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Integrated Systems Under No-Tillage, and Improved Pastures: One Pathway Toward Restoring Soil Carbon and Organic Matter Pools in the Brazilian Semi-Arid Region

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ABSTRACT

In Brazil, the semi-arid region has undergone significant degradation due to deforestation for agriculture, livestock and the use of firewood. In this context, nature-based solutions (NbS) that prioritize environmental sustainability in semi-arid regions are crucial. Thus, this study aimed to evaluate the impact of the conversion from native vegetation (dense Caatinga) to improved and degraded pastures, and integrated livestock-forestry (ILF) systems under conventional and no-tillage (NT). Soil samples were collected to a depth of 1 m in 5 different land uses: native vegetation (NV), ILFsystem with gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) + signal grass (*Urochloa decumbens* (Stapf) R.D. Webster) (ILFug) under NT for 8 years, an ILF system with gliricidia + forage cactus (*Opuntia cochenillifera* (Linnaeus) Miller) (ILFcg) under conventional tillage for 12 years, improved pasture (ImpP) and degraded pasture (DegP), both having been established for 15 years. SOC stocks, water-stable aggregates (WSA), microbial biomass carbon (MB-C), SOM pools and soil carbon indices were analysed. The ILFug system under NT showed the highest stocks of mineral-associated organic matter, at all soil depths, resulting in increased SOC stocks, thus placing this system with the greatest SOC stock of 112.92 Mg ha^{-1}, which represents a 21.8% increase compared to NV. The DegP presented the lowest soil quality among the studied systems, as evidenced by reduced particulate organic matter, MB-C, WSA and carbon management index. By promoting practices that enhance carbon sequestration, reduce greenhouse gas emissions and improve ecosystem resilience, NbS provides a sustainable approach to mitigating the impacts of climate change, while supporting local communities in the semi-arid.

1 | Introduction

In Brazil, the semi-arid regions are predominantly situated in the northeastern part of the country. This area is characterized by housing most of the exclusively Brazilian biome named Caatinga, which consists of thorny shrubs, cacti, drought-resistant trees, dry seasons and limited rainfall (Araújo and Tabarelli 2002; Maia et al. 2007). The Caatinga biodiversity is vital for the Brazilian semi-arid ecosystem functioning, particularly regarding carbon cycling and soil health. Studies show that intact Caatinga vegetation maintains soil organic matter (SOM) levels and promotes carbon sequestration, resulting in

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greater soil organic carbon (SOC) stocks in the semi-arid region (Althoff et al. 2018; Menezes et al. 2021; Medeiros, Soares, and Maia 2022).

However, the soils of this region have undergone significant degradation due to deforestation for agriculture, livestock and the use of firewood (Althoff et al. 2018; Maia et al. 2025). Under conventional tillage, these soils lose organic matter very rapidly, as well as substantial losses of SOC stocks, microbial biomass carbon (MB-C) and labile and recalcitrant carbon fractions have been documented (Maia et al. 2025; Medeiros, Soares, and Maia 2022). For example, Medeiros, Soares, and Maia (2022) found that after only 4 years of deforestation for conventional tillage on a semiarid sandy soil, 75.5% (5.77 Mg C ha^{-1}) of the labile carbon stock was lost in the top 30 cm of soil. In semiarid regions, the labile carbon fraction is nearly entirely oxidized under conventional management and degradation processes, far exceeding the losses typically observed in more humid Brazilian ecosystems.

Additionally, this swift depletion of labile carbon reduces the substrate available to sustain soil microorganisms, which reduces MB-C, since microbial biomass depends on these labile substrates for growth and activity (Camelo et al. 2021; Gao et al. 2023; Souza et al. 2025). Several studies have observed that degraded soils in semi-arid regions are characterized by MB-C concentrations generally remaining below 130 mg kg^{-1} in surface soil layers (Neves et al. 2021; Souza et al. 2025), corresponding to < 50% of the concentrations commonly reported for other humid ecosystems. Soil microbial biomass, although comprising only a minor fraction of total SOM, represents its most biologically active component and is widely regarded as one of the most important indicators of soil quality (dos Santos et al. 2025; Maia et al. 2025; Souza et al. 2025) and plays a central role in the decomposition of organic residues, nutrient cycling and mineralization (Camelo et al. 2021; Souza et al. 2025).

The rapid carbon loss, coupled with severe climatic conditions, is a key driver of desertification in the Brazilian semi-arid region. Sousa et al. (2012) and Tomasella et al. (2018) highlight an increasing trend of desertification in the Brazilian semi-arid region, which presents significant challenges for biodiversity, as the Caatinga biome demonstrates limited capacity to adapt to climatic changes over time. Vieira et al. (2021) project a 53% expansion in areas at high risk of desertification in the Brazilian semi-arid region by 2040, driven primarily by land use management under various climatic scenarios. The Brazilian semi-arid zone is expanding, resulting in increased aridity and the emergence of arid hotspots, with previously humid areas in the country transitioning to semi-arid conditions (da Silva et al. 2023). Nevertheless, the desertification process can be restrained by exploring agricultural practices that prioritize environmental sustainability in semi-arid regions.

In this context, nature-based solutions (NbS) have shown potential to address desertification, soil degradation and improve SOC, including actions such as ecosystem restoration, sustainable land management and conservation practices that aim to provide ecological benefits while enhancing resilience against climate-related stressors (Girardin et al. 2021; Soterroni et al. 2023). Integrated systems and well-managed pastures illustrate NbS that can rebuild SOC to improve soil health and SOM. Recent work in a Cerrado (Brazilian Savanna)-Caatinga transition zone showed that converting low-productive pastures into agrosilvopastoral systems under no-tillage (NT) restored SOC to levels comparable with native vegetation, with annual carbon accruals of 1.0 to 4.3 Mg C ha^{-1} $year^{-1}$ (Freitas et al. 2022). Therefore, NT systems play a crucial role in securing these gains. Sá et al. (2025) indicated that NT systems in Brazil often recover 80% to 100% of the original native SOC stock and, in some cases, can exhibit SOC stocks that exceed those under native vegetation. Unfortunately, despite this proven potential, NT remains rare in the semi-arid region, since only 20.1% of croplands were under NT in 2017 (Fuentes-Llanillo et al. 2021). This issue is connected to the extended drought that occurred from 2012 to 2017, which resulted in a significant decrease in both the number of farms under NT and the overall area under this system, due to the challenges of managing crops under NT on smallholdings with degraded soils (Fuentes-Llanillo et al. 2021). Nonetheless, deeper structural constraints as difficulty in maintaining residue cover, challenging relief and soils, low levels of formal education among many producers, and weak extension and credit access, limit farmers' capacity and willingness to invest in long-term conservation practices, which contributes to the persistently low NT adoption in the semi-arid.

In essence, by avoiding soil disturbance and keeping residues on the surface, NT systems can rebuild SOC nearly back to baseline, given sufficient time (Sá et al. 2025). Simultaneously, NT promotes the formation and stability of soil aggregates, particularly macroaggregates that occlude particulate organic matter (POM) and facilitate subsequent conversion into mineral-associated organic matter (MAOM) (Abiven et al. 2009; Plaza-Bonilla et al. 2013; Okolo et al. 2020). This mechanism enhances the physical protection of SOM from decomposition, increases carbon residence time in the soil, and supports the long-term sequestration of atmospheric carbon in stable soil organic matter pools (Álvaro-Fuentes et al. 2008; Fernández-Ugalde et al. 2011; Okolo et al. 2020).

Moreover, the correlation between elevated greenhouse gas (GHG) emissions and climate change has established C storage in SOM as a feasible approach for sequestering atmospheric CO_2 (Cotrufo et al. 2019). Consequently, understanding the composition and stability of SOM is essential for assessing its role in carbon dynamics, particularly in semi-arid regions where organic matter inputs are often limited (Medeiros, Soares, and Maia 2022). The physical fractionation of SOM is a common method for studying the various pools of organic matter and their respective contributions to soil health (Cambardella and Elliott 1992). The two main fractions of SOM are POM and MAOM (Kunde et al. 2018; Lavallee et al. 2020). The POM consists of relatively undecomposed organic material, such as plant residues and is more readily available for microbial decomposition (Lavallee et al. 2020), and the MAOM, on the other hand, is composed of smaller organic molecules that are stabilized through interactions with soil minerals, making it more resistant to decomposition (Cotrufo and Lavallee 2022; Six et al. 2002). The balance between these fractions is critical for long-term carbon sequestration, as POM provides a short-term source of nutrients, while MAOM contributes to the stable storage of carbon over longer periods (Maia et al. 2007). NbS can

enhance the formation of MAOM in semi-arid soils by promoting the accumulation of organic matter in stable aggregates, helping to increase SOC levels and improving soil resilience to environmental stressors (Medeiros, Soares, and Maia 2022). Research by Neto et al. (2021) has shown that these land-use practices that increase organic inputs into the soil can enhance both POM and MAOM.

Considering these aspects, this study was conducted to determine whether NbS can enhance SOC stocks, SOM pools, soil aggregate stability and MB-C, establishing a pathway for sustainable land management and contributing to climate change solutions, alongside other sectors in the Brazilian semi-arid region. We hypothesized that the ILF system under NT would preserve soil aggregation, SOC stocks, SOM pools and MB-C at levels comparable to NV, whereas the degraded pasture would hinder these soil health indicators. Thus, this study aimed to evaluate the impact of the conversion from native vegetation to improved/degraded pastures and ILF systems under conventional tillage and NT on the SOC stocks and SOM pools in the semi-arid of Brazil.

2 | Material and Methods

2.1 | Site Description

The study was carried out at the Semi-Arid Experimental Station of the Brazilian Agricultural Research Corporation (EMBRAPA), in the municipality of Nossa Senhora da Glória, Sergipe, Brazil (10° 13′S, 37° 25′W). The climate of the region is classified as semi-arid BSh according to Köppen's classification, characterized by annual precipitation of 710 mm with great irregularity in its distribution, and average maximum and minimum temperatures of 32°C and 20°C, respectively (Francisco et al. 2015). The soil was classified as an Eutric Podzol according to the WRB.

2.2 | Soil Sampling and Analysis

Five replications of disturbed soil samples were collected in April 2023 in 0–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm layers in five different land uses (Figure 1): native vegetation (NV), ILF system with gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) + signal grass (*Urochloa decumbens* (Stapf) R.D. Webster) (ILFug), an ILF system with gliricidia + forage cactus (*Opuntia cochenillifera* (Linnaeus) Miller) (ILFcg), improved pasture (ImpP) and degraded pasture (DegP). In addition, undisturbed soil samples were collected using Kopeck rings for the assessment of soil bulk density (BD).

The area of native vegetation (NV) was used as the reference for evaluating the impacts of land-use change on the soil. The ILFug system is managed through a NT approach, with gliricidia cultivated with a 1.5 m plant spacing and signal grass cultivated between the rows, which are spaced 5 m apart. This system has been in place for the past 8 years and entails the regular pruning of gliricidia, with its biomass used as a cover crop on the soil; however, the signal grass is not subjected to cutting, maintaining its natural growth patterns. The integrated livestock-forest system consisting of gliricidia and forage cactus (ILFcg) features a row spacing of 3 m, with two lines of forage cactus cultivated in the interrows, and gliricidia cultivated with a plant spacing of 1 m. The forage cactus cutting is performed every 2 years, and this system has been in place for 10 years, being managed under conventional tillage. Every 2 years, the soil is tilled, followed by the planting of sorghum (*Sorghum bicolor* (L.) Moench.) in the interrow spaces between gliricidia and forage cactus. The sorghum is cut after about 110 days, and if there is enough rainfall, a second cut is made after regrowth. Both integrated systems are kept free from grazing cattle, and no fertilizers are applied. However, herbicides are used. Table 1 lists the chemical and physical properties of the soil.

The improved pasture (ImpP) represents a sustainably managed grassland system, characterized by species improvement practices: this pasture system is composed of three grass species: buffel grass (*Cenchrus ciliaris* L.), guinea grass (*Panicum maximum cv.* Mombasa) and African liverseed grass (*Urochloa mosambicensis* (Hack.) Dandy). The degraded pasture (DegP) represents a moderately degraded grassland. In this area, there are no management interventions, and the pasture consists of guinea grass. Both areas have unrestricted access for 50 beef cattle throughout the year and have been in place for a period of 15 years.

Undisturbed soil samples were dried in an oven at 105°C for 48 h and weighed. Bulk density (BD, g/cm^{-3}) was calculated by dividing the soil dry mass by the volume of the Kopeck ring (Donagemma et al. 2011).

Thereafter, disturbed soil samples were air-dried, homogenized and passed through 2.0 mm mesh sieves in order to remove stone fragments and roots before analysis. Total organic carbon (TOC) content was determined by the dry combustion method using an elemental analyser (TOC-Shimadzu, coupled to the SSM-5000A Shimadzu solid sample module). SOM was physically fractionated into particulate organic matter (POM) and mineral-associated organic matter (MAOM) according to Mendonça and Matos (2017), adapted from Cambardella and Elliott (1992). Carbon content was also determined in the POM fraction by the dry combustion method, whereas the MAOM fraction was calculated by the difference between TOC and POM carbon.

Different agricultural management practices lead to varying BD, which results in comparing different soil masses when the sampling depth remains consistent across all areas. To minimize discrepancies caused by differences in BD, the TOC, C-POM and C-MAOM stocks were adjusted (Equation 1) for the 0–10, 0–30, 0–50 and 0–100 cm layers based on equivalent soil mass, following the method proposed by Sisti et al. (2004).

$$Cs = \sum CTi + \left[MTn - \left(\sum MTi - \sum MSi\right)\right] CTn \quad (1)$$

where ΣCTi is the sum of the total carbon content (Mg ha^{-1}) from layer 1 to layer n^{-1} (penultimate) in the soil profile under treatment; MTn is soil mass (Mg ha^{-1}) in the last layer of the soil profile under treatment; ΣMTi is the sum of soil mass (Mg ha^{-1}) from layer 1 to layer n (last layer) in the treatment profile; ΣMSi is the sum of soil mass (Mg ha^{-1}) from layer 1 (surface) to layer n in the reference soil profile; and CTn is

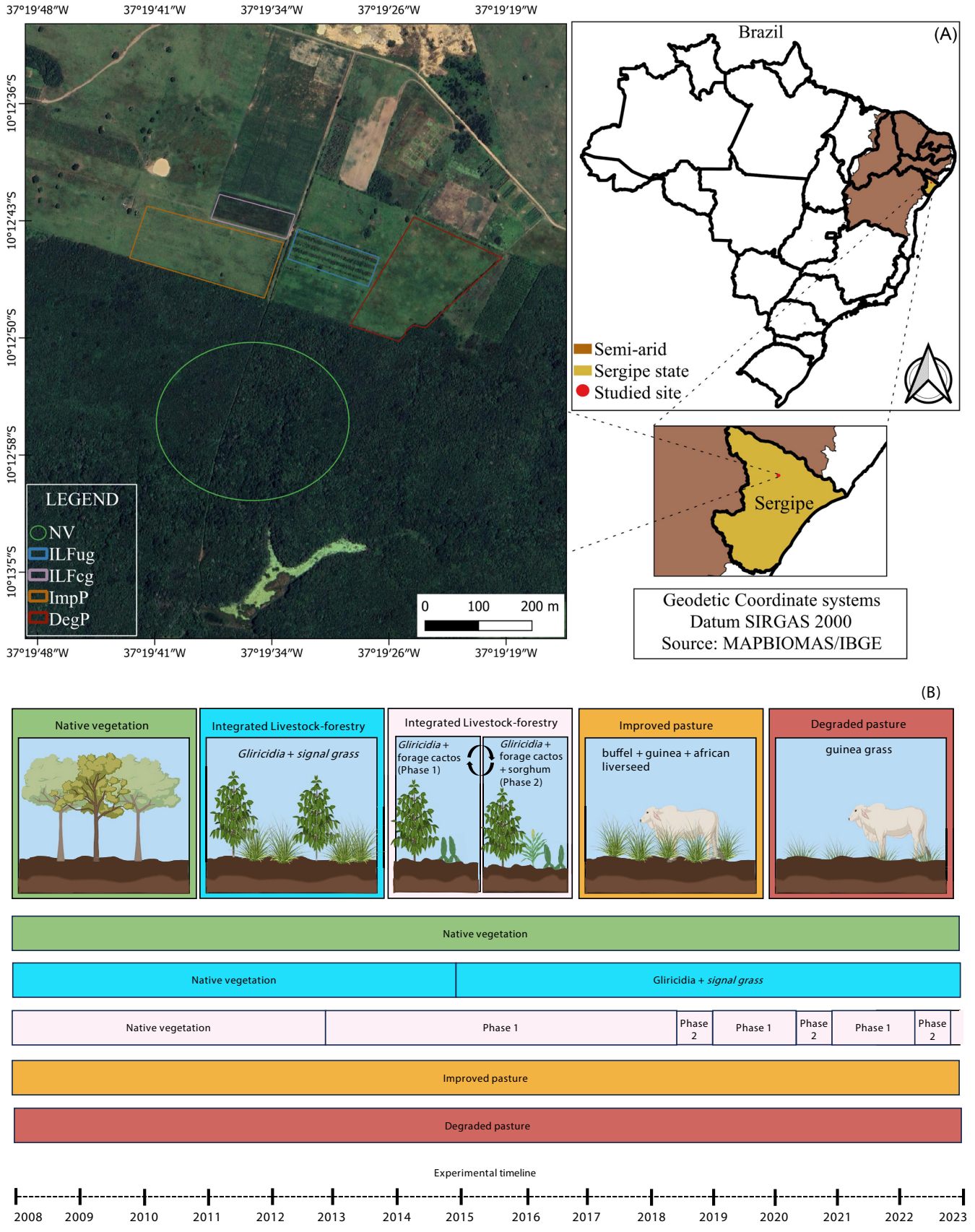


FIGURE 1 | Study area (A) and land use timeline (B) of native vegetation (NV), ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP), and degraded pasture (DegP) (A).

TABLE 1 | Physical and chemical characterization of studied soils at the 0–100 cm layer.

	Land uses				
Attributes	**NV**	**ImpP**	**DegP**	**ILFug**	**ILFcg**
Clay ($g\,kg^{-1}$)	243.77	318.58	317.86	296.69	347.41
Silt ($g\,kg^{-1}$)	305.93	242.52	260.04	254.22	222.47
Sand ($g\,kg^{-1}$)	449.24	458.21	451.46	449.08	439.19
pH in H_2O	5.32	5.83	5.38	5.21	5.16
CEC ($Cmol_c\,dm^{-3}$)	14.34	11.96	11.25	10.48	10.77
Na ($mg\,dm^{-3}$)	70.06	239.11	128.17	57.56	74.33
P ($mg\,dm^{-3}$)	2.03	2.17	1.67	4.00	1.61
K ($mg\,dm^{-3}$)	238.89	102.67	118.56	91.28	56.39
Ca^{2+} ($Cmol_c\,dm^{-3}$)	2.02	2.22	1.46	2.71	1.69
Mg^{2+} ($Cmol_c\,dm^{-3}$)	7.44	5.47	5.22	2.82	3.65
Al^{3+} ($Cmol_c\,dm^{-3}$)	0.30	0.09	0.17	0.12	0.33
$H^+ + Al^{3+}$ ($Cmol_c\,dm^{-3}$)	3.96	2.96	3.71	4.47	4.96
V (%)	68.44	72.00	61.50	56.28	51.94
m (%)	4.00	1.33	3.22	2.17	7.06

Note: m (%) = aluminium saturation.

carbon concentration (Mg C g $soil^{-1}$) in the last layer of the soil profile under treatment.

Then, based on the TOC changes between the NV (Caatinga) and the land-use systems, the carbon management index (CMI) was calculated for the 0–10, 0–30, 0–50 and 0–100 cm layers (Blair et al. 1995) according to Equation (2):

$$CMI = CPI \times LI \times 100 \quad (2)$$

where CPI is the carbon pool index and LI is the carbon lability index.

The CPI and LI were calculated as follows (Equations 3–5):

$$CPI = \frac{\text{TOC in Land} - \text{use system}}{\text{TOC in REF}_{area}} \quad (3)$$

$$L = \frac{C - POM}{C - MAOM} \quad (4)$$

$$LI = \frac{\text{L in land} - \text{use system}}{\text{L in REF}_{area}} \quad (5)$$

where REF_{area} is the reference area (NV/DegP), C-POM and C-MAOM are the labile and non-labile carbon fractions for each land use.

SOC change rates were determined using the classical annual rate approach (Maia et al. 2013). This method estimates SOC accretion or depletion between different land-use systems compared to the reference (native vegetation) and is based on Equation (6):

$$\text{Classical annual rate} = \frac{SOC_C - SOC_{REF}}{T} \quad (6)$$

where SOC_C is the SOC stock under the current land-use system; SOC_{REF} is the SOC stock of the reference area; and T is the time since the land-use change.

Considering that Brazil has a vast area of degraded pastures and the urgent need to recover these pastures, we included DegP as an additional reference alongside NV for calculating the CMI and SOC change rates. This decision allows us to (i) quantify the SOC restoration potential associated with converting DegP into more sustainable land uses and (ii) estimate CMI improvements under recovery scenarios that are priorities for the semi-arid region.

The MB-C was determined using the irradiation-extraction method (Islam and Weil 1998). The extracts were analysed for organic carbon content (TOC—V Shimadzu), and the microbial biomass was determined from the difference between the values obtained from the irradiated and non-irradiated samples. The microbial quotient (*q*MIC) was obtained by the ratio between MB-C and soil carbon content and expressed as a percentage. MB-C and *q*MIC were assessed only in the 0–30 cm soil layer, as microbial activity and biomass are predominantly concentrated in surface layers.

WSA were quantified using the wet-sieving procedure as described by Teixeira et al. (2017). Aggregate analysis was conducted in duplicate using 50 g of air-dried soil placed on a nest of sieves with mesh sizes of 2.000, 0.250 and 0.053 mm. The samples were subjected to vertical oscillation for 15 min, after which the material retained on each sieve was carefully transferred to pre-weighed containers, backwashed and oven-dried at 60°C for 48 h. Once dried, the mass of aggregates retained in each sieve was determined. Aggregates were then classified into three size classes: macroaggregates (> 2.000 mm), mesoaggregates (0.250–2.000 mm) and microaggregates (0.053–0.250 mm), according to Costa Junior et al. (2012). After determining the aggregate mass, a sand correction was applied to each aggregate size fraction to exclude the sand component, which is not considered part of the soil aggregates, following the procedure described by Plaza-Bonilla et al. (2013). Subsequently, the aggregate stability index (ASI) was calculated based on Equation (7) (Medeiros et al. 2018).

$$ASI = \frac{WDS - wp_{25} - sand}{WDS - sand} \quad (7)$$

where wp_{25} is the dry weight of aggregates of class < 0.250 mm, WDS is the weight of each dried sample, and sand is the particle size fraction of sand.

2.3 | Experimental Design and Statistical Analysis

The data were tested for the main ANOVA assumptions using Tukey's test for non-additivity to assess model additivity, the

Durbin-Watson test for residual independence, the Shapiro–Wilk test for normality, and Levene's test to verify the homogeneity of variances ($p > 0.05$). The statistical analysis was performed based on a randomized complete block design with five replications, structured as a split-plot design. In this arrangement, the main plots were represented by the land-use systems, and the subplots corresponded to the soil's sampling layers (0–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm). When significant differences were detected, means were compared using Tukey's test ($p < 0.05$). In cases where one or more ANOVA assumptions were not met, the non-parametric Friedman test was applied: when significant ($p < 0.05$), pairwise comparisons were performed using the Siegel-Castellan post hoc test with Bonferroni correction. All statistical analyses were conducted using R software (R Core Team 2022).

3 | Results

3.1 | Soil Carbon Content and Bulk Density

The highest carbon content was observed in the upper soil layers (0–10 cm) and significantly decreased ($p < 0.05$) with depth across all land uses until the 50–70 and 70–100 cm layers, where no difference ($p < 0.05$) was found. Considering the land use systems, the highest carbon content was found in the ILFug, with values of 20.7, 13.0, 8.1, 7.40, 5.4 and 4.4 g kg^{-1} for the 0–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm layers, respectively (Figure 2).

Regarding soil bulk density, results showed low variation across different land uses (Figure 2). Significant differences were found only in the 70–100 cm soil layer ($p < 0.05$). In this layer, the highest BD of 1.65 g cm^3 was found in the ImpP, while the lowest BD of 1.23 g cm^3 was observed in the ILFcg system ($p < 0.05$) (Table S2). The ImpP consistently showed the highest BD values across most soil layers, with values of 1.39, 1.49, 1.55, 1.57, 1.47 and 1.66 g cm^3 for the 0–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm layers.

3.2 | Soil Carbon Stocks

The changes in SOC stocks varied by land use, with the most significant reductions observed in the NV-DegP conversion across all soil layers (Figure 3). The SOC losses were higher in the surface layer (0–10 cm), where the stocks were reduced by 40.5%, 45.4% and 53.4% in the ILFcg, ImpP and DegP, respectively (Table S1). The NV-DegP conversion generally resulted in greater losses, reducing the SOC by 13.5, 16.0, 18.6 and 22.1 Mg ha^{-1} for the 0–10, 0–30, 0–50 and 0–100 cm layers ($p < 0.05$). Inversely, although not statistically significant ($p > 0.05$), the NV-ILFug conversion increased SOC from 6.5% to 21.8% (i.e., 1.8 and 25.1 Mg C ha^{-1}) between the shallowest and deepest layers (Figure 3).

Table 2 shows the rates of SOC change calculated using the classical method. The conversion from NV to ILFcg, ImpP and DegP results in a decrease in SOC stocks across all layers. In contrast, converting NV to ILFug increases SOC stocks by 0.22, 1.04, 1.91 and 3.13 Mg ha^{-1} year^{-1} for the 0–10, 0–30, 0–50 and 0–100 cm layers, respectively. In the 0–100 cm layer, the NV-DegP conversion results in the greatest loss of SOC, at 1.47 Mg ha^{-1} year^{-1}. On the other hand, when we consider the DegP as the reference condition, the conversion to other land uses in general increased SOC. For example, in the 0–100 cm soil layer, these increases were 5.89, 0.80 and 0.22 Mg C ha^{-1} year^{-1} for the ILFug, ILFcg and ImpP, respectively.

3.3 | Particulate and Mineral-Associated Organic Matter Fractions

Across the soil profile, the NV exhibited the highest POM stocks compared to other land-use systems, though a significant difference was observed only in the NV-DegP conversion ($p < 0.05$). The most substantial loss of POM occurred during this conversion, reducing POM by 74.5%, 75.8%, 73.8% and 74.7% in the 0–10, 0–30, 0–50 and 0–100 cm layers, respectively (Figure 4). When comparing only the integrated systems and pastures, the ILFug system showed higher POM values in the 0–10 and 0–30 cm layers (6.0 and 10.9 Mg ha^{-1}, respectively), while the ImpP showed higher values in the 0–50 and 0–100 cm layers, with 15.6 and 23.2 Mg ha^{-1}, respectively (Figure 4). In the DegP area, the lowest POM values were observed across all layers, with values of 2.0, 4.0, 5.2 and 7.57 Mg ha^{-1}, for the 0–10, 0–30, 0–50 and 0–100 cm layers, respectively.

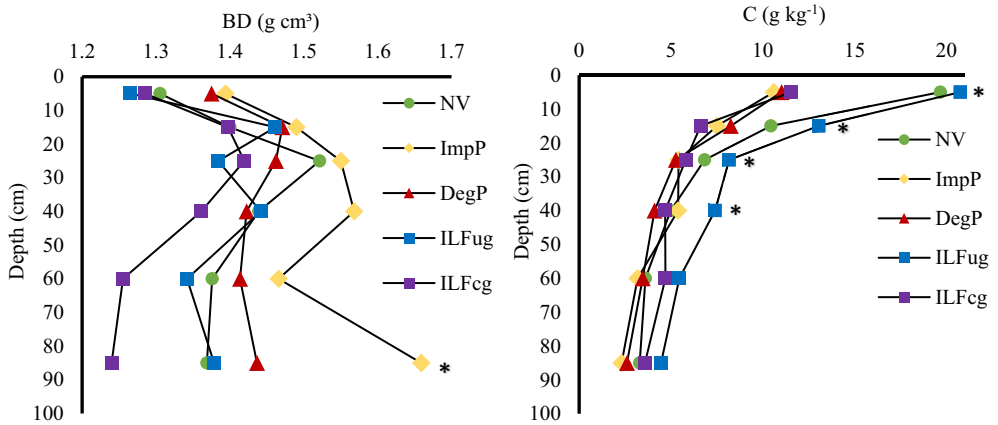


FIGURE 2 | Soil carbon (C) content and bulk density (BD) in 0–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm soil layers under native vegetation (NV), ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region. * Indicates significant difference by Tukey's test ($p < 0.05$) for BD and Friedman's test for carbon (C) in the same soil layer.

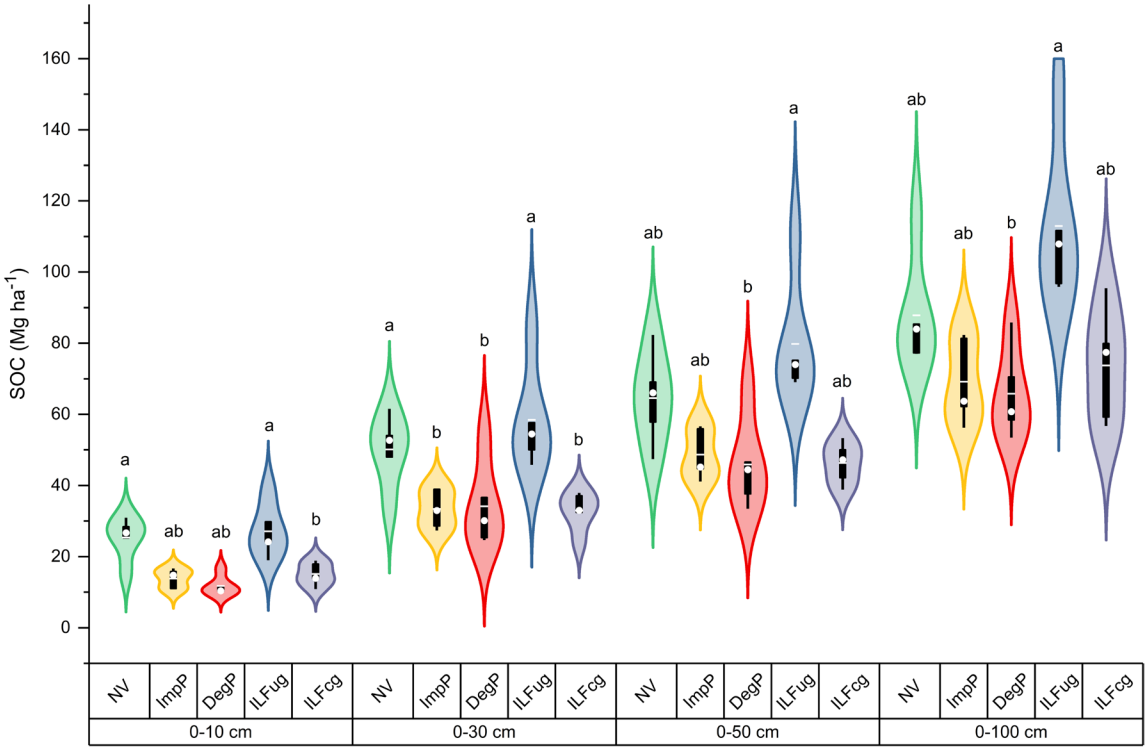


FIGURE 3 | Soil organic carbon (SOC) stocks in 0–10, 0–30, 0–50 and 0–100 cm soil layers under native vegetation (NV), integrated ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP), in the Brazilian semi-arid region. SOC (Mg ha^{-1}). Means followed by the same letter between the land uses for the same layer do not differ by Friedman's test ($p < 0.05$). In the boxplot, the line inside the box indicates the mean, and the '*x*' indicates the median. The violin plot represents a Kernel's distribution of the data.

TABLE 2 | Rates of SOC change (Mg ha^{-1} year^{-1}) in 0–10, 0–30, 0–50 and 0–100 cm soil layers when converting native vegetation (NV) and degraded pasture (DegP) to ILF of signal grass + *gliricidia* (ILFug), ILF of cactus forage + *gliricidia* (ILFcg) and improved pasture (ImpP).

		Rates of SOC change (Mg ha^{-1} year^{-1})			
		0–10 cm	0–30 cm	0–50 cm	0–100 cm
Land-use change	Years of cultivation	NV as reference			
NV/ILFug	8	0.22 ± 0.70	1.04 ± 1.28	1.91 ± 1.53	3.13 ± 1.97
NV/ILFcg	10	−1.03 ± 0.26	−1.72 ± 0.36	−1.82 ± 0.46	−1.41 ± 1.26
NV/ImpP	15	−0.77 ± 0.15	−1.11 ± 0.30	−1.06 ± 0.40	−1.25 ± 0.67
NV/DegP	15	−0.90 ± 0.12	−1.06 ± 0.22	−1.24 ± 0.59	−1.47 ± 0.65
		DegP as reference			
DegP/ILFug	8	1.91 ± 0.37	3.04 ± 0.68	4.23 ± 0.81	5.89 ± 1.05
DegP/ILFcg	10	0.33 ± 0.17	−0.12 ± 0.24	0.04 ± 0.30	0.80 ± 0.84
DegP/ImpP	15	0.14 ± 0.15	−0.05 ± 0.30	0.19 ± 0.40	0.22 ± 0.67

Regarding MAOM, the ILFug system had the highest stocks, showing values of 21.0, 47.4, 65.1 and 90.0 Mg ha^{-1} for the 0–10, 0–30, 0–50 and 0–100 cm layers, respectively. This represents increases of 18.2%, 29.3%, 31.8% and 35.7% when compared to NV (Figure 4). The ImpP showed the lowest MAOM values in the 0–30 cm (23.9 Mg ha^{-1}), 0–50 cm (33.1 Mg ha^{-1}) and 0–100 cm (Mg ha^{-1}) layers. Notably, in the 0–10 cm layer, DegP had the lowest value with 9.7 Mg ha^{-1}, followed by ImpP with 10.9 Mg ha^{-1}.

A quantitative evaluation of SOM fractions revealed that the MAOM compartment accounted for the largest portion of SOC across all land-use systems, with an average contribution ranging from 65.9% to 88.5% (Figure 5). The NV had the highest contribution of POM to SOC in all soil layers, with values ranging from 31.3% (0–50 cm layer) to 33.6% (0–100 cm layer). In contrast, in the DegP, the lowest contributions of POM to SOC were observed, with values of 17.5%, 11.7%, 11.5% and 11.5% for the 0–10, 0–30, 0–50 and 0–100 cm layers, respectively.

3.4 | Carbon Management Index

In all soil layers, there was a decrease in the CMI values for the integrated systems and pastures compared to NV (Figure 6A). However, evaluating only the managed systems, the highest CMI values for the 0–10 and 0–30 cm layers were observed in the ILFug, with percentages of 45.6% and 30.5%, respectively. For the 0–50 and 0–100 cm layers, the ImpP showed the highest values, measuring 61.7% and 63.2%, respectively. Conversely, the DegP had the lowest CMI values across all layers ($p < 0.05$), with values of 13.5%, 10.0%, 15.9% and 15.3% for the 0–10, 0–30, 0–50 and 0–100 cm layers, respectively (Figure 6A).

When using DegP as the reference area for the CMI (Figure 6B), all other land uses exhibited higher values (> 100%). In this scenario, NV presented the highest CMI in the 0–10 and 0–50 cm layers, with values of 476.0% and 407.6%, respectively. In the 0–100 cm layer, the higher CMI was observed in ImpP, followed by NV, ILFug and ILFcg, with values of 421.3%, 417.6%, 338.7% and 335.7%, respectively.

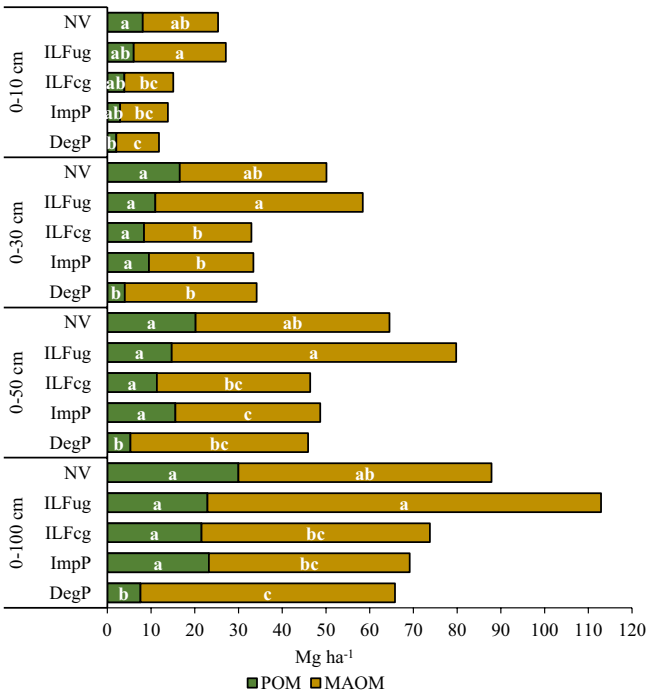


FIGURE 4 | Particulate organic matter (POM) and mineral-associated organic matter (MAOM) stocks in 0–10, 0–30, 0–50 and 0–100 cm soil layers under native vegetation (NV), ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region. Means followed by the same letter between the land uses for the same layer do not differ by Friedman's test ($p < 0.05$).

3.5 | Microbial Biomass Carbon and Microbial Quotient

In the 0–10 cm layer, the NV had the greatest MB-C (62.07 mg kg^{-1}), while the DegP showed the lowest MB-C at 18.97 mg kg^{-1} ($p < 0.05$). Almost all land uses showed their lowest MB-C at the 20–30 cm layer, except for the ILFcg system (Figure 7), with values of 34.85, 22.60 and 25.48 mg kg^{-1} ($p > 0.05$) in the 0–10, 10–20 and 20–30 layers, respectively. In the 10–20 cm layer, no significant differences were found among land uses (Figure 7), with the ILFug system showing the highest MB-C of 27.87 mg kg^{-1}. In the 20–30 cm layer, the ILFug system again showed the greatest MB-C (25.91 mg kg^{-1}), followed by ILFcg, ImpP, NV and DegP, with values of 25.48, 13.82, 10.02 and 4.48 mg kg^{-1}, respectively ($p < 0.05$).

The ILFcg system presented a higher *q*MIC in the 10–20 and 20–30 cm layers compared to the other land uses, with values of 4.55% and 3.90%, while in the 0–10 cm layer, the NV had the highest MB-C of 3.70%. A significant difference was only observed in the 20–30 cm layer (Figure 7), where the NV (1.40%) and DegP (1.00%) differed from ImpP, ILFug, and ILFcg, with values of 2.47%, 3.02%, and 4.55%, respectively.

3.6 | Distribution of Water-Stable Aggregates and Aggregate Stability Index

Across land uses, the topsoil (0–10 cm) was dominated by macroaggregates (> 2.000 mm), with the greatest proportion

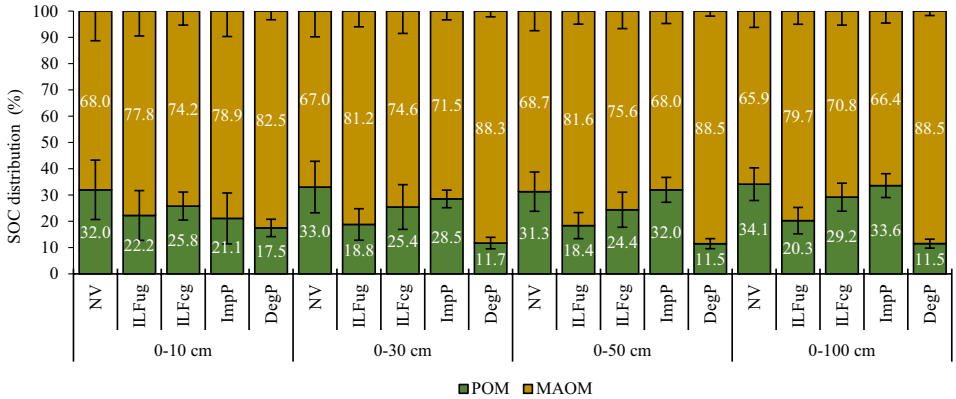


FIGURE 5 | Particulate organic matter (POM) and mineral-associated organic matter (MAOM) distribution (%) in 0–10, 0–30, 0–50 and 0–100 cm soil layers under native vegetation (NV), ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid. Error bars show the standard deviation ($n = 5$).

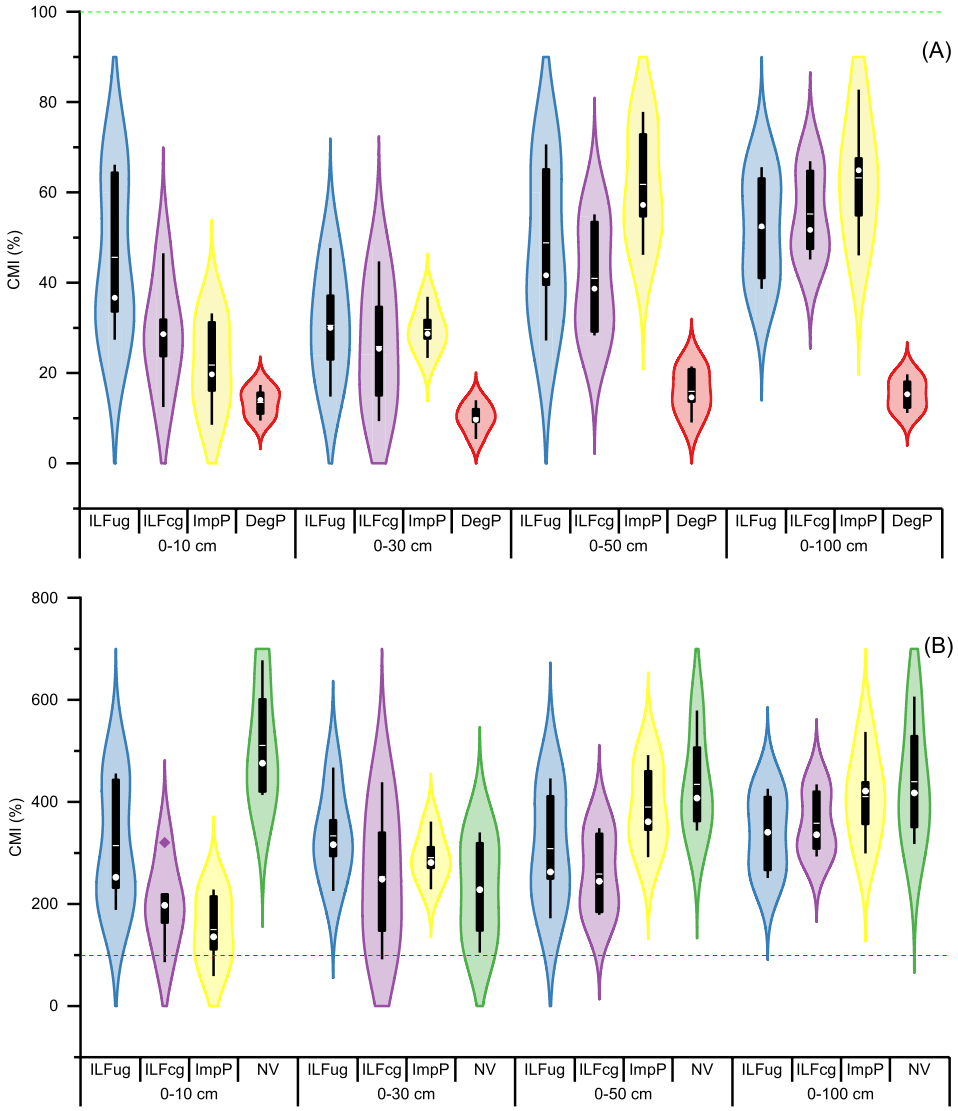


FIGURE 6 | Carbon management index (CMI) using NV as the reference area (A) and DegP (B) as the reference area in 0–10, 0–30, 0–50 and 0–100 cm soil layers under ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region. In the boxplot, the line inside the box indicates the mean and the circle indicates the median. The violin plot represents a kernel's distribution of the data.

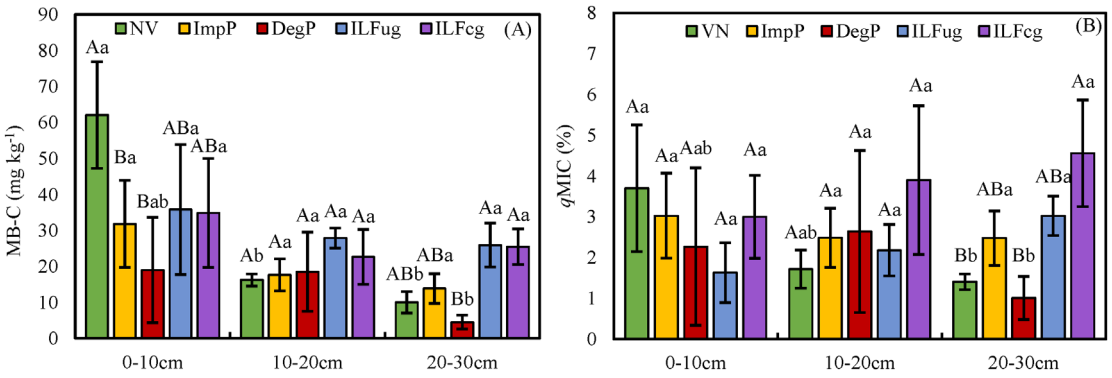


FIGURE 7 | Microbial biomass carbon (MB-C) (A) and microbial quotient (*q*MIC) (B) in 0–10, 10–20 and 20–30 cm soil layers under ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region. Different uppercase letters for land use systems at the same layer and lowercase letters for soil layers at the same land use do not differ by Tukey's test ($p < 0.05$). Error bars show the standard deviation.

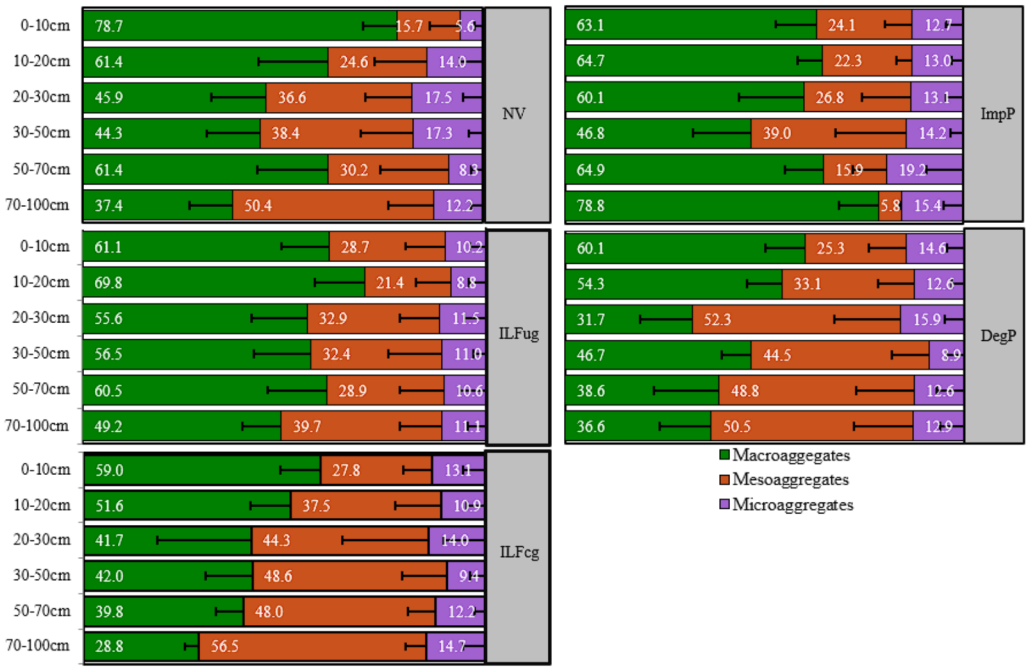


FIGURE 8 | Distribution of water-stable aggregate (WSA) classes under ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region. Error bars represent the SD ($n = 5$).

observed under NV (78.7%) and the smallest under the ILFcg system (59.0%) (Figure 8). The improved pasture (ImpP) differed from the other land uses at the 70–100 cm layer, where the macroaggregate fraction represented 78.8% of the total WSA ($p < 0.05$), while mesoaggregates (0.250–2.000 mm) and microaggregates (0.053–0.250 mm) comprised 5.8% and 15.4%, respectively (Table S4). Overall, microaggregates constituted the smallest share of WSA across soil layers and land uses, except in the ImpP at 50–70 cm and 70–100 cm, where the microaggregate class accounted for 19.2% and 15.4% of WSA, respectively.

Highest ASI was observed in the 0–10 cm layer under NV (89.1%), and reached its minimum values (70.3%) in the DegP at the 20–30 and 30–50 cm layers (Figure 9). Significant differences among land-use systems were detected at the 0–10 cm and 30–50 cm layers ($p < 0.05$). Only the NV and the ILFcg system showed statistical differences among soil layers, with the 20–30 and 30–50 cm layers presenting the lowest ASI.

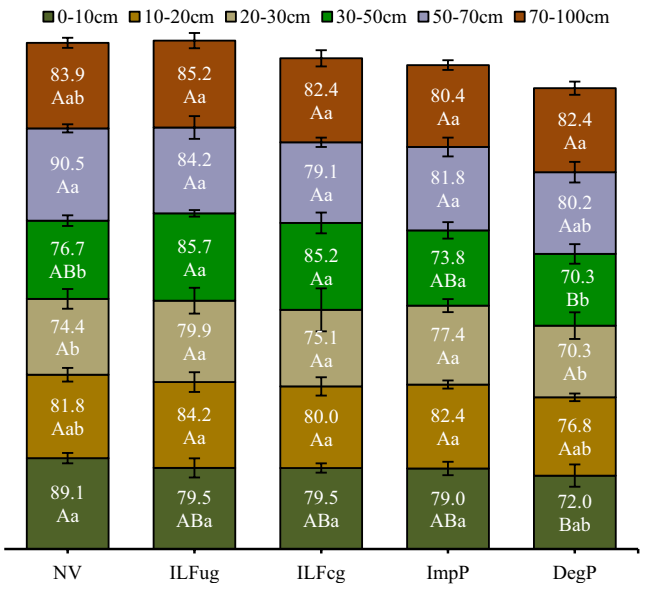


FIGURE 9 | Aggregate stability index (ASI) under ILF of signal grass + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP), and degraded pasture (DegP) in the Brazilian semi-arid region. Different uppercase letters for land use systems at the same layer and lowercase letters for soil layers at the same land use do not differ by Tukey's test ($p < 0.05$). Error bars show the standard deviation ($n = 5$).

4 | Discussion

4.1 | Soil Carbon Stocks

The 87.8 Mg ha^{-1} stock of SOC found in this study for the NV was similar to the average 89.8 Mg ha^{-1} SOC stocks at 1 m depth under dense Caatinga in the main soil classes of this biome, observed by Menezes et al. (2021). They further report that dense Caatinga stocks approximately 125 Mg C ha^{-1} in total ecosystem C, with around 72% of that amount retained in SOC, underscoring the critical role of soil as the main long-term carbon reservoir in these dry forest environments.

The ILFug system showed the highest SOC stocks, highlighting the significance of NbS and the potential of integrated systems to stock carbon in the soil, which can help mitigate climate change. This potential will clearly depend on aspects such as the species involved, the design of the integrated system and the type of soil management. Nutrient accumulation, such as phosphorus (P), can also affect SOC stocks, indirectly influencing plant productivity, the quality of plant residues and root development. In the ILFug system, the P availability is at 4.00 mg dm^{-3}, likely contributing to an increase in SOC.

Liu et al. (2026) indicated that P can promote SOC accumulation, with reported increases of up to 10.6%. They also observed that the positive impact of P availability on SOC is more pronounced in sustainably managed agricultural systems, such as ILFug, than in pastures or forests (Liu et al. 2026).

In the Brazilian semi-arid, the signal grass present in the ILFug has been used in integrated systems due to its efficiency in accumulating carbon in the soil, mostly due to its production of biomass and roots (Cavalcante et al. 2019; Neto et al. 2021). Coutinho et al. (2025) found in signal grasses with different cropping systems a mean root biomass production of 7.4 t ha^{-1}, implying a large annual root carbon input via turnover, which can represent a substantial source of carbon inputs to the soil (Baptistella et al. 2020). While most studies primarily emphasize aboveground biomass production, the significant potential of signal grass as a cover or intercropping species is found in its roots (Baptistella et al. 2020). This increase in root biomass also favours microbial activity, leading to greater exudation of organic compounds in the soil, which raises MB-C due to the enhanced supply of nutrients and energy available for microbial biomass (dos Santos et al. 2025).

The signal grass not only produces a large amount of biomass, but also contains higher levels of recalcitrant compounds that decompose more slowly, ensuring longer-lasting soil coverage, reducing exposure to temperature and enhancing carbon inputs to the soil (Coutinho et al. 2025). Neto et al. (2021) also found greater SOC content (14.1 g C kg^{-1}) under systems intercropped with signal grass at 1 m soil depth.

Additionally, the gliricidia in the ILFug can produce substantial biomass as well, and their typical pruning generates on the order of 8 to 20 Mg of dry mass ha^{-1} $year^{-1}$ into the soil (Castro Filho et al. 2016). Moreover, the gliricidia, which is a leguminous plant, provides a litter that is well-distributed throughout the soil in integrated systems and decomposes quickly due to its low C/N ratio (Apolinário et al. 2015). This rapid decomposition can lead to higher levels of fulvic acid in the SOM, which is more mobile than other fractions of SOM and contributes more significantly to SOC over shorter periods (Assunção et al. 2019; Junior et al. 2020). In addition, Neto et al. (2021) also noted that integrated/silvopastoral systems help moderate the amplitude of temperature at the soil surface, favouring the microbial activity of the soil.

Another key driver of the SOC increases observed in our study is NT, which preserves macro and microaggregates, maintains surface residue cover, reduces the exposure of protected organic matter to rapid oxidation and moderates soil surface temperature and moisture (Sá et al. 2025), all processes that favor the accumulation and stabilization of SOC. Long-term NT consistently increases SOC stocks, and can, on top of that, restore a large fraction of SOC lost after land-use change (Freitas et al. 2022; Sá et al. 2025). These findings support our hypothesis that greater carbon inputs from crop residue, combined with NT management in integrated systems, positively affect SOC stocks. This highlights the critical role of land management practices like NbS in maintaining and improving SOC stocks, particularly in the semi-arid regions of Brazil. Integrated systems, especially those involving signal grass and gliricidia, offer a feasible strategy for mitigating climate change impacts.

Nonetheless, adopting an integrated system does not guarantee the sustainability of the system (Neto et al. 2021). The benefits of SOC under integrated systems encompass practices such as NT (as implemented in the ILFug system), crop rotation, amount of residue input, time since adoption, and the maintenance of crop residues on the soil surface (Derpsch et al. 2014). In addition to these management factors, soil nutrient availability also plays a relevant role in regulating SOC. Liang et al. (2025) observed that K is an important macronutrient whose shortage can lead to reductions of up to 5% in SOC. Notably, the ILFcg system exhibited the lowest soil K concentration (56.39 mg dm^{-3}) among the systems studied, a condition that likely contributed to the observed decrease in SOC in this system. In contrast, the NV presented a K concentration of 238.89 mg dm^{-3}, which can increase soil dispersion and promote particle flocculation and stabilization, which in turn enhances macroporosity and reduces soil compaction (Souza et al. 2025). These processes favour the formation of aggregate pores, resulting in greater particle cohesion and BD, thereby creating conditions that facilitate enhanced carbon accumulation in SOM (Souza et al. 2025). Consequently, the conversion from NV to ILFcg led to reductions in SOC stocks across all soil layers.

The fact that the soil in the ILFcg system is tilled every 2 years may also help to explain these decreases. Conventional tillage can cause soil aggregates to break apart, altering the soil's structure and exposing SOM to higher oxidation levels (Medeiros, Santos, and Maia 2022). Soil tillage has a medium and long-term detrimental impact on soil quality and contributes to soil degradation in the semi-arid region of Brazil. As a result, a decline in physical, chemical and biological soil attributes, including SOC stocks and SOM pools, can be observed (Maia et al. 2025; Medeiros, Soares, and Maia 2022).

In addition, another characteristic that can account for the SOC decreases in the ILFcg system is that the cactus forage produces lower amounts of biomass both above and below ground compared to species like signal grass in the ILFug system. Total biomass production of forage cactus in semi-arid conditions varies significantly depending on genotype, irrigation and fertilization. For example, Lopes et al. (2021) reported average total biomass production values of 3.5 Mg ha^{-1} $year^{-1}$ in areas with fertilization. This limited biomass production, combined with the sparse soil coverage provided by cactus forage, leaves the soil more exposed to solar radiation, increasing soil surface temperatures and accelerating SOM decomposition (Neto et al. 2021; Rigon and Calonego 2020). Low P accumulation in the ILFcg system (1.61 mg dm^{-3}) likely further constrained the low cactus forage above-ground biomass production. Moreover, forage cactus typically develops a shallow, relatively modest root system concentrated near the soil surface, rather than the deep, extensive root systems common in many perennial signal grasses. Such root architecture may have been further constrained by the low K availability (56.39 mg dm^{-3}) in this system, given that K inputs have been shown to have the potential to increase root biomass by up to 9% (Liang et al. 2025), and implies smaller belowground carbon inputs and less root-derived protection of mineral-associated organic matter (Lopes et al. 2021;

Neto et al. 2021). This shallow root system is an adaptation that enables the forage cactus to capture the water of the scarce rainfall in arid environments.

According to de Oliveira et al. (2022), approximately 64 million hectares of pastures in Brazil are showing signs of degradation, which contributes to a significant loss of SOC. The conversion of NV to ImpP and DegP resulted in reductions of 21.2% and 25.1%, respectively, in the 0–100 cm layer. Since this reduction also occurs in deeper soil layers, it is important to include sub-superficial soil layers in studies on the impacts of land-use change on SOC dynamics, as these changes are not restricted to topsoil (Locatelli et al. 2022; dos Santos et al. 2023). These results suggest that, although improved pastures are better managed, their ability to preserve SOC stocks is limited, particularly in the Brazilian semi-arid region, as observed by Medeiros et al. (2021). They reported SOC losses ranging from 12% to 16% in the 0–100 cm soil layer when native vegetation was converted to grasslands over a period of 5 to 30 years. Therefore, the similarity in SOC losses between ImpP and DegP highlights that improving pasture management alone, without more substantial changes, is insufficient to address the challenges imposed by the semi-arid environment. This contrasts with results observed in other regions, where well-managed pastures have demonstrated greater efficiency in SOC retention. Maia et al. (2009), for example, reported a 9% decrease in SOC resulting from the conversion of native vegetation to degraded grasslands, along with a 19% increase in improved grasslands in the Cerrado (Brazilian savannah) biome. Supporting this, de Oliveira et al. (2022) reported an 8% increase in SOC stocks under improved pastures compared to native vegetation, whereas degraded pastures showed a 10% reduction. To mitigate these losses in the semi-arid region, it is essential to invest in more integrated and diversified practices, such as pasture rotation including leguminous plants and the adoption of integrated systems, especially under NT. These practices help maintain soil cover, reduce compaction, and enhance SOC stocks (Sá et al. 2025).

The annual rate of SOC stock change evaluates carbon dynamics after land-use conversion (Deng et al. 2018; Maia et al. 2013; Medeiros et al. 2020). The NV-ILFug conversion resulted in accruals of 3.13 Mg C ha^{-1} $year^{-1}$, showing that the implementation of ILF systems and NT together allows the maintenance of carbon over time, playing a crucial role in carbon sequestration. Consistent with this interpretation, Mazumder et al. (2025) stated that integrated systems can retain larger amounts of SOC than some native forests, reinforcing their role in reducing atmospheric GHG concentrations. International initiatives, such as the '4 per mille', highlight the role of SOC as a key tool for climate mitigation, suggesting that increasing SOC stocks by approximately 0.4% per year could offset roughly 20% to 35% of anthropogenic CO_2 emissions worldwide (Minasny et al. 2017). Observed SOC gains can be translated into CO_2 removals using a factor of 44/12 (IPCC 2006). For example, an accrual of 3.13 Mg C ha^{-1} $year^{-1}$ in the NV-ILFug conversion corresponds to 11.45 Mg CO_2 ha^{-1} $year^{-1}$ sequestered.

Similar to our hypothetical conversion of DegP to the other systems, which resulted in increases in the rate of SOC stock change by 0.22 to 5.89 Mg ha^{-1} $year^{-1}$, which corresponds to 0.80 and 21.55 Mg CO_2 ha^{-1} $year^{-1}$ sequestered, Braz et al. (2013) found that restoring degraded pastures in Brazil led to an increase in SOC stock change of 1.03 to 2.95 Mg ha^{-1} $year^{-1}$, over a period of 9 years, within the 0–100 cm soil layer, pointing out the importance of more conservationist soil management in the semi-arid region of Brazil. Chatterjee et al. (2018) reported that ILF systems, on average, can increase the rate of SOC change by approximately 26% when compared to pasture areas. Moreover, Silva et al. (2024) observed that the implementation of integrated systems can promote increased SOC sequestration rates at about 1.09 and 1.21 Mg CO_2 ha^{-1} $year^{-1}$ (0–30 cm soil depth) in areas previously occupied by degraded pastures in Minas Gerais, Brazil. In a broader context, Cerri et al. (2024) indicated that the implementation of best management practices across approximately 30% of agricultural land in the Americas, covering around 334 million hectares, could result in the sequestration of about 13.1 Pg CO_2e over a 20-year period, potentially offsetting nearly 39% of agricultural GHG emissions during the same timeframe.

In addition to providing various environmental benefits, these improvements could also help the country reduce GHG emissions. As a method for addressing climate change, soil carbon sequestration provides a temporary solution in the next 10–20 years while we wait for other effective carbon capture and low-emission technologies to become practical (Minasny et al. 2017). These approaches not only benefit the soil's physical and chemical properties but also contribute to the socioeconomic well-being of local communities by improving agricultural productivity and resilience to climatic variability.

4.2 | Particulate and Mineral-Associated Organic Matter

In addition to the quantitative assessment of carbon stocks, evaluating the SOM compartments with different lability is also crucial in studies related to the effect of management practices on SOM dynamics (Figueiredo et al. 2010; Medeiros, Soares, and Maia 2022). While POM contributes less to SOC stocks than MAOM (Figure 5), its role is critically important, functioning as a connection to the more stable fraction (MAOM) and serving as a highly sensitive indicator of management's influence on SOC.

The NV showed the highest stocks of POM across the soil profile. Santos et al. (2019) also found that native vegetation had greater stocks of the labile fraction of SOM. They attributed the elevated levels of POM in native vegetation to the growth of dominant perennial species, which produce large quantities of residues continuously.

Our findings confirm the hypothesis that the POM is more sensitive to soil management (Blair et al. 1995; Maia et al. 2007), since the NV-DegP conversion showed the most significant reductions in POM, reinforcing the adverse impact of degradation on labile carbon pools in the soil.

The observed increase in POM stocks in well-managed pasture areas may be attributed to the higher input of belowground biomass found in deeper soil layers. This accumulation of root biomass can play a crucial role in neutralizing the reductions in POM stocks that are often recorded in deeper soil layers.

However, it is important to note that despite this increment in POM, there was no corresponding increase in SOC stocks, indicating that while pasture improvement practices are effective in increasing POM stocks, other factors may be at play that prevent the stabilization or increase of SOC stocks in these pasture environments.

The MAOM is the most recalcitrant and stable fraction of SOM, primarily composed of root exudates and products of microbial decomposition that form organo-mineral complexes, which hinder decomposition (Santos et al. 2011). As a result, MAOM is less sensitive to different types of management practices (Medeiros, Soares, and Maia 2022). The ILFug showed the greatest stocks of MAOM at all soil depths, which consequently contributed to increases in the SOC stocks. The greater MAOM stock in the ILFug system may be linked to the elevated Ca^{2+} availability (Table 1), which favors the formation of hyphae-forming bacteria that generate by-products and necromass that bind to mineral surfaces, enhancing organo-mineral associations and promoting MAOM formation (Shabtai et al. 2023). Thus, Ca^{2+} contributes to SOC persistence through both chemical stabilization and biologically mediated pathways that link microbial processing to mineral protection.

Furthermore, the roots of gliricidia and signal grass can contribute to an increase in organic matter in deeper soils, as these plants have a perennial growth pattern and continuously renew their root systems (Junior et al. 2020; Luna et al. 2019), which may result in the accumulation of MAOM in depth. According to Santos et al. (2019), POM can swiftly turn into more complex recalcitrant molecules (i.e., MAOM), due to the accumulation of organic compounds. This change in the lability of SOM can be affected by pH, nutrient availability and interactions with low molecular weight organic compounds released by roots, all of which influence biogeochemical cycling and soil quality (Mosquera et al. 2012; Santos et al. 2019). This result is highly positive for soil quality, as the more recalcitrant organic matter (which has greater resistance to decomposition) contributes to the improvement of soil physical properties, such as aggregate stability and has a lower turnover rate, contributing to both climate change mitigation and the sustainability of agricultural systems in the semi-arid region (Maia et al. 2007; Medeiros, Soares, and Maia 2022; Neto et al. 2021).

The results obtained for the MAOM fraction corroborate with other studies, indicating that the MAOM has high stability and can be increased through carbon inputs from NT practices and crop residues, particularly in integrated systems with forage grasses (Neto et al. 2021). The higher stocks of SOC and MAOM in the ILFug and NV can be explained by the constant input of organic residues to the soil, along with the lack of conventional soil management practices, which favour the maintenance of SOM (Medeiros, Soares, and Maia 2022; Santos et al. 2011).

4.3 | Carbon Management Index

The carbon management index (CMI) is an index that considers the total carbon stock and its lability (Table S3), providing a sensitive measurement of the rate of change in soil carbon dynamics compared to a more stable reference soil (Blair et al. 1995; Maia et al. 2007; dos Santos et al. 2023). Nonetheless, given our analysis, we made the decision to also include the DegP as a reference point in our study.

None of the treatments presented CMI values higher than 100% when compared to NV as a reference, across the soil profile. This effect is related to the higher POM values in the NV, which highlights the challenges in surpassing more stable reference soil conditions. Conversely, when DegP was utilized as the reference area, all other land use systems presented CMI values exceeding 100%, that is, their CMI exceeded that of DegP, demonstrating these systems' potential to restore SOC and SOM pools relative to DegP. de Oliveira et al. (2022) say that restoring degraded pastures can significantly enhance soil health, lead to an impressive 23% increase in SOC stocks, and this recovery has the potential to sequester up to 3445 Tg of CO_2. This lower DegP CMI values in all soil layers suggests that the soil environment in this area is showing signs of degradation and that there is no trend of recovery over time since this area has been in place for 15 years. According to Medeiros et al. (2021), who derived SOC stock change factors for grassland management in the Brazilian semi-arid, the conversion of native vegetation to native and planted grasslands starts to show recovery of SOC stocks (4%) after 30 years.

Consistent with the POM stocks, the ImpP had the greatest CMI values for the 0–50 and 0–100 cm layers when comparing only the managed systems. This fact can probably be explained by the higher input of grassroots biomass from the buffel, guinea and African liverseed pastures, which play an important role in the stabilization of SOM (Conceição et al. 2014; Medeiros, Soares, and Maia 2022). Additionally, through the actions of mycorrhiza and root hairs, especially in deeper soil layers and chemical interactions with metal ions (i.e., Ca^{2+}), the root system of different grasses also contributes to the physicochemical preservation of SOM (Medeiros, Santos, and Maia 2022; Rasse et al. 2005). These findings reinforce the critical role of diverse and well-managed grass species in the restoration of degraded areas, particularly in semi-arid regions where land degradation threatens agricultural productivity and ecosystem resilience.

4.4 | Microbial Biomass Carbon

The results demonstrate that land use systems and soil depth significantly influence MB-C and *q*MIC in the Brazilian semi-arid region. The observed decrease in MB-C with increasing soil depth (Figure 7A) is a consistent finding, primarily attributed to the greater accumulation of SOM, higher root density and more favourable conditions in the surface layers, which collectively support a larger microbial community.

According to Maia et al. (2025), the MB-C is considered one of the main indicators of soil quality, and soils in semi-arid environments are particularly prone to degradation due to biotic and abiotic constraints on microbial biomass and activity (Maia et al. 2025; Souza et al. 2025).

In this study, it is noteworthy that, in general, the losses of MB-C were more pronounced in the DegP, which is a clear indicator of soil degradation. This reduction in MB-C is a

common consequence of overgrazing and/or inadequate management, leading to losses of SOM, soil compaction and reduced plant cover, thereby limiting the energy and carbon sources available to the soil microbiota (Neves et al. 2021; Gao et al. 2023; Souza et al. 2025). The same trend was observed by Gao et al. (2023), where MB-C was higher under NV compared to pastures under severe, moderate and light degradation in the semi-arid of China. Degraded soils often exhibit a reduced MB-C as a consequence of oxidative metabolic disturbances, which can directly impact the soil's ability to perform essential biochemical functions (Neves et al. 2021). Nevertheless, according to Souza et al. (2025), when animals and human activities are excluded, microbial communities in the soil can recover their functional resilience even after a relatively short period of 3 years, because the absence of disturbances allows for proper oxidative metabolism to take place (Souza et al. 2025). Consequently, degraded pastures can recover their MB-C with cattle exclusion or restoration management; however, longer-term studies are needed to evaluate their actual recovery potential, since it may be limited under the harsh semi-arid conditions.

The NV exhibited the highest MB-C in the 0–10 cm layer. This reflects a stable environment with continuous and diverse organic inputs from litterfall and root turnover, promoting a robust microbial biomass (Ferreira et al. 2016). In contrast, at the 10–20 and 20–30 cm layers, MB-C under NV decreased markedly, whereas ILF systems maintained substantially higher MB-C in these subsurface layers. This suggests that the implementation of plants (especially leguminous trees) that differ in their quantity, decomposition rate and residue quality in integrated systems can enhance both the quantity and diversity of belowground carbon inputs, creating a more favourable environment for MB-C deeper in the soil profile (Ferreira et al. 2016). These findings are consistent with the research conducted by dos Santos et al. (2025), which also reported a beneficial effect of ILF systems on MB-C in the Brazilian semi-arid region. They also emphasized that similar positive outcomes may be achieved in other regions and integrated systems, as long as species are carefully selected based on local climatic and soil conditions, which can improve soil quality by increasing MB-C and promoting more efficient nutrient cycling.

The analysis of *q*MIC, which represents the proportion of total SOC incorporated into the microbial biomass, provides a deeper insight into the efficiency of the microbial community (Figure 7B). The ILF systems, particularly at the 20–30 cm depth, maintained a high *q*MIC along with greater MB-C, which reflects a more efficient microbial community. This can be attributed to the greater organic matter inputs supplied by gliricidia in these systems. As a deciduous leguminous tree, gliricidia provides substantial high-quality organic inputs with a relatively low C:N ratio due to biological nitrogen fixation, enhancing soil microbiological conditions and stimulating organic matter mineralization, which can promote higher *q*MIC values and greater incorporation of carbon into microbial biomass (Camelo et al. 2021). The role of nitrogen in these systems was inferred from the presence of leguminous species, which are known to possess the ability to fix atmospheric nitrogen. This process likely contributed to an enhancement in substrate quality, thereby promoting increased microbial activity in the soil. However, it is important to note that direct measurements of nitrogen dynamics were not conducted in this study. Consequently, the complex interactions between carbon and nitrogen within these systems remain only partially understood. To gain a clearer and more comprehensive understanding of these interactions, further research is needed in future studies, particularly focusing on quantifying and analysing nitrogen and its impact on carbon cycles.

4.5 | Soil Aggregation

The NV exhibited the largest proportion of macroaggregates in the 0–10 cm layer (78.7%). A similar proportion of macroaggregates was also reported by Garcia-Franco et al. (2015) for a 20-year afforested site in the semi-arid southeast of Spain. Such patterns are frequently attributed to the continuous accumulation and incorporation of litter in forested systems, which increases soil organic matter inputs and stimulates microbial activity that promotes aggregate formation and stabilization (Blanco-Canqui and Lal 2004; Okolo et al. 2020).

The ILFcg system exhibited the overall lowest proportion of macroaggregates, a pattern that is linked to the periodic biennial soil tillage. Numerous studies have documented reductions in macroaggregate proportion under conventional tillage regimes (Hajabbasi and Hemmat 2000; Álvaro-Fuentes et al. 2008; Plaza-Bonilla et al. 2013; Kabiri et al. 2015; Okolo et al. 2020). Conventional tillage increases the turnover (formation and breakdown) of macroaggregates, which reduces the persistence of large stable aggregates (Six et al. 2000). Supporting this, Ponyane et al. (2025) reported a strong correlation between conventional tillage and the formation of mesoaggregates and microaggregates fractions, indicating that tillage alters both aggregate structure, size distribution and stability.

Along with tillage, the limited surface residue provided by forage cactus in the ILFcg system may contribute to the reduced formation of macroaggregates. This occurs because the lack of surface residue fails to protect the integrity of the aggregates. Similarly, in the DegP, a low organic matter input and continuous trampling hinder the biologically mediated formation of macroaggregates and accelerate structural degradation (Wiesmeier et al. 2012).

The decrease in macroaggregates in the ILFcg system was matched by an increase in mesoaggregates across most soil depths. Similar patterns have been reported under conventional tillage in semi-arid regions, where Hajabbasi and Hemmat (2000) observed a greater proportion of smaller aggregate size classes (< 0.250 mm). According to the hierarchical aggregation theory, macroaggregates are progressively formed from microaggregates and mesoaggregates, and at the same time, the organic matter occluded within these larger structures is gradually decomposed, leading to the formation of smaller aggregates within macroaggregates over time (Bronick and Lal 2005). When soil is subjected to tillage, this natural hierarchical organization is disrupted, resulting in macroaggregate disintegration and the liberation of microaggregates and mesoaggregates into the soil, altering aggregate size distribution.

In contrast, the ILFug system, managed under NT, minimizes mechanical disturbance of the soil and thereby preserves aggregate integrity, while simultaneously stimulating microbial activity in the surface layer (Madejón et al. 2009; Plaza-Bonilla et al. 2013), which promotes the release of organic binding agents, facilitating macroaggregate formation and increasing their structural stability (Abiven et al. 2009; Plaza-Bonilla et al. 2013). Additionally, long-term adoption of NT has been shown to progressively increase the proportion of macroaggregates in the topsoil (Plaza-Bonilla et al. 2013).

The ILFug system exhibited the highest ASI at the 10–20, 20–30, 30–50 and 70–100 cm depths, whereas NV showed greater ASI values in the 0–10 cm and at 50–70 cm layers. These results are consistent with previous findings indicating that soils under integrated systems managed with NT and forests typically demonstrate greater aggregate stability than those under other conventional land uses (Six et al. 2000; Álvaro-Fuentes et al. 2008). The retention of larger amounts of plant residues on the soil surface in these systems promotes SOC accumulation and creates favorable conditions for soil biota, which in turn contribute to the formation of larger and more stable aggregates (Hernanz et al. 2002). Evidence from semi-arid Mediterranean regions further supports that greater residue inputs under NT are positively related to aggregate stability (Álvaro-Fuentes et al. 2008; Fernández-Ugalde et al. 2011). In addition, the presence of gliricidia plants contributes to improved soil structural stability, as leguminous species are known to enhance aggregation through their root systems and associated biological activity, resulting in higher proportions of WSA compared with non-leguminous plants (Bronick and Lal 2005).

The ImpP exhibited a higher proportion of macroaggregates and ASI (except in the 70–100 cm layer) when compared to the DegP, which is consistent with observations reported by Fonte et al. (2014), who found greater soil aggregation under well-managed pastures than under degraded conditions. Well-managed pastures typically promote the development of deeper and more vigorous root systems, which enhance soil aeration, stimulate biological activity and facilitate the binding of soil particles, thereby strengthening soil structure (Fonte et al. 2014). Because aggregate formation is largely driven by biotic processes, particularly the action of plant roots, soil microorganisms and soil fauna, reduced organic matter inputs and microbial biomass in degraded pastures lead to lower aggregate formation and overall structural stability (Fonte et al. 2014).

In the 70–100 cm layer, the ImpP system exhibited a greater proportion of macroaggregates compared to all other land uses, despite presenting the lowest ASI. Previous studies have shown that macroaggregates formed predominantly in the rhizosphere at deeper soil layers tend to be structurally less stable than those developed in the surface soil through plant senescence and residue incorporation (Gale et al. 2000; Álvaro-Fuentes et al. 2007).

Collectively, these results demonstrate that both land use and soil management strategies play a central role in controlling soil aggregate formation and stability in semi-arid environments, where maintaining soil structure is critical for long-term agricultural sustainability. Furthermore, practices aligned with NbS, by enhancing aggregate stability and increasing SOC stocks, contribute simultaneously to climate change mitigation and adaptation, while also supporting the achievement of multiple Sustainable Development Goals (SDGs).

5 | Conclusion

The observed reductions in SOC stocks under conventional practices, such as tillage (ILFcg) and pasture degradation (DegP), emphasize the vulnerability of the semi-arid regions to unsustainable land-use management.

The disparity in the carbon management index between the DegP and ImpP underscores the significance of adopting management strategies aimed at restoring soil quality. Improved pastures can act as a key tool for reversing degradation trends by integrating conservation principles into pasture management. However, it is noteworthy that even after 15 years, SOC stocks in ImpP remain similar to those in DegP. This suggests that while improved pastures can act as a tool to reverse degradation trends, their effectiveness may be limited under semi-arid conditions if not complemented with additional strategies such as pasture rotation with leguminous plants and the adoption of integrated systems, especially under NT.

Overall, the results indicate that soils under degradation processes and conventional tillage are currently, or potentially in the future, at risk of significant losses of SOM, and may face constraints related to soil structure, microbial biomass and nutrient availability and cycling. Such limitations are closely associated with diminished microbial biomass, a low proportion of macroaggregates and declining soil fertility. To address this knowledge gap, we recommend conducting targeted research and monitoring of long-term experiments, along with paired measurements of GHG fluxes and biogeochemical modelling, to assess the carbon sequestration potential resulting from the restoration of these areas, as well as to evaluate the environmental consequences if such areas remain without restoration management.

Considering all the factors discussed, adopting NbS positively impacted SOC and SOM dynamics, especially in integrated systems under NT. Therefore, both farmers and policymakers should recognize these benefits and prioritize the expansion of NbS in semi-arid regions, where water scarcity and high temperatures often exacerbate soil degradation. However, the implementation of NbS typically requires modest upfront investment and does not always deliver substantial financial returns in the short term; therefore policymakers should consider implementing legislation that actively encourages farmers to adopt these sustainable practices, providing targeted financial assistance, such as low-interest loans and carbon credit programs, to help cover the costs of transitioning degraded and conventional agriculture areas to NbS that provide agronomic and ecosystem benefits, improved soil health, greater resilience to climatic variability and often increased productivity over time. By promoting these benefits alongside C sequestration, upscaling NbS can contribute to climate mitigation objectives and, simultaneously, support local livelihoods and community resilience.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Soil organic carbon (SOC) stocks in 0–10, 0–30, 0–50 and 0–100 cm soil layers under native vegetation (NV), integrated ILF of signal grass+ gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP), in the Brazilian semi-arid region. **Table S2:** Bulk density and soil C content under native vegetation (NV), ILF of signal grass+ gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP). **Table S3:** Carbon pool index (CPI), lability (L) and lability index (LI) in 0–10, 0–30, 0–50 and 0–100 cm soil layers under native vegetation (NV), ILF of signal grass+ gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region. **Table S4:** Distribution of water-stable aggregate (WSA) classes in different land use systems in the Brazilian semi-arid areas.