



Conversion of degraded pasture to cocoa agroforestry in the Brazilian Amazon: Improvements in soil physical and biological properties

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ABSTRACT

The conversion of degraded pastures into sustainable production systems in the Brazilian Amazon has been recognized as a relevant strategy to address climate challenges, restore ecosystem functions, and support low-emission agricultural models. In this study, we evaluated the effects of converting a degraded extensive pasture into commercial cocoa-based agroforestry systems (AFSs) established for 12 and 25 years on soil physical and biological properties, using a remaining pasture and a native forest fragment as reference land-use systems. The following variables were determined: soil organic matter, carbon stock, bulk density, total porosity, macroporosity, microporosity, and penetration resistance (0–0.1, 0.1–0.2, and 0.2–0.4 m depth), Visual Evaluation of Soil Structure (VESS) (0–0.25 m depth), and soil macrofauna (0–0.1 m depth). The AFSs showed higher soil organic matter, greater carbon stock, and higher porosity, along with reduced soil bulk density and lower penetration resistance compared with the pasture, with more pronounced improvements in the surface layers. The 25-year AFS exhibited greater macrofauna abundance and higher taxonomic richness, with a notable contribution of ecosystem engineers, indicating advances in soil structural and functional reorganization. Multivariate analysis revealed a clear degradation–restoration gradient, positioning the AFSs along a progressive trajectory toward native-forest conditions. These results demonstrate that cocoa-based AFSs represent an effective proposal to restore degraded soils in the Amazon, reinforce ecosystem processes, and enhance the sustainability of productive landscapes.

1. Introduction

Planted pastures occupy approximately 59 million hectares in the Brazilian Amazon and are currently associated with more than 90 % of regional deforestation (IMAZON, 2024). It is estimated that over 50 % of these areas exhibit some stage of degradation (Barreto et al., 2024), representing one of the largest environmental liabilities in the region. Extensive pasture systems generally show low livestock productivity,

lead to inefficient land use, and impose substantial environmental costs (Garcia et al., 2017). Soil degradation in pastures is expressed through compaction, loss of organic matter, reduced fertility, decreased vegetation cover, and intensified erosion, resulting in severe impairment of key ecosystem functions such as hydrological regulation, nutrient cycling, and carbon sequestration (Rocha et al., 2016; Moratelli et al., 2023), often culminating in further pasture expansion and increased deforestation pressure (França et al., 2021; Telles et al., 2024).

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The search for sustainable land-use alternatives has become a strategic priority for the Amazon (Souza et al., 2025a). In this context, agroforestry systems (AFS) emerge as a promising option, integrating agricultural production with the restoration of ecosystem services and the mitigation of climate change (Gama-Rodrigues et al., 2021; Rodriguez et al., 2021a). Converting degraded areas into AFS has the potential to restore soil ecological functionality while generating income and productive diversification (Souza et al., 2007; Villa et al., 2020).

Among agroforestry models, cacao (*Theobroma cacao* L.) stands out as a native Amazonian species with high commercial value (Ceplac, 2018). Cultivating *T. cacao* in agroforestry arrangements provides advantages by meeting the growing global demand for sustainable production while forming landscape-scale mosaics that interconnect with natural forests and enhance agroecosystem resilience (Gama-Rodrigues et al., 2021). Studies indicate that *T. cacao*-based AFS can act as carbon sinks (Goñas et al., 2022; Adiyah et al., 2023), in addition to improving soil physical, chemical, and biological properties (Rodriguez et al., 2021b; Suárez et al., 2021).

The presence of trees and litter inputs to the soil surface in agroforestry systems promote soil particle aggregation, reduce bulk density, and increase macroporosity and total porosity, creating favorable conditions for root growth and water infiltration (Rodriguez et al., 2021a; Souza et al., 2025a). Soil penetration resistance (PR), which is highly sensitive to livestock trampling in pasture systems, tends to decrease in tree-based systems because trees contribute to soil structural recovery (Couto et al., 2016; Silva-Olaya et al., 2022). In addition, indicators such as soil organic matter and the Visual Evaluation of Soil Structure jointly demonstrate improvements in soil physical quality and in the capacity to provide environmental services in tree-based integrated systems in the Amazon (Cherubin et al., 2019; Brasil Neto et al., 2021).

In the biological domain, soil macrofauna represents one of the most sensitive and functionally relevant indicators of soil quality (Lavelle et al., 2022; North et al., 2025). Organism groups such as earthworms, ants, and termites not only reflect soil conservation status but also actively participate in key edaphic processes, including litter fragmentation, nutrient cycling, bioturbation, and pore formation (Jouquet et al., 2018; Insfrán Ortiz et al., 2023). In degraded pastures, the abundance and diversity of these organisms tend to decline due to compaction and limited organic matter inputs (Chiappero et al., 2024). In contrast, cacao-based AFS provide shading and increased organic inputs, creating favorable conditions for the reestablishment of soil macrofauna communities, which can be interpreted as an unequivocal signal of soil functional restoration (Rodriguez et al., 2021a; Awazi et al., 2025).

In the Amazon, a critical knowledge gap persists regarding the understanding of long-term soil restoration trajectories in cacao-based agroforestry systems (AFS) established through the conversion of degraded pastures. Addressing this gap is essential to provide a robust scientific basis for public policies related to technical assistance, rural extension, and payment for environmental services (PES). This need is particularly relevant in Brazil, which has committed to restoring approximately 30 million hectares of degraded pastures by 2030 (Brasil, 2021) as part of its Nationally Determined Contribution (NDC) and broader sustainability targets. In this context, the environmental recovery promoted by cacao-based AFS must be evaluated beyond isolated scientific metrics or narrowly focused assessments of system performance. The combined use of soil physical indicators and soil macrofauna enables an integrated assessment of restoration, as physical attributes capture changes in soil structure and compaction following land-use conversion, while macrofauna communities reflect the recovery of biological functioning and key ecosystem processes. Together, these complementary indicators allow a more comprehensive evaluation of soil restoration pathways, linking structural recovery to functional resilience and generating scientifically grounded evidence to support the design and consolidation of policies such as PES.

Based on the hypothesis that soil physical and biological attributes in

conventional pasture can progressively improve over time following the establishment of commercial cacao agroforestry systems (AFS), this study aimed to assess the extent to which cacao-based AFS of different ages in the Eastern Amazon promote soil physical and biological recovery when implemented as replacements for degraded pastures. To contextualize the recovery trajectory observed in these systems, an active pasture remnant derived from the original area and an adjacent native forest fragment were used as reference conditions.

2. Material and methods

2.1. Study area

The study was conducted in four adjacent areas located between 3°08'11" and 3°08'68" S and 47°16'58" and 47°17'40" W, in the municipality of Medicilândia, Pará State, Amazon, Brazil (Fig. 1). The municipality has an Am-type climate according to the Köppen classification, with a mean temperature of 27.3 °C and a mean annual precipitation of 2240.5 mm (Köppen Brasil, 2025).

Soil of the study area is classified as a Nitossolo Vermelho with a very clayey texture (clay content > 700 g kg⁻¹), according to the Brazilian Soil Classification System (Santos et al., 2018), occurring on gently undulating to undulating terrain and corresponding to a Rhodic Kandudult in the USDA Soil Taxonomy (Soil Survey Staff, 2014). The management systems evaluated in this study were: (1) Pasture (PAS) – *Urochloa* sp. under 40 years of extensive grazing with signs of degradation (exposed soil and invasive plants); (2) a 12-year Agroforestry System with planted native tree species intercropped with seed-propagated cacao (*T. cacao*) (AFS12); (3) a 25-year Agroforestry System with planted native tree species intercropped with *T. cacao* (AFS25); and (4) a fragment of native forest (FOR). Prior to the establishment of AFS12 and AFS25, the entire area was under pasture. Subsequently, part of the area was converted into commercial cacao agroforestry systems, while a fragment remained as pasture.

The pasture area (PAS) has been managed under an extensive grazing system, with continuous grazing and a stocking rate lower than 0.3 AU ha⁻¹. Its land-use history includes forest conversion by clear-cutting and burning, followed by the establishment of *Urochloa* spp. pasture. Since establishment, the area has not received maintenance fertilization, and fire has been used sporadically for invasive plant control. These long-term management practices resulted in a structurally simplified pasture, characterized by continuous herbaceous cover without trees, the occurrence of invasive plant species, exposed soil patches, and clear signs of pasture degradation.

The 25- and 12-year AFS were established in January 1999 and 2012, respectively, using plowing and harrowing operations down to 0.25 m depth, followed by manual planting of *T. cacao* in 40 × 40 × 40 cm pits, spaced 3 × 3 m and intercropped with five native Amazonian tree species at 8 × 6 m spacing (Table 1). During planting, approximately 1.5 L of composted poultry litter was applied to each pit. No chemical fertilization was used. The soil surface in both AFS12 and AFS25 was fully covered by litter.

2.2. Data collection

In each management system, ten independent plots of 300 m² (30 m × 10 m) were established using a stratified random approach, ensuring plot allocation within homogeneous areas of each system and avoiding edges, roads, animal trails, and other atypical microsites. A minimum distance of 30 m between plots was maintained to ensure spatial independence.

During May 2024 (rainy season in the Amazon), undisturbed and disturbed soil samples were collected at 0–0.1, 0.1–0.2, and 0.2–0.4 m depth in each plot. Undisturbed samples, obtained using volumetric soil cores, were used to determine soil bulk density, total porosity, macroporosity, microporosity, and soil moisture, resulting in 10 independent

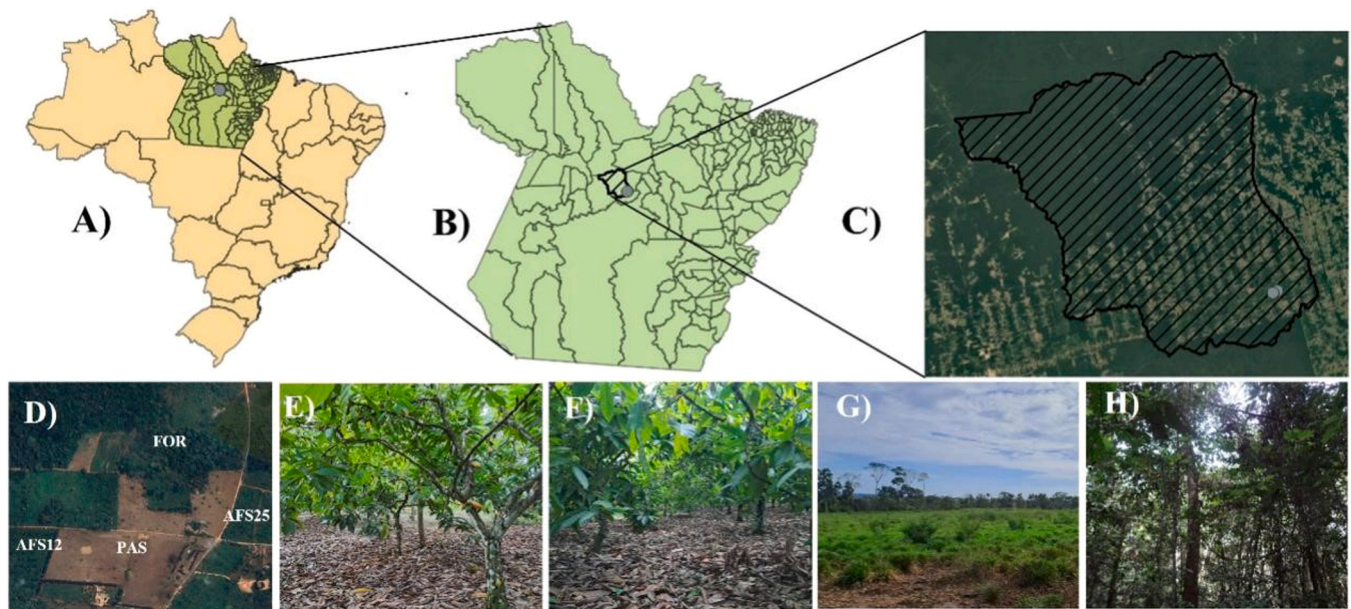


Fig. 1. Location of the study area in Brazil (A), in the state of Pará (B), and in the municipality of Medicilândia (C). Spatial arrangement of the systems in the landscape (D), images of the 12- and 25-year Agroforestry Systems (E and F), pasture (G), and Native Forest (H).

Table 1

Characterization of the land-use systems evaluated in the study: 12- and 25-year-old agroforestry systems (AFS12 and AFS25), conventional pasture (PAS), and native forest (FOR).

System	Area (ha)	Predominant Species	Spatial Arrangement
AFS12	11.3	<i>T. cacao</i> intercropped with native tree species (<i>Khaya ivorensis</i> , <i>Bagassa guianensis</i> , <i>Cedrela odorata</i> , <i>Carapa guianensis</i> , <i>Copaifera langsdorffii</i>).	<i>T. cacao</i> planted at 3 × 3 m spacing, intercropped with native trees in alternating rows at 8 × 6 m spacing; agroforestry system established in 2012.
AFS25	8.64	<i>T. cacao</i> intercropped with native tree species (<i>Khaya ivorensis</i> , <i>Bagassa guianensis</i> , <i>Cedrela odorata</i> , <i>Carapa guianensis</i> , <i>Copaifera langsdorffii</i>).	<i>T. cacao</i> planted at 3 × 3 m spacing, intercropped with native trees in alternating rows at 8 × 6 m spacing; agroforestry system established in 1999.
FOR	8.9	Native Amazon rainforest tree species	Continuous canopy, stratified vertical structure, and floristic diversity characteristic of mature forests.
PAS	17.7	<i>Urochloa</i> sp., with the presence of invasive plant species.	Continuous herbaceous cover without trees; extensive pasture approximately 40 years old, showing signs of degradation (exposed soil and invasive plant species).

samples per system and depth. Disturbed samples collected at the same depths were used to determine soil organic matter and soil organic carbon content, and soil organic carbon stocks were subsequently calculated based on soil organic carbon concentration, bulk density, and layer thickness, also totaling 10 independent samples per system and depth.

In addition, soil penetration resistance, soil macrofauna, and Visual Evaluation of Soil Structure (VESS) were assessed in the field in each plot, resulting in 10 independent samples per variable. All measurements were conducted in the same plots and during the same sampling period.

2.3. Analysis of soil organic matter, carbon stock, and physical attributes

Soil organic matter content was determined from the organic carbon (C org) quantified using the wet oxidation method with potassium dichromate in sulfuric medium, as described by Teixeira et al. (2017). Using the organic carbon values, soil organic matter content was calculated using the formula: soil organic matter content (g kg⁻¹) = C org (g kg⁻¹) × 1.724. The carbon stock was estimated by multiplying the organic carbon percentage (%) by soil bulk density (g cm⁻³) and sampling layer thickness (cm), and subsequently corrected using the equivalent soil mass approach, as described by Ellert and Bettany (1995).

Undisturbed soil samples were collected using 100 cm³ steel cores, from which soil bulk density, total porosity, macroporosity, and microporosity were obtained. Soil bulk density (BD) was determined using the core method. Total porosity (TP) was calculated as TP = (1 - BD/PD), where PD (particle density) was determined using the pycnometer method. Microporosity was obtained from the soil water retention curve at a tension of 6 kPa. Macroporosity was calculated as the difference between total porosity and microporosity. All variables were determined according to the methodology described by Teixeira et al. (2017).

In each plot, soil penetration resistance tests were carried out at 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40 m depth using a Falker Penetrolog. Ten measurements were collected per system. Gravimetric moisture was determined simultaneously with penetration resistance, and the resulting values are presented in Table 2.

Table 2

Mean ± standard deviation of gravimetric moisture in the land-use systems: 12- and 25-year-old agroforestry systems (AFS12 and AFS25), conventional pasture (PAS), and native forest (FOR).

	Gravimetric moisture (%)		
	0-0.1 m	0.1-0.2 m	0.2-0.4 m
AFS12	18.9	17.8	18.0
AFS25	22.6	18.5	7.8
FOR	31.7	25.9	24.1
PAS	13.3	13.4	14.5

2.4. Soil macrofauna analysis and Visual Evaluation of Soil Structure (VESS)

The soil macrofauna was assessed in each plot ($n = 10$) by extracting 0.25×0.25 m monoliths at a 0–0.1 m depth. Macroinvertebrates larger than 2 mm were manually removed down to a 10 cm depth following the method of Aquino (2001), stored in containers with alcohol, and identified at the order level. Macrofauna density in each system was estimated from these data and expressed as the number of individuals per square meter (ind. m^2). The Visual Evaluation of Soil Structure (VESS) was determined by extracting a 0.15×0.20 m soil slice at a 0–0.25 m depth, following the method proposed by Ball et al. (2007).

2.5. Statistical analysis

Data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Bartlett’s test for soil bulk density, total porosity, macroporosity, microporosity, soil organic matter, soil carbon stock, soil penetration resistance, and the Visual Evaluation of Soil Structure. All variables met the assumptions of normality and homoscedasticity ($p > 0.05$). After confirming these assumptions, Analysis of Variance (ANOVA) was performed, and mean comparisons were conducted using Tukey’s test at a 5 % probability level.

Descriptive statistics were applied to the soil macrofauna dataset to summarize patterns of abundance and variability among the evaluated systems prior to multivariate analysis. Principal Component Analysis (PCA) was applied as an exploratory multivariate technique to evaluate patterns of association between soil physical attributes and soil macrofauna across land-use systems. The analysis included the five most abundant soil macrofauna orders, selected based on their relative abundance and ecological representativeness, in combination with selected soil physical attributes.

Soil physical variables were preferentially selected from the most superficial soil layer, where the most pronounced differences among land-use systems were observed, aiming to better capture management-induced changes in soil structure and biological activity. The only exception was the Visual Evaluation of Soil Structure (VESS), which was assessed considering the 0–0.25 m soil layer.

Prior to PCA, all variables were standardized by centering to zero mean and scaling to unit variance (z-score standardization) to minimize the influence of different measurement units and variable magnitudes. PCA was performed using the `prcomp` function with centered and scaled data, and the resulting ordination was used for descriptive and graphical interpretation.

All statistical analyses were conducted using R software (R Core

Team). Normality and homogeneity tests, ANOVA, and Tukey’s test were implemented using functions from the `stats` and `agricolae` packages, while descriptive statistics and PCA were carried out using the `factoextra` and `ggplot2` packages.

3. Results

3.1. Soil organic matter, carbon stock, bulk density, and porosity

At the 0–0.1 m depth, soil organic matter (SOM) contents differed significantly among land-use systems ($p < 0.001$) (Table 3). Native forest (FOR) showed the highest SOM value (54.03 ± 9.41 g kg^{-1}), differing from all other systems. The *T. cacao* agroforestry systems, both at 25 years (AFS25; 38.66 ± 6.59 g kg^{-1}) and 12 years (AFS12; 33.76 ± 4.0 g kg^{-1}), exhibited significantly higher SOM contents than the degraded pasture (PAS; 24.41 ± 3.53 g kg^{-1}). At the 0.1–0.2 m depth, no significant differences were observed among systems ($p = 0.147$), with SOM values ranging from 11 to 20 g kg^{-1} . At the 0.2–0.4 m depth, however, FOR presented higher SOM contents (14.77 ± 5.0 g kg^{-1}) ($p < 0.001$) compared with the other systems.

The soil organic carbon stock (SOCS) showed a pattern similar to that observed for SOM (Table 3). In the surface layer (0–0.1 m), FOR exhibited the highest SOCS (33.08 ± 5.68 Mg ha^{-1}) ($p < 0.001$), followed by AFS25 (23.17 ± 3.38 Mg ha^{-1}) and AFS12 (20.21 ± 2.28 Mg ha^{-1}), whereas PAS presented the lowest carbon stock (14.40 ± 1.93 Mg ha^{-1}). In the 0.1–0.2 m soil layer, SOCS did not vary significantly among the evaluated systems ($p = 0.216$). In the deeper layer (0.2–0.4 m), FOR showed significantly higher SOCS (21.18 ± 7.41 Mg ha^{-1}) ($p = 0.007$) than the other systems, while AFS25, AFS12, and PAS did not differ from each other.

Bulk density (BD) varied significantly among systems ($p < 0.001$), showing an inverse relationship with soil organic matter and carbon stocks (Table 3). In the 0–0.1 m depth layer, PAS exhibited the highest BD (1.55 ± 0.13 kg dm^{-3} ; letter “a”), followed by AFS12 and AFS25 (1.32 ± 0.03 and 1.25 ± 0.07 kg dm^{-3}), whereas FOR showed the lowest value (1.06 ± 0.07 kg dm^{-3}). At a 0.1–0.2 m depth, the same pattern was observed: PAS had the highest values (1.53 ± 0.05 kg dm^{-3}), FOR the lowest (1.15 ± 0.11 kg dm^{-3}), and AFS12 and AFS25 showed intermediate values (1.42 ± 0.04 and 1.41 ± 0.06 kg dm^{-3}). In the 0.2–0.4 m depth layer, no significant differences were observed among AFS12, AFS25, and PAS, with BD ranging from 1.43 to 1.49 kg dm^{-3} , all significantly higher than FOR (1.24 ± 0.05 kg dm^{-3}).

Total porosity (TP) varied significantly among systems at all evaluated depths ($p < 0.001$), showing an inverse trend relative to bulk density (Table 3). At a 0–0.1 m depth, FOR exhibited the highest TP

Table 3

Soil organic matter, soil organic carbon stock, bulk density, total porosity, macroporosity, and microporosity in four land-use systems ($n = 10$; 12- and 25-year-old agroforestry systems – AFS12 and AFS25; conventional pasture – PAS; and native forest – FOR) at the 0–0.1, 0.1–0.2, and 0.2–0.4 m depths in the Amazon, Brazil. Different letters within each column indicate statistically significant differences at the 5 % level ($p < 0.05$) according to Tukey’s test.

Systems	Soil organic matter	Soil organic carbon stock	Bulk density	Total porosity	Macroporosity	Microporosity
	g kg^{-1} 0–0.1 m	t ha^{-1}	kg dm^{-3}	m ³ m ⁻³		
AFS12	33.76 ± 3.98 b	20.21 ± 2.28 b	1.32 ± 0.03 b	0.51 ± 0.01 b	0.22 ± 0.03 b	0.29 ± 0.02 ab
AFS25	38.66 ± 6.59 b	23.17 ± 3.38 b	1.25 ± 0.07 b	0.53 ± 0.03 b	0.24 ± 0.03 ab	0.29 ± 0.03 b
FOR	54.03 ± 9.41 a	33.08 ± 5.68 a	1.06 ± 0.07c	0.61 ± 0.02 a	0.28 ± 0.05 a	0.33 ± 0.03 a
PAS	24.41 ± 3.53c	14.4 ± 1.93c	1.55 ± 0.13 a	0.41 ± 0.06c	0.2 ± 0.03 b	0.21 ± 0.05c
AFS12	16.54 ± 6.23 a	11.01 ± 4.1 a	1.42 ± 0.04 b	0.48 ± 0.02 b	0.2 ± 0.03 b	0.29 ± 0.01 ab
AFS25	18.5 ± 8.27 a	12.27 ± 5.02 a	1.41 ± 0.06 b	0.49 ± 0.01 b	0.23 ± 0.02 ab	0.25 ± 0.03 bc
FOR	20.83 ± 6.73 a	14.01 ± 4.93 a	1.15 ± 0.11c	0.57 ± 0.04 a	0.27 ± 0.05 a	0.3 ± 0.02 a
PAS	11.57 ± 5.31 a	7.66 ± 3.46 a	1.53 ± 0.05 a	0.41 ± 0.02c	0.19 ± 0.04 b	0.22 ± 0.02c
AFS12	8.9 ± 2.98 b	12.68 ± 4.28 b	1.43 ± 0.07 a	0.49 ± 0.03 b	0.22 ± 0.04 a	0.27 ± 0.03 ab
AFS25	8.26 ± 3.87 b	11.69 ± 5.26 b	1.46 ± 0.08 a	0.49 ± 0.04 b	0.21 ± 0.04 a	0.26 ± 0.02 bc
FOR	14.77 ± 5.01 a	21.18 ± 7.41 a	1.24 ± 0.05 b	0.49 ± 0.05 a	0.24 ± 0.04 a	0.32 ± 0.03 a
PAS	5.95 ± 4.17 b	8.45 ± 5.93 b	1.49 ± 0.06 a	0.49 ± 0.06c	0.21 ± 0.03 a	0.22 ± 0.01 c

($0.61 \pm 0.02 \text{ m}^3 \text{ m}^{-3}$), followed by AFS12 and AFS25 (0.51 ± 0.01 and $0.53 \pm 0.03 \text{ m}^3 \text{ m}^{-3}$), while PAS showed the lowest value ($0.41 \pm 0.06 \text{ m}^3 \text{ m}^{-3}$). At a 0.1–0.2 m depth, the same pattern was observed: FOR had the highest porosity ($0.57 \pm 0.04 \text{ m}^3 \text{ m}^{-3}$), AFS12 and AFS25 showed intermediate values (0.48 ± 0.02 and $0.49 \pm 0.01 \text{ m}^3 \text{ m}^{-3}$), and PAS remained the lowest ($0.41 \pm 0.02 \text{ m}^3 \text{ m}^{-3}$). At a 0.2–0.4 m depth, FOR again showed the highest TP ($0.56 \pm 0.02 \text{ m}^3 \text{ m}^{-3}$), followed by AFS12 and AFS25 (0.49 ± 0.03 and $0.47 \pm 0.03 \text{ m}^3 \text{ m}^{-3}$), and finally PAS ($0.43 \pm 0.03 \text{ m}^3 \text{ m}^{-3}$).

Macroporosity (Macro) showed significant differences among systems ($p < 0.001$) in the surface layers (Table 3e). At a 0–0.1 m depth, FOR and AFS25 did not differ from each other (0.28 ± 0.05 and $0.24 \pm 0.03 \text{ m}^3 \text{ m}^{-3}$), and FOR was significantly higher than AFS12 and PAS (0.22 ± 0.03 and $0.20 \pm 0.03 \text{ m}^3 \text{ m}^{-3}$). At a 0.1–0.2 m depth, FOR and AFS25 again did not differ significantly (0.27 ± 0.05 and $0.24 \pm 0.02 \text{ m}^3 \text{ m}^{-3}$), with FOR remaining significantly higher than AFS12 and PAS (0.20 ± 0.03 and $0.19 \pm 0.04 \text{ m}^3 \text{ m}^{-3}$). At a 0.2–0.4 m depth, no significant differences were observed among systems ($p = 0.45$).

Microporosity (Micro) showed less variation among systems compared with macroporosity; however, significant differences were still observed at some depths ($p < 0.001$) (Table 3f). At the 0–0.1 m depth, FOR and AFS12 did not differ (0.33 ± 0.03 and $0.29 \pm 0.02 \text{ m}^3 \text{ m}^{-3}$, respectively), and FOR exhibited significantly higher microporosity than PAS ($0.21 \pm 0.05 \text{ m}^3 \text{ m}^{-3}$). At the 0–0.2 m and 0.2–0.4 m depths, PAS showed significantly lower microporosity compared with AFS12 and FOR.

3.2. Penetration resistance and Visual Evaluation of Soil Structure (VESS)

Soil mechanical penetration resistance showed marked differences among systems and increased with depth across all conditions (Fig. 2a). PAS exhibited high resistance already at the surface layer (> 2.0 MPa at a 0.05 m depth) and reached values above 3.5 MPa from a 0.15 m depth onward, remaining significantly higher than the other systems ($p < 0.001$), except at a 0.35 m depth, where it did not differ from AFS12 ($p = 0.003$). AFS12, AFS25, and FOR showed low initial values (< 1.0 MPa at a 0.05 m depth), increasing gradually with depth to approximately 2.0 MPa at a 0.35–0.40 m depth, indicating lower restriction to root growth.

VESS values at a 0–0.25 m depth differed significantly among systems ($p < 0.001$) (Fig. 2). PAS exhibited the poorest structural condition (3.98 ± 0.36), indicating a more compacted soil with low friability and reduced expression of biopores. In contrast, AFS12, AFS25, and FOR showed significantly lower values (2.63 ± 0.32 ; 2.65 ± 0.23 ; 2.42

± 0.36), corresponding to moderate to good structural quality, with greater aggregation, higher visible porosity, and increased biological activity associated with the formation of biopores.

3.3. Soil macrofauna

Total soil macrofauna abundance varied among systems, with the highest value observed in AFS25 ($377.6 \pm 287.5 \text{ ind. m}^{-2}$), followed by AFS12 ($302.4 \pm 109.2 \text{ ind. m}^{-2}$) and FOR ($288 \pm 221.8 \text{ ind. m}^{-2}$). PAS recorded the lowest abundance ($96 \pm 119.5 \text{ ind. m}^{-2}$) (Table 4). Among the dominant groups, earthworms (Haplotaxida) were more abundant in AFS12 and AFS25 (176 ± 71.2 and $161.6 \pm 25.5 \text{ ind. m}^{-2}$), although they still represented an important component of the fauna in the forest ($81.6 \pm 66.8 \text{ ind. m}^{-2}$), a value higher than that recorded in PAS ($57.6 \pm 59.0 \text{ ind. m}^{-2}$).

Blattodea (Isoptera) were most numerous in AFS25 ($134.4 \pm 304.9 \text{ ind. m}^{-2}$), although the Forest also showed expressive values ($67.2 \pm 90.4 \text{ ind. m}^{-2}$), contrasting with the lower averages observed in AFS12 ($22.4 \pm 39.3 \text{ ind. m}^{-2}$) and PAS ($24 \pm 75.9 \text{ ind. m}^{-2}$). The Forest stood out for having the greatest number of predator and decomposer orders, with the highest means for Geophilomorpha ($24 \pm 25.3 \text{ ind. m}^{-2}$) and Coleoptera ($30.4 \pm 23.2 \text{ ind. m}^{-2}$). Hymenoptera, including ants, were recorded in all systems, but the Forest again exhibited the highest mean ($38.4 \pm 100.1 \text{ ind. m}^{-2}$), whereas AFS12 ($19.2 \pm 29.0 \text{ ind. m}^{-2}$), AFS25 ($14.4 \pm 11.8 \text{ ind. m}^{-2}$), and PAS ($14.4 \pm 27.7 \text{ ind. m}^{-2}$) showed lower values.

Other groups with restricted occurrence, such as Trichoptera, Polydesmida, and Hemiptera, were recorded only in the Forest, highlighting its role as the most diverse habitat. In contrast, PAS exhibited the lowest number of orders and the lowest individual abundance, with a complete absence of orders such as Araneae, Coleoptera, Geophilomorpha, Isoptera, and Stylommatophora, reflecting the biological simplification of the degraded extensive pasture system.

3.4. Relationship between soil physical and biological attributes

Principal Component Analysis (PCA) explained 61.9 % of the total variation, with 48.4 % accounted for by Axis 1 (Dim1) and 13.5 % by Axis 2 (Dim2) (Fig. 3). The ordination is interpreted in a descriptive and exploratory manner, reflecting multivariate patterns of association among soil physical attributes and soil macrofauna across land-use systems. Axis 1 clearly separated the land-use systems, positioning the degraded pasture (PAS) on the left side of the ordination. This system was associated with higher soil bulk density (BD), greater penetration resistance at 0.05 m (PR5) and 0.10 m (PR10), as well as lower VESS

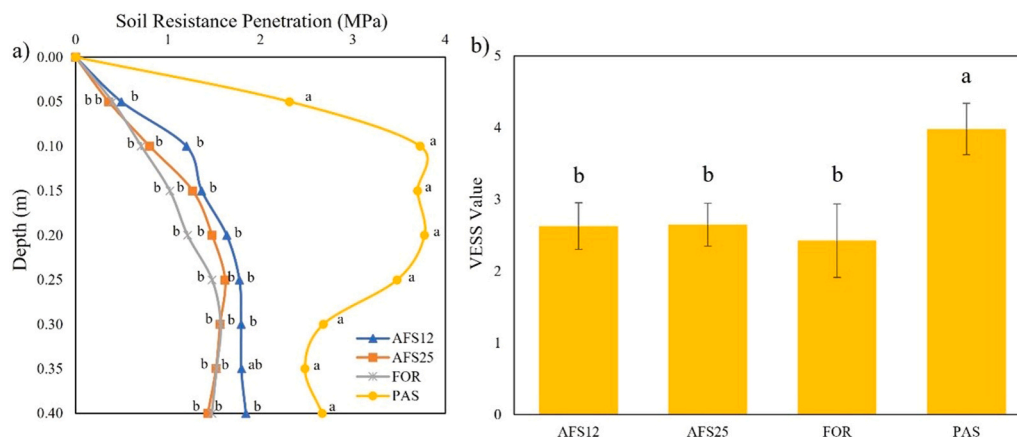


Fig. 2. Soil penetration resistance in MPa at a 0–0.4 m depth (a) and Visual Evaluation of Soil Structure (VESS) at a 0–0.25 m depth (b) in four systems ($n = 10$; 12- and 25-year agroforestry systems – AFS12 and AFS25; conventional pasture – PAS; and native forest – FOR). Equal letters within each depth indicate no statistical differences at the 5 % significance level according to Tukey's test.

Table 4

Mean ± SD of soil macrofauna density (individuals m⁻²) at a 0.10 m depth in four land-use systems (n = 10; 12- and 25-year-old agroforestry systems – AFS12 and AFS25; conventional pasture – PAS; and native forest – FOR) in the Amazon, Brazil, organized by functional groups (ecosystem engineers, predators, and decomposers/detritivores).

Functional group	Taxonomic groups (orders)	AFS12	AFS25	FOR	PAS
Ecosystem engineers	Haplotaxida	176 ± 71.2	161.6 ± 25.5	81.6 ± 66.8	57.6 ± 59
	Blattodea	22.4 ± 39.3	134.4 ± 304.9	67.2 ± 90.4	24 ± 75.9
	(Isoptera)	12.8 ± 30	0 ± 0	0 ± 0	0 ± 0
	Isopoda	9.6 ± 13.5	6.4 ± 11.2	8 ± 11.3	0 ± 0
Predators	Araneae	4.8 ± 7.7	38.4 ± 15.5	17.6 ± 21.9	0 ± 0
	Scolopendrida	19.2 ± 34.4	0 ± 0	24 ± 25.3	0 ± 0
	Geophilomorpha	0 ± 0	1.6 ± 5.1	3.2 ± 6.7	0 ± 0
	Hemiptera	17.6 ± 29.6	16 ± 21.3	30.4 ± 23.2	0 ± 0
	Coleoptera	19.2 ± 29	14.4 ± 11.8	38.4 ± 100.1	14.4 ± 27.7
Decomposers / detritivores	Stylommatophora	8 ± 13.6	3.2 ± 10.1	1.6 ± 5.1	0 ± 0
	Diptera	1.6 ± 5.1	0 ± 0	3.2 ± 10.1	0 ± 0
	Lepidóptera	6.4 ± 11.2	0 ± 0	3.2 ± 6.7	0 ± 0
	Polydesmida	0 ± 0	0 ± 0	1.6 ± 5.1	0 ± 0
	Trichoptera	0 ± 0	0 ± 0	3.2 ± 6.7	0 ± 0
	Oribatida	1.6 ± 5.1	0 ± 0	0 ± 0	0 ± 0
	Thysanoptera	1.6 ± 5.1	0 ± 0	4.8 ± 15.2	0 ± 0
	Rhabditida	1.6 ± 5.1	0 ± 0	0 ± 0	0 ± 0
	Siphonaptera	0 ± 0	1.6 ± 5.1	0 ± 0	0 ± 0
	Abundance	302.4 ± 109.2	377.6 ± 287.5	288 ± 221.8	96 ± 119.5

scores.

On the positive side of Axis 1, the native forest (FOR) and the agroforestry systems (AFS12 and AFS25) were grouped, associated with higher total porosity (TP), macroporosity (Macro), microporosity (Micro), soil organic matter (SOM), and soil organic carbon stock (SOCS). These systems were also associated with the macrofauna orders Haplotaxida (Haplo), Hymenoptera (Hyme), and Coleoptera (Coleo), indicating more favorable soil physical and biological conditions.

Axis 2 contributed to the vertical differentiation among systems, highlighting AFS25 in the upper region of the ordination. This system was associated with total macrofauna abundance (Abd) and the orders Blattodea (Blatt) and Scolopendrida (Scolo). However, given the inherently high spatial variability of soil macrofauna abundance, these associations should be interpreted with caution, as they may reflect local heterogeneity rather than consistent system-level patterns. AFS12 and the native forest (FOR) remained close in the PCA plane, while the degraded pasture (PAS) remained isolated from the other systems.

Importantly, the PCA does not imply temporal trajectories or strict causal relationships among land-use systems, but rather summarizes patterns of multivariate similarity and contrast within the evaluated dataset.

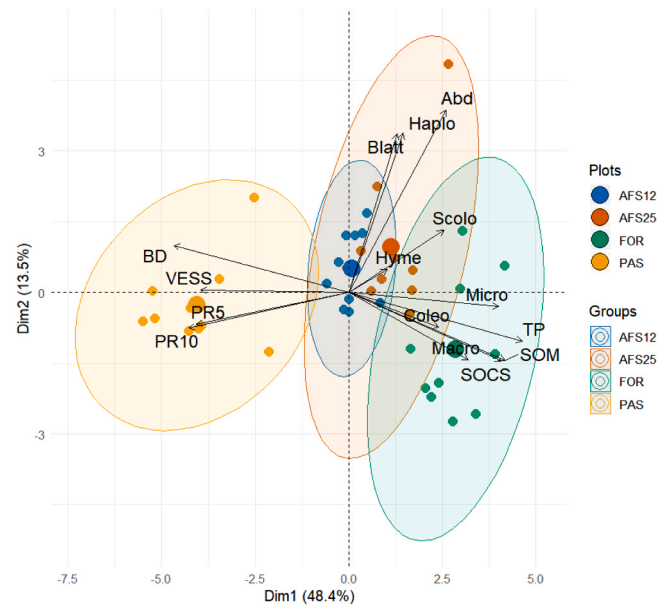


Fig. 3. Principal Component Analysis (PCA) of soil physical attributes, soil organic matter (SOM), soil organic carbon stock (SOCS), soil bulk density (BD), total porosity (TP), macroporosity (Macro), and microporosity (Micro), and the five most abundant soil macrofauna orders: Haplotaxida (Haplo), Blattodea (Blatt), Hymenoptera (Hyme), Coleoptera (Coleo), and Scolopendrida (Scolo), as well as total abundance (Abd). Soil penetration resistance was evaluated at depths of 0.05 m (PR5) and 0.10 m (PR10), and the Visual Evaluation of Soil Structure (VESS) at a depth of 0–0.25 m. The analysis was conducted for four land-use systems (n = 10): 12- and 25-year-old agroforestry systems (AFS12 and AFS25), conventional pasture (PAS), and native forest (FOR), in the Amazon region, Brazil.

4. Discussion

4.1. Recovery of soil organic matter and carbon stock in cocoa agroforestry systems

Within twelve years, the AFS12 system promoted significant increases in soil organic matter (SOM) and soil organic carbon stock (SOCS) in the surface layer compared with the pasture (PAS) (Table 3). During this period, these attributes had already reached levels comparable to those observed in AFS25 at a 0–0.1 m depth. These results are mainly attributed to the accumulation of litter on the soil surface from the components of cocoa agroforestry systems (Sauvadet et al., 2019), which favors the incorporation of organic matter at the surface (Brasil Neto et al., 2025; Souza et al., 2025b). Cocoa agroforestry systems recover organic matter and carbon stock in soils previously occupied by degraded pastures (Suárez et al., 2021). In contrast, the lower SOM content and carbon stock in PAS are primarily due to exposed soil areas, typical of degraded extensive pastures, which increase organic matter losses through oxidation (Rocha et al., 2016; Brasil Neto et al., 2021). In subsurface layers, the effect of land use was less pronounced. Pereira et al. (2025) emphasize that the impacts of agroforestry land use are more evident in surface layers, whereas subsurface layers are mainly influenced by pedogenetic processes.

The higher soil organic matter content and greater carbon stock observed in the native forest (FOR), compared with the AFS12 and AFS25 agroforestry systems, are likely related to the maturity and high diversity of this ecosystem, as forests exhibit more complex and specific biogeochemical cycles and dynamics (Souza et al., 2025a). However, the results obtained in the agroforestry systems indicate that within only twelve years it is already possible to achieve substantial improvements in surface-layer organic matter accumulation and carbon stock, reflecting rapid beneficial changes for soil recovery compared with

pasture.

4.2. Improvements in soil physical properties

The conversion of extensive pasture into agroforestry systems (AFSs) promoted marked changes in soil physical structure, evidenced by reduced soil bulk density and increased total porosity at the surface (Table 3). These attributes are critical for aeration, water infiltration, and root growth, which were severely compromised in the pasture system, as soil compaction is one of the main degradation factors in extensive pasture areas (Rocha et al., 2016; Brasil Neto et al., 2021). As a direct reflection of this compaction, mechanical resistance to penetration showed pronounced contrasts between systems: in pasture, values exceeded critical limits (>2 MPa), indicating restriction to root growth, which is generally associated with animal trampling (Lai and Kumar, 2020), exposed soil areas, and reduced soil moisture (Bengough et al., 2011; Suzuki et al., 2024). In contrast, values observed in the AFSs and native forest were significantly lower, reinforcing that the recovery of soil physical properties was promoted by converting pasture into cocoa agroforestry systems.

In the 12- and 25-year-old AFSs, total porosity increased significantly, with a trend toward higher macro- and microporosity at the surface compared with pasture. These improvements were directly associated with better VESS scores, reflecting the presence of porous, rounded aggregates between 2 mm and 7 cm without clods in the 0–0.1 m layer (VESS 2), and a mixture of porous aggregates between 2 mm and 10 cm with less than 30 % smaller than 1 cm and some clods from 0.1 m depth (VESS 3), according to Ball et al. (2007). These findings indicate that agroforestry systems promoted soil aggregation and structuring in previously extensive pasture.

The pasture remnant exhibited the lowest total porosity, highlighting the negative impact of animal trampling and exposed soil areas typical of degraded pastures in the Amazon (Brasil Neto et al., 2021). In contrast, the structural improvements observed in AFS12 and AFS25 are consistent with enhanced vegetation cover, increased soil organic matter, and greater soil biological activity, all of which contribute to aggregate formation and stabilization (Suárez et al., 2021; Rodríguez et al., 2021a). These results confirm that replacing degraded pastures with *Theobroma cacao* agroforestry systems not only mitigates soil compaction but also restores physical conditions essential for maintaining soil ecosystem functions. Furthermore, the improvement in soil structural quality observed in the AFSs corroborates findings from other studies conducted in the region (Suárez et al., 2021; Rodríguez et al., 2021; Souza et al., 2025a), demonstrating the effectiveness of AFSs in promoting physical soil recovery in degraded Amazonian landscapes.

4.3. Ecological resilience mediated by soil macrofauna

Soil macrofauna is a sensitive bioindicator of soil quality, responding rapidly to changes in land use and management (Brasil Neto et al., 2021; Chiappero et al., 2024). In this study, the abundance and number of macroinvertebrate orders were significantly higher in the agroforestry systems compared to degraded pasture, approaching the values observed in the native forest. These results demonstrate that the conversion of pasture into agroforestry systems contributes to the restoration of soil macrofauna communities.

Earthworms (Haplotaxida) stood out as the dominant group, particularly in AFS12 and AFS25, playing a key role in bioturbation, aggregate formation, and nutrient cycling (Insfrán Ortiz et al., 2023). Their higher abundance in the agroforestry systems indicates that the diversified vegetation cover and organic inputs promote the reestablishment of conditions favorable for their survival and activity.

Termites (Isoptera) were more abundant in AFS25, suggesting that system maturity promotes their colonization and expansion. As ecosystem engineers, they contribute to organic matter decomposition and, through gallery formation, enhance soil physical quality and water

infiltration (Garg et al., 2023; Wu et al., 2025; Duran-Bautista et al., 2025).

The increase of soil predator groups, such as Araneae, Scolopendrida, Geophilomorpha, and some Hymenoptera, serves as an indicator of functional ecosystem restoration (Serra et al., 2021). These organisms require a sufficiently structured trophic base, composed of detritivores, herbivores, and ecosystem engineers, to support higher trophic levels (Potapov et al., 2022). In the present study, the presence of these predators in the native forest and, to a lesser extent, in the SAFs contrasts sharply with their absence in the pasture. This distribution demonstrates that the SAFs, especially AFS25, already exhibit trophic complexity capable of sustaining specialized predators, whereas the pasture remains in a degraded state, lacking the biological structure necessary to support this component of the soil community.

These results also highlight the codependence between established vegetation and soil quality. As vegetation develops, environmental heterogeneity and resource inputs, such as litter, nutrients, fine roots, and microhabitats, increase, supporting the lower trophic levels of the soil macrofauna (Mamabolo et al., 2024; Awazi et al., 2025; Medeiros-Sarmento et al., 2025). These organisms, in turn, facilitate the establishment of predators and ecosystem engineers, which enhance organic matter decomposition and soil structural reorganization (Potapov et al., 2022). This feedback process continuously contributes to vegetation regeneration and maintenance, forming a cycle essential for the functionality and resilience of agroecosystems (Sanghaw et al., 2023). It is important to acknowledge that macrofauna was identified only at the order level and sampled in a single soil depth, which restricts functional and biodiversity interpretations.

4.4. Influence of SAF age and integration of soil physical and biological attributes

Principal Component Analysis (PCA) revealed a clear distinction among the land-use systems, reflecting the degradation–environmental recovery gradient. Axis 1 explained most of the total variation and positioned the degraded pasture (PAS) alone on the left side of the diagram, while the agroforestry systems (AFS12 and AFS25) and the native forest (FOR) clustered on the right. This spatial arrangement indicates that AFSs, regardless of stand age, display soil physical and biological conditions more similar to native forest than to degraded pasture, highlighting their role as intermediate systems that restore surface soil quality (Suárez et al., 2021).

Variables with the highest positive loadings on Axis 1 (total porosity – TP, macroporosity – Macro, microporosity – Micro, soil organic matter – SOM, and soil organic carbon stock – SOCS) were key in grouping the AFSs and the forest. These variables indicate structural improvements and increases in carbon and organic matter content, directly associated with the reactivation of the soil biota. Furthermore, the abundance of functional groups such as Haplotaxida (earthworms), Hymenoptera (ants), and Isopoda (termites), which were positively correlated with the axis, reinforces the role of soil organisms in maintaining and restoring soil physical properties (Demetrio et al., 2024).

AFS25 exhibited a more pronounced displacement along Axis 2, reflecting its higher total abundance of soil macrofauna and the notable presence of Isoptera, a group widely recognized for contributing to soil structural quality (Garg et al., 2023; Wu et al., 2025; Duran-Bautista et al., 2025). This result supports the interpretation that longer establishment periods promote greater trophic complexity and environmental heterogeneity, signaling the consolidation of more mature ecological processes (Vicente et al., 2010). In contrast, AFS12 occupied an intermediate position between pasture and native forest, showing consistent improvements in soil physical and biological attributes over twelve years, although it still represents an early stage in the restoration gradient compared to AFS25.

The degraded pasture (PAS) remained clearly separated from the other systems and associated with variables indicative of degradation,

such as high soil bulk density (BD), greater penetration resistance (PR5 and PR10), and poorer structural scores (VESS). This configuration demonstrates that compaction, loss of porosity, and reduced biological activity continue to dominate pasture functioning, compromising fundamental processes such as water infiltration, aeration, and nutrient cycling (Rocha et al., 2016; Lai and Kumar, 2020). The absence of key soil fauna groups in PAS further highlights the collapse of basic ecological functions typical of soils subjected to long periods of intensive grazing (Brasil Neto et al., 2021).

The PCA highlights that the recovery trajectory promoted by *T. cacao* agroforestry systems (AFSs) drives the system toward the ecological and functional condition of native forest, characterized by a greater balance between physical and biological attributes. The progression from pasture to AFS12 and then AFS25 underscores the importance of establishment time in consolidating soil structural recovery and bio-complexity, conferring ecological value and resilience potential to AFSs in degraded Amazonian landscapes. These patterns, however, should be interpreted as part of a restoration gradient rather than as evidence of temporal convergence between AFS12 and AFS25 or between AFSs and native forest, given the observational nature of the chronosequence.

This study presents several methodological and conceptual strengths regarding soil recovery in tropical landscapes of the Amazon. First, the integrated use of soil physical (BD, PR, TP, Macro, Micro, VESS) and biological indicators (abundance and functional groups of soil macrofauna) represents a comprehensive diagnostic approach capable of capturing multiple dimensions of soil functioning along the degradation–recovery gradient (Brasil Neto et al., 2021). Second, the inclusion of agroforestry systems of different ages (AFS12 and AFS25) strengthens the interpretation of restoration dynamics, allowing the identification of progressive ecological trajectories under real management conditions (Souza et al., 2025a). Third, the adoption of degraded pasture (PAS) and native forest (FOR) as reference points provides a clear ecological framework to contextualize the magnitude and direction of changes observed in the AFSs. (Suárez et al., 2021). Additionally, the field-based and in situ nature of the assessment increases ecological validity, reflecting actual soil processes, land-use history, and management legacies typical of Amazonian production landscapes. Collectively, these strengths enhance the relevance of the findings for sustainable land management, evidence-based decision making, and the design of restoration strategies targeting degraded agricultural areas in tropical regions (Brasil et al., 2021; Rodriguez et al., 2021a).

4.5. Implications for Sustainable Management and Public Policy

The results of this study are highly relevant for sustainable management strategies and the development of public policies in the Amazon. The conversion of degraded pastures into *T. cacao* agroforestry systems (AFSs) has proven to be a solution that reconciles agricultural production with environmental restoration, contributing to the recovery of essential soil functions for sustainability, as also reported by Schroth et al. (2016) and Suárez et al. (2021).

From an environmental perspective, the recovery of carbon stocks, soil physical structure, and soil macrofauna enhances the contribution of agroforestry systems (AFSs) to climate mitigation, water conservation, and fertility maintenance (Rodríguez et al., 2021a; Rodríguez et al., 2021b). This suite of benefits positions AFSs strategically to integrate into initiatives and mechanisms that value ecosystem services. It is important to acknowledge, however, that ecosystem service implications discussed here are based solely on soil-related indicators, representing only a partial and indirect assessment of broader ecosystem functions.

Public policies promoting AFSs, combined with technical assistance and access to differentiated markets, can significantly increase the adoption of this model in the Amazon, particularly for the restoration of areas previously occupied by degraded pastures (Schroth et al., 2016). Thus, from a soil perspective, cocoa-based agroforestry systems (*T. cacao*

AFSs) should be considered a key policy for the environmental restoration of degraded pastures in the Amazon. Strengthening this strategy represents a concrete pathway to reconcile development and conservation in the region.

5. Conclusion

The conversion of degraded pastures into commercial cocoa-based agroforestry systems (AFSs) promoted substantial improvements in soil physical and biological properties at the surface, demonstrating their effectiveness as an environmental recovery strategy in the Amazon. After 12 years, AFSs increased soil organic matter, carbon stock, and porosity while reducing bulk density and penetration resistance in the 0–0.1 m depth, approaching native forest conditions, whereas 25-year-old systems supported greater macrofauna abundance, functional groups, and taxonomic richness, indicating advanced structural and biological recovery. Multivariate analysis revealed a clear degradation–recovery gradient, confirming that stand age is a decisive driver of soil restoration and that AFSs function as intermediate systems progressively converging toward forest-reference conditions. These improvements reflect enhanced soil structure, carbon accumulation, and biological activity, evidencing the ecosystem services derived from soil-based indicators. The results strongly support the need for public policies, such as technical assistance, credit mechanisms, and ecosystem-service valuation, to accelerate recovery and expand the adoption of cocoa-based agroforestry systems, thereby strengthening the long-term sustainability of productive Amazonian landscapes.

CRedit authorship contribution statement

Sandra Andrea Santos da Silva: Writing – review & editing, Validation, Methodology, Conceptualization. **Josiane Martins de Queiroz Xavier Silveira:** Writing – original draft, Writing – review & editing. **Eduardo Jorge Maklouf Carvalho:** Validation, Resources, Methodology, Formal analysis, Data curation. **Alberto Bentes Brasil Neto:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Vivian Dielly da Silva Farias:** Writing – review & editing, Methodology, Conceptualization. **Norberto Cornejo Noronha:** Writing – review & editing, Methodology, Conceptualization. **Nilza Martins de Queiroz Xavier Brasil:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization.

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

The data that has been used is confidential.

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