations within the same management area, serving as replicates, with an average spacing of approximately 125 m ( $\pm 25$  m) between trenches. This spacing was adopted as a criterion to ensure spatial independence among replicates. The native forest was used as a reference, corresponding to areas that had been fallow for approximately 30 years after selective logging, with a homogeneous canopy and tree heights ranging from 15 to 25 m.

In the Af site, the agricultural area corresponded to a commercial oil palm (*Elaeis guineensis* Jacq.) plantation established around 2014 on land previously used as pasture, with NPK (12–12–17) fertilization applied three times per year. The intensive pasture consisted of *Urochloa humidicola* cv. Quicuío, managed intensively between 2015 and 2021, with annual applications of 100 kg ha<sup>-1</sup> monoammonium phosphate (MAP) and 100 kg ha<sup>-1</sup> urea, 1.5 t ha<sup>-1</sup> dolomitic limestone, and chemical weed control.

The nominal pasture consisted of the same cultivar (*U. humidicola* cv. Quicuío), maintained productive only through weed control, without fertilizer application, irrigation, or the use of improved cultivars. It was characterized as a managed area without technological intensification, following the criteria of Intergovernmental Panel on Climate Change (IPCC) (2006) and De Oliveira et al. (2022).

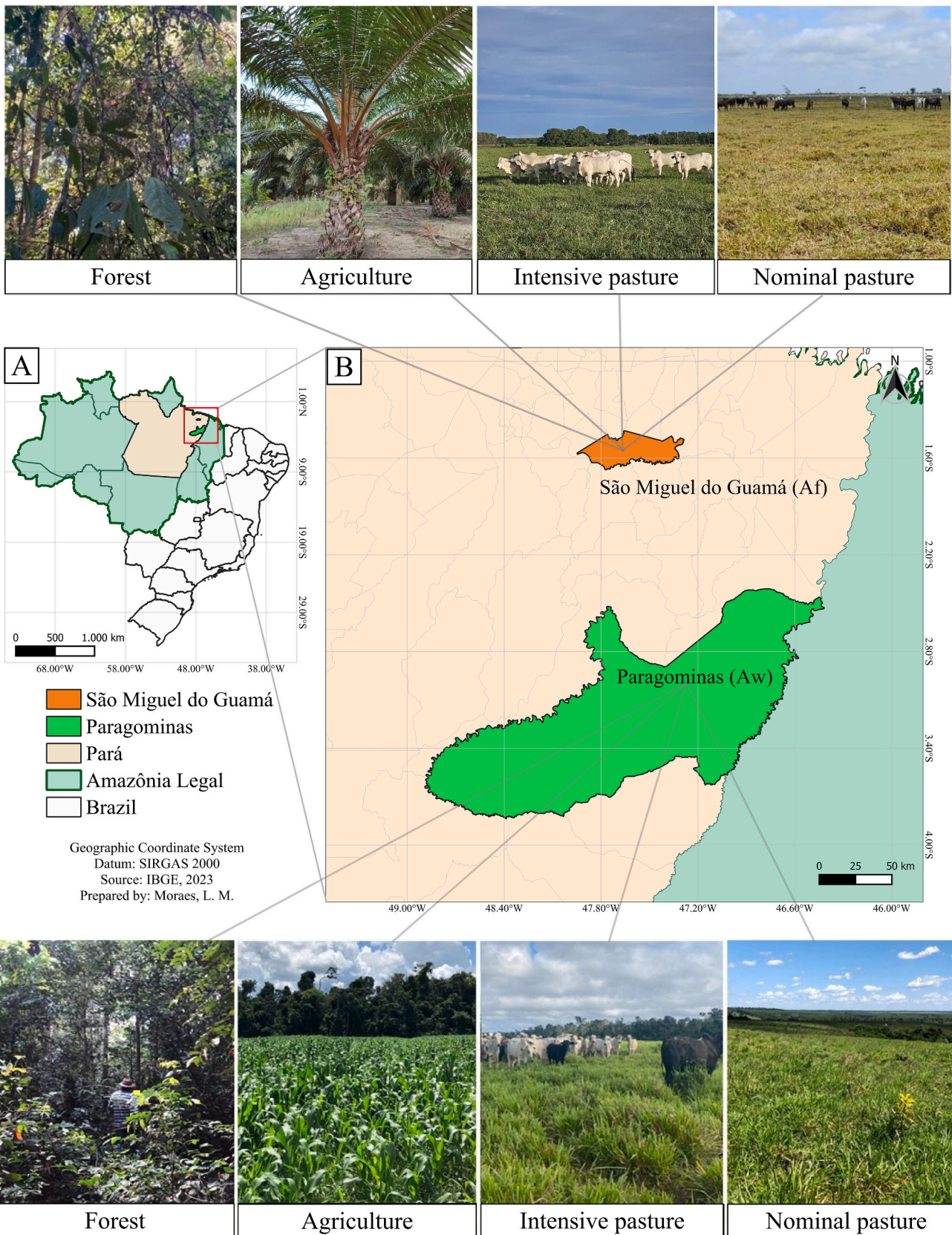
In the Aw site, the agricultural area corresponded to an integrated crop livestock (ICL) system under no tillage practices since 2016. Annual crops included soybean (*Glycine max*), maize (*Zea mays*), and forage grasses. Soybean and maize received annual applications of NPK fertilizer, lime, and KCl, including fertilization of the second-season maize in 2021. During the forage phases, the pasture benefited indirectly from nutrient inputs derived from the crop phases.

The nominal pasture included areas with *Urochloa humidicola* cv. Quicuío and *Urochloa brizantha* cv. Xaraés, without fertilization since 2017. Productivity was maintained through weed control, maintenance of forage cover, and adjustment of stocking rate according to the soil's carrying capacity, without technological intensification.

### 2.3. Soil sampling

Soil samples were collected at eight depths of 0–5, 5–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm from two opposite sides of each trench (1.0 m<sup>3</sup>). Undisturbed samples were collected from both sides of the trench using stainless-steel rings of known volume (100.6 cm<sup>3</sup>), positioned at the midpoint of each depth interval, following the method described by Sisti et al. (2004). After oven-drying at 105 °C for 72 h, bulk density was calculated separately for each ring, and the mean value of the two sides was used as the representative bulk density for that depth.

Disturbed soil samples were collected at the same depths from both sides of each trench and combined before sieving to form a single composite sample per depth per trench. The composite samples were air-dried, gently macerated, and sieved through a 2-mm mesh to remove coarse plant residues and fragments prior to laboratory analyses. After sieving, samples were manually homogenized until a visually uniform mixture was obtained. These samples were used to determine total C and N concentrations and the natural isotopic abundance of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ .



**Fig. 1.** Location of the study area (A) and the municipalities of São Miguel do Guamá (Af site) and Paragominas (Aw site), Pará, Brazil (B). Land use systems evaluated include forest, agriculture, intensive pasture, and nominal pasture under two climatic subtypes: Af (humid tropical) and Aw (tropical with a dry season).

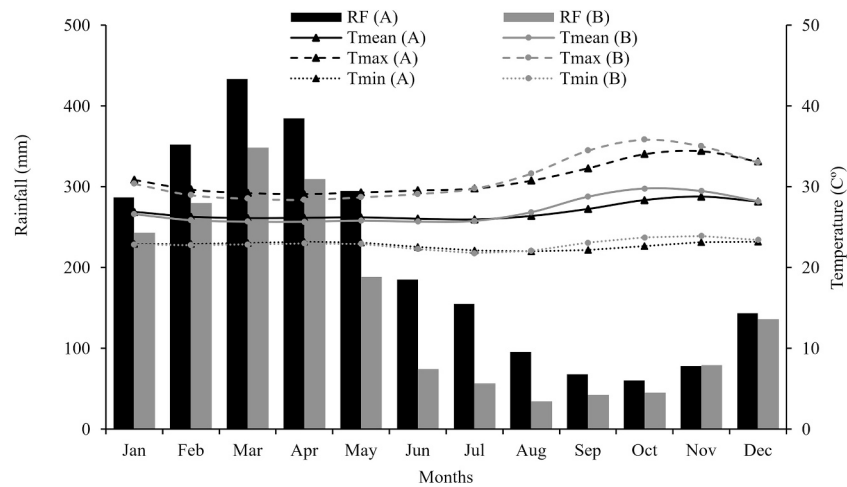


Fig. 2. Monthly meteorological data for São Miguel do Guamá (A) and Paragominas (B), Pará, Brazil, including total precipitation (mm) and mean, maximum, and minimum air temperatures ( $^{\circ}\text{C}$ ). Values represent monthly averages for the 1992–2022 period.

Table 1

Chemical and physical characterization (0–20 cm) of the study sites under different land use systems in Af site (São Miguel do Guamá) and Aw site (Paragominas), Pará, Brazil.

Land Use	pH	OM	P	K	Ca	Mg	Al	H + Al	S.B.	Sand	Silt	Clay
	$\text{H}_2\text{O}$	$\text{g kg}^{-1}$	$\text{mg dm}^{-3}$		$\text{cmol}_c \text{ dm}^{-3}$					$\text{g kg}^{-1}$		
<b>Site I - São Miguel do Guamá (Af)</b>												
Forest	4.5	16.9	4.2	22.7	1.4	0.2	0.3	2.2	1.6	765.5	79.5	155.0
Agriculture	4.9	16.6	12.1	19.9	0.7	0.2	0.3	1.9	1.0	788.3	36.8	175.0
Intensive pasture	5.2	15.1	5.9	21.9	1.1	0.3	0.2	1.6	1.5	761.3	33.8	205.0
Nominal pasture	4.9	14.0	6.9	14.9	0.3	0.1	0.5	1.6	0.4	712.8	77.3	210.0
<b>Site II - Paragominas (Aw)</b>												
Forest	4.3	25.1	5.4	28.5	0.9	0.5	1.3	3.4	1.5	44.3	140.8	815.0
Agriculture	6.2	25.7	64.8	65.7	4.4	1.2	0.4	2.2	5.8	43.0	187.0	770.0
Intensive pasture	5.9	25.7	5.6	79.3	3.4	0.6	0.1	1.9	4.1	27.8	117.3	855.0
Nominal pasture	5.4	22.9	8.0	28.5	2.6	1.1	0.2	2.8	3.7	34.0	126.0	840.0

OM - Organic Matter, P - Phosphorus, K - Potassium, Ca - Calcium, Mg - Magnesium,  $\text{Al}^{3+}$  - Exchangeable Aluminum, H + Al - Potential Acidity, and SB - Sum of Exchangeable Bases. OM was determined using the Walkley-Black method, H + Al by extraction with 1 N calcium acetate at pH 7.0, P and K using the Mehlich 1 extractor.

Additionally, in the surface layer (0–20 cm), composite samples were collected using a Dutch auger for chemical and physical soil analyses, as described by Teixeira et al. (2017). Litter and root samples were also collected for isotopic analyses used to estimate the contribution of  $\text{C}_3$  and  $\text{C}_4$  plants to soil organic carbon (Santos et al., 2019).

#### 2.4. C and N concentration and isotopic analyses of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

Isotopic analyses were performed at the Stable Isotope Center of UNESP in Botucatu-SP, Brazil. Before analysis, the samples were dried in an oven at  $50^{\circ}\text{C}$  for 48 h and homogenized to between 60 and 100 mesh using a cryogenic mill (Geno/Grinder 2010 – SPEX SamplePrep, USA). An aliquot of 30.0–35.0 mg was weighed into  $5.0 \times 8.0$  mm tin capsules using a balance with a 0.1 mg resolution. Drying and homogenization ensured representative dry mass aliquots. No acid pretreatment was performed prior to EA/IRMS analysis.

Total carbon and nitrogen concentrations (C and N) and isotopic analyses ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) were determined simultaneously using a continuous-flow isotope ratio mass spectrometry (CF-IRMS) system. The CF-IRMS, composed of an elemental analyzer (Flash HT) with a thermal conductivity detector (TCD) coupled to an IRMS (Delta V Advantage) via a gas interface (ConFlo IV), was manufactured by Thermo Scientific, Germany.

During the analytical sequence, an empty capsule and a working standard were inserted at the beginning of each run and after every

group of 10 samples to monitor instrumental drift and potential memory effects. Instrument performance was continuously verified through the analysis of certified reference materials and a laboratory soil standard. Samples producing mass spectra with maximum amplitudes below 300 mV were reanalyzed with increased sample mass (up to 40 mg) to ensure adequate signal intensity and analytical reliability.

The standard uncertainty estimated for C and N was  $\pm 0.20\%$ . The C/N ratio was calculated as the ratio between C and N concentrations in each sample. The C and N concentration values were calibrated using a soil standard (Peat, PN BRE0011294, Thermo Scientific, Germany). The  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values were expressed in per mil (‰) relative to the international standard ratios Vienna-Pee Dee Belemnite (VPDB) for  $\delta^{13}\text{C}$  and Air for  $\delta^{15}\text{N}$  (Coplen, 2011). The  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  results were normalized from certified reference standards NBS-22, USGS61, USGS63 and IAEA-N1 (Paul et al., 2007; IAEA – International Atomic Energy Agency, 2009; Schimmelmann et al., 2016). Analytical precision was assessed based on repeated measurements of standards throughout the runs, with standard uncertainties estimated at  $\pm 0.15\%$  for  $\delta^{13}\text{C}$  and  $\pm 0.20\%$  for  $\delta^{15}\text{N}$ .

#### 2.5. Soil C and N stock calculations

Soil C and N stocks ( $\text{Mg ha}^{-1}$ ) were calculated, accounting for variations in bulk density across the soil profile to avoid overestimation caused by soil compaction. The methodology followed the equivalent

**Table 2**

Characteristics of the land use systems in Af site (São Miguel do Guamá) and Aw site (Paragominas), Pará, Brazil.

Land use	Site I Af (São Miguel do Guamá)	Site II Aw (Paragominas)
Forest	Secondary forest under natural regeneration for ~30 years after selective logging. Characterized by a homogeneous canopy with tree heights from 15 to 25 m.	Old growth secondary forest left to regenerate for ~30 years after logging disturbance. The canopy is relatively uniform, with trees typically ranging from 15 to 25 m in height.
Agriculture	Oil palm ( <i>Elaeis guineensis</i> Jacq.) cultivated since 2014 on land previously used as pasture, with 9 m spacing between plants and 7.8 m between rows (~143 plants ha <sup>-1</sup> ). The system receives regular fertilization with NPK (12–12–17) applied three times per year, ensuring adequate nutrient supply throughout the production cycle.	Integrated crop livestock (ICL) system under no-tillage since 2016. Annual crops include soybean, maize, and forage species. Soybean and maize receive NPK fertilization, liming, and KCl applications every year, including fertilization of the second-season maize in 2021. During forage phases, pastures benefit indirectly from nutrient inputs derived from the crop phases.
Intensive pasture	<i>Urochloa humidicola</i> cv. Quicúio, managed intensively between 2015 and 2021. Periodic applications of 100 kg ha <sup>-1</sup> MAP, 100 kg ha <sup>-1</sup> urea, 1.5 t ha <sup>-1</sup> dolomitic lime, and chemical weed control.	<i>Megathyrus maximus</i> cv. Mombaça, managed with fertilization, liming, and poultry litter between 2018 and 2021, with maintenance of forage cover and grazing management compatible with the system's carrying capacity.
Nominal pasture <sup>1</sup>	<i>U. humidicola</i> cv. Quicúio, maintained productive only through weed control, without fertilization, irrigation, or technological intensification.	<i>U. humidicola</i> cv. Quicúio and <i>U. brizantha</i> cv. Xaraés, without fertilization since 2017. Productivity maintained through weed control, maintenance of forage cover, and adjustment of stocking rate to the soil's carrying capacity, without technological intensification.

<sup>1</sup> Nominal pasture: sustainably managed area without signs of degradation, but also without significant technological improvements (Intergovernmental Panel on Climate Change (IPCC), 2006; De Oliveira et al., 2022).

soil mass (ESM) approach proposed by Vallis (1972), adapted by Sisti et al. (2004) and refined by Lee et al. (2009). To ensure standardized comparisons among different land use systems, the correction was applied to the last layer of each target depth (20–30 cm for the 0–30 cm interval and 80–100 cm for the 0–100 cm interval), using as reference the soil mass of the land use system with the lowest bulk density at each site and target depth.

The reference system was defined separately for each study site and depth interval based on the lowest bulk density. In the Af site, the oil palm system was used as the reference for the 0–30 cm interval, whereas the native forest was used for the 0–100 cm interval. On the Aw site, the native forest was used as the reference for the 0–30 cm interval, while the nominal pasture was used for the 0–100 cm interval. This criterion was adopted to minimize biases associated with soil compaction and ensure consistent comparisons among land use systems.

The final C and N stock calculations were performed for two depth intervals: 0–30 cm (surface layer) and 0–100 cm (total soil profile). The corrected C or N stock was calculated according to Eq. 1:

$$E_{corrected,f} = \sum_{i=1}^{n-1} E_i + \left[ M_f - \left( \sum_{i=1}^{n-1} M_i - \sum_{i=1}^{n-1} M_{ref} \right) \right] \times C_f \times 10^{-3} \quad (1)$$

where:  $E_{corrected,f}$  is the corrected C or N stock for the target depth  $f$  (Mg ha<sup>-1</sup>);  $\sum_{i=1}^{n-1} E_i$  represents the sum of C or N concentrations in the upper layers (g kg<sup>-1</sup>);  $M_f$  is the soil mass of the target layer (20–30 cm or

80–100 cm; Mg ha<sup>-1</sup>);  $\sum_{i=1}^{n-1} M_i$  represents the sum of soil mass in the upper layers (Mg ha<sup>-1</sup>);  $\sum_{i=1}^{n-1} M_{ref}$  is the sum of soil mass at the equivalent depth in the reference system, defined for each site and depth interval as the land use presenting the lowest bulk density (Mg ha<sup>-1</sup>);  $C_f$  is the C or N concentration (g kg<sup>-1</sup>) in the target layer.

After correction, the total soil C or N stock (Mg ha<sup>-1</sup>) was obtained by adding the corrected stock ( $E_{corrected,f}$ ) to the sum of the uncorrected layers, as shown in Eq. 2:

$$E_{total,f} = \sum_{i=1}^{n-1} E_i + E_{corrected,f} \quad (2)$$

## 2.6. Proportion of organic carbon derived from C<sub>3</sub> and C<sub>4</sub> plants

The determination of the organic carbon proportions derived from C<sub>3</sub> and C<sub>4</sub> plants in the different land use systems was performed based on soil  $\delta^{13}C$  values and total carbon content (g kg<sup>-1</sup>) at each sampled depth, following the methodology proposed by Cerri et al. (1985). The carbon contents of C<sub>3</sub> and C<sub>4</sub> origin (kg m<sup>-3</sup>) were obtained by multiplying the total carbon concentration (g kg<sup>-1</sup>) by the soil bulk density (kg dm<sup>-3</sup>) corresponding to each layer. The carbon fraction of C<sub>3</sub> origin was determined by Eq. 3:

$$\%C_{C3} = \frac{(\delta^{13}C_{soil} - \delta^{13}C_4)}{(\delta^{13}C_{C3} - \delta^{13}C_4)} \times 100 \quad (3)$$

where:  $\%C_{C3}$  represents the proportion of carbon derived from C<sub>3</sub> plants;  $\delta^{13}C_{soil}$  is the  $\delta^{13}C$  value of the soil sample from the treatment;  $\delta^{13}C_{C4}$  corresponds to the  $\delta^{13}C$  value of litter at the 0–5 cm depth or in roots at depths greater than 5 cm;  $\delta^{13}C_{C3}$  corresponds to the  $\delta^{13}C$  value of forest soil organic carbon at the same depth as the analyzed sample. The fraction of carbon derived from C<sub>4</sub> plants was calculated according to Eq. 4:

$$\%C_{C4} = 100 - \%C_{C3} \quad (4)$$

In this calculation, it was assumed that litter represents the dominant pathway of carbon input in the 0–5 cm soil layer, whereas root-derived carbon predominates at depths greater than 5 cm, as described by Santos et al. (2019). Accordingly,  $\delta^{13}C$  values measured in litter and roots were used as depth-specific C<sub>4</sub> reference values. For pasture systems, the  $\delta^{13}C$  values measured in litter and roots of each pasture type were used directly as C<sub>4</sub> endmembers. For agricultural systems, C<sub>4</sub> reference values were defined as the arithmetic mean of  $\delta^{13}C$  values measured in intensive and nominal pasture systems within the same climatic subtype.

In the Af site, where the oil palm plantation was established on former pasture land, the C<sub>4</sub> endmember represents residual carbon derived from the previous C<sub>4</sub>-dominated pasture phase rather than the current C<sub>3</sub> oil palm crop. The corresponding C<sub>4</sub> reference values were  $-14.67 \pm 3.00\%$  for litter and  $-14.56 \pm 2.21\%$  for roots. In the Aw site, the ICL system includes C<sub>4</sub> components (pasture and maize), and the C<sub>4</sub> endmember represents these inputs. The corresponding C<sub>4</sub> reference values were  $-13.33 \pm 0.02\%$  for litter and  $-12.48 \pm 0.35\%$  for roots.

The variability associated with the selection of these reference values was not propagated in the mixing calculations and is therefore acknowledged as an additional source of uncertainty in the estimates.

## 2.7. Statistical analysis

Statistical analyses were performed separately for each site (Af and Aw), without direct comparisons between climates. For each site, all response variables were analyzed using a one-way inferential design, considering the land use system as the only fixed factor. Soil variables (BD, C and N concentrations,  $\delta^{13}C$ ,  $\delta^{15}N$ , C/N ratio, and C derived from C<sub>3</sub> and C<sub>4</sub> plants) were analyzed at each soil depth, while soil C and N stocks (SCS and SNS) were evaluated for the 0–30 and 0–100 cm layers.

Normality of residuals and homogeneity of variances were assessed

using the Shapiro–Wilk test (*stats::shapiro.test*) and Levene's test (*car::leveneTest*). Given the small sample size ( $n = 4$ ), model assumptions were verified through residual diagnostics (*stats::plot.lm* and *car::qqPlot* functions), including the inspection of Q-Q plots and residuals versus fitted values plots, to ensure the inferential results.

When assumptions were satisfied, one-way ANOVA was applied (*stats::aov*), followed by Tukey's HSD test (*DescTools::PostHocTest*, *method = "hsd"*). For variables showing heteroscedasticity, Welch's ANOVA (*stats::oneway.test*, *var.equal = FALSE*) followed by the Games–Howell test (*rstatix::games\_howell\_test*) was applied (Field, 2015). Pairwise mean differences were reported with 95% confidence intervals (CI) to provide a comprehensive assessment of the precision and magnitude of land use effects across all studied variables. Effect sizes were additionally estimated using eta-squared ( $\eta^2$ ) (*DescTools::etaSquared*) to complement the  $p$ -value based interpretation for all variables. Values of  $\eta^2$  were interpreted as small ( $\geq 0.01$ ), moderate ( $\geq 0.06$ ), and large ( $\geq 0.14$ ) according to Cohen (1988). A significance level of 5% ( $\alpha = 0.05$ ) was adopted for all analyses. All analyses were conducted in R (v. 4.3.0; R Core Team).

### 3. Results

#### 3.1. Soil physical and chemical properties

Texture varied among land uses and soil depths, with a predominance of sand in the Af site and clay in the Aw site (Table 3). In the Af

**Table 3**  
Sand, silt, and clay contents ( $\text{g kg}^{-1}$ ) in the soil profile (0–100 cm) under different land use systems in Af site (São Miguel do Guamá) and Aw site (Paragominas), Pará, Brazil.

Land use	Depth (cm)	Af site (São Miguel do Guamá) <sup>1</sup>			Aw site (Paragominas) <sup>2</sup>			
		Sand	Silt	Clay	Sand	Silt	Clay	
		$\text{g kg}^{-1}$						
Forest	0–5	793	87	120	55	165	780	
	5–10	823	37	140	46	154	800	
	10–20	723	97	180	38	122	840	
	20–30	775	5	220	28	92	880	
	30–40	662	78	260	26	54	920	
	40–60	727	33	240	33	27	940	
	60–80	725	15	260	23	97	880	
	80–100	716	4	280	27	133	840	
	Agriculture	0–5	833	27	140	64	256	680
		5–10	818	22	160	44	236	720
10–20		751	49	200	32	128	840	
20–30		733	7	260	34	86	880	
30–40		692	28	280	45	55	900	
40–60		674	6	320	20	80	900	
60–80		666	14	320	23	97	880	
80–100		650	30	320	39	121	840	
Intensive pasture		0–5	762	78	160	32	148	820
		5–10	795	25	180	27	133	840
	10–20	744	16	240	26	94	880	
	20–30	690	50	260	21	79	900	
	30–40	754	66	180	22	58	920	
	40–60	747	13	240	20	60	920	
	60–80	692	28	280	23	57	920	
	80–100	669	31	300	24	96	880	
	Nominal pasture	0–5	719	81	200	41	159	800
		5–10	726	74	200	33	127	840
10–20		703	77	220	31	109	860	
20–30		702	58	240	39	81	880	
30–40		651	69	280	30	70	900	
40–60		607	33	360	29	71	900	
60–80		585	55	360	26	214	760	
80–100		586	34	380	29	221	750	

<sup>1</sup> In Af site (São Miguel do Guamá), agriculture refers to oil palm (*Elaeis guineensis* Jacq.); in Aw site (Paragominas), it refers to an Integrated Crop–Livestock (ICL) system.

site, sand contents were higher in the surface layers across all land uses, whereas clay contents increased with depth. The nominal pastures showed the highest clay contents in the deeper layers (80–100 cm). In the Aw site, clay predominated in all systems and increased with depth, particularly in the nominal pastures, which presented the highest clay contents. The silt content was low at both sites, regardless of land use or depth.

In the Af site, soil bulk density (BD) varied along the profile, but no differences ( $p > 0.05$ ) were observed in the 0–40 cm layers (Fig. 3a), despite effect sizes ranged from small to large ( $\eta^2$  between 0.04 and 0.68). At the 40–60 cm depth, land use effects were identified ( $p = 0.024$ ;  $\eta^2 = 0.77$ ), with the nominal pasture showing the highest BD ( $1.71 \text{ g cm}^{-3}$ ; 95% CI: 1.66–1.76). In this layer, the nominal pasture differed from the intensive pasture ( $1.59 \text{ g cm}^{-3}$ ;  $p = 0.031$ ), with a mean difference of  $0.12 \text{ g cm}^{-3}$  (95% CI: 0.01–0.22). In the deeper layers (60–100 cm), BD did not differ ( $p > 0.05$ ), ranging from 1.53 to  $1.67 \text{ g cm}^{-3}$ , with effect sizes between 0.36 and 0.70.

In the Aw site, BD varied along the profile, with differences identified at specific depths (Fig. 3b). In the surface layers (0–30 cm), no differences were observed among land use systems ( $p > 0.05$ ), although effect sizes were high ( $\eta^2$  between 0.53 and 0.66). However, at the 30–40 cm depth, land use influenced soil density ( $p = 0.025$ ;  $\eta^2 = 0.74$ ). At this depth, agriculture exhibited higher BD than nominal pasture ( $p = 0.017$ ), with a mean difference of  $0.15 \text{ g cm}^{-3}$  (95% CI: 0.03–0.27). Similarly, differences were found in the 40–60 cm layer ( $p = 0.014$ ;  $\eta^2 = 0.80$ ), where the forest recorded higher values than intensive pasture ( $p = 0.009$ ), with a mean difference of  $0.10 \text{ g cm}^{-3}$  (95% CI: 0.03–0.16). In the deeper layers (60–100 cm), BD returned to similar values across all systems ( $p > 0.05$ ), ranging from 1.26 to  $1.45 \text{ g cm}^{-3}$ .

#### 3.2. Soil organic carbon and total nitrogen storage

In the Af site, soil C concentration varied along the soil profile, with no differences ( $p > 0.05$ ) among land use systems at any depth (Fig. 4a). In the surface layer (0–5 cm), values ranged from  $8.45 \text{ g kg}^{-1}$  (forest) to  $14.57 \text{ g kg}^{-1}$  (intensive pasture), decreasing gradually with depth to a range of 3.11 to  $3.79 \text{ g kg}^{-1}$  in 40–60 cm layer. In the deepest layers (60–100 cm), concentrations remained low, ranging from 2.81 to  $3.69 \text{ g kg}^{-1}$ . Although high effect sizes were observed in some layers, such as 0–5 cm and 30–40 cm ( $\eta^2 = 0.58$  and 0.65, respectively), pairwise contrasts were not significant ( $p > 0.05$ ) due to overlapping 95% confidence intervals.

In the Aw site, soil C concentration was influenced by land use at specific depths (Fig. 4b). Surface SOC values in this clay-rich site were numerically higher than those observed in the Af site. In the surface layer (0–5 cm), land use effect was observed ( $p = 0.003$ ;  $\eta^2 = 0.91$ ). At this depth, nominal pasture exhibited the highest concentration ( $45.00 \text{ g kg}^{-1}$ ; 95% CI: 36.68–53.32), surpassing agriculture ( $24.52 \text{ g kg}^{-1}$ ;  $p = 0.008$ ), with a mean difference of  $20.48 \text{ g kg}^{-1}$  (95% CI: 8.71–32.26). Between 5 and 60 cm, C concentrations decreased gradually and showed no differences among systems ( $p > 0.05$ ), despite moderate to high effect sizes ( $\eta^2$  ranging from 0.16 to 0.47). In the 60–80 cm layer, land use effects were again detected ( $p = 0.022$ ;  $\eta^2 = 0.76$ ), where intensive pasture ( $6.53 \text{ g kg}^{-1}$ ; 95% CI: 6.07–6.99) maintained higher levels than nominal pasture ( $5.37 \text{ g kg}^{-1}$ ;  $p = 0.014$ ), with a mean difference of  $1.15 \text{ g kg}^{-1}$  (95% CI: 0.31–2.00).

In the Af site, soil N concentration varied along the soil profile, with no differences ( $p > 0.05$ ) observed among land use systems at any depth (Fig. 5a). Effect sizes ranged from moderate to large ( $\eta^2$  between 0.20 and 0.67). From 0 to 30 cm, soil N concentrations ranged from  $0.31 \text{ g kg}^{-1}$  (intensive pasture, 20–30 cm) to  $1.18 \text{ g kg}^{-1}$  (intensive pasture, 0–5 cm; 95% CI: 0.74–1.61), whereas from 30 to 100 cm, values ranged from 0.17 to  $0.31 \text{ g kg}^{-1}$ . Although high effect sizes were noted in the surface layer (0–5 cm,  $\eta^2 = 0.67$ ) and deeper layers (80–100 cm,  $\eta^2 = 0.52$ ), pairwise comparisons were not significant ( $p > 0.05$ ) due to the overlapping of 95% confidence intervals.

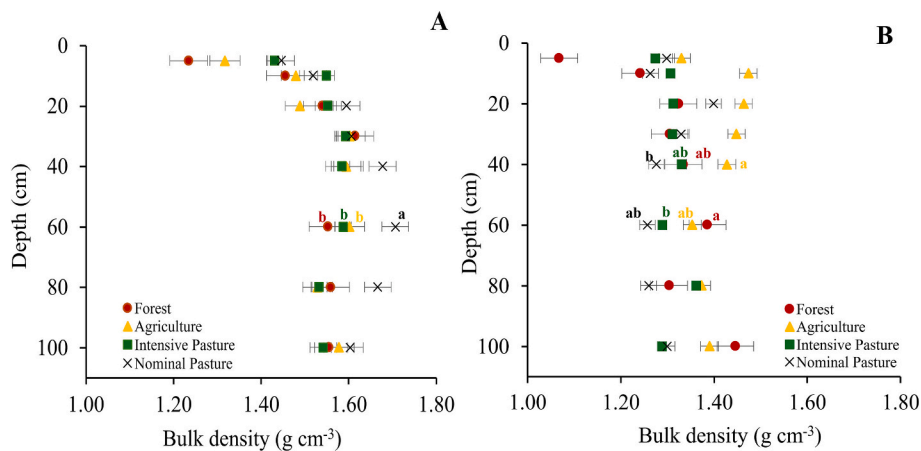


Fig. 3. Soil bulk density ( $\text{g cm}^{-3}$ ) in the 0–100 cm soil profile under different land use systems in the Af site (A) and Aw site (B), Pará, Brazil. Means followed by the same letter within the same soil layer do not differ significantly ( $p < 0.05$ ; Welch's ANOVA followed by the Games–Howell test).

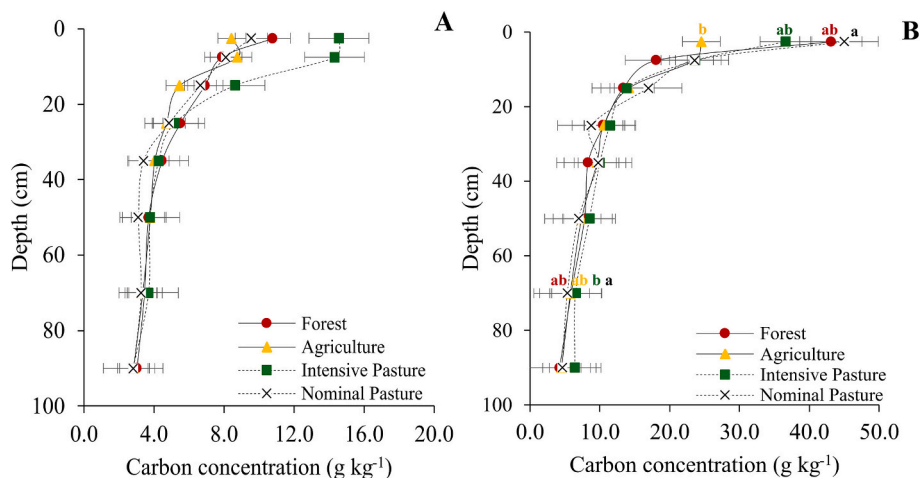


Fig. 4. Soil carbon concentration ( $\text{g C kg}^{-1}$ ) in the 0–100 cm soil profile under different land use systems in the Af site (A) and Aw site (B), Pará, Brazil. Different letters within the same soil layer indicate significant differences among land use systems ( $p < 0.05$ ; Welch's ANOVA followed by the Games–Howell test).

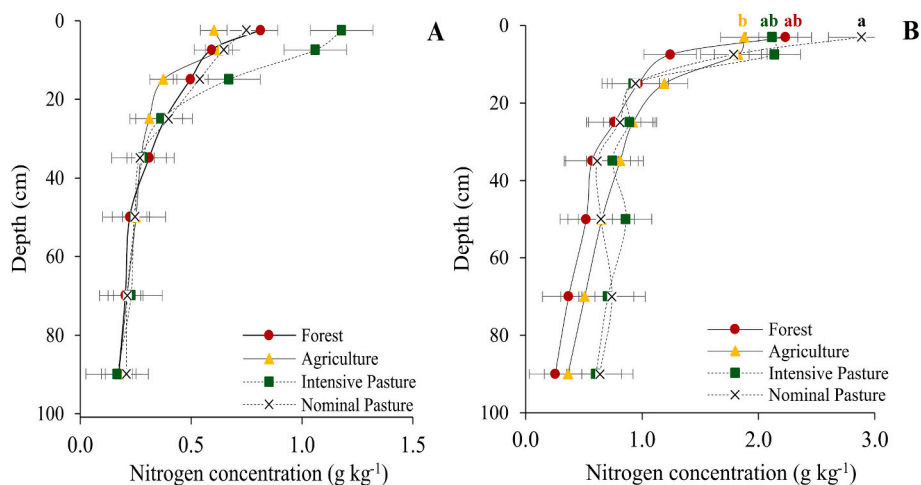


Fig. 5. Soil nitrogen concentration ( $\text{g N kg}^{-1}$ ) in the 0–100 cm soil profile under different land use systems in the Af site (A) and Aw site (B), Pará, Brazil. Different letters within the same soil layer indicate significant differences among land use systems ( $p < 0.05$ ; Welch's ANOVA followed by the Games–Howell test).

In the Aw site, soil N concentration ranged from 0.34 to 2.79  $\text{g kg}^{-1}$  (Fig. 5b). At the 0–5 cm layer, land use effect was observed ( $p = 0.002$ ,  $\eta^2 = 0.90$ ). At this layer, nominal pasture exhibited a higher N

concentration (2.89  $\text{g kg}^{-1}$ ; 95% CI: 2.55–3.22) than agriculture (1.88  $\text{g kg}^{-1}$ ;  $p = 0.002$ ), with a mean difference of 1.01  $\text{g kg}^{-1}$  (95% CI: 0.55–1.47). Forest (2.97  $\text{g kg}^{-1}$ ; 95% CI: 1.89–4.06) and intensive

pasture (2.12 g kg<sup>-1</sup>; 95% CI: 0.66–3.57) did not differ from the other systems ( $p > 0.05$ ). At the remaining depths (5–100 cm), N concentrations decreased gradually, ranging from 0.34 to 2.14 g kg<sup>-1</sup>, with no significant differences among systems ( $p > 0.05$ ), despite the observation of high effect sizes in deeper layers, such as 80–100 cm ( $\eta^2 = 0.69$ ).

In the Af site, the soil C/N ranged from 12.14 to 17.60 (Table 4). Differences among land use systems were observed at the 0–5, 10–20, 20–30, 40–60, and 80–100 cm depths ( $p \leq 0.01$ ;  $\eta^2 = 0.81$ –0.92). In the 0–5 cm layer, agriculture had the greatest ratio (14.05; 95% CI: 13.57–14.54), while pastures recorded the lowest (intensive: 12.34, 95% CI: 12.00–12.69; nominal: 12.65, 95% CI: 11.76–13.54). Agriculture maintained higher ratios (14.81–15.15) from 10 to 30 cm depth, differing from pastures. At 40–60 cm, forest showed the highest ratio (16.64; 95% CI: 14.50–18.78) and nominal pasture the lowest (12.62; 95% CI: 11.67–13.56). Finally, at 80–100 cm, nominal pasture remained with the lowest ratio (13.68; 95% CI: 12.23–15.13) compared to forest and agriculture (17.60 and 16.25, respectively). At other depths, values were similar ( $p > 0.05$ ;  $\eta^2 = 0.17$ –0.65).

In the Aw site, the C/N ratio in the soil profile ranged from 10.30 to 19.77 (Table 5). Significant differences among systems were observed only at the 0–5 cm depth ( $p = 0.037$ ;  $\eta^2 = 0.71$ ). At this layer, the nominal pasture (15.57; 95% CI: 13.97–17.18) showed a higher ratio than agriculture (13.08; 95% CI: 12.00–14.16;  $p = 0.031$ ). Notably, although the intensive pasture presented the highest numerical mean (18.25), it did not differ from the other systems due to high variability (95% CI: 5.00–31.50). No differences were found at other depths ( $p > 0.05$ ;  $\eta^2 = 0.33$ –0.69).

In the Af site, the soil C and N stocks for the 0–30 cm and 0–100 cm layers are presented in Table 6. In the 0–30 cm layer, although no differences were observed for SCS ( $p = 0.08$ ;  $\eta^2 = 0.42$ ), the intensive pasture exhibited the highest numerical values (42.36 Mg ha<sup>-1</sup>; 95% CI: 26.03–58.69), while the agriculture system showed the lowest (27.63 Mg ha<sup>-1</sup>; 95% CI: 18.99–36.27). In the 0–100 cm layer, land use affected C accumulation ( $p = 0.03$ ;  $\eta^2 = 0.54$ ), with the intensive pasture (80.21 Mg ha<sup>-1</sup>; 95% CI: 56.42–103.99) surpassing the agriculture and nominal pasture systems.

Regarding nitrogen, differences were detected in both depth intervals. For the 0–30 cm layer ( $p = 0.02$ ;  $\eta^2 = 0.54$ ), the intensive pasture (3.23 Mg ha<sup>-1</sup>; 95% CI: 2.20–4.26) had higher SNS than the agriculture system (1.91 Mg ha<sup>-1</sup>; 95% CI: 1.27–2.54). Similarly, in the 0–100 cm layer ( $p = 0.04$ ;  $\eta^2 = 0.49$ ), the intensive pasture (5.31 Mg ha<sup>-1</sup>; 95% CI: 4.22–6.40) surpassed the agriculture system (3.95 Mg ha<sup>-1</sup>; 95% CI: 2.99–4.91). Forest and nominal pasture systems showed intermediate stocks for both C and N across all depths, with overlapping confidence intervals.

In the Aw site, the SCS values were similar among systems in both the 0–30 cm ( $p = 0.28$ ;  $\eta^2 = 0.26$ ) and 0–100 cm ( $p = 0.24$ ;  $\eta^2 = 0.29$ ) layers (Table 7). Values ranged from 63.9 to 77.4 Mg ha<sup>-1</sup> (95% CI: 50.9–94.5) and 117.1–134.5 Mg ha<sup>-1</sup> (95% CI: 94.8–165.7) for the 0–30 and 0–100 cm depths, respectively. Similarly, no differences were detected for SNS

in the 0–30 cm ( $p = 0.64$ ;  $\eta^2 = 0.13$ ) or 0–100 cm ( $p = 0.51$ ;  $\eta^2 = 0.17$ ) layers. The SNS ranged from 5.17 to 5.84 Mg ha<sup>-1</sup> (95% CI: 4.03–7.25) in the upper layer and from 9.75 to 10.79 Mg ha<sup>-1</sup> (95% CI: 7.66–13.10) in the full profile.

### 3.3. Isotopic composition and carbon origin (C<sub>3</sub> and C<sub>4</sub> plants)

In the Af site, all layers differed in the soil abundance of  $\delta^{13}\text{C}$  ( $p < 0.05$ ;  $\eta^2$  between 0.90 and 0.99), ranging from -29.3‰ to -18.2‰ across the land use systems (Fig. 6a). The forest presented the most negative isotopic signature in the entire profile (-29.28‰; 95% CI: -29.74 to -28.82‰ at 0–5 cm). From 30 to 100 cm, isotopic enrichment was more subtle among the systems, but the forest maintained the lowest isotopic signature (-26.42‰; 95% CI: -26.85 to -25.99‰ at 80–100 cm). The intensive pasture system recorded the least negative isotopic values (-18.15‰; 95% CI: -20.00 to -16.29‰ at 0–5 cm), differing from the forest by 11.13‰ ( $p < 0.05$ ), which is in line with the  $\delta^{13}\text{C}$  range commonly observed under C<sub>4</sub> influenced inputs.

In the AW site, the  $\delta^{13}\text{C}$  signature differed among land use systems in nearly all layers ( $p < 0.05$ ;  $\eta^2$  between 0.75 and 0.97), except from 80 to 100 cm ( $p = 0.127$ ), and ranged from -28.5‰ to -21.5‰ (Fig. 6b). The forest showed the most negative  $\delta^{13}\text{C}$  values throughout the profile (-28.53‰; 95% CI: -28.62 to -28.44‰ at 0–5 cm), consistent with C<sub>3</sub> derived organic matter. Agriculture, intensive and nominal pasture showed more enriched values, which are compatible with partial inputs from C<sub>4</sub> vegetation, especially in the surface layers (-21.46 to -23.15‰ at 0–5 cm). From the 20–30 cm layer, the intensive pasture presented the least negative  $\delta^{13}\text{C}$  values among the systems (-24.74‰; 95% CI: -25.34 to -24.14‰), differing significantly from the forest (mean difference of 1.86‰;  $p = 0.002$ ).

The abundance of  $\delta^{15}\text{N}$  in the soil, in the Af site, ranged from 3.43‰ to 7.90‰ across the land use systems and soil layers ( $\eta^2$  between 0.65 and 0.95) (Fig. 7a). The nominal pasture showed a more enriched isotopic signature at all depths ( $p < 0.05$ ), except for the 80–100 cm layer ( $p = 0.090$ ), with values ranging from 5.76‰ (95% CI: 4.61–6.92‰) to 7.96‰ (95% CI: 7.64–8.28‰). The lowest  $\delta^{15}\text{N}$  values were observed in the superficial layers (0–30 cm) of agriculture (3.43 to 5.64‰) and intensive pasture (3.59 to 5.51‰). In the 20–30 cm layer, where the highest land use effect was observed ( $\eta^2 = 0.93$ ), the nominal pasture differed significantly from the intensive pasture by 2.33‰ ( $p = 0.002$ ). The forest showed intermediate  $\delta^{15}\text{N}$  values along the profile (4.26 to 6.36‰; 95% CI: 1.78–7.89‰), generally not differing significantly from the other systems ( $p > 0.05$ ).

In the Aw site, the soil abundance of  $\delta^{15}\text{N}$  ranged from 8.97‰ to 11.81‰ among land use systems ( $\eta^2$  between 0.18 and 0.80) (Fig. 7b). The nominal pasture showed the most enriched isotopic signature along the entire profile, reaching 11.77‰ (95% CI: 11.40–12.14‰) at the 20–30 cm layer, where a significant land use effect was observed ( $p = 0.032$ ;  $\eta^2 = 0.80$ ). At this specific depth, the nominal pasture differed significantly from the forest (mean difference of 0.59‰;  $p = 0.042$ ).

**Table 4**

Carbon to nitrogen (C/N) ratio in the 0–100 cm soil profile under different land use systems in Af site (São Miguel do Guamá), Pará, Brazil.

Depth (cm)	Land Use				CV (%)	P-value	$\eta^2$
	Forest	Agriculture <sup>1</sup>	Intensive pasture	Nominal pasture			
0–5	13.20 ± 0.72 ab	14.05 ± 0.31 a	12.34 ± 0.22 b	12.65 ± 0.56 b	3.5	0.001	0.92
5–10	13.37 ± 0.71	14.10 ± 1.03	13.26 ± 1.42	12.40 ± 0.52	6.9	0.110	0.59
10–20	13.82 ± 0.43 ab	14.81 ± 1.48 a	12.80 ± 0.53 b	12.35 ± 0.37 b	5.0	0.010	0.81
20–30	14.40 ± 0.67 ab	15.15 ± 1.04 a	14.23 ± 1.70 ab	12.14 ± 0.58 b	7.1	0.006	0.84
30–40	14.55 ± 2.05	14.97 ± 1.21	15.25 ± 1.70	12.67 ± 0.85	10.0	0.069	0.65
40–60	16.64 ± 1.35 a	15.17 ± 1.57 ab	16.00 ± 3.11 ab	12.62 ± 0.59 b	10.6	0.009	0.84
60–80	17.01 ± 1.38	15.97 ± 1.43	16.42 ± 2.85	15.39 ± 3.14	14.7	0.736	0.17
80–100	17.60 ± 0.81 a	16.25 ± 1.32 a	17.00 ± 1.54 a	13.68 ± 0.91 b	7.1	0.005	0.85

<sup>1</sup> Oil palm (*Elaeis guineensis* Jacq.). CV.: coefficient of variation.  $\eta^2$ : Effect size interpreted as small ( $\geq 0.01$ ), moderate ( $\geq 0.06$ ), and large ( $\geq 0.14$ ), according to Cohen (1988). Values are means ± standard deviation. Means followed by the same letter within a row do not differ significantly ( $p < 0.05$ ; Welch's ANOVA followed by the Games–Howell test).

**Table 5**  
Carbon/nitrogen (C/N) ratio in the 0–100 cm soil profile under different land use systems in Aw site (Paragominas), Pará, Brazil.

Depth (cm)	Land Use				CV (%)	P-value	$\eta^2$
	Forest	Agriculture <sup>1</sup>	Intensive pasture	Nominal pasture			
0–5	14.45 ± 0.84 ab	13.08 ± 0.68 b	18.25 ± 8.33 ab	15.57 ± 1.01 a	15.8	0.037	0.71
5–10	10.96 ± 1.72	12.88 ± 0.58	11.83 ± 3.26	12.70 ± 2.16	16.2	0.370	0.41
10–20	10.30 ± 1.10	11.80 ± 0.39	15.04 ± 2.97	19.77 ± 9.24	20.1	0.080	0.69
20–30	10.30 ± 1.35	11.48 ± 0.44	14.09 ± 5.14	11.10 ± 0.64	14.8	0.385	0.37
30–40	10.67 ± 0.92	11.81 ± 0.63	13.73 ± 2.38	11.04 ± 0.43	8.8	0.131	0.57
40–60	15.40 ± 8.38	11.32 ± 0.40	9.97 ± 1.60	11.20 ± 0.35	20.2	0.449	0.33
60–80	11.89 ± 0.28	11.47 ± 0.41	11.95 ± 0.74	11.42 ± 0.29	3.7	0.217	0.48
80–100	12.51 ± 0.40	12.60 ± 0.93	11.64 ± 1.68	11.94 ± 0.29	6.9	0.249	0.47

<sup>1</sup> Integrated Crop-Livestock (ICL) system; CV: coefficient of variation.  $\eta^2$ : Effect size interpreted as small ( $\geq 0.01$ ), moderate ( $\geq 0.06$ ), and large ( $\geq 0.14$ ), according to Cohen (1988). Values are means ± standard deviation. Means followed by the same letter within a row do not differ significantly ( $p < 0.05$ ; Welch's ANOVA followed by the Games–Howell test).

**Table 6**  
Soil C and N stocks (Mg ha<sup>-1</sup>) in the 0–30 cm and 0–100 cm depth layers under different land use systems in Af site (São Miguel do Guamá), Pará, Brazil.

Depth (cm)	Land Use				CV (%)	P-value	$\eta^2$
	Forest	Agriculture <sup>1</sup>	Intensive pasture	Nominal pasture			
<b>Carbon Stock (Mg ha<sup>-1</sup>)</b>							
0–30	31.82 ± 2.56	27.63 ± 5.43	42.36 ± 10.26	30.53 ± 9.33	20.6	0.079	0.42
0–100	65.11 ± 4.70 ab	59.35 ± 9.51 b	80.21 ± 9.57 a	60.26 ± 8.94 b	13.6	0.029	0.54
<b>Nitrogen Stock (Mg ha<sup>-1</sup>)</b>							
0–30	2.31 ± 0.17 ab	1.91 ± 0.40 b	3.23 ± 0.65 a	2.45 ± 0.7 ab	19.0	0.023	0.54
0–100	4.34 ± 0.31 ab	3.95 ± 0.60 b	5.31 ± 0.68 a	4.61 ± 0.68 ab	12.5	0.040	0.49

<sup>1</sup> Oil palm (*Elaeis guineensis* Jacq.); CV: Coefficient of variation.  $\eta^2$ : Effect size interpreted as small ( $\geq 0.01$ ), moderate ( $\geq 0.06$ ), and large ( $\geq 0.14$ ), according to Cohen (1988). Values are means ± standard deviation. Means followed by the same letter within a row do not differ significantly ( $p < 0.05$ ; ANOVA followed by Tukey HSD test).

**Table 7**  
Soil C and N stocks (Mg ha<sup>-1</sup>) in the 0–30 cm and 0–100 cm depth layers under different land use systems in Aw site (Paragominas), Pará, Brazil.

Depth (cm)	Land Use				CV (%)	P-value	$\eta^2$
	Forest	Agriculture <sup>1</sup>	Intensive pasture	Nominal pasture			
<b>Carbon Stock (Mg ha<sup>-1</sup>)</b>							
0–30	65.30 ± 11.98	63.86 ± 8.15	70.50 ± 9.81	77.39 ± 10.75	14.0	0.284	0.26
0–100	117.10 ± 14.00	117.23 ± 10.75	130.93 ± 11.11	134.48 ± 19.63	11.1	0.238	0.29
<b>Nitrogen Stock (Mg ha<sup>-1</sup>)</b>							
0–30	5.64 ± 1.01	5.17 ± 0.72	5.42 ± 0.67	5.84 ± 0.48	13.1	0.635	0.13
0–100	9.78 ± 1.33	9.75 ± 1.00	10.56 ± 0.88	10.79 ± 1.45	11.4	0.514	0.17

<sup>1</sup> Integrated Crop-Livestock (ICL) system; CV: Coefficient of variation.  $\eta^2$ : Effect size interpreted as small ( $\geq 0.01$ ), moderate ( $\geq 0.06$ ), and large ( $\geq 0.14$ ), according to Cohen (1988). Values are means ± standard deviation. Means followed by the same letter within a row do not differ significantly ( $p < 0.05$ ; ANOVA followed by Tukey HSD test).

Intensive pasture and agriculture showed intermediate isotopic signatures with no differences between them in almost all layers ( $p > 0.05$ ); their values ranged from 9.01‰ (95% CI: 8.26–9.76‰) at the surface to 10.69‰ (95% CI: 10.14–11.24‰) in the deepest layer.

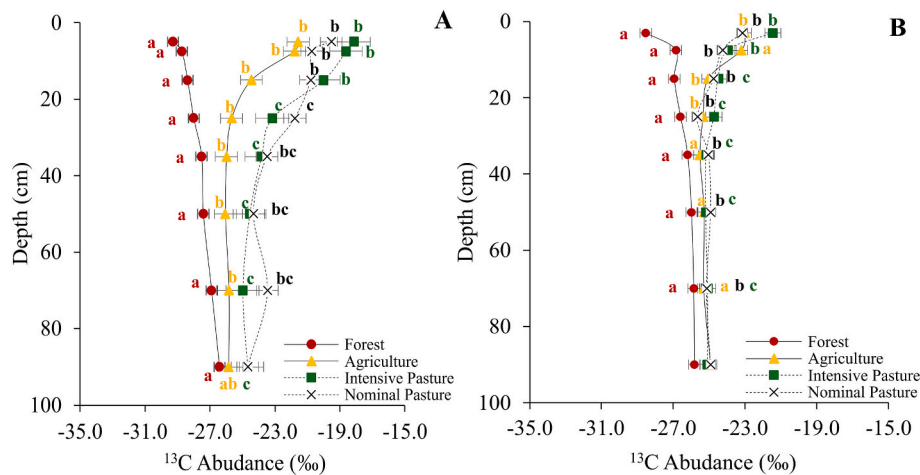
In the land use systems of the Af site, partial substitution of C<sub>3</sub> derived carbon by C<sub>4</sub> was observed, particularly in the 0–20 cm layers (Fig. 8). At 0–5 cm, C<sub>4</sub> contribution reached 89% in intensive pasture, 59% in nominal pasture, and 54% in agriculture. The relative contribution of C<sub>4</sub> carbon decreased with depth, though nominal pasture still maintained 17% at 80–100 cm.

The C<sub>3</sub> carbon stock (Table 8) ranged from 1.09 to 10.90 Mg ha<sup>-1</sup> with land use effects observed primarily at 20–30 cm ( $p = 0.004$ ;  $\eta^2 = 0.86$ ) and 60–80 cm ( $p = 0.020$ ;  $\eta^2 = 0.76$ ). At 20–30 cm, agriculture (6.20 Mg ha<sup>-1</sup>; 95% CI: 4.99–7.40) and intensive pasture (5.57 Mg ha<sup>-1</sup>; 95% CI: 3.88–7.26) surpassed nominal pasture (3.46 Mg ha<sup>-1</sup>; 95% CI: 2.55–4.36). For C<sub>4</sub> carbon, stocks (0.40–9.30 Mg ha<sup>-1</sup>) differed across almost all layers ( $\eta^2$  between 0.39 and 0.80), except at 5–10 cm ( $p = 0.082$ ) and 60–80 cm ( $p = 0.072$ ). Intensive pasture showed the greatest values, particularly at 0–5 cm (9.30 Mg ha<sup>-1</sup>; 95% CI: 5.01–13.59),

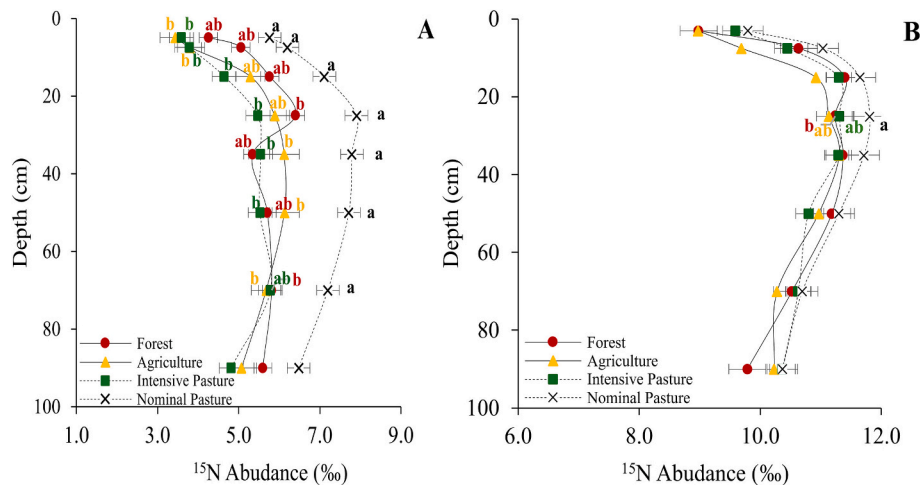
where it surpassed agriculture ( $p = 0.025$ ). Although C<sub>4</sub> stocks decreased with depth, intensive pasture maintained higher values than agriculture in deeper layers, such as at 80–100 cm (1.10 vs 0.40 Mg ha<sup>-1</sup>;  $p = 0.002$ ).

At the Aw site, a substitution of C<sub>3</sub> carbon by C<sub>4</sub> occurred primarily in the 0–20 cm layer (Fig. 9). At 0–5 cm, C<sub>4</sub> contribution was 47% in nominal pasture, 50% in intensive pasture, and 37% in agriculture. This contribution decreased with depth, with nominal pasture maintaining 11% at 80–100 cm, while agriculture ranged between 3% and 7% in the 40–100 cm interval.

The C<sub>3</sub> carbon stocks (Table 9) ranged from 5.2 to 52.7 Mg ha<sup>-1</sup>. Land use effects were observed across the profile ( $p < 0.05$ ;  $\eta^2$  between 0.85 and 0.96), with the exception of the 5–10 cm layer ( $p = 0.089$ ;  $\eta^2 = 0.61$ ). Nominal pasture showed the highest C<sub>3</sub> stocks in the 0–20 cm depth (e.g., 52.70 Mg ha<sup>-1</sup> at 0–5 cm; 95% CI: 36.72–68.68). From 20 to 100 cm, the highest C<sub>3</sub> stocks were consistently recorded in agriculture. For C<sub>4</sub> carbon, stocks ranged from 0.4 to 46.8 Mg ha<sup>-1</sup>. Variation among systems was restricted to the 0–5 cm layer ( $p = 0.015$ ;  $\eta^2 = 0.58$ ), where nominal pasture (46.78 Mg ha<sup>-1</sup>; 95% CI: 29.52–64.04) surpassed



**Fig. 6.** Carbon 13 isotope abundance ( $\delta^{13}\text{C}$ , ‰) in the 0–100 cm soil profile under different land use systems in the Af site (A) and Aw site (B), Pará, Brazil. Different letters within the same soil layer indicate significant differences among land use systems ( $p < 0.05$ ; Welch's ANOVA followed by the Games–Howell test).



**Fig. 7.** Nitrogen 15 isotope abundance ( $\delta^{15}\text{N}$ , ‰) in the 0–100 cm soil profile under different land use systems in the Af site (A) and Aw site (B), Pará, Brazil. Different letters within the same soil layer indicate significant differences among land use systems ( $p < 0.05$ ; Welch's ANOVA followed by the Games–Howell test).

agriculture ( $6.02 \text{ Mg ha}^{-1}$ ; 95% CI: 3.36–8.68). In the remaining depths (5–100 cm), no differences were identified among the land use systems ( $p \geq 0.07$ ).

#### 4. Discussion

SOC concentrations in forest systems fall within the typical range reported for tropical forest soils, particularly considering the clay-rich conditions of the Aw site. This pattern suggests that SOC storage capacity is largely constrained by soil texture and local edaphoclimatic conditions, providing essential context for interpreting the magnitude of land use effects.

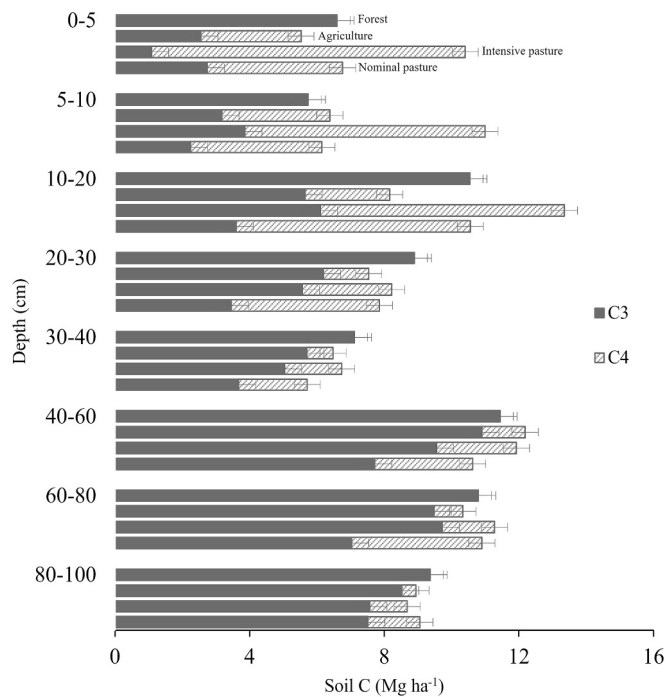
##### 4.1. Soil texture and density

In the Af site, the sandy surface texture ( $>750 \text{ g kg}^{-1}$  sand), combined with high rainfall (Fig. 2), likely enhances leaching and reduces physical protection of organic matter, promoting faster microbial turnover and helping explain the lower C and N stocks (Liang et al., 2022). Management effects were mainly expressed in the surface layers. Intensive pastures with continuous grass cover likely enhance organic inputs and reduce erosion, contributing to aggregate stability (Marcatto et al., 2021). In contrast, the higher bulk density observed below 20 cm

in the Af site appears to reflect intrinsic pedological characteristics, particularly increasing clay content with depth, rather than management induced compaction.

The very clay-rich texture in the Aw site (Table 3), with clay contents exceeding  $800 \text{ g kg}^{-1}$  in the surface layer, likely promotes aggregate formation, organomineral protection of organic matter, and high water retention (Jones et al., 2019; Lu et al., 2020). These conditions help buffer the impact of management on soil structure, which is consistent with the relatively stable bulk density values even under machinery traffic when soil cover is maintained. In contrast, higher bulk density observed in areas with lower inter-row cover suggests localized structural vulnerability associated with traffic-induced compaction, which can reduce macroporosity, infiltration, and root growth (Centeri, 2022; Lustosa Filho et al., 2024).

Lower bulk density values under forest (Fig. 3b), particularly in the surface layer ( $1.1 \text{ g cm}^{-3}$ ), primarily reflect the high microporosity inherent to the very clay-rich texture of the soil, rather than being mainly driven by biological or management factors. Although soil texture is a relatively stable property, bulk density responds rapidly to management intensity. Thus, even in clay-rich soils with high structural resilience, intensive land use can still induce structural changes (Souza et al., 2024). These results indicate that bulk density remains a sensitive indicator of physical degradation, particularly in systems lacking



**Fig. 8.** Relative contribution of carbon derived from C<sub>3</sub> and C<sub>4</sub> plants (%) along the 0–100 cm soil profile under different land use systems (forest, agriculture, intensive pasture, and nominal pasture) in the Af site (São Miguel do Guamá), Pará, Brazil.

permanent cover or conservation practices.

**4.2. Soil C and N stocks**

In the Af site, the higher C and N stocks observed in the intensive pasture (Table 6) likely result from the combined effects of regular N fertilization, enhanced nutrient cycling via animal excreta, and the dominance of C<sub>4</sub> tropical grasses such as *Urochloa humidicola*, which supply large amounts of low C/N residues through extensive root systems (Durigan et al., 2017; Cardoso et al., 2020; Souza et al., 2024). The magnitude of these stocks, reaching 80.21 Mg ha<sup>-1</sup> in the 0–100 cm layer, highlights the potential role of well-managed intensive pastures even in sandy soils.

**Table 8**

Carbon derived from C<sub>3</sub> and C<sub>4</sub> plants (Mg ha<sup>-1</sup>) in the 0–100 cm soil profile under different land use systems in Af site (São Miguel do Guamá), Pará, Brazil.

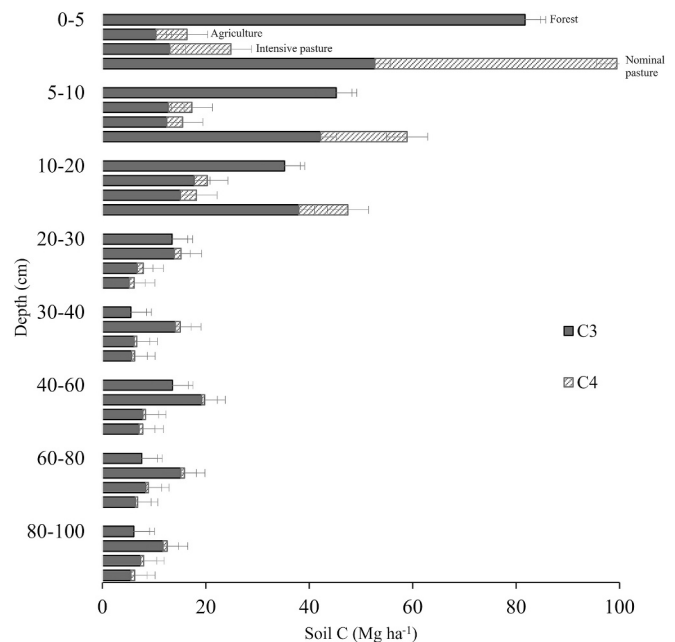
Depth (cm)	C3						C4					
	Agriculture <sup>1</sup>	Intensive pasture	Nominal pasture	CV (%)	P-value	η <sup>2</sup>	Agriculture <sup>1</sup>	Intensive pasture	Nominal pasture	CV (%)	P-value	η <sup>2</sup>
0–5	2.55 ± 0.75	1.09 ± 0.88	2.74 ± 0.60	44.1	0.065	0.61	3.00 ± 1.30 b	9.30 ± 2.70 a	4.00 ± 1.40 b	36.6	0.025	0.42
5–10	3.18 ± 0.55	3.86 ± 1.78	2.25 ± 1.09	37.3	0.322	0.36	3.20 ± 1.20	7.10 ± 3.30	3.90 ± 1.60	41.6	0.082	0.28
10–20	5.65 ± 1.05	6.10 ± 1.69	3.60 ± 0.97	24.4	0.055	0.63	1.60 ± 0.30 b	7.20 ± 3.30 a	7.00 ± 3.90 a	51.4	<0.001	0.80
20–30	6.20 ± 0.76 a	5.57 ± 1.06 a	3.46 ± 0.57 b	15.9	0.004	0.86	1.30 ± 0.50 b	2.60 ± 0.50 a	4.40 ± 2.60 ab	38.2	0.001	0.62
30–40	5.70 ± 1.34	5.04 ± 0.75	3.67 ± 0.70	19.2	0.058	0.63	0.80 ± 0.30 b	1.70 ± 0.10 a	2.00 ± 0.80 a	27.0	0.001	0.67
40–60	10.90 ± 2.48	9.55 ± 0.91	7.72 ± 1.10	15.5	0.008	0.60	1.30 ± 0.30 b	2.40 ± 0.40 a	2.90 ± 0.90 a	24.0	<0.001	0.68
60–80	9.48 ± 2.35 ab	9.72 ± 0.75 a	7.03 ± 0.97 b	15.5	0.020	0.76	0.80 ± 0.10 b	1.60 ± 0.20 a	3.90 ± 0.70 a	39.0	0.042	0.39
80–100	8.52 ± 1.16	7.57 ± 1.06	7.51 ± 0.54	11.6	0.393	0.30	0.40 ± 0.20 b	1.10 ± 0.20 a	1.60 ± 0.70 a	35.0	0.002	0.78

<sup>1</sup> Oil palm (*Elaeis guineensis* Jacq.); CV: coefficient of variation. η<sub>2</sub>: effect size interpreted as small (≥ 0.01), moderate (≥ 0.06), and large (≥ 0.14), according to Cohen (1988). Values are means ± standard deviation. Means followed by the same letter within a row do not differ significantly (p < 0.05, Welch's ANOVA followed by Games-Howell test).

Furthermore, the absence of soil disturbance possibly favors relative organic matter stabilization and protection against losses (De Oliveira et al., 2022). In contrast, the intermediate values recorded in the forest and nominal pasture suggest relatively stable stocks sustained, respectively, by the continuous input of litter and root exudates, and by the maintenance of vegetation cover, although without external nutrient inputs (Ziviani et al., 2024; Lustosa Filho et al., 2024).

The higher C/N ratio under agriculture (Table 4) likely reflects low N inputs in oil palm cultivation and the accumulation of more recalcitrant residues, such as branches and carbonized material (Gomes et al., 2019; Silva et al., 2024). Ratios above ~14 may constrain microbial activity (Cui et al., 2022), whereas in pastures (~12), lower C/N values are generally associated with faster residue turnover.

In the forest, elevated C/N values in deeper layers are consistent with



**Fig. 9.** Relative contribution of carbon derived from C<sub>3</sub> and C<sub>4</sub> plants (%) along the 0–100 cm soil profile under different land use systems (forest, agriculture, intensive pasture, and nominal pasture) in the Aw site (Paragominas), Pará, Brazil.

Table 9

Carbon derived from C<sub>3</sub> and C<sub>4</sub> plants (Mg ha<sup>-1</sup>) in the 0–100 cm soil profile under different land use systems in Aw site (Paragominas), Pará, Brazil.

Depth (cm)	C3					C4						
	Agriculture <sup>1</sup>	Intensive pasture	Nominal pasture	CV (%)	P-value	$\eta^2$	Agriculture <sup>1</sup>	Intensive pasture	Nominal pasture	CV (%)	P-value	$\eta^2$
0–5	10.33 ± 0.53 b	13.04 ± 1.63 b	52.70 ± 10.04 a	12.1	0.005	0.95	6.02 ± 1.67 b	11.85 ± 7.49 b	46.78 ± 10.85 a	38.0	0.015	0.58
5–10	12.75 ± 1.32	12.42 ± 1.78	42.14 ± 19.71	23.8	0.089	0.61	4.58 ± 2.25	3.05 ± 0.51	16.78 ± 10.96	43.7	0.130	0.19
10–20	17.74 ± 5.28 b	15.10 ± 2.77 b	37.96 ± 5.48 a	20.8	0.002	0.90	2.54 ± 0.36	3.09 ± 1.09	9.50 ± 5.36	35.3	0.135	0.39
20–30	13.90 ± 1.96 a	6.70 ± 1.30 b	5.20 ± 0.50 b	14.5	0.004	0.94	1.32 ± 0.33	1.15 ± 0.23	0.97 ± 1.32	60.7	0.710	0.05
30–40	14.10 ± 1.40 a	6.16 ± 0.59 b	5.65 ± 0.76 b	10.9	0.001	0.95	0.90 ± 0.34	0.50 ± 0.20	0.58 ± 0.45	51.6	0.245	0.34
40–60	19.19 ± 3.75 a	7.80 ± 1.70 b	7.07 ± 2.56 b	25.7	0.007	0.85	0.59 ± 0.51	0.52 ± 0.18	0.74 ± 0.29	53.5	0.510	0.01
60–80	15.14 ± 1.46 a	8.39 ± 0.82 b	6.4 ± 0.4 b	8.6	<0.001	0.96	0.73 ± 0.48	0.51 ± 0.14	0.38 ± 0.24	51.5	0.480	0.27
80–100	11.71 ± 0.96 a	7.40 ± 2.20 b	6.39 ± 0.42 b	17.7	0.003	0.95	0.82 ± 0.50	0.57 ± 0.09	0.70 ± 0.32	41.0	0.574	0.12

<sup>1</sup> Integrated Crop-Livestock (ICL) system; CV: coefficient of variation.  $\eta^2$ : effect size interpreted as small ( $\geq 0.01$ ), moderate ( $\geq 0.06$ ), and large ( $\geq 0.14$ ), according to Cohen (1988). Values are means  $\pm$  standard deviation. Means followed by the same letter within a row do not differ significantly ( $p < 0.05$ , Welch's ANOVA followed by Games-Howell test).

the accumulation of slowly decomposing organic residues under low N availability and reduced microbial activity (Silva et al., 2024). This pattern suggests relatively slower organic matter turnover and persistence of C<sub>3</sub> carbon at depth, while the gradual incorporation of C<sub>4</sub> inputs over time contributes to shifts in the isotopic signature of the soil profile (Cotrufo and Lavallee, 2022).

In the Aw site, soil C and N stocks remained high across land uses (Table 7), indicating limited sensitivity of these stocks to management under this soil condition. This pattern is consistent with the strong retention capacity of clay-rich soils, the higher organic matter content in surface layers (Table 1), and the lower annual rainfall (Fig. 2), which together reduce leaching losses (Gomes et al., 2019; Liang et al., 2022).

In such environments, organomineral interactions, aggregate protection, and mineral buffering are known to enhance the persistence of soil organic matter (Lal et al., 2021; Cotrufo and Lavallee, 2022). The absence of significant differences among land uses therefore suggests a texture-driven resilience, in which clay-associated protection may buffer soil C and N stocks against short- to medium-term land use changes. However, in the 0–100 cm layer, nominal pasture showed numerically higher C stocks (134.48 Mg ha<sup>-1</sup>) than the forest (117.10 Mg ha<sup>-1</sup>), representing an absolute difference of 17.38 Mg ha<sup>-1</sup>, although not statistically significant. This contrast suggests that well-managed pastures can maintain substantial carbon stocks even in deep soil layers.

This pattern is consistent with systems dominated by deep-rooted grasses such as *Megathyrus maximus* cv. Mombaça and with previous organic inputs (e.g., poultry litter), which increase belowground biomass inputs (Durigan et al., 2017; Tinos et al., 2020). In clay-rich soils, such inputs interact with mineral surfaces and aggregates, a mechanism commonly associated with enhanced organic matter persistence (Cotrufo and Lavallee, 2022).

The C/N ratio in the Aw site remained relatively stable across land uses (Table 5), a pattern consistent with a balance between organic matter inputs and decomposition (Ziviani et al., 2024). Forest and pasture systems showed similar N values, whereas agriculture exhibited lower N in the surface layer, possibly reflecting greater soil exposure and nutrient export by soybean and maize crops. The persistence of similar C/N values throughout the profile aligns with the high buffering capacity of clay-rich soils, where aggregate protection and organomineral interactions regulate organic matter turnover and mineral N release (Peng et al., 2023; Ziviani et al., 2024).

#### 4.3. Isotopic dynamics of carbon and nitrogen and origin of carbon in soil

Forest soils showed the most negative  $\delta^{13}\text{C}$  values, consistent with dominance of C<sub>3</sub> vegetation, which typically exhibits stronger isotopic discrimination during photosynthesis, whereas C<sub>4</sub> grasses produce less negative signatures. Agricultural and pasture systems exhibited isotopic enrichment reflecting the historical replacement of SOM sources by C<sub>4</sub> derived inputs (Azevedo et al., 2024; Yang et al., 2020). This pattern indicates vegetation legacy rather than current sequestration, as  $\delta^{13}\text{C}$  integrates long-term inputs and turnover of SOM pools.

At the Af site, oil palm soils showed lower negative  $\delta^{13}\text{C}$  values than forest (Fig. 6a), indicating persistence of C<sub>4</sub> signatures from previous pasture phases. Intensive pasture exhibited the strongest enrichment, while nominal pasture showed greater vertical variability, suggesting partial retention of C<sub>3</sub> derived carbon in surface layers. The depth distribution of C<sub>3</sub> and C<sub>4</sub> stocks (Fig. 8) supports this interpretation, with C<sub>4</sub> dominance near the surface and increasing C<sub>3</sub> contribution with depth.

In the Aw site, intermediate  $\delta^{13}\text{C}$  values in ICL agriculture reflect alternating C<sub>3</sub>/C<sub>4</sub> inputs, whereas pastures maintained signatures dominated by C<sub>4</sub> grasses (Fig. 6b). Across land uses, isotopic profiles show that deeper layers preserve earlier vegetation signals, while surface layers respond more rapidly to recent management (Neves et al., 2021).

Soil  $\delta^{15}\text{N}$  values (Figs. 7a–b) fall within the typical range for tropical soils and varied among systems in patterns consistent with differences in N cycling intensity. Enrichment in nominal pasture may reflect greater SOM turnover, whereas lower values in agriculture and intensive pasture suggest inputs of isotopically lighter N sources (Inácio et al., 2020; Oliveira et al., 2021). Although  $\delta^{15}\text{N}$  is widely used as an indicator of N transformation pathways, these interpretations remain indicative, as N transformation processes were not directly measured.

Together,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  patterns suggest that vegetation type and land use history structure both carbon origin and nitrogen cycling pathways, linking isotopic signals to long-term SOM replacement rather than short-term flux dynamics.

#### 4.4. Challenges and gaps in the assessment of C and N as a function of land use and climate

This study provides an integrated assessment of soil C and N stocks,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  abundance, and C<sub>3</sub>/C<sub>4</sub> derived carbon along deep soil profiles, allowing land use effects to be interpreted within their

respective edaphoclimatic contexts rather than as direct climate contrasts. This approach highlights how soil texture, mineralogy, and rainfall regimes modulate SOM behavior at each site.

However, several inferences rely on indirect indicators. Isotopic patterns and C/N ratios were used as functional proxies for SOM sources and nitrogen cycling, but processes such as mineralization, volatilization, and denitrification were not directly measured. Likewise, interpretations of SOM persistence and stabilization are based on texture, depth distribution, and isotopic composition, since no physical or chemical SOM fractionation was performed. These results should therefore be interpreted as indicative of mechanisms rather than direct evidence of stabilization pathways.

The study adopts a space-for-system framework, and thus represents cross-sectional contrasts among land uses rather than temporal trajectories. Rates of change, recovery processes, and long-term sequestration dynamics cannot be inferred from the present dataset. In addition, although replication ( $n = 4$  per system) is typical for deep-profile studies, the limited sample size reduces statistical power in depth resolved analyses, meaning that some non-significant results may reflect constrained sensitivity rather than true absence of land use effects.

Future research integrating SOM fractionation, direct N flux measurements, microbial indicators, and long-term climatic monitoring would strengthen the mechanistic understanding of carbon persistence and nitrogen cycling under contrasting land uses, particularly in relation to the interaction between soil texture and land use legacy.

## 5. Conclusion

Soil C and N stocks in the studied Amazonian systems were strongly associated with soil physical properties, land use history, and management context. In the sandy Af site, intensive pastures showed higher C and N stocks, a pattern consistent with greater organic inputs and limited soil disturbance. In the clay-rich Aw site, C and N stocks varied less among land uses, consistent with the strong organomineral protection typical of highly weathered tropical soils.

Overall, vegetation origin, land use transitions, and soil texture jointly shaped the replacement and persistence of soil organic matter along the soil profile. Isotopic evidence indicates that these patterns reflect long-term vegetation legacy and soil processes rather than short-term sequestration dynamics.

These findings emphasize the value of land use systems that maintain soil cover, minimize disturbance, and sustain organic inputs, particularly in coarse-textured soils where C and N stocks appear more sensitive to management. In clay-rich soils, physical protection may buffer short-to medium-term land use effects, although this does not imply immunity to long-term degradation.

## CRedit authorship contribution statement

**Lorena Maués Moraes:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jorge Cardoso de Azevedo:** Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Nauara Moura Lage Filho:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **João Victor Costa de Oliveira:** Visualization, Methodology, Investigation, Data curation. **Natan Lima Abreu:** Methodology, Investigation, Formal analysis, Data curation. **Ana Cláudia Ruggieri:** Writing – review & editing, Supervision, Resources, Formal analysis. **Angélica Santos Rabelo de Souza Bahia:** Supervision, Investigation. **Abmael da Silva Cardoso:** Writing – review & editing, Supervision. **Bruno Carneiro e Pedreira:** Writing – review & editing, Supervision, Formal analysis. **Vladimir Eliodoro Costa:** Methodology, Investigation, Formal analysis. **Thiago Carvalho da Silva:** Supervision, Formal analysis. **Cristian Faturi:** Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization. **Aníbal Coutinho do Rêgo:** Writing

– review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

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## Declaration of competing interest

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

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## Data availability

Soil carbon, nitrogen, isotopic composition ( $\delta^{13}\text{C}$ ), fertility and texture under different land-use systems in northeastern Amazonia (AF and AW climates). (Original data) (Mendeley Data)

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