



Organic Carbon Compartments and Chemical Attributes of Sandy Soil in Response to Crop Succession Under Conventional Management and Fallow Long-term in the Semi-arid Region

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Abstract

This study aimed to evaluate the effects of crop succession, under both conventional cultivation and fallow management, on soil organic carbon (SOC) compartments, enzyme activity, and chemical properties of a sandy-textured soil in the Brazilian semi-arid region. The sequence of cultivation, crop succession, and fallows was as follows: 2014-Crotalaria (*Crotalaria juncea* L.); 2015-Corn (*Zea mays* L.); 2016-Cowpea (*Vigna unguiculata* L.); 2017-First fallow; 2018-Melon (*Cucumis melo* L.); 2018-Sorghum (*Sorghum bicolor* [L.] Moench); 2019-Second fallow; 2020-Sorghum; 2020–2022-Third fallow (COVID-19 pandemic); 2023-Melon; 2024-Corn; 2024-Cowpea. Soil samples were collected at depths of 0–10 and 10–20 cm and analyzed for total SOC, labile carbon (LC), microbial biomass carbon (MBC), particulate organic carbon (POC), humic fractions (fulvic acid, humic acid, humin), β -glucosidase activity, and chemical attributes. Multivariate statistical analyses were conducted to integrate and distinguish the responses. Results indicated that systems cultivated

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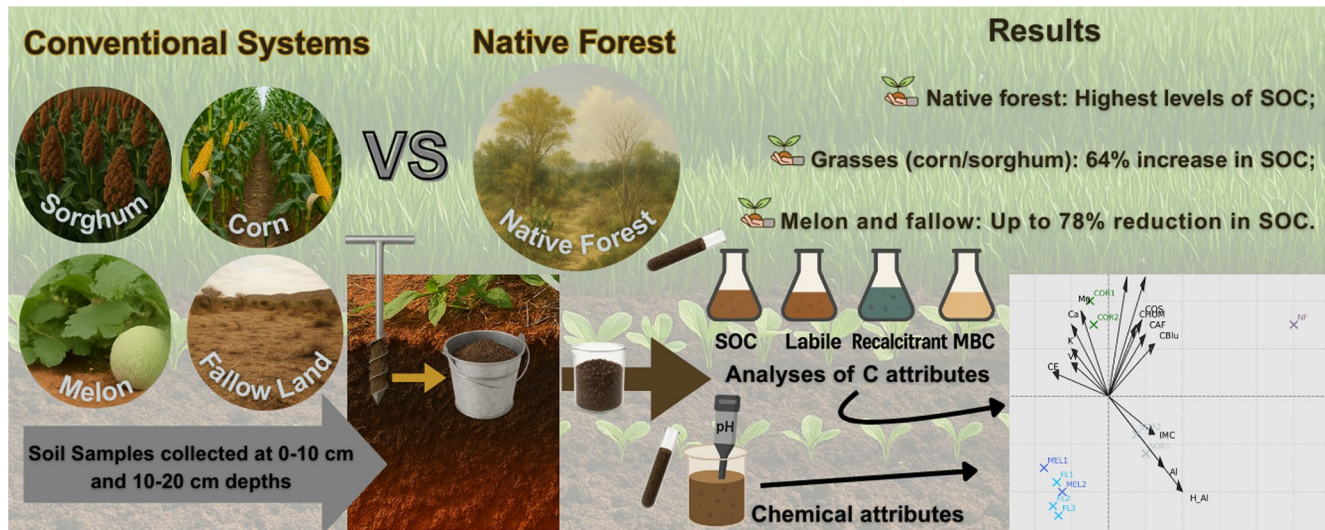
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with corn and sorghum significantly increased SOC stocks (over 40%) and boosted LC, MBC, POC, and enzyme activity, compared to systems with melon and fallow, which experienced SOC losses exceeding 70% and suppressed enzyme activity. The Carbon Management Index (CMI) confirmed the superiority of grass-based systems in terms of sustainability. These findings emphasize the potential of diversified, residue-rich cropping systems to restore biological functionality and improve organic matter quality in degraded sandy soils under semi-arid conditions.

Graphical Abstract



Highlights

- Land use changes in semiarid Brazil compromise soil carbon and function.
- Land use intensification reduces soil carbon by up to 70% in semiarid Brazil.
- Enzymatic activity decreased by > 70% under conventional monocultures.
- Corn and sorghum improved the carbon management index and biological activity.

Keywords Grass and legume cultivation · Labile and recalcitrant organic fractions · Soil enzyme · Microbial biomass · Particulate organic carbon

1 Introduction

Agricultural sustainability in arid and semi-arid regions depends strongly on soil quality, particularly on sandy soils, which occupy approximately 900 million hectares worldwide (Yost and Hartemink 2019; Huang and Hartemink 2020; Rebonatti et al. 2023). The functionality and resilience of these soils are closely linked to soil organic carbon (SOC) (Alencar et al. 2024), yet arid and semi-arid regions hold low to moderate SOC stocks (35–42 t C ha⁻¹), representing about 10% of the global soil carbon pool (Moharana et al. 2021). Under such climates, high temperatures, limited rainfall, low vegetation cover, and low plant biomass inputs restrict carbon accumulation and accelerate organic matter mineralization, resulting in persistent SOC deficits in sandy soils (Rey et al. 2017; Khairallah et al. 2025).

In Brazil, arid and semi-arid zones cover approximately 974,752 km², of which about 844,000 km² correspond to the semi-arid region (Corrêa et al. 2019; Brasil 2020), encompassing nearly 33 million hectares of agricultural land, with around 20% consisting of sandy soils dominated by Neosols and Latosols (Santos et al. 2025). These soils exhibit low organic matter contents, high hydraulic conductivity, and limited nutrient retention capacity (Giongo et al. 2018; Huang and Hartemink 2020; Medeiros et al. 2020), increasing system fragility under climate change scenarios that project intensified aridity (Marengo et al. 2018) and associated declines in soil organic carbon (SOC) (Hu et al. 2022; Li et al. 2023a, b; Ren et al. 2024). While SOC is a key indicator of soil quality and climate mitigation, the fractionation of soil organic matter into pools with distinct turnover times

provides a more sensitive assessment of soil responses to management and degradation processes (Dash et al. 2019).

Labile carbon represents the most responsive component of soil organic carbon (SOC), closely linked to particulate organic matter, microbial biomass, and enzymatic activity, and is therefore widely used to detect short-term changes in soil functioning under different land-use and management systems (Li et al. 2018; Wang et al. 2020). This sensitivity underlies the Carbon Management Index (CMI), which integrates the quantity and quality of soil organic matter and has been broadly applied to assess management impacts in semi-arid regions (Blair et al. 1995; Marinho et al. 2016; Monroe et al. 2021; Ameer et al. 2023; Vasconcelos et al. 2025). In contrast, more recalcitrant fractions, mainly humic substances, exhibit slower turnover and longer residence times, contributing to carbon stabilization, soil structure, nutrient retention, and water-holding capacity, and serving as reliable indicators of long-term soil responses to land use and management in semi-arid environments (Kotzé et al. 2016; Rakesh et al. 2020; Raiesi 2021; Maia et al. 2025). Beyond carbon storage, these stable fractions play a key role in nutrient availability and overall soil fertility, with direct implications for microbial dynamics, plant health, and agricultural productivity (Zavarzina et al. 2021; Gerke 2022; Vikram et al. 2022).

Crop succession regulates soil organic carbon (SOC) dynamics by modifying biomass inputs, residue quality, root turnover, and crop diversity, which together control organic matter decomposition and carbon stabilization over time (Tiemann et al. 2015; Kumar et al. 2019; Ardeni et al. 2023; Oliveira et al. 2024). Although the effects of crop rotation on soil organic matter in semi-arid regions have been widely documented (Liu et al. 2020, 2022; Wei et al. 2020; Man et al. 2021; Jaziri et al. 2022; Luz et al. 2023; Thapa et al. 2023), long-term evidence on how crop diversification affects organic carbon fractions in sandy soils remains scarce, despite the decisive role of the balance between labile and recalcitrant pools in determining carbon stability and agroecosystem resilience (Li et al. 2023a, b).

Crop succession involving grasses and legumes has consistently demonstrated potential to improve soil chemical properties and enhance soil organic carbon (SOC) accumulation in tropical sandy soils (Silva et al. 2020; Cordeiro et al. 2021; Li et al. 2023a, b). Likewise, fallow systems are widely adopted to conserve soil moisture and promote soil fertility and SOC recovery (Tiessen et al. 1992; Nyamadzawo et al. 2008; Mechri et al. 2016; Ghimire et al. 2018). Despite these recognized benefits, the influence of fallow on the distribution and stability of SOC fractions in semi-arid sandy soils remains poorly understood, underscoring a critical knowledge gap for the

development of sustainable soil management strategies in these fragile agroecosystems.

The selection of indicators in this study addressed SOC, labile, and recalcitrant fractions of SOM and soil fertility, based on parameters such as practicality, simplicity, low cost, and efficiency of response, always to use crops in succession that represented the reality of rural producers in the semi-arid region of northeastern Brazil. Based on the hypothesis that grasses and fallow are essential for increasing SOC, organic fractions, and improving soil chemistry, this article aimed to evaluate the organic carbon compartments and chemical attributes of a sandy soil in response to crop succession under conventional planting and fallow over 10 years of cultivation in a semi-arid environment.

2 Materials and Methods

2.1 Description of the Site

The study was conducted at the Experimental Station of the Federal Rural University of the Semi-Arid (UFERSA), located at Rafael Fernandes Farm, in the district of Alagoinha, municipality of Mossoró, Rio Grande do Norte State, Brazil. The geographical coordinates are 5°03'44" S and 37°24'08" W, at an altitude of 72 m above sea level (Fig. 1). The local climate is classified as semi-arid (BSh), according to the Köppen classification, with the rainy season extending from January to June. The native vegetation corresponds to the hyperxerophilous Caatinga Biome (Alvares et al. 2013). Annual temperature and rainfall data for the study period (2014–2024) are presented in Fig. 2.

The soil was classified as Ferralsols according to the World Reference Base for Soil Resources (IUSS, 2022) and Latossolo Vermelho-Amarelo according to the Brazilian Soil Classification System (Santos et al. 2025), with a sandy texture, which was classified by Rêgo et al. (2016). The chemical attributes and granulometry of the soil before the study are shown in Supplementary Table 1.

2.2 Crop Succession (Treatments)

When selecting crops for succession, species adapted to semi-arid conditions and representative of the farming practices of rural producers in Rio Grande do Norte were chosen. Soil was collected over 10 years (2014–2024), alternating between crops and fallow phases. The sequence of cultivation, succession crops, and fallows was as follows: 2014-Crotalaria (*Crotalaria juncea* L.); 2015-Corn (*Zea mays* L.); 2016-Cowpea (*Vigna unguiculata* L.); 2017-First fallow; 2018-Melon (*Cucumis melo* L.); 2018-Sorghum

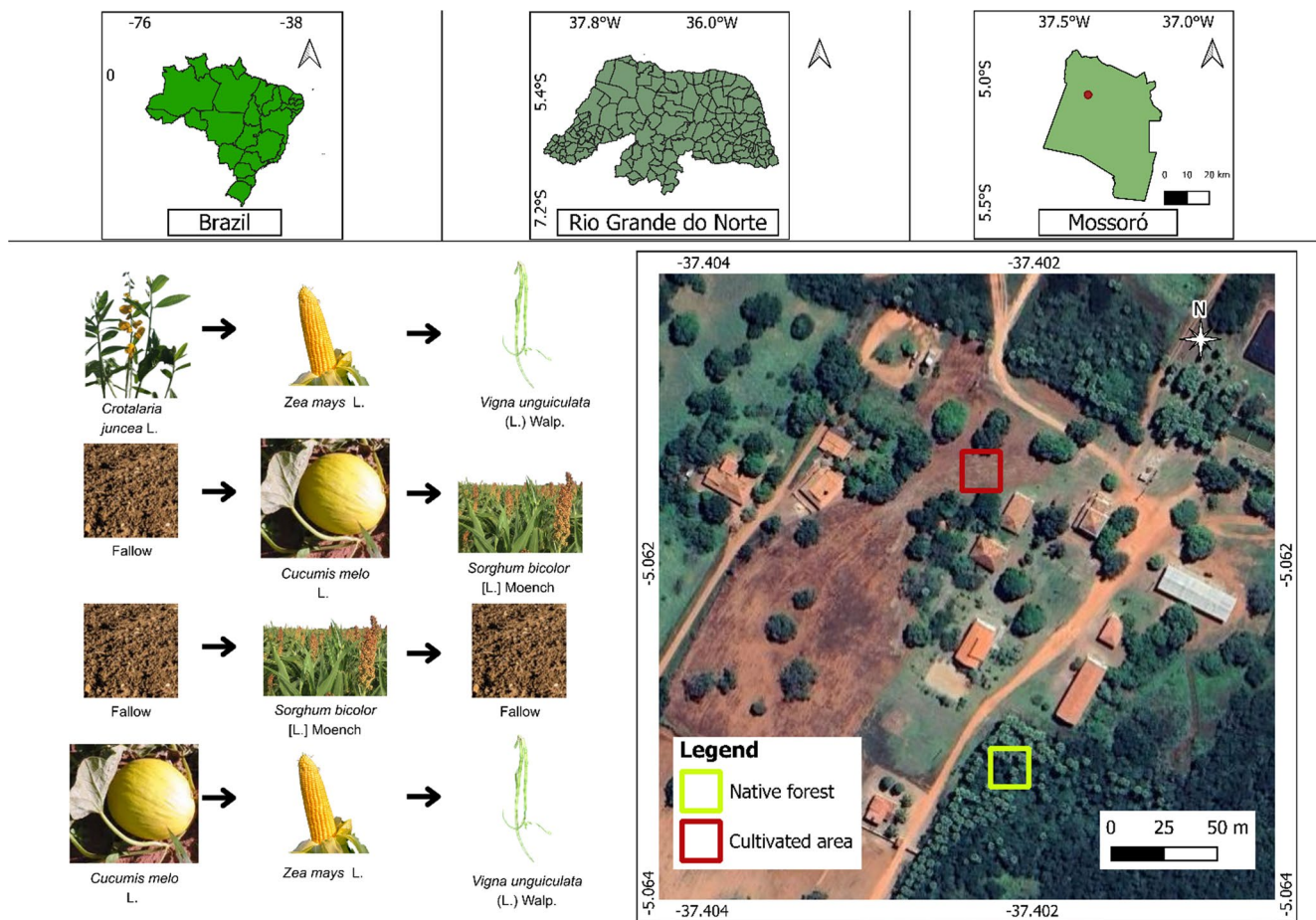


Fig. 1 Map of the location of the experimental area at Rafael Fernandes Farm, in the district of Alagoinha, in the municipality of Mossoró, Rio Grande do Norte State, Brazil. Highlighted is the point of the

study where the experimental plots were set up, as well as the area of native forest (Caatinga)

(*Sorghum bicolor* [L.] Moench); 2019-Second fallow; 2020-Sorghum; 2020–2022-Third fallow (COVID-19 pandemic); 2023-Melon; 2024-Corn; 2024-Cowpea. The native forest (hyperxerophilous Caatinga) was used as a reference in the analyses. Supplementary Table 2 provides a summary of the crop succession history, fertilization practices, and soil sampling periods.

2.3 Soil Sampling, Irrigation and Experimental Design

Soil sampling was performed with an aluminum mug due to the sandy texture of the soil at 0–10 and 10–20 cm depths, packed in plastic bags, identified, and taken to the UFERSA Soil, Water, and Plant Analysis Laboratory (LASAP), with the periods described in Supplementary Table 1. Each soil sample collected from the plot represents a repetition of five sub-samples. Drip irrigation was used for the main crops, with a medium flow rate and drippers spaced according to the needs of each crop, using one drip line per row of plants.

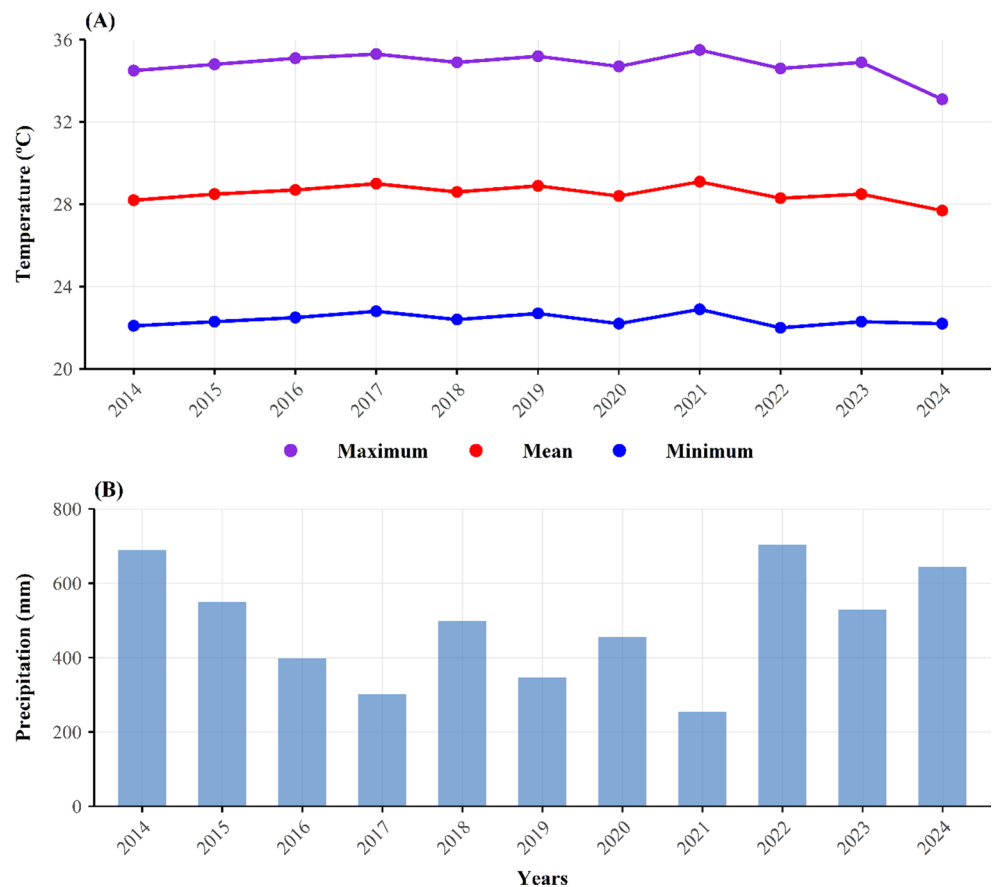
The cultivated area was 2700 m² (45 m wide x 60 m long). All the crops were planted in a randomized block design with four replications.

2.4 Soil Analysis

2.4.1 Chemical Analyses

For chemical analysis, the soil samples were air-dried and passed through 2 mm sieves to obtain the fine air-dried soil (FADS). For the analysis of total organic carbon and some carbon fractions, subsamples of FADS were crushed and passed through a 0.210 mm sieve (60 mesh). The chemical attributes of the soil quantified were hydrogen potential (pH) in water and electrical conductivity (EC) in the water-saturated extract, measured using a pH meter and a bench conductivity meter, respectively. Exchangeable calcium (Ca²⁺), magnesium (Mg²⁺), and aluminum (Al³⁺) were extracted with KCl and quantified by atomic absorption (Ca²⁺ and Mg²⁺) and Al³⁺ by titration. Phosphorus (P),

Fig. 2 Temporal variation of annual accumulated maximum (purple), mean (red), and minimum (blue) temperatures (A) and rainfall (B) in the Alagoinha district, municipality of Mossoró-RN, Brazil, from 2014 to 2024



sodium (Na^+), and potassium (K^+) were extracted with Mehlich-1 and quantified by colorimetry in the case of P, and Na^+ and K^+ by flame photometry. Potential acidity ($\text{H}+\text{Al}$) was extracted with calcium acetate ($\text{C}_4\text{H}_6\text{CaO}_4$) for soil analysis and quantified by titration. For total nitrogen, the soil samples were digested, distilled, and quantified by titration using the Kjeldahl method. All the analyses were carried out by Teixeira et al. (2017).

2.4.2 Soil Organic Carbon, Organic Fractions and Carbon Management Index

Organic carbon soil was quantified in soil samples (0.210 mm) using the wet oxidation method with sulfuric acid and potassium dichromate, with external heating (Yeomans and Bremner 1988). Labile carbon oxidized by KMnO_4 was quantified in sub-samples of 1.0 g of soil (0.210 mm), placed in a 50 mL centrifuge tube, together with 25 mL of 0.033 mol L^{-1} potassium permanganate solution (KMnO_4) and quantified in a spectrophotometer at 565 nm, according to the methodology of Shang and Tiessen (1997). According to the modifications in SOC and LC, carbon lability (L), carbon lability index (LI), carbon reserve index (CPI) and carbon management index were calculated using Eqs. (1), (2), (3) and (4) (Blair et al. 1995), respectively:

$$\text{Lability } (L) = \frac{LC}{(SOC - LC)} \quad (1)$$

$$\text{Lability Index } (LI) = \frac{L_{\text{soil use}}}{L_{\text{native forest}}} \quad (2)$$

$$\text{Carbon Pool Index } (CPI) = \frac{SOC_{\text{soil use}}}{SOC_{\text{native forest}}} \quad (3)$$

$$\text{Carbon Management Index } (CMI) = CPI \times LI \times 100 \quad (4)$$

The carbon of microbial biomass was determined using the irradiation-extraction method, in which each repetition, carried out in triplicate, required 20 g of soil passed through a 2.0 mm sieve. Potassium sulphate (K_2SO_4 0.5 mol L^{-1}) extractant solution was used and titrated with ammoniacal ferrous sulphate at 0.03 mol L^{-1} , according to the methodology of Islam and Weil (1998). The analysis of the enzymatic activity of β -Glucosidase in the soil was carried out by colorimetry, in which p-nitrophenol was released by the enzyme from the incubation of the soil with its specific substrate (p-nitrophenyl- β -D-glucoside) according to the methodology of Eivazi and Tabatabai (1988).

Particulate organic carbon of the soil was measured in FADS using the sodium hexametaphosphate extraction

method and wet sieving (Gao et al. 2024; Cambardella and Elliott 1992). The mineral-associated organic carbon (MAOC) was obtained from the difference between SOC and POC. The recalcitrant fractions represented by humic substances were determined in soil samples (0.210 mm) and subjected to chemical fractionation according to the International Humic Substances Society (IHSS) method (Swift 2001). By differential solubility in acid and alkaline solutions, fulvic acid (CFA), humic acid (CHA), and humin (CHUM) were obtained, and the sum of these fractions yielded to the humic substances. The carbon content of these fractions was obtained using the methodology described by Yeomans and Bremner (1988).

2.5 Statistical Analysis

Data were expressed as mean ± standard error of the mean. Reductions in SOC and organic carbon fractions, with negative values indicating carbon loss, were calculated using Eq. (5):

$$\text{Reductions SOC} = 100 \times \left(\frac{C_{\text{succession or fallow land}} - C_{\text{native forest}}}{C_{\text{native forest}}} \right) \quad (5)$$

Principal Component Analysis (PCA) was used to organize the data structure, detect patterns, relationships and

groupings between variables and observations. In addition, Hierarchical Cluster Analysis (HCA) was used to analyze the homogeneous subsets (clusters) with a view to similarities and dissimilarities between the crop successions. Finally, the ANOVA Ranking Transform-Bonferroni analysis was combined. The ANOVA Ranking Transform (ANOVA-RT) was used to check for significant differences between the means of two or more groups, while the Bonferroni test controlled for the type I error rate (false positivity) that can occur when performing multiple comparison tests. PCA and Cluster were performed using the R software (Core Team 2021), and ANOVA RT-Bonferroni using the Python programming language (Van Rossum 2023).

3 Results

3.1 Principal Component Analysis

The principal component analysis (PCA) applied to the chemical, biological, and organic attributes of the soil in the 0–10 cm layer explained 75% of the total variance, 54.3% by the first component (PC1) and 20.7% by the second (PC2) (Fig. 3-A). The soil under native forest (NF) was in the upper right quadrant, being associated with both

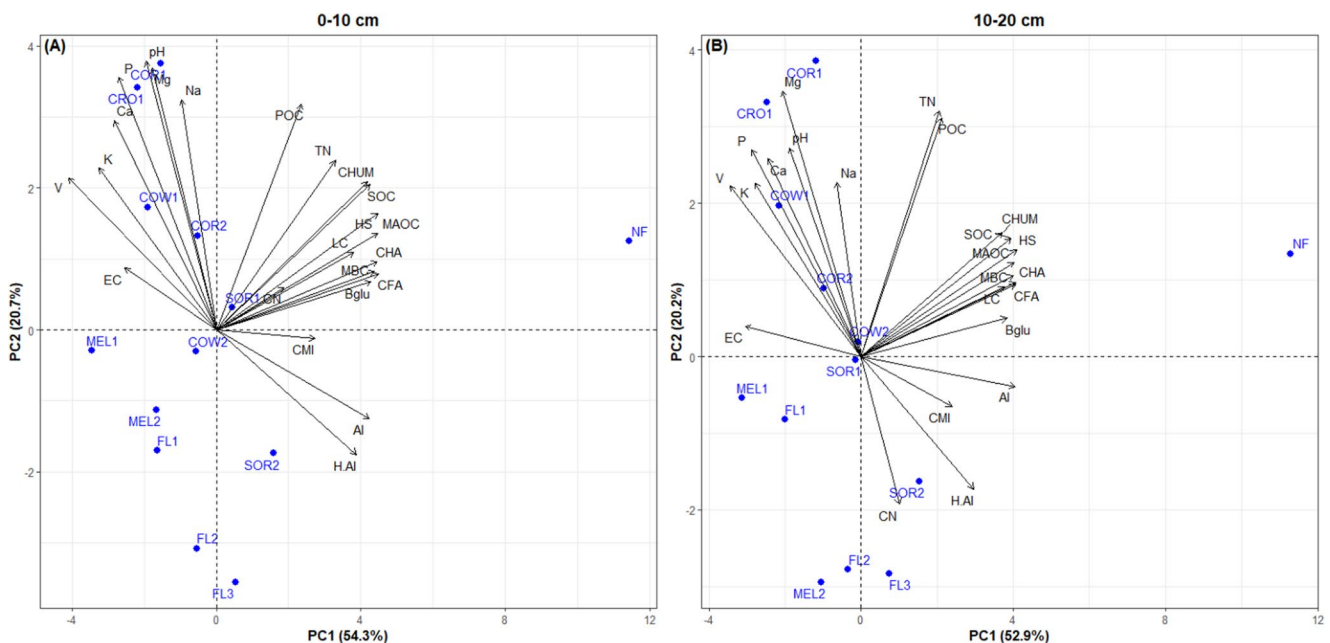


Fig. 3 Principal component analysis (PCA) of soil organic carbon and fractions, and chemical attributes, under different crop successions and fallow, in sandy soil in the semi-arid region at depths of 0–10 (A) and 10–20 cm (B). CRO1=Crotalaria, 2014; COR1=Corn, 2015; COW1=Cowpea, 2016; FL1=First fallow, 2017; MEL1=Melon, 2018; SOR1=Sorghum, 2018; FL2=Second fallow, 2019; SOR2=Sorghum, 2020; FL3=Third fallow, 2020–2022; MEL2=Melon, 2023; COR2=Corn, 2024; COW2=Cowpea, 2024; NF=Native forest, pH=Hydrogen Potential, EC=Electrical Conductivity, P=Phos-

phorus, K^+ = Potassium, Na^+ = Sodium, Ca^{2+} = Calcium, Mg^{2+} = Magnesium, Al^{3+} = Aluminum, $H+Al$ =Potential Acidity and $V\%$ = Base Saturation, SOC=Soil Organic Carbon; LC=Labile Carbon; CHUM=Humin Carbon; CHA=Humic Acid Carbon; CFA= Fulvic Acid Carbon; HS=Humic Substances; MBC=Carbon from Microbial Biomass; POC=Particulate Organic Carbon; Bglu= β -glucosidase; TN=Total Nitrogen; C/N=Carbon/Nitrogen Ratio; MAOC=Mineral-associated organic carbon; CMI=Carbon Management Index

the humified fractions and the mineral-associated organic carbon, as well as the labile fractions, C of the microbial biomass and the activity of the β -glucosidase enzyme, reflecting the organic stability and ecological quality of the soil (Fig. 3-A).

The initial years of agricultural succession (e.g. CRO1, COR1 and COW1 - years with crotalaria, corn and cowpea between 2014 and 2016) were grouped together in the positive portion of the axis, indicating an association with variables indicative of soil edaphic quality, such as total organic carbon (SOC), microbial biomass carbon (MBC), labile carbon (LC), particulate organic carbon (POC), mineral-associated organic carbon (MAOC), carbon management index (CMI), as well as β -glucosidase enzymes (Bglu). On the other hand, the fallow years (FL1, FL2, FL3) and melon crops (MEL1-2018 and MEL2-2023) were distributed in the opposite quadrants, correlating with attributes such as electrical conductivity (EC) and lower carbon content.

Principal component analysis for soil attributes in the 10–20 cm layer explained 73.1% of the total variance, with 52.9% attributed to the first component (PC1) and 20.2% to the second (PC2) (Fig. 3-B). Although the clustering pattern was less pronounced than in the surface layer, relevant trends were observed in the distribution of land uses along the axes. The soil under native forest (NF) maintained its prominent position in the biplot, associated with variables related to carbon stability, such as humin (CHUM), humic substances (HS) and total organic carbon. The systems of the first agricultural successions, CRO1, COR1 and COW1, showed a positive correlation with attributes such as LC, MBC, MAOC and enzymatic activities, demonstrating that the beneficial effect of diversified management extends partially to the subsurface, albeit to a lesser extent than in the 0–10 cm layer. In contrast, the fallow years (FL1, FL2, FL3) and melon crops remained in the same position in the plot.

3.2 Cluster Analysis

O dendrograma segregou as sucessões de culturas em cinco grupos principais, mostrando padrões de similaridade funcional ao longo da cronossequência agrícola (0–10 cm) (Fig. 4-A). Cluster 1 was formed exclusively by the native forest, which stood out due to its higher levels of SOC, humic substances carbon and its fractions (humin, humic and fulvic acids), microbial biomass carbon and carbon cycle enzyme (β glu), reflecting the state of ecological balance and high functionality of the soil under preserved Caatinga vegetation. Cluster 2 grouped together the initial years of agricultural succession, CRO1 (Crotalaria), COR1 (Corn) and COW1 (Cowpea), which showed an association with attributes indicative of the accumulation of LC, MBC,

POC and higher enzyme activity, because of the agricultural practices adopted in the first years.

Cluster 3 focused on sorghum cultivation, which showed intermediate attributes, reflecting the potential for recovering soil organic matter. Cluster 4 refers to the years of fallow (FL1, FL2, FL3), with lower organic matter content, but with better performance than the soil under melon. Cluster 5 shows the soil under the melon crops grouped together based on reduced SOC levels and degradation of the organic fractions, as well as correlation with higher sodium levels (Na^+) and low pH.

In the 10–20 cm layer, cluster analysis enabled the formation of four main groupings, although with a less pronounced separation pattern compared to the surface layer, indicating that the effects of crop succession and fallow were attenuated with increasing depth (Fig. 4-B). Even so, the native forest remained isolated from the other systems, demonstrating the vertical stability of soil quality attributes in preserved environments in cluster 1. In cluster 2, CRO1, COR1 and COW1 remained the same, demonstrating the benefits of the first years of rotation.

Sorghum crops and fallow periods (FL2, FL3), on the other hand, formed their own clusters, but were interconnected in cluster 3 with relative closeness to each other, indicating that the impact of conventional management, combined with the absence of consistent organic cover, compromised soil quality even in the deepest layers, but with indications of recovery of the organic fractions. In cluster 4, the repeated presence of melons (MEL 1 and 2) and fallow (FL1) indicate losses of soil carbon and labile and recalcitrant fractions in the lower layers, and despite the improvement in quality of more labile fractions in the soil under corn and cowpea cultivation (COR2 and COW2), these remained in the same cluster.

3.3 ANOVA RT with Bonferroni

An analysis of variance was carried out using the Treatment Ranking (ANOVA-RT) and then the Bonforreni correction was used to make the multiple treatment comparisons more rigorous. The data showed that crop succession (S) significantly affected all the chemical attributes of the soil ($p < 0.001$), while depth (P) influenced most of the variables, except EC, Al^{3+} and $\text{H} + \text{Al}$. The $S \times P$ interaction was not significant for any soil chemical attribute (Supplementary Table 3). Bonferroni comparisons showed that the soil under native forest had the lowest pH, EC, basic cations (Ca^{2+} , Mg^{2+} , K^+) and base saturation (V%) values, and the highest potential acidity ($\text{H} + \text{Al}$) and exchangeable aluminum (Al^{3+}) values, confirming its naturally acidic character and lower soil fertility (Table 1). In contrast, the first years of rotation

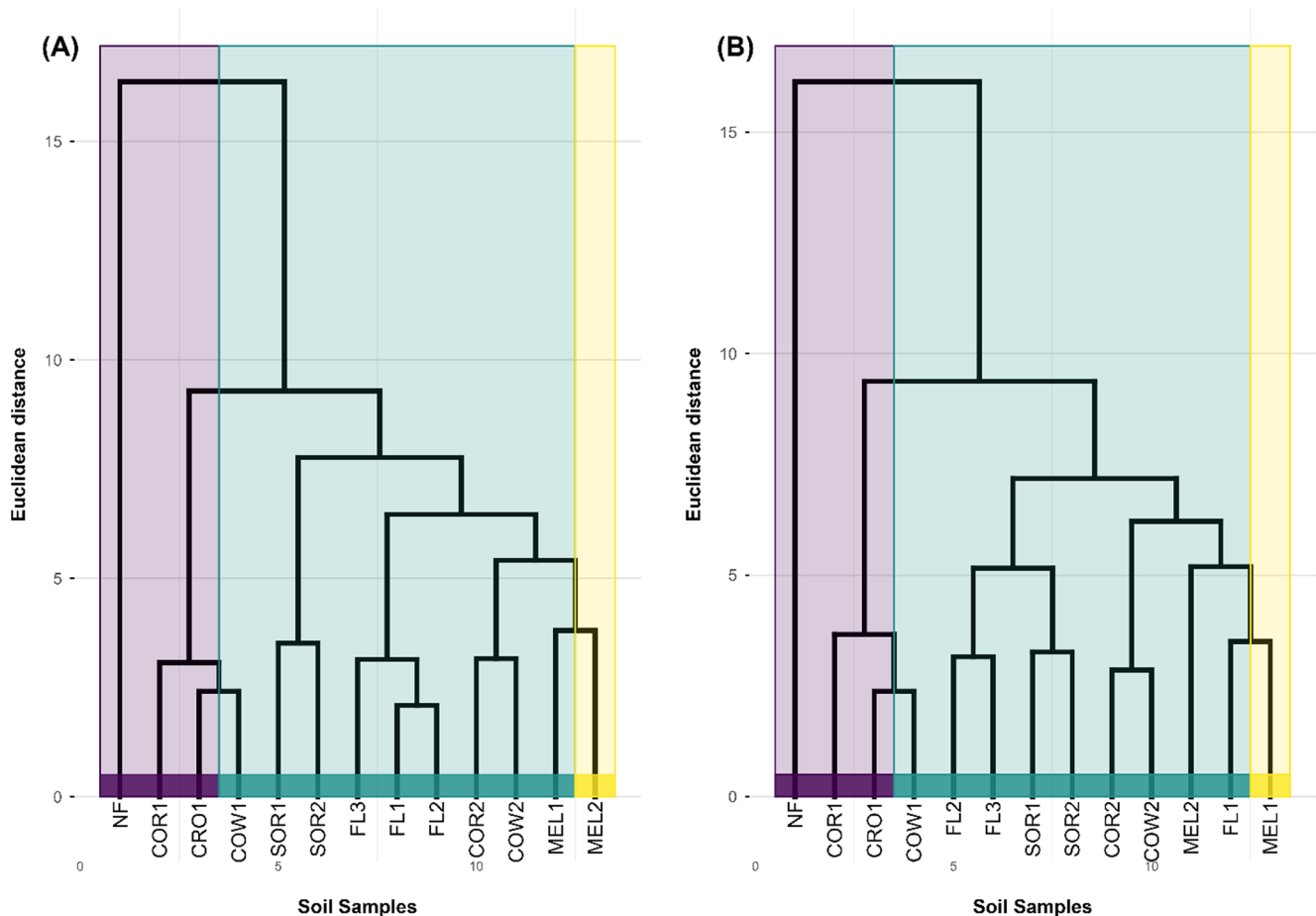


Fig. 4 Hierarchical Cluster Dendrogram based on Euclidean distance and Ward's linkage method for different crop successions and fallow in a sandy soil in the semi-arid region, at a depth of 0–10 cm (A) and 10–20 cm (B). CRO1=crotalaria, 2014; COR1=corn, 2015;

COW1=cowpea, 2016; FL1=first fallow, 2017; MEL1=melon, 2018; SOR1=sorghum, 2018; FL2=second fallow, 2019; SOR2=sorghum, 2020; FL3=third fallow, 2020–2022; MEL2=melon, 2023; COR2=corn, 2024; COW2=cowpea, 2024; and NF=native forest

with the CRO1, COR1 and COW1 successions showed significantly higher pH, Ca^{2+} , Mg^{2+} and V% values, reflecting an increase in chemical fertility due to initial liming before the crotalaria was planted and fertilization according to the respective crop. The lowest levels of chemical fertility were observed in more recent and intensive systems such as the second and third fallow (FL2 and FL3) and the melon (MEL2), which showed low concentrations of P and K^+ , a reduction in V% and an increase in Na^+ and CE (Table 1), suggesting nutrient depletion and low organic input.

The ANOVA-RT results for organic fractions and biological activity indicated highly significant effects ($p < 0.001$) of both crop succession and depth on practically all soil organic fractions and the Carbon Management Index. Regarding the variables microbial biomass carbon, total nitrogen (TN) and mineral-associated organic carbon, there was no interaction between succession and depth, both being analyzed individually. For the C/N ratio, there was statistical significance only for depth (Supplementary Table 4).

SOC contents under different crop successions, fallow and native forest varied between 3.17 and 14.5 g kg^{-1} (0–10 cm) and 2.75 and 9.97 g kg^{-1} (10–20 cm), with the highest values associated with native forest (Tables 2 and 3). Bonferroni analysis confirmed that the native forest also maintained the highest HS, POC and β glucosidase levels at the 0–10 and 10–20 cm depths, respectively (Tables 2 and 3). Analyzing only the successions, the native forest stood out with the highest average values for MBC, NT and MAOC, respectively, acting as a functional reference for ecological stability and edaphic resilience (Table 4).

On the other hand, the soil under fallow (FL1, FL2 and FL3) and melon crops (MEL1 and MEL2) showed the greatest reductions in SOC, HS and its fractions, and POC. The soil under fallow also showed lower biological activities, microbial biomass carbon and carbon management index, showing a loss of ecological functionality and degradation of organic matter. Compared to the native forest (reference), SOC losses were -72% , -71% and -68% (0–10 cm)

Table 1 Soil chemical attributes under different crop successions and fallow on a sandy soil in the semi-arid region

Succession	pH	EC (dS m ⁻¹)	P (mg dm ⁻³)	K ⁺ (cmol _c dm ⁻³)	Na ⁺ (cmol _c dm ⁻³)	Ca ²⁺ (cmol _c dm ⁻³)	Mg ²⁺ (cmol _c dm ⁻³)	Al ³⁺ (cmol _c dm ⁻³)	H + Al (cmol _c dm ⁻³)	V (%)
CROI	6.68±0.18a	0.138±0.018a	13.75±2.21a	0.83±0.21a	0.058±0.026abc	3.51±0.49a	1.02±0.19a	0.00±0.00d	0.59±0.05d	89.91±1.68a
CORI	6.46±0.24ab	0.138±0.012a	13.27±1.58a	0.65±0.18ab	0.057±0.018abc	3.35±0.45a	1.01±0.12a	0.00±0.00d	0.75±0.06cd	88.55±2.87a
COW1	6.20±0.35bc	0.138±0.023a	13.58±2.08a	0.76±0.16a	0.039±0.011c	3.50±0.34a	0.74±0.16b	0.00±0.00d	0.81±0.12c	85.47±3.35b
FL1	5.30±0.07e	0.133±0.015a	8.53±1.84b	0.59±0.12bc	0.040±0.013c	2.46±0.39c	0.57±0.11cd	0.15±0.05c	1.00±0.15c	77.85±0.70d
MEL1	5.95±0.11cd	0.130±0.008a	13.76±1.45a	0.77±0.13a	0.033±0.008c	2.96±0.42b	0.62±0.10bc	0.00±0.00d	0.70±0.09cd	86.30±1.87b
SOR1	5.75±0.13d	0.138±0.006a	9.14±1.49b	0.67±0.12ab	0.044±0.017bc	2.40±0.41c	0.46±0.07de	0.14±0.05c	0.83±0.11c	81.14±1.57c
FL2	4.96±0.13f	0.120±0.015ab	6.62±0.71bc	0.55±0.12c	0.062±0.013ab	1.54±0.41d	0.36±0.09e	0.44±0.06b	1.39±0.21b	64.35±1.17f
SOR2	4.80±0.12f	0.131±0.013a	6.67±0.67bc	0.53±0.14c	0.059±0.011abc	1.50±0.42d	0.40±0.07e	0.40±0.04b	1.46±0.08b	60.01±2.16g
FL3	5.38±0.23e	0.101±0.006bc	5.20±0.84c	0.40±0.09d	0.069±0.015a	1.39±0.26d	0.34±0.06e	0.18±0.06c	1.39±0.15b	57.99±1.44g
MEL2	6.19±0.19bc	0.079±0.011cd	8.55±0.81b	0.25±0.09e	0.024±0.009c	1.29±0.18d	0.43±0.05de	0.00±0.00d	0.82±0.14c	69.34±3.87e
COR2	6.73±0.22a	0.066±0.010d	14.87±2.45a	0.62±0.11bc	0.041±0.008c	1.13±0.22d	0.41±0.06de	0.03±0.05d	0.99±0.09c	84.76±1.31b
COW2	6.06±0.11c	0.060±0.007d	8.13±0.43b	0.33±0.09de	0.034±0.008c	1.48±0.14d	0.53±0.05cd	0.00±0.00d	0.76±0.05cd	85.18±1.74b
NF	5.33±0.15e	0.054±0.004d	4.55±1.02c	0.10±0.08f	0.034±0.008c	0.79±0.23e	0.39±0.07e	1.04±0.36a	2.68±0.12a	38.85±3.78h

CROI = croatalaria, 2014; COR1 = cowpea, 2016; FL1 = first fallow, 2017; MEL1 = melon, 2018; SOR1 = sorghum, 2018; FL2 = second fallow, 2019; SOR2 = sorghum, 2020; FL3 = third fallow, 2020–2022; MEL2 = melon, 2023; COR2 = corn, 2024; COW2 = cowpea, 2024; NF = native forest, pH = hydrogenionic potential, EC = electrical conductivity, P = phosphorus, K⁺ = potassium, Na⁺ = sodium, Ca²⁺ = calcium, Mg²⁺ = magnesium, Al³⁺ = aluminum, H + Al = potential acidity and V% = base saturation. For crop succession, fallow and native forest, different lowercase letters indicate significant differences ($p < 0.001$) based on paired F-tests with Bonferroni correction $\pm$ standard error of the mean.

and –68%, –66% and –65% (10–20 cm) for FL1, FL2 and FL3, respectively. For melons, the loss in SOC was –78% and –74% (–10 cm) and –72% and –70% (10–20 cm) for MEL1 and MEL2, respectively. Regardless of depth, with the introduction of melons into the crop succession system there were losses in both the recalcitrant and biological fractions of –76%, –71% and –75% and, with the fallow, losses of –73%, –90% and –79% in the HS, β glu and MBC variables, respectively.

In contrast, the introduction of grasses (corn and sorghum) into the crop succession system promoted increases in SOC, LC, HS and POC levels compared to the previous crops. The greatest carbon gains were in the labile and particulate fractions of the soil, both on the surface and in the subsurface, which was reflected in the positive CMI 6 and 16 with sorghum in the first and second succession. In addition, the C/N ratio increased significantly with depth (8.75 at 0–10 cm vs. 13.41 at 10–20 cm), reflecting the accumulation of more recalcitrant organic matter with lower N content.

4 Discussion

The results obtained in this study clearly and consistently show the remarkable sensitivity of the soil in terms of organic fractions and soil chemical attributes to long-term crop successions implemented under conventional planting in the edaphic conditions of the semi-arid region under sandy-textured soils. Using a multivariate and integrative approach, it was possible not only to diagnose the immediate responses to the different management strategies, but above all to identify solid trajectories of functional and structural transformation of the soil, reinforcing the potential of these practices as strategic tools for promoting soil quality and sustainability in agricultural systems in highly vulnerable climatic environments.

The dynamics of soil organic carbon (SOC) compartments and chemical attributes evaluated over a decade of agricultural succession in semi-arid sandy soil reveal contrasting responses between the different land uses, highlighting the critical role of crop diversity and management in soil sustainability. The results showed that the soil under native forest (hyperxerophilous Caatinga), despite its acidic character, with higher active and potential acidity and low levels of basic cations (Ca²⁺, Mg²⁺, K⁺), had the highest levels of SOC, labile and humic fractions, microbial biomass carbon and enzymatic activity, reaffirming its function as an ecological and biochemical reference, even in naturally restrictive environments such as the semi-arid (Santana et al. 2019; Menezes et al. 2021; Gava et al. 2022; Ameer et al. 2023; Souza et al. 2025). The combination of liming

Table 2 Organic carbon and organic fractions in sandy soil in the semi-arid region under different crop successions, fallow and native forest, at a depth of 0–10 cm

Succession	SOC (g kg ⁻¹)	LC (g kg ⁻¹)	C HUM (g kg ⁻¹)	CAH (g kg ⁻¹)	CAF (g kg ⁻¹)	HS (g kg ⁻¹)	POC (g kg ⁻¹)	β glu mg pNP g ⁻¹ soil h ⁻¹
CRO1	5.99±1.08c	1.94±0.09de	5.24±1.36 cd	0.54±0.09b	0.31±0.18c	6.09±1.43c	3.38±1.02bc	49.82±16.02c
COR1	7.89±1.02b	2.11±0.23 cd	7.07±0.73b	0.36±0.05 cd	0.33±0.02bc	7.76±0.77b	3.58±0.51ab	47.72±6.73 cd
COW1	5.19±0.47 cd	1.97±0.13de	4.77±0.33de	0.45±0.07c	0.41±0.07b	5.63±0.34 cd	3.45±0.60bc	45.97±4.97 cd
FL1	4.01±0.71de	1.72±0.30de	6.54±0.82bc	0.36±0.07 cd	0.34±0.05bc	4.30±0.71e	1.97±0.38d	34.99±5.02de
MEL1	3.17±0.37f	1.34±0.34f	4.77±0.33de	0.27±0.05e	0.21±0.06d	3.48±0.30f	1.68±0.34e	66.68±10.26b
SOR1	6.92±0.75bc	2.94±0.15b	6.54±0.82bc	0.40±0.05 cd	0.36±0.14bc	7.30±0.96bc	3.68±0.36ab	49.38±4.40c
FL2	4.26±1.11de	1.73±0.30de	3.72±1.00e	0.34±0.07d	0.32±0.09bc	4.38±1.05e	1.96±0.20d	32.75±4.52e
SOR2	6.47±0.58bc	2.87±0.26b	5.85±0.50bc	0.28±0.04e	0.32±0.03bc	6.53±0.49bc	3.32±0.28bc	46.69±3.79 cd
FL3	4.56±0.87de	1.85±0.10de	4.50±0.94de	0.39±0.05 cd	0.36±0.05bc	5.24±0.98d	2.07±0.19d	2.25±0.52f
MEL2	3.77±0.53ef	1.61±0.13e	3.54±0.41e	0.28±0.04e	0.32±0.07bc	4.13±0.39e	1.72±0.28de	68.25±6.81b
COR2	6.56±0.81bc	2.38±0.52c	6.17±0.83bc	3.65±0.49a	0.29±0.05c	6.83±0.88bc	3.52±0.53bc	44.74±4.99 cd
COW2	5.74±1.15 cd	1.92±0.16de	5.26±1.24 cd	0.35±0.03d	0.30±0.05c	5.91±1.24 cd	3.45±0.38bc	44.81±7.68 cd
NF	14.57±2.63a	3.38±0.35a	12.07±2.40a	3.65±0.49a	3.08±0.15a	18.80±2.53a	4.14±0.52a	236.61±46.49a

CRO1=crotalaria, 2014; COR1=corn, 2015; COW1=cowpea, 2016; FL1=first fallow, 2017; MEL1=melon, 2018; SOR1=sorghum, 2018; FL2=second fallow, 2019; SOR2=sorghum, 2020; FL3=third fallow, 2020–2022; MEL2=melon, 2023; COR2=corn, 2024; COW2=cowpea, 2024, NF=native forest, SOC=soil organic carbon, LC=labile carbon, CHUM=humic carbon, CHA=humic acid carbon, CAF=fulvic acid carbon, HS=humic substances, POC=particulate organic carbon, Bglu=β-glucosidase. For depth, fallow and native forest, different lowercase letters indicate significant differences ($p<0.001$ and $p<0.01$) based on paired F-tests with Bonferroni correction ± standard error of the mean.

Table 3 Organic carbon and organic fractions in sandy soil in the semi-arid region under different crop successions, fallow and native forest, at a depth of 10 to 20 cm

Succession	SOC (g kg ⁻¹)	LC (g kg ⁻¹)	C HUM (g kg ⁻¹)	CAH (g kg ⁻¹)	CAF (g kg ⁻¹)	HS (g kg ⁻¹)	POC (g kg ⁻¹)	β glu (mg pNP g ⁻¹ soil h ⁻¹)
CRO1	3.24±0.56de	1.50±0.10de	2.86±0.71de	0.44±0.07b	0.41±0.04b	3.71±0.70de	2.14±0.48ab	42.85±4.54b
COR1	5.74±0.40b	1.85±0.10 cd	5.26±0.32b	0.34±0.06 cd	0.32±0.07bc	5.92±0.43b	2.08±0.28ab	24.89±3.84 cd
COW1	3.62±0.98d	1.60±0.30cde	3.30±1.05d	0.36±0.03c	0.35±0.06bc	4.01±1.02d	1.95±0.58abc	25.03±5.61 cd
FL1	3.20±0.56de	1.33±0.37f	2.97±0.58de	0.34±0.08 cd	0.34±0.07bc	3.65±0.52de	1.73±0.19bc	19.31±3.77e
MEL1	2.75±0.42f	1.34±0.19ef	2.59±0.38ef	0.25±0.08e	0.29±0.07 cd	3.13±0.46ef	1.49±0.27 cd	41.64±5.99b
SOR1	4.74±0.96bc	1.92±0.11c	2.97±0.58de	0.36±0.02c	0.38±0.05bc	5.22±0.80bc	2.05±0.32ab	25.74±4.80 cd
FL2	3.34±0.52d	1.35±0.25ef	3.17±0.48de	0.31±0.04 cd	0.30±0.05 cd	3.78±0.50de	1.80±0.08abc	21.09±3.66de
SOR2	4.98±0.31bc	2.18±0.20b	2.48±0.43f	0.36±0.07c	0.36±0.07bc	5.30±0.27bc	1.87±0.31abc	24.88±3.70 cd
FL3	3.46±0.29d	1.69±0.11cde	3.29±0.24d	2.59±0.36a	0.33±0.04bc	3.94±0.19d	1.71±0.16bc	1.78±0.12f
MEL2	2.97±0.59ef	1.58±0.04cde	2.48±0.43f	0.26±0.05de	0.25±0.07d	2.98±0.51f	1.37±0.24d	41.39±3.45b
COR2	4.52±0.30c	2.64±0.31a	4.19±0.41c	0.31±0.06 cd	0.32±0.05bc	4.81±0.40c	2.04±0.28ab	25.69±3.04 cd
COW2	5.07±0.34bc	1.66±0.20cde	4.75±0.54bc	0.27±0.05de	0.26±0.04 cd	5.28±0.47bc	2.01±0.45ab	26.38±5.86c
NF	9.97±0.98a	1.75±0.07 cd	7.80±1.12a	2.59±0.36a	2.32±0.34a	12.71±1.00a	2.31±0.37a	143.43±23.75a

CRO1=crotalaria, 2014; COR1=corn, 2015; COW1=cowpea, 2016; FL1=first fallow, 2017; MEL1=melon, 2018; SOR1=sorghum, 2018; FL2=second fallow, 2019; SOR2=sorghum, 2020; FL3=third fallow, 2020–2022; MEL2=melon, 2023; COR2=corn, 2024; COW2=cowpea, 2024, NF=native forest, SOC=soil organic carbon, LC=labile carbon, CHUM=humic carbon, CHA=humic acid carbon, CAF=fulvic acid carbon, HS=humic substances, POC=particulate organic carbon, Bglu=β-glucosidase. For depth, fallow and native forest, different lowercase letters indicate significant differences ($p<0.001$ and $p<0.01$) based on paired F-tests with Bonferroni correction ± standard error of the mean.

and crop fertilization represented one of the most effective strategies for improving soil fertility, especially in the first years of the study (2014–2016). The application of acidity correctives with dolomitic limestone, before planting the crotalaria, raised the pH of the soil, reduced the toxicity of exchangeable aluminum (Al^{3+}), and favored the availability of essential macronutrients such as phosphorus, calcium and magnesium, corroborating the results observed by Lipiec and Usowicz (2021), Souza et al. (2022) and Naorem et al. (2023) in sandy soils.

The inclusion of grasses, particularly corn and sorghum, in agricultural successions promoted significant gains in SOC and labile fractions, especially labile carbon (LC) and particulate organic carbon (POC), as well as improvements in microbial biomass carbon (MBC) indices and β-glucosidase enzyme activity. This corroborates studies highlighting the effectiveness of crops with high residue inputs and an intermediate C/N ratio in stimulating microbial processes and organic stabilization (Xie et al. 2022; Pingthaisong et al. 2024). The increase in the Carbon

Table 4 Bonferroni analysis for organic soil analysis for crop succession only

Succession	MBC ($\mu\text{g g}^{-1}$)	TN (g kg^{-1})	MAOC (g kg^{-1})	CMI (%)
CRO1	62.00 $\pm$ 8.43b	0.87 $\pm$ 0.18b	1.85 $\pm$ 1.68de	74.55 $\pm$ 18.68c
COR1	52.20 $\pm$ 10.33bc	0.71 $\pm$ 0.15bc	3.99 $\pm$ 1.12b	71.99 $\pm$ 16.48c
COW1	54.17 $\pm$ 12.36bc	0.75 $\pm$ 0.30bc	1.71 $\pm$ 0.96e	78.20 $\pm$ 16.13bc
FL1	36.86 $\pm$ 6.74c	0.49 $\pm$ 0.16de	1.76 $\pm$ 0.79e	68.69 $\pm$ 24.85c
MEL1	55.18 $\pm$ 13.79bc	0.29 $\pm$ 0.14f	1.37 $\pm$ 0.42e	68.60 $\pm$ 38.55c
SOR1	48.91 $\pm$ 13.34bc	0.43 $\pm$ 0.10e	2.97 $\pm$ 0.79bc	106.06 $\pm$ 26.59ab
FL2	48.78 $\pm$ 15.17bc	0.49 $\pm$ 0.19de	1.92 $\pm$ 0.93de	73.21 $\pm$ 36.14c
SOR2	50.76 $\pm$ 11.60bc	0.54 $\pm$ 0.15de	3.13 $\pm$ 0.46bc	115.80 $\pm$ 30.60 ^a
FL3	59.06 $\pm$ 11.31bc	0.53 $\pm$ 0.14de	2.12 $\pm$ 0.83de	83.94 $\pm$ 19.85bc
MEL2	56.38 $\pm$ 20.83bc	0.29 $\pm$ 0.13f	1.83 $\pm$ 0.70de	82.93 $\pm$ 24.27bc
COR2	53.02 $\pm$ 17.77bc	0.52 $\pm$ 0.17de	2.76 $\pm$ 0.81 cd	87.18 $\pm$ 31.63bc
COW2	64.47 $\pm$ 21.13b	0.59 $\pm$ 0.24 cd	2.67 $\pm$ 0.93 cd	67.96 $\pm$ 10.20c
NF	224.33 $\pm$ 63.88a	1.08 $\pm$ 0.41a	9.04 $\pm$ 2.27a	100.00 $\pm$ 0.00ab

CRO1 = crotalaria, 2014; COR1 = Corn, 2015; COW1 = cowpea, 2016; FL1 = first fallow, 2017; MEL1 = melon, 2018; SOR1 = sorghum, 2018; FL2 = second fallow, 2019; SOR2 = sorghum, 2020; FL3 = third fallow, 2020–2022; MEL2 = melon, 2023; COR2 = Corn, 2024; COW2 = cowpea, 2024, NF = native forest. MBC = microbial biomass carbon; NT = total nitrogen; MAOC = mineral-associated organic carbon; CMI = carbon management index. For crop succession, fallow and native forest, different lowercase letters indicate significant differences ($p < 0.001$ and $p < 0.01$) based on paired F-tests with Bonferroni correction $\pm$ standard error of the mean.

Management Index (CMI) in the grass treatments confirms the potential of corn and sorghum species as restorers of edaphic quality in degraded sandy soils (Blair et al. 1995). These parameters, widely used as early indicators of soil quality, have shown sensitivity to management practices, indicating that crops with a higher return of plant residues under the soil surface favor biological activity and carbon sequestration, even in soils with low retention capacity, such as sandy soils (Xu et al. 2021; Silva et al. 2022; Pradhan et al. 2023; Yang et al. 2024).

The multivariate analysis confirmed the clear distinction between systems with greater accumulation of stable carbon (NF, CRO1, COR1, COW1), indicating improvements in soil edaphic quality also with the introduction of legumes in the succession system (Nath et al. 2019; Hu et al. 2023). However, he pointed out signs of degradation related to melon cultivation and fallow systems, especially in the surface layers. Short-cycle crops such as melons, with low inputs of root and aerial biomass, combined with intensive management and the absence of permanent cover, result in reduced fresh carbon input and accelerated mineralization of organic matter, intensifying losses of C and N (Nath et al. 2019; Qin et al. 2023). Fallow, on the other hand, in semi-arid conditions, presents sparse and seasonal vegetation cover, with low addition of labile carbon and absence of active nutrient replenishment, allowing continuous mineralization of organic matter. Although the effects of management are attenuated at a depth of 10–20 cm, they persist, showing that structural changes in soil quality are not restricted to the surface. The vertical stability of carbon

under native forest confirms its importance in soil protection and ecosystem functionality (Tesfaye et al. 2016; Liu et al. 2023).

On the other hand, prolonged fallow and intensive cropping systems, such as melon cultivation, have shown a drastic reduction in carbon levels and indicators of soil biological and chemical functionality. Losses of up to 78% in SOC and 90% in MBC in these conditions, even when compared to native vegetation, are indicative of functional degradation, reflecting low soil cover, the absence of balanced fertilization that keeps nutrients in the soil, and a reduction in the input of organic residues. Intensive melon cultivation, especially on sandy soils in the semi-arid region, has been associated with a reduction in soil organic carbon (SOC) levels and its labile fractions, such as labile carbon (LC), microbial biomass carbon (MBC) and particulate organic carbon (POC), due to the low input of plant residues, high nutrient removal and the frequent use of mechanized practices and intensive irrigation (Ryan et al. 2009; Basílio et al. 2023; Marcos-Pérez et al. 2023). This trend reinforces previous studies that unbalanced agricultural systems can accelerate the mineralization of organic matter, compromising soil resilience (Lehman et al. 2015).

In soils under fallow, Lintemani et al. (2020) reported that fallow for periods of more than 15 years has the potential to recover the soil's chemical and physical properties, bringing them closer to the levels seen in areas of native forest and in systems that have never been managed with slash-and-burn agriculture. In the case of this study, the short fallow periods between crop successions were probably not enough to

bring about significant improvements in the soil's chemical properties and organic fractions. On the other hand, reducing the length and duration of fallow periods through the use of cover crops, double cropping systems, or conversion to pasture can promote rapid improvements in the functionality indicators of soil in agricultural systems, so it depends on the choice of crops in rotation (Blanco-Canqui et al. 2013; Williams et al. 2022; Gorooei et al. 2023; Thapa et al. 2023; Gazoulis et al. 2025).

The data also indicated that the accumulation of recalcitrant fractions such as humin, humic and fulvic acids was significantly higher in the treatments with native vegetation and grasses, while melon and fallow had the lowest levels of these fractions. This pattern is associated with the chemical nature of plant residues and their decomposition, humic substances being fundamental for the stability of organic matter and the retention of nutrients in sandy soils (Raiesi 2021).

The differentiation between land use systems was unequivocally proven by multivariate cluster analysis (Carvalho et al. 2018), which revealed a clear and consistent segregation between systems under conservation management (NF, COR1, COW1) and those associated with practices with lower soil carbon input (FL3, MEL1). The results show that the effects of management are not limited to the surface layer but extend significantly to the subsurface layers (10–20 cm). Although the changes in physical and chemical attributes are more evident in the 0–10 cm layer, the data indicate a cumulative and vertically persistent impact, resulting from the continuous dynamics of addition, decomposition, and translocation of organic matter and nutrients.

These findings reinforce the importance of incorporating depth-stratified approaches into soil quality and functionality assessments to adequately capture the medium and long-term effects of different management strategies. This evidence corroborates Lal's (2016) perspective, according to which the stability, functionality, and cycling of soil organic carbon are fundamental to maintaining soil health, directly influencing its structure, efficiency in the use of water and nutrients, biogeochemical processes and the regulation of climate impacts. In summary, crop succession with grasses and legumes, associated with appropriate management practices, has shown promise in recovering the quality of sandy soils in the semi-arid region, while intensive use, without the contribution of residues such as melon or unattended short-term fallow, can severely compromise carbon stocks and edaphic functionality. This study reaffirms the importance of crop diversification as a strategy for climate resilience, soil conservation, and carbon sequestration in vulnerable agroecosystems.

5 Conclusions

This long-term field experiment demonstrates that the trajectory of soil organic carbon in sandy soils of semi-arid regions is primarily controlled by management-driven mechanisms that regulate organic residue inputs, biological activity, and carbon stabilization processes. Crop succession systems dominated by grasses promoted more favorable pathways of soil functioning by sustaining continuous organic inputs, stimulating microbial processes, and preserving carbon pools, thereby enhancing soil resilience under conditions of water limitation and low buffering capacity. In contrast, intensive horticultural systems and short-term fallow disrupted these mechanisms, accelerating organic matter mineralization and leading to severe depletion of soil carbon and fertility. These findings confirm the study hypothesis by showing that management strategies capable of maintaining organic inputs and biological activity are essential for preserving soil quality and carbon stocks in sandy semi-arid environments. Beyond advancing mechanistic understanding, this study provides robust evidence to support grass-based crop succession as a practical and scalable strategy for sustainable land management, climate change mitigation through carbon sequestration, and the formulation of public policies aimed at conserving fragile soils and improving agricultural resilience in semi-arid regions.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethical Approval Not applicable.

Consent to Participate All authors consented to participate.

Consent to Publish All authors read and approved of the final manuscript.

Competing interests The authors declare that they have no conflict of interest.

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