

Research Article

Silvopastoral Systems Enhance Soil Health and Carbon Stocks in the Brazilian Semiarid Region

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Aiming to expand the database of research on integrated production systems in Brazilian drylands, this study evaluated the soil carbon and nitrogen stocks and the soil chemical, physical, and biological attributes following the conversion of low-productivity pastures (LPPs) into silvopastoral systems in the semiarid region of Bahia State, Brazil. The following land uses were assessed: native vegetation (NV), LPP, and two silvopastoral systems arranged with single row (SSP1) and quadruple row (SSP4) of *Eucalyptus urograndis* integrated with *Urochloa decumbens*. Soil bulk density (BD) and carbon (C) and nitrogen (N) contents and stocks were determined 7 years after the implementation of the integrated systems. Additionally, microbial biomass carbon (C_{mic}), microbial quotient (qMIC), the activity of β -glucosidase (β G) and arylsulfatase (ARS) enzymes, and soil fertility parameters were evaluated during the dry and rainy seasons. Furthermore, the Soil Health Index (SHI) was calculated using the Soil Management Assessment Framework (SMAF) tool. Both the SSP1 and SSP4 systems restored soil carbon contents and stocks to values similar to those observed under NV to a depth of 100 cm. Seasonality and soil management influenced microbial activity. Higher values of β G, MBC, and qMIC were observed in SSP1 and SSP4 during the dry season. Both SSP1 and SSP4 restored the SHI. These results indicate that converting LPPs into integrated crop–livestock systems boosts soil carbon stocks and enhances soil health in the edaphoclimatic conditions evaluated, demonstrating that such systems represent a viable and effective strategy for restoring degraded soils in Brazilian drylands.

Keywords: β -glucosidase; arylsulfatase; carbon stocks; drylands; microbial carbon

1. Introduction

In 2023, the agricultural sector in Brazil emitted 631,176,931 Mt of greenhouse gases (GHGs) [1]. Therefore, it is necessary to adopt agricultural management practices that emphasize conservation techniques to reduce GHG emissions. In this context, the new targets established in Brazil's

Nationally Determined Contribution aim to reduce GHG emissions by 59%–67% by 2035, based on 2005 levels. These values correspond to a reduction of 850 million to 1.05 billion tons of CO₂ equivalent [2]. Thus, the use of integrated production systems, as the integrated crop–livestock–forest (ICLF) systems, is an alternative for the sustainable intensification of agriculture in Brazil.

ICLF systems are included in the Sectoral Plan for Mitigation and Adaptation to Climate Change, which supports the transition to a Low Carbon Agriculture economy (ABC + Plan) [1]. These systems contribute to increasing soil carbon in areas previously occupied by low-productivity pastures (LPPs) [3]. In 2009, the Low Carbon Agriculture Plan (ABC Plan) set a goal to expand 4 million hectares with integrated systems by 2020 in Brazil. In this context, between 2010 and 2015, the addition of 5.96 million hectares occupied by ICLF sequestered 21.8 million tons of CO₂ eq [4]. Thus, after Brazil adopted the Paris Agreement on Climate Change in 2016, the government expanded the ABC Plan target to include an additional 5 million hectares with ICLF systems. The total area under these systems could reach nine million hectares by 2030 [4]. From 2015/2016 to 2020/2021, the area under ICLF grew by 52%, with an estimated 17.43 million hectares planted [4].

The combined effect of management practices and species interactions promotes a continuous and diverse input of organic matter into the soil (SOM) of integrated systems. As a result, these systems are being efficiently adopted in Brazil as a strategy for carbon sequestration in LPPs. They have achieved accumulation rates of 0.82–2.58 Mg ha⁻¹ year⁻¹ [3] and have contributed to increasing soil quality (SQ) [5]. Additionally, integrated systems can improve soil physical quality by reducing compaction [6]. They can also increase microbial biomass carbon (C-mic) levels [3] and enhance the activity of arylsulfatase (ARS) and β-glucosidase (βG) enzymes [7]. Furthermore, these systems may raise soil pH and increase the availability of potassium (K) and phosphorus (P) [8]. In this regard, the determination of physical, chemical, and biological attributes related to the main soil functions constitutes useful tools for assessing SQ, with a focus on microbiological bioindicators, which are sensitive and respond quickly to management variations [9].

However, because SQ is complex to evaluate, tools with multiple approaches have been developed to generate robust indices for this purpose [10, 11]. These indices help identify and distinguish the impacts caused by different types of management [12]. Among these tools, the Soil Management Assessment Framework (SMAF) was created by Andrews et al. [13] for its precision and sensitivity in responding to changes in soil characteristics after management interventions [11, 13]. The SMAF tool operates in three steps: indicator selection, interpretation of indicators, and integration into a single index [13]. Since different soil characteristics can be listed as quality indicators, analyzing a single factor in isolation does not accurately reflect the current state of the soil. Therefore, an SQ index should encompass physical, chemical, and biological properties, grouping indicators that are sensitive to environmental variations and different management practices [12]. Thus, applying the tool in a chronosequence of land use, consisting of native vegetation–pasture–silvopastoral systems (common in Brazil), will elucidate the effect of integrated management on soil health and how close these systems are to the reference ecosystem.

Several studies have evaluated the physical, chemical, and biological attributes of soil within integrated systems [5, 6, 8, 14]. However, the potential for carbon accumulation and the chemical and biological characteristics of the soil in integrated systems in semiarid climates are not well explored [15]. Therefore, it is important to intensify studies in these regions, which, although vulnerable to the impacts of climate change, contribute substantially to global agricultural production. Hence, this study hypothesized that the conversion of LPPs into silvopastoral systems in the semiarid region increases in soil carbon stocks and improves the soil chemical, physical, and biological attributes. Thus, the objective of this study was to evaluate the impact of converting LPPs into silvopastoral systems on carbon and nitrogen stocks and soil health indicators at different sampling times in the semiarid region of Bahia State, Brazil.

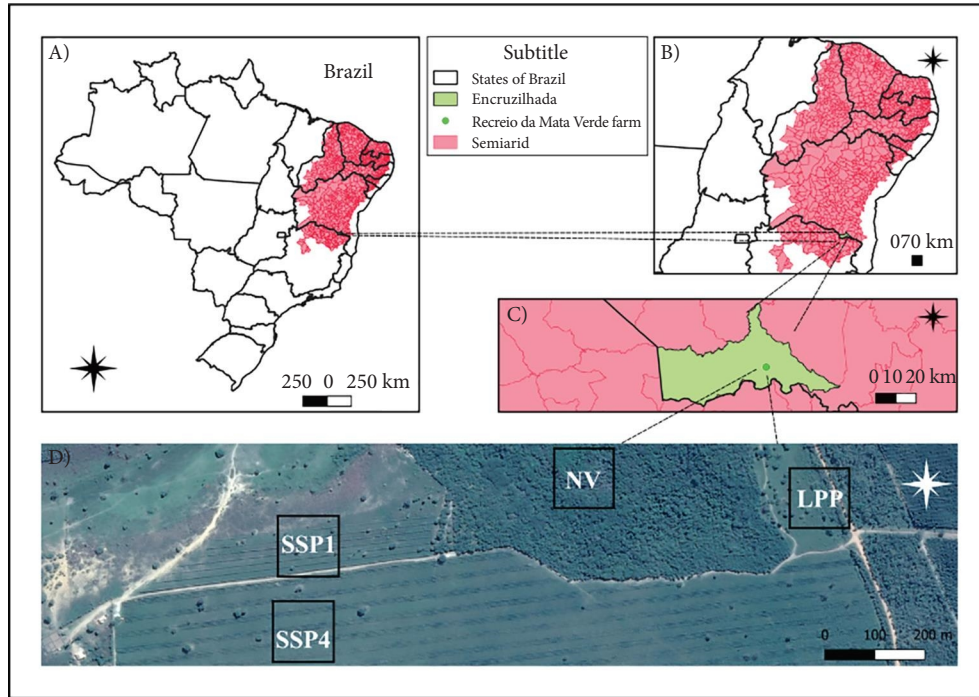
2. Material and Methods

2.1. Location, Characterization, and History of Land Use.

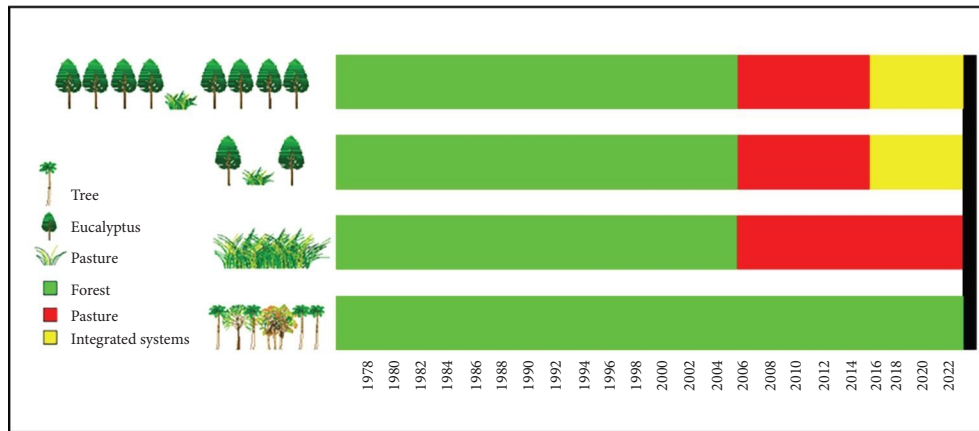
The study was conducted at the Recreio da Mata Verde farm (15°35'29" S, 40°51'11" W), located in the municipality of Encruzilhada (Figure 1(a)), Bahia, Brazil. The municipality lies in a transition zone between the Atlantic Forest and Caatinga biomes and is approximately 792.19 m above sea level. According to Köppen's classification [16], the region's climate is classified as Cwa, with rainfall concentrated in the summer and a dry period in the winter. The average air temperature and rainfall over the last 10 years were 20.5°C and 680 mm, respectively [17]. The local soil was classified as Udox, with a sandy loam texture, consisting of 67.1% sand, 14.89% silt, and 18.01% clay.

This study evaluated a land-use chronosequence (Figure 1(b)) consisting of the following treatments: T₁—native vegetation (NV) of Atlantic Forest (characterized by low species diversity, with a predominance of *Annona coriacea*), used as a reference soil, with no intervention for over the last 30 years; T₂—LPP of *Urochloa decumbens*—signal grass (LPP) (15 years); T₃—seven years of silvopastoral system (SSP1), arranged with a single row of *Eucalyptus urograndis* and *U. decumbens*; and T₄—seven years of silvopastoral system, arranged with quadruple row of *E. urograndis* and *U. decumbens* (SSP4). The experiment was conducted in a completely randomized design with five replicates, totaling 20 experimental units.

In 2007, part of the native vegetation area was converted into signal grass pasture. For 9 years, the forage was extensively grazed by beef cattle (at an average stocking rate of 1 AU per hectare) without management practices such as reseeding, soil correction, or fertilizer application. As a result, the area was substantially replaced by spontaneous vegetation, giving rise to the LPP. In 2016, part of the local soil underwent harrowing and subsoiling, and land use was replaced with integrated production systems. These are characterized as silvopastoral or integrated livestock–forest (ICF) systems, consisting of a consortium of *E. urograndis* (clone 2034) and *U. decumbens*.



(a)



(b)

FIGURE 1: Continued.

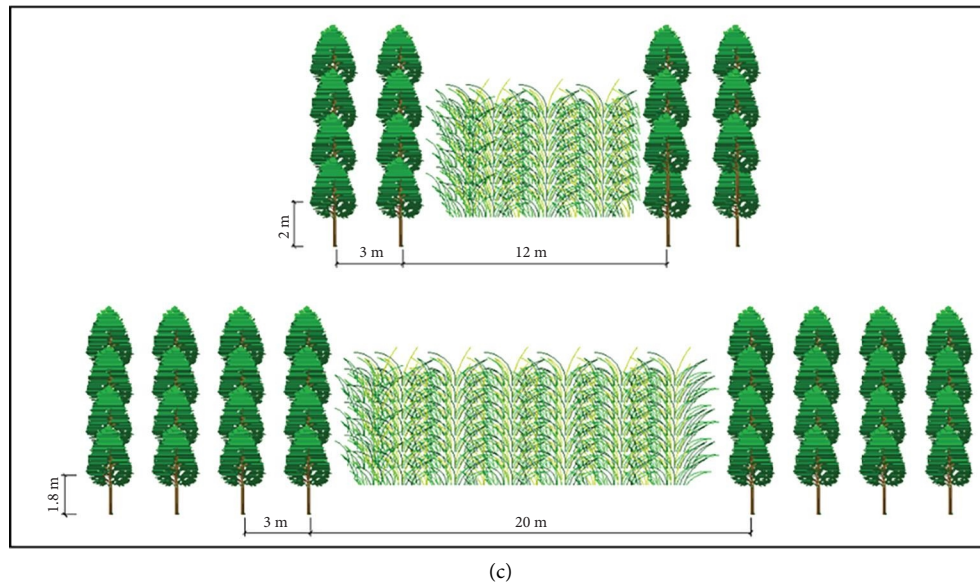


FIGURE 1: Location of the experimental area (a); chronosequence of land use (b); and arrangements of the silvopastoral systems (*E. urograndis* + *U. decumbens*) arranged with single row and quadruple row (c), evaluated at the Recreio da Mata Verde farm in the semiarid region of Bahia State, Brazil.

The integrated systems were implemented with two productive arrangements. In the silvopastoral system 1 (SSP1), eucalyptus was planted in single rows, with a spacing of 1 m between plants and 14-m alleys occupied by *U. decumbens* (Figure 1(c)). In the silvopastoral system 4 (SSP4), eucalyptus was planted in clusters of quadruple rows (1.8 m × 3 m), with 20-m alleys also occupied by *U. decumbens* (Figure 1(a) (D)). The areas received four tons of lime in 2016 and topdressing fertilization in 2017. After these initial interventions, no additional inputs, such as fertilizers, fungicides, insecticides, or herbicides, were applied. Currently, the only management practice is mechanized mowing during the dry season to control the emergence of spontaneous plants. Grazing in the area is continuous throughout the year, alternating between beef cattle and horses, with a stocking rate of 1 AU per hectare. In 2022, six years after the silvopastoral systems were established, 100% of the eucalyptus was mechanically harvested, with the wood being used for charcoal production. Following the harvest, regrowth was managed through thinning, leaving two shoots per regrowth.

2.2. Soil Sampling. Two sampling events were conducted in the experimental area, the first in February 2023 (rainy season) and the second in September 2023 (dry season). Soil samples for the evaluation of total organic carbon (TOC) and total nitrogen (TN) were collected from 1-m-deep trenches (1 × 1 m), with sampling conducted at the following layers: 0–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm.

Considering the heterogeneous deposition of soil organic matter (OM) within integrated production systems, sampling in SSP1 and SSP4 followed the recommendations proposed by Oliveira et al. [18]. Composite

samples were collected by opening two trenches per replicate, distributed linearly in the following spatial arrangement: tree rows and the alley center. Composite samples were also collected for biological evaluations, including C-mic, ARS enzyme activity, and β G enzyme activity, in the 0–10- and 10–20-cm layers. The soil bulk density (BD) was estimated using the volumetric ring method for all evaluated layers [19].

After collection, the soil samples for microbiological assessments were stored in refrigerators at 4°C until analysis. The remaining samples were air-dried and then passed through 2.0-mm sieves. Subsequently, the roots were removed, and the samples were allocated for chemical and biological assessments. To determine the contents of TOC and TN, the soil was ground and classified using a 0.150-mm sieve.

2.3. Evaluation of Soil Attributes

2.3.1. Soil Density and Fertility. Soil BD was estimated according to Teixeira et al. [19], using undisturbed samples collected with volumetric rings. Soil fertility attributes were determined based on the guidelines proposed by Raji et al. [20].

2.3.2. Soil C and N Levels and Stocks. For the determination of TOC and TN levels, the samples were analyzed using dry combustion in an elemental analyzer (Leco CN-2000, St. Joseph, MI, USA), which measures carbon content through infrared absorption and nitrogen content through thermal conductivity. The carbon and nitrogen stocks were calculated using the equivalent soil mass method to account for differences in soil densities induced by management practices [21, 22]. For this purpose, NV was used as the reference area. The soil mass was adjusted using the ratio of the BD of LPP,

SSP1, and SSP4 to the BD of NV up to a depth of 30 cm. Then, the soil C and N stocks were determined from the multiplication of C or N content by the BD and soil depth layer.

The annual C accumulation rates were calculated by subtracting the C stocks of the SSP1 and SSP4 management systems from the C stocks of LPP. The results were then divided by the implementation time of the silvopastoral systems (7 years) in comparison to LPP (17 years), which was adopted as the baseline. For LPP, the accumulation rates were calculated in comparison to NV, using the method applied to the integrated systems.

2.3.3. Soil C-mic and Enzymatic Activity. Soil C-mic was determined using the fumigation–extraction method proposed by Vance et al. [23] and Silva and Mendonça, [24]. The microbial quotient (qMic) was calculated according to Sparling [25], based on the obtained values of Cmic and TOC. The activity of ARS and β G enzymes was determined following the methodology suggested by Tabatabai [26].

2.3.4. Diagnosis of Soil Health Using SMAF. Seven indicators were selected for the SMAF approach: TOC, Cmic, β G, pH, K, P, and BD. These indicators were selected because they broadly represent the three fundamental pillars for assessing soil health—chemical, physical, and biological attributes—and are responsive to changes imposed by management in integrated production systems [10]. The value of each indicator measured in the laboratory was transformed into scores ranging from 0 to 1 using nonlinear curves in the SMAF [13, 27]. Subsequently, the scores of each indicator were integrated into an overall soil health assessment, referred to as the Soil Health Index (SHI), using a weighted additive approach:

$$SHI = \sum ni = 1 SiWi, \quad (1)$$

where S_i = indicator score and W_i = weighted score of the indicators.

The indicators were weighted based on the chemical (pH, P, and K), physical (BD), and biological (TOC, Cmic, and β G) components. Thus, regardless of the number of indicators used, the groups were assigned equal weights (33.33%) in the final index [28].

2.4. Data Analysis. The obtained results were subjected to the Shapiro–Wilk and Bartlett tests to verify if the means followed a normal distribution and if the variances were homogeneous. A logarithmic transformation of the data was applied when these assumptions were not met. Subsequently, the data were subjected to analysis of variance (ANOVA), and when significant, the means were compared using the Tukey test ($p < 0.05$). The data analyses of Cmic, qMIC, and β G and ARS enzymes activity were performed using a simple factorial design. Principal component analysis (PCA) was also performed to interpret and integrate the studied variables in a combined manner. For this, the software R Version 4.0.4 was used.

3. Results

3.1. Soil BD. The conversion of NV (0.94 g cm^{-3}) into different land uses promoted an increase in soil BD in the LPP (1.24 g cm^{-3}), SSP1 (1.15 g cm^{-3}), and SSP4 (1.18 g cm^{-3}) systems in the 0–10-cm layer. Ds in LPP (1.26 g cm^{-3}) was higher in the 10–20 cm soil layer compared to the other treatments. No differences in BD were observed in the other layers up to a depth of 100 cm (Table 1).

3.2. Soil C and N Levels and Stocks. The TOC contents ranged from 4.93 (LPP) to 15.64 g kg^{-1} (SSP1) up to 1 m of depth. The soil under LPP showed the lowest TOC contents compared to SSP1 and SSP4 at all evaluated depths, except in the 70–100-cm layer (Figure 2(a)). The TN contents were higher in SSP1 (1.11 g kg^{-1}) compared to SSP4 (0.75 g kg^{-1}) and LPP (0.68 g kg^{-1}) in the 20–30-cm layer (Figure 2(b)). No differences in TN contents were observed at the other evaluated depths. The C/N ratio ranged from 8.34 (LPP) to 13.69 (SSP4) up to 1-m depth and did not differ among the land uses (Figure 2(c)).

The SSP1, SSP4, and NV systems showed similar C stocks at the 0–30 and 0–100-cm depths (Figure 2(d)), with the lowest values observed in LPP at the 0–30 cm (26.74 Mg ha^{-1}) and 0–100 cm (68.42 Mg ha^{-1}). Sixteen years after the conversion of NV into pasture, the management adopted in LPP promoted a significant reduction in C stocks. In the 0–30-cm and 0–100-cm layers, the losses were 26.50% (9.64 Mg ha^{-1}) and 26.00% (23.94 Mg ha^{-1}), respectively, corresponding to loss rates of 0.60 and $1.50 \text{ Mg ha}^{-1} \text{ year}^{-1}$. However, the management practices adopted after the introduction of the integrated systems (SSP1 and SSP4) recovered the C stocks. The SSP1 system promoted increases of 57.85% (15.47 Mg ha^{-1}) in the 0–30-cm layer and 49.25% (33.69 Mg ha^{-1}) in the 0–100-cm layer, with accumulation rates of 2.21 and $4.81 \text{ Mg ha}^{-1} \text{ year}^{-1}$, respectively. In SSP4, the increases were 47.68% (12.75 Mg ha^{-1}) and 32.24% (22.06 Mg ha^{-1}) in the same layers, with accumulation rates of 1.82 and $3.15 \text{ Mg ha}^{-1} \text{ year}^{-1}$. Both systems promoted the recovery of C stocks to levels similar to those found in native vegetation. The N stocks were similar between SSP1 (3.80 Mg ha^{-1}), SSP4 (3.27 Mg ha^{-1}), and NV (3.16 Mg ha^{-1}) at the 0–30-cm depth (Figure 2(e)). LPP (2.60 Mg ha^{-1}) had lower stocks compared to SSP1 (Figure 2(e)). There was no difference in N stocks between treatments at the 0–100-cm profile.

3.3. Cmic and Enzymatic Activity. Microbial carbon did not differ between land uses at 0–10- and 10–20-cm layers during the rainy season. However, the SSP1 and SSP4 systems showed higher Cmic levels in these layers. The NV and LPP treatments were not influenced by seasonality at any of the evaluated depths (Table 2).

The activity of the ARS enzyme was higher in the soil under NV ($453.31 \mu\text{g pNP g}^{-1} \text{ h}^{-1}$) and LPP ($421.92 \mu\text{g pNP g}^{-1} \text{ h}^{-1}$) at the 0–10 cm depth and higher than in the integrated systems during the rainy season (Table 2). In the dry season, the enzyme activity was higher in SSP1 ($323.90 \mu\text{g}$

TABLE 1: Soil bulk density under different land use managements in the semiarid region of Bahia State, Brazil.

Depth (cm)	Land uses				CV (%)
	NV	LPP	SSP1	SSP4	
Soil bulk density ($\text{g}\cdot\text{cm}^{-3}$)					
0–10	0.94 ^b	1.24 ^a	1.15 ^a	1.18 ^a	7.45
10–20	1.07 ^b	1.26 ^a	1.12 ^b	1.09 ^b	5.98
20–30	1.09 ^{ns}	1.19 ^{ns}	1.12 ^{ns}	1.08 ^{ns}	6.71
30–50	1.11 ^{ns}	1.18 ^{ns}	1.10 ^{ns}	1.09 ^{ns}	5.78
50–70	1.04 ^{ns}	1.14 ^{ns}	1.05 ^{ns}	1.05 ^{ns}	5.53
70–100	1.08 ^{ns}	1.17 ^{ns}	1.06 ^{ns}	1.03 ^{ns}	3.58

Note: Land-use managements: NV = Atlantic Forest native vegetation; LPP = low-productivity pasture of *Urochloa decumbens*; SSP1 = single-row silvopastoral system; SSP4 = quadruple-row silvopastoral system. Means followed by the same letters and ns in the row did not differ from each other according to the Tukey and F tests at the 5% probability level.

pNP $\text{g}^{-1} \text{h}^{-1}$) than in SSP4 ($113.23 \mu\text{g pNP g}^{-1} \text{h}^{-1}$) but did not differ from the other treatments. At the 10–20-cm depth, NV ($236.96 \mu\text{g pNP g}^{-1} \text{h}^{-1}$) showed the lowest activity and only differed from LPP ($445.27 \mu\text{g pNP g}^{-1} \text{h}^{-1}$) during the rainy season. Meanwhile, SSP4 ($123.51 \mu\text{g pNP g}^{-1} \text{h}^{-1}$) had the lowest activity during the dry season. The rainy season favored ARS activity in LPP, SSP1, and SSP4 (Table 2).

The βG enzyme activity was similar among the evaluated systems during the rainy season at the 0–10-cm depth, with values ranging from $67.08 \mu\text{g pNP g}^{-1} \text{h}^{-1}$ (SSP1) to $105.35 \mu\text{g pNP g}^{-1} \text{h}^{-1}$ (NV). The integrated systems SSP1 ($226.75 \mu\text{g pNP g}^{-1} \text{h}^{-1}$) and SSP4 ($214.32 \mu\text{g pNP g}^{-1} \text{h}^{-1}$) showed higher activity compared to LPP ($105.36 \mu\text{g pNP g}^{-1} \text{h}^{-1}$) during the dry season. At the 10–20-cm depth, the βG activity did not differ between treatments and sampling periods (Table 2).

3.4. Soil Chemical Attributes. The PCA 1 (63.4%) and 2 (25.3%) explained 88.8% of the variation in the data related to the chemical attributes of the evaluated soils (Figure 3). The analysis showed that the SSP1 and SSP4 systems had greater similarity with each other in comparison to the parameters of OM, Mg, Ca, SB, pH, and V. On the other hand, NV showed a low correlation with the described variables, demonstrating a better association with the values of CTC, P, H + Al, Al, and m. The analysis also showed that the LPP system had low similarity with the other treatments and a lower association with the evaluated attributes.

3.5. Soil Health Diagnosis Using SMAF. The soil under NV showed higher scores (0.99) for the physical component compared to LPP (0.70) at the 0–10-cm depth. At the 10–20-cm depth, the scores for NV (0.96), SSP4 (0.93), and SSP1 (0.91) were similar to each other and higher than LPP (0.66), indicating that the introduction of integrated systems improved the soil physical quality at this depth. The chemical component was higher in SSP4 (0.91) compared to LPP (0.86) and NV (0.80) at the 0–10-cm depth, and there was no difference between treatments at

the 10–20-cm depth. The biological component means were similar across treatments, ranging from 0.60 (LPP) to 0.79 (NV) at the 0–10-cm depth and from 0.45 (LPP) to 0.61 (NV) at the 10–20-cm depth (Table 3). The conversion of NV to LPP reduced the SHI from 0.86 to 0.72 at the 0–10-cm depth and from 0.81 to 0.68 at the 10–20-cm depth. The SSP4 (0.84) and SSP1 (0.82) systems increased the SHI at the 10–20-cm layer, supporting the hypothesis that integrated management promotes improved soil health (Table 3).

4. Discussion

4.1. Soil BD. The higher BD values (Table 1) observed in LPP at depths of 0–10 and 10–20 cm are attributed to the continuous presence of animals and the absence of pasture management [29]. Feltran-Barbieri and Féres [30] describe that pasture degradation results from a lack of agronomic management of the crop and livestock, including adjustments in stocking rates, control of spontaneous plants and pests, and nutrient replenishment. Under this approach, the absence of mineral fertilizer replacement and the low frequency of harrowing to control invasive species in LPP led to a decline in biomass production and the regenerative capacity of palisade grass, initiating physical degradation in the system [6].

The increase in BD (0–10 cm) (Table 1) observed in the integrated management systems SSP1 and SSP4 can be explained by the recent intensive machinery traffic during the eucalyptus harvest, which occurred nine months prior to soil sampling. Additionally, the movement of cattle and horses within these systems during the rainy season exerted higher pressure on the soil [29]. Despite this, the integrated systems (SSP1 and SSP4) presented BD values similar to NV at the 10–20-cm depth, supporting the hypothesis that these systems improve soil physical health. This is associated with a greater increase in SOM, stimulated by the combination of C3 (eucalyptus) and C4 (signal grass) species. Signal grass has an intense root renewal process and produces compounds that decompose easily, promoting carbon accumulation in the soil. When combined with the deeper rooting system of eucalyptus, this minimizes compressive forces and promotes greater structuring and aggregation of soil particles [6, 31].

4.2. Soil C and N Levels and Stocks. The higher TOC levels and the positive annual C accumulation rates observed in SSP1 and SSP4 after 7 years of management are attributed to the greater litter input, the main source of carbon entering the soil [32]. It is estimated that an annual eucalyptus cycle can contribute 7.44 Mg ha^{-1} of litter to the soil, of which 4.5 Mg ha^{-1} (60%) correspond to leaves [33]. Furthermore, the interaction between C3 and C4 species promotes intense root renewal, contributing to the increase in soil TOC through the exudation of highly decomposable compounds [8]. Moreover, greater microbial diversity in integrated management enhances nutrient cycling and induces C and N transformations in the soil [5].

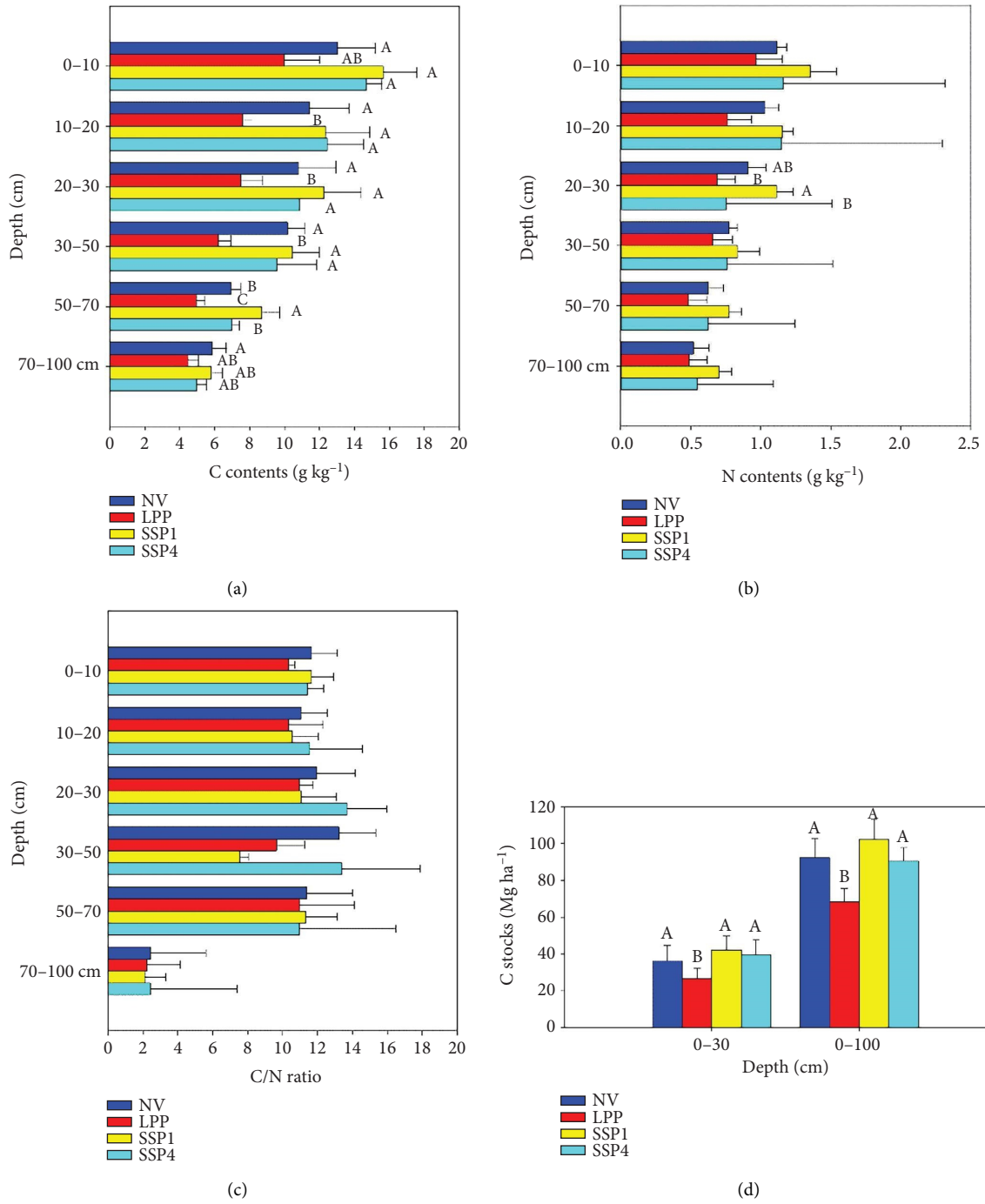


FIGURE 2: Continued.

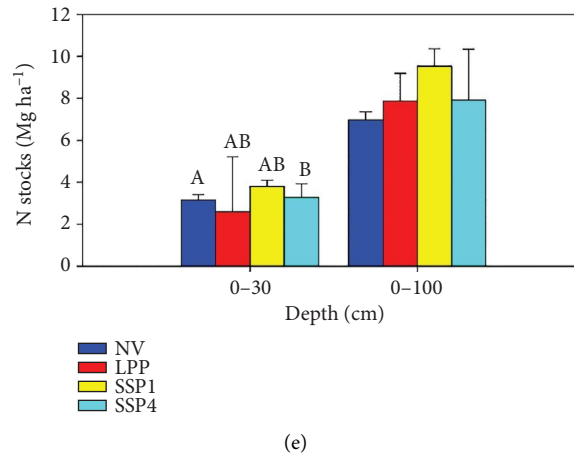


FIGURE 2: Soil organic carbon (a) and nitrogen (b) contents, C/N ratio (c), and soil C (d) and N (e) stocks under different land-use managements in the semiarid region of Bahia State, Brazil. Means followed by the same letters or no letters did not differ from each other according to the Tukey and F tests at the 5% probability level. NV = Atlantic forest native vegetation; LPP = low productivity pasture of *Urochloa decumbens*; SSP1 = single-row silvopastoral system; SSP4 = quadruple-row silvopastoral system.

TABLE 2: Microbial biomass carbon, microbial quotient, and the activity of the enzymes arylsulfatase and β -glucosidase, evaluated at the 0–10 cm and 10–20-cm depths, during the dry and rainy seasons, under different land use managements in the semiarid region of Bahia State, Brazil.

Season	Depth (cm)	Land uses				CV (%)
		NV	LPP	SSP1	SSP4	
<i>Microbial biomass carbon (mg kg⁻¹)</i>						
Rainy	0–10	190.30 ^{ns,NS}	145.21 ^{ns,NS}	158.65 ^{nsB}	146.20 ^{nsB}	28.56
Dry	0–10	167.80 ^{bNS}	126.20 ^{bNS}	306.21 ^{aA}	329.68 ^{aA}	
Rainy	10–20	108.78 ^{ns,NS}	112.17 ^{ns,NS}	134.59 ^{nsB}	153.97 ^{nsB}	21.86
Dry	10–20	134.40 ^{bNS}	125.97 ^{bNS}	242.86 ^{aA}	299.06 ^{aA}	
<i>Microbial quotient</i>						
Rainy	0–10	1.49 ^{ns,NS}	1.48 ^{ns,NS}	1.05 ^{nsB}	1.00 ^{nsB}	30.05
Dry	0–10	1.29 ^{bNS}	1.26 ^{bNS}	1.98 ^{abA}	2.25 ^{aA}	
Rainy	10–20	1.00 ^{ns,NS}	1.45 ^{ns,NS}	1.10 ^{nsB}	1.23 ^{nsB}	21.86
Dry	10–20	1.24 ^{cNS}	1.67 ^{bcNS}	2.06 ^{abA}	2.45 ^{aA}	
<i>Arylsulfatase activity ($\mu\text{g pNP g}^{-1} \text{h}^{-1}$)</i>						
Rainy	0–10	454.32 ^{aA}	421.94 ^{aA}	216.94 ^{bNS}	146.95 ^{bNS}	6.09
Dry	0–10	274.65 ^{aB}	200.16 ^{abB}	323.90 ^{aNS}	113.22 ^{bNS}	
Rainy	10–20	236.97 ^{bNS}	445.28 ^{aA}	304.15 ^{abA}	271.72 ^{abA}	5.95
Dry	10–20	278.86 ^{aNS}	174.98 ^{abB}	198.58 ^{abB}	123.52 ^{bB}	
<i>β-Glucosidase activity ($\mu\text{g pNP g}^{-1} \text{h}^{-1}$)</i>						
Rainy	0–10	105.35 ^{ns, NS}	83.29 ^{ns,NS}	67.08 ^{nsB}	67.98 ^{nsB}	6.89
Dry	0–10	147.02 ^{abNS}	105.36 ^{bNS}	226.57 ^{aA}	214.32 ^{aA}	
Rainy	10–20	69.78 ^{ns,NS}	81.49 ^{ns,NS}	63.48 ^{ns,NS}	59.43 ^{ns,NS}	21.11
Dry	10–20	102.10 ^{ns,NS}	65.51 ^{ns,NS}	99.65 ^{ns,NS}	98.34 ^{ns,NS}	

Note: Land use managements: NV = native Atlantic Forest vegetation; LPP = low-productivity pasture of *Urochloa decumbens*; SSP1 = simple-row silvopastoral system; SSP4 = quadruple-row silvopastoral system. Means—in the row and column—followed by the same letters (uppercase or lowercase) or by ns and NS did not differ among themselves by the Tukey and F tests at the 5% probability level.

Lower levels of TOC (Figure 2(a)) and annual accumulation rates were found in the LPP system, in response to the absence of agronomic management of signal grass (such as reseeding and fertilization) and the animals after 16 years of system implementation. This resulted in lower OM inputs into the soil and reduced TOC levels [34]. Thus, although grasses have a high recycling root system that increases C in the soil over time, the efficiency of this process depends on the management adopted in the system.

The introduction of integrated production systems (SSP1 and SSP4) restored soil carbon stocks to levels similar to those found under NV, consistent with results from previous studies [35–37]. The authors attributed the decline in carbon in pastures primarily to the lack of agronomic management, including fertilization and weed control. In this study, the LPP system showed the presence of spontaneous plants and low biomass production, which limited carbon inputs into the soil via residue deposition [36].

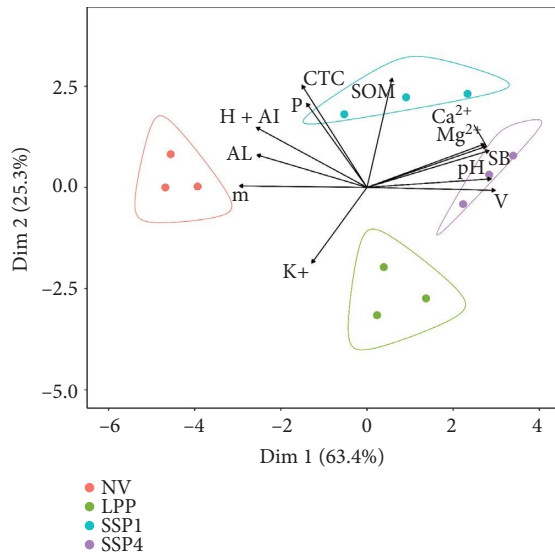


FIGURE 3: Principal component analysis (PCA) of the soil chemical attributes at a depth of 0–30 cm in Encruzilhada/BA. NV = native vegetation; LPP = low-productivity pasture of *Urochloa decumbens*; SSP1 = single-row silvopastoral system; SSP4 = quadruple-row silvopastoral system; pH = hydrogen ion concentration in water; P = Mehlich-1 phosphorus; Ca²⁺ = exchangeable calcium; Mg²⁺ = exchangeable magnesium; K⁺ = potassium; AL = exchangeable acidity; H + AL = potential acidity; CTC = cation exchange capacity; SOM = soil organic matter; V = base saturation; and m = aluminum saturation.

TABLE 3: Scores of the chemical, physical, biological components, and soil health index evaluated at the 0–10 and 10–20-cm layers under different land use managements in the semiarid region of Bahia State, Brazil.

Components	Depth (cm)	Land uses				CV (%)
		NV	LPP	SSP1	SSP4	
<i>Scores</i>						
Chemical	0–10	0.80 ^c	0.86 ^b	0.89 ^{ab}	0.91 ^a	3.07
Physical	0–10	0.69 ^a	0.70 ^b	0.85 ^{ab}	0.81 ^{ab}	13.98
Biological	0–10	0.79 ^{ns}	0.60 ^{ns}	0.61 ^{ns}	0.63 ^{ns}	21.12
Chemical	10–20	0.94 ^{ns}	0.95 ^{ns}	0.95 ^{ns}	0.95 ^{ns}	0.83
Physical	10–20	0.96 ^a	0.66 ^b	0.91 ^a	0.93 ^a	7.93
Biological	10–20	0.51 ^{ns}	0.45 ^{ns}	0.58 ^{ns}	0.63 ^{ns}	25.07
<i>Soil health index</i>						
—	0–10	0.86 ^a	0.72 ^b	0.78 ^{ab}	0.78 ^{ab}	8.55
—	10–20	0.81 ^a	0.68 ^b	0.84 ^a	0.84 ^a	7.56

Note: Land use managements: NV = native Atlantic Forest vegetation; LPP = low-productivity pasture of *Urochloa decumbens*; SSP1 = single-row silvopastoral system; SSP4 = quadruple-row silvopastoral system. Means followed by the same letters and ns in the line did not differ from each other by the Tukey and F tests at the 5% probability level.

However, 7 years of implementing the SSP1 and SSP4 management systems restored carbon stocks in the evaluated depths. These results can be attributed to the combination of C3 and C4 species in these systems. Eucalyptus promotes SOM accumulation through the continuous input of leaves, branches, and roots. Gradually, these residues decompose, increasing soil C and N levels [38, 39]). Additionally, palisade grasses are highly

effective in increasing soil C due to the aggressive activity of their root system and the input of litter. This litter consists of components with higher lability compared to eucalyptus residues, enhancing decomposition processes and positively impacting soil health [6, 40, 41].

4.3. Soil Cmic and Enzymatic Activity. The dry season affected the stability of microbial communities. However, all systems exhibited qMIC values above 1%, suggesting a potential increase in soil C over time [42]. According to Jenkinson and Powlson [43], qMIC typically represents 1%–4% of the soil’s TOC under conditions favorable to microbial activity, while values below 1% may indicate limiting conditions [14], which were not observed in this study.

The highest qMIC values found in SSP1 and SSP4 during the dry season are attributed to system management practices and the unusual rainfall events in July and August. It is well known that higher qMIC values indicate the availability of SOM for microbial communities [44]. Thus, it can be inferred that thinning and pruning operations of eucalyptus during the dry season led to litter accumulation in the soil, contributing to the observed increase in qMIC during this period [44].

The differences observed in ARS and βG responses indicate that land management practices, in addition to seasonal dynamics, influence soil microbiological variables. They also show that the behavior of each enzyme depends on the availability of its specific substrate. Higher βG activity was observed in the SSP1 and SSP4 systems compared to LPP in the 0–10-cm layer during the dry season (Table 2). Preliminary studies reported different results, with higher enzymatic activity during the rainy season [45, 46], as increased soil moisture activates microbial biomass and the activity of several enzymes. In this study, soil sampling for microbiological purposes was carried out during both the dry season (end of winter) and the rainy season (during summer). However, irregular rainfall occurred during the dry season, particularly in July and August. These factors, combined with management practices in the integrated system areas, influenced the microbiological responses observed.

It is well known that the activity of βG increases with higher levels of SOM [47]. Thus, rainfall events after autumn (July and August) increased litter accumulation in the soil. The higher moisture from these sporadic rains stimulated litter decomposition, which resulted in greater βG activity in the SSP1 and SSP4 systems during the dry season. Additionally, soil sampling in the SSP1 and SSP4 systems, conducted during the rainy season, took place 9 months after the full mechanized harvest of eucalyptus, and the intercropped components—eucalyptus and *Brachiaria*—were in the primary reconduction stage. Therefore, it is assumed that smaller amounts of labile residues were contributed by the system during this period, as a predominance of more complex and lignified fragments, such as bark, wood pieces, and branches, was observed on the soil. With this in mind, it is noteworthy that glycosidases are important enzymes that act in the final stage of cellulose degradation, breaking it down into glucose, which serves as an energy source for

microbial communities [26]. In this regard, the quality of the substrate, in addition to its quantity, is an important factor for the metabolic pathways of this enzyme group. More complex compounds with high lignin content tend to decrease β G activity, which is usually associated with less complex residues [48].

At the 10–20-cm layer, the absence of significant variations in the β G activity between land uses and seasons may be related to the greater chemical stability of the subsoil, which tends to reduce enzymatic activity [49], as well as to the lower availability of C at depth [50].

In the collection made in February 2023, the ARS activity was higher in NV and LPP in the 0–10-cm layer, with values higher than those in the September 2023 collection for both land uses (Table 2). During the dry season, SSP4 showed the lowest activity in the same layer. In contrast to β G—which is intrinsically linked to the quality and composition of OM [51]—ARS has a greater correlation with the amount of material added [48]. Therefore, the results suggest that NV and LPP provided more substrate during the rainy season compared to the SSP1 and SSP4 systems, which were undergoing the reconduction process, as previously described. Additionally, Li and Sarah [52] report that sulfatases are substantially affected by temperature. Thus, in NV and LPP, the greater substrate input, together with the humidity and high summer temperatures, created an environment favorable to enzyme production by plants and microorganisms. This may explain the higher values observed in February (rainy season).

Kunito et al. [53] reported reduced ARS activity under conditions of low soil S levels. Thus, the authors suggested that the enzyme's activity is stimulated in S-deficient environments. Accordingly, our results showed higher ARS activity in NV and LPP, indicating a strong dependence of these systems on soil organic S. Under these conditions, plants and microorganisms are stimulated to produce greater amounts of ARS to hydrolyze organic S into SO_4^{2-} and meet their individual and community demands for the macronutrient [54]. Similarly, it is hypothesized that the SSP4 system has a lower dependence on organic S compared to NV and LPP, as this management system showed lower ARS activity (0–10 cm) in both seasons evaluated.

At the 10–20-cm depth, the ARS activity showed a different response pattern, indicating that multiple factors can influence microbial processes in the soil. The consistently higher ARS activity in LPP suggests that agricultural practices promote S mineralization from organic sources, an important pathway for crop development [55]. Temperature and moisture favor microbial and enzymatic activities [45, 56]. In native environments, greater soil cover and the resulting microclimate may have reduced fluctuations in soil moisture during the dry season. This could explain the higher ARS activity observed in NV.

4.4. Soil Chemical Attributes. LPP showed a weaker association with SOM levels, while SSP1 and SSP4 performed better. Similar results were reported by Baldotto et al. [57],

who found higher SOM levels in integrated systems compared to NV and pasture monocultures.

The better association of SSP1 and SSP4 with pH, V (%), SB, Ca, and Mg values compared to NV is attributed to the application of fertilizers and soil amendments for eucalyptus planting in 2016 [58]. Furthermore, as reported by Vasquez et al. [8], the presence of trees in integrated systems increases OM inputs and promotes nutrient cycling over time, improving the chemical attributes of the soil.

The PCA results (Figure 3) show a decrease in K levels in SSP1 and SSP4, indicating that cultivating eucalyptus intercropped with signal grass can reduce the availability of this element in the soil. The weaker association of LPP with nutrient levels, except for K, is attributed to 16 years without agronomic management of *U. decumbens*. The low biomass production in the system reduces OM inputs into the soil, leading to a decline in C and nutrient levels over time [34]. The strong association of K with the LPP system may be linked to several factors, such as greater K cycling in this system, reduced losses, and the release of nonexchangeable K by the grass root system [28].

4.5. Diagnosis of Soil Health Using SMAF. The lower physical component scores in the 0–10- and 10–20-cm layers in LPP are associated with an increase in BD, a physical indicator used in the SMAF approach, likely resulting from the absence of pasture and animal management. Continuous grazing promotes soil compaction due to the surface pressure exerted by cattle trampling. Additionally, the low forage production by *Brachiaria* reduces soil C inputs, further contributing to the compaction process [28]. However, the silvopastoral systems recovered the physical component in the 10–20-cm layer, achieving higher values than LPP. These systems add more residues to the soil, which mitigate the pressure from animal trampling. Furthermore, eucalyptus has a well-developed root system that reaches deeper layers, contributing to better soil structuring [31].

The higher chemical component value found in SSP4 compared to LPP in the 0–10-cm layer is attributed to the greater litter input and the excreta deposited by grazing animals. The decomposition of these residues promotes nutrient cycling and positively affects chemical attributes. Additionally, fertilization and soil correction for eucalyptus planting contributed to the better performance of the chemical component in the silvopastoral system [58].

Sixteen years of LPP implementation without pasture management and control of animal stocking rate induced soil compaction and increased BD, negatively impacting the physical component scores, which may have contributed to the lower SHI observed in LPP [28]. In contrast, the introduction of silvopastoral systems improved chemical, physical, and biological soil attributes after 7 years of implementation. This is evidenced by the increase in SHI in both systems. Integrated management raises TOC and TN levels in the soil, enhancing SQ over time [5]. Eucalyptus contributes residues throughout its cultivation cycle [59], including root exudates, leaves, flowers, seeds, stems, and roots [14]. Additionally, signal grass has a root system composed of fine roots with high turnover, which releases

organic residues through the exudation of highly decomposable compounds [60]. This process increases soil C through the rhizosphere and necromass, benefiting microbial communities [7]. Furthermore, the larger volume of surface residues reduces grazing pressure on the soil, minimizing compaction and resulting in an increase in BD [61].

5. Conclusion

The conversion of LPPs to silvopastoral systems in the Brazilian semiarid region enhanced soil carbon stocks to a depth of 100 cm, with annual increases up to 4.81 Mg ha⁻¹. Additionally, it enhanced chemical, physical, and biological soil attributes, with the responses of the microbiological variables being driven by both management practices and climatic seasonality.

Our results demonstrated that silvopastoral systems increased the chemical, physical, and biological soil health indices calculated using SMAF, demonstrating that integrated agricultural systems represent a viable and effective strategy for restoring degraded soils in Brazilian drylands.

Data Availability Statement

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

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Marcos Fernando Gonçalves Lessa: formulation of research questions, experimental design, methodology, investigation, interpretation and analysis of results, and scientific writing; Igor Costa de Freitas: methodology, experimental design, and validation of results. Marco Antônio Couto Barbosa, Alissam de Sá Cardoso, and Rafael Sales de Castro: methodology and scientific writing; Leonardo Máximo Silva: analysis of results; Maurício Roberto Cherubin: analysis of results and funding acquisition; and Leidivan Almeida Frazão: supervision and project administration, funding acquisition, formulation of research questions, experimental design, investigation, interpretation of results, and manuscript review and editing.

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