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Soil aggregate stability influenced by different integrated livestock-forest systems, pastures, and tillage in the Brazilian semi-arid areas Post-print

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Abstract

Soil aggregation is a fundamental process that influences various soil properties, including structure, porosity, water infiltration, and resistance to erosion. In the Caatinga biome, preserving the soil' s physical quality is crucial to the development of sustainable agriculture. In this biome, soil aggregation is critical due to the susceptibility of the semi-arid area to erosion and degradation. This study aims to evaluate the impact of converting native vegetation (NV; dense Caatinga) into two grasslands and two integrated livestock-forestry (ILF) systems on soil organic carbon (SOC) content and soil physical quality through water-stable aggregate (WSA) classes (macroaggregates, mesoaggregates, and microaggregates) and aggregation indices (mean weight diameter (MWD), geometric mean diameter (GMD), and aggregate stability index (ASI)). Soil samples were collected at 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm layers in Nossa Senhora da Glória Municipality, Sergipe State, Brazil. The land use systems analyzed in this study included NV, an ILF system with Gliricidia (Gliricidia sepium (Jacq.) Kunth ex Walp.)+Urochloa (Urochloa decumbens (Stapf) R.D. Webster) under no-tillage (ILFug), another ILF system with Gliricidia+forage cactus (Opuntia cochenillifera (Linnaeus) Miller) under convention tillage (ILFcg), improved pasture (ImpP), and degraded pasture (DegP). Almost all parameters studied were significantly correlated with SOC content, demonstrating that soil organic matter (SOM) is a primary agent in binding soil particles together, influencing the variation in WSA and aggregation indices. The ImpP and DegP exhibited similar SOC content; however, the ImpP showed a higher ASI and increased amount of macroaggregates (particle diameter>2.000 mm). The highest SOC content was found in the ILFug system across the soil profile. There was a predominance of macroaggregates in topsoil (0-10 cm layer) regardless of land use, with the highest proportion found in NV

(78.7%); while the lowest was observed in the ILFcg system (59.0%). The ILFug system also showed the greatest ASI at almost all soil layers; the exception was the 0-10 and 50-70 cm layers, where the NV had the highest values of 89.1% and 90.5%, respectively. This study demonstrates that implementing integrated systems under no-tillage as a nature-based solution can enhance SOC content and stability of soil aggregates in semi-arid environments.

Full Text

Preamble

J Arid Land (2026) 18(3): 477-500 Soil aggregate stability influenced by different integrated livestock-forest systems, pastures, and tillage in the Brazilian semi-arid areas Handerson Brandão Melo de LIMA , Marcelo CAVALCANTE Rafael Dantas dos SANTOS , Maurício Roberto CHERUBIN Carlos Eduardo Pellegrino CERRI , Stoécio Malta Ferreira MAIA 1 Campus of Engineering and Agrarian Sciences, Federal University of Alagoas, Rio Largo 57100000, Brazil; 2 Federal Institute of Education, Science, and Technology of Alagoas, Maragogi 57955000, Brazil; 3 Brazilian Agricultural Research Corporation (EMBRAPA), Aracaju 49025040, Brazil; 4 Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba 13418900, Brazil; 5 Federal Institute of Education, Science, and Technology of Alagoas, Marechal Deodoro 57160000, Brazil

Abstract

Soil aggregation is a fundamental process that influences various soil properties, including structure, porosity, water infiltration, and resistance to erosion. In the Caatinga biome, preserving the soil’ s physical quality is crucial to the development of sustainable agriculture. In this biome, soil aggregation is critical due to the susceptibility of the semi-arid area to erosion and degradation. This study aims to evaluate the impact of converting native vegetation (NV; dense Caatinga) into two grasslands and two integrated livestock-forestry (ILF) systems on soil organic carbon (SOC) content and soil physical quality through water-stable aggregate (WSA) classes (macroaggregates, mesoaggregates, and microaggregates) and aggregation indices (mean weight diameter (MWD), geometric mean diameter (GMD), and aggregate stability index (ASI)). Soil samples were collected at 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm layers in Nossa Senhora da Glória Municipality, Sergipe State, Brazil. The land use systems analyzed in this study included NV, an ILF system with Gliricidia Gliricidia sepium (Jacq.) Kunth ex Walp.)+ Urochloa Urochloa decumbens (Stapf) R.D. Webster) under no-tillage (ILFug), another ILF system with liricidia+forage cactus (Opuntia cochenillifera (Linnaeus) Miller) under convention tillage (ILFcg), improved pasture (ImpP), and degraded pasture (DegP). Almost all parameters studied were significantly correlated with SOC content, demonstrating that soil organic matter (SOM) is a primary agent in binding soil particles together, influencing the variation in WSA and aggregation indices. The ImpP and DegP exhibited similar SOC content; however, the ImpP showed a higher ASI and increased amount of macroaggregates (particle diameter>2.000 mm). The highest SOC content was found in the ILFug system across the soil profile. There was a predominance of macroaggregates in topsoil (0–10 cm layer) regardless of land use, with the highest proportion found in NV (78.7%); while the lowest was observed in the ILFcg system (59.0%). The ILFug system also showed the greatest ASI at almost all soil layers; the exception was the 0–10 and 50–70 cm layers, where the NV had the highest values of 89.1% and 90.5%, respectively. This study demonstrates that implementing integrated systems under no-tillage as a nature-based solution can enhance SOC content and stability of soil aggregates in semi-arid environments. © 2026 Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, and Science Press. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd.

Keywords

no-tillage; water-stable aggregate (WSA); Nature-based Solutions (NbS); agroforestry; Caatinga; soil organic carbon (SOC); degradation pasture Citation:

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1 Introduction

Soil aggregation is a fundamental process that influences various soil properties, including structure, porosity, water infiltration, and resistance to erosion (Bronick and Lal, 2005; Medeiros et al., 2023). Aggregates are formed through the binding of individual soil particles by organic matter, root exudates, microbial activity, clay minerals, and carbonates (Bronick and Lal, 2005; Cotrufo and Lavallee, 2022). The aggregates are frequently divided by size, including macroaggregates (>2.000 mm), mesoaggregates (0.250–2.000 mm), and microaggregates (0.053–0.250 mm) (Costa Junior et al., 2012). The distribution and stability of soil aggregates are crucial indicators of soil structure and overall physical quality (Castro Filho et al., 2002; Plaza-Bonilla et al., 2013; Medeiros et al., 2023), providing valuable insights into the impact of land use practices and soil management strategies on soil health.

In the Caatinga biome, preserving the soil' s physical quality is important to the development of sustainable agriculture (Fernández-Ugalde et al., 2011). In this biome, soil aggregation is critical due to the susceptibility of the semi-arid area to erosion and degradation (Maia et al., 2007; Medeiros et al., 2020, 2023). Moreover, high temperatures and low moisture availability in semi-arid areas can exacerbate soil particle detachment, leading to the loss of fertile topsoil and a decline in soil organic carbon (SOC) (Wiesmeier et al., 2019).

A thorough understanding of how soil aggregates interact with SOC is essential for developing sustainable management strategies, especially in semi-arid areas where environmental pressures and land-use changes present significant challenges to soil sustainability (Okolo et al., 2020). The soil organic matter (SOM) acts as the main cementing agent, facilitating the aggregation of soil particles into microaggregates, mesoaggregates, and macroaggregates, which results in a better soil structure, enhancing aeration and drainage and improving the ability of the soil to retain water (Tivet et al., 2013; Ferreira et al., 2018; Thapa et al., 2018). In turn, stable soil aggregates protect SOC from microbial decomposition by creating physical barriers that isolate SOM within aggregates (Six et al., 2000; Plaza-Bonilla et al., 2013). Furthermore, according to Okolo et al. (2020), soil aggregation is fundamental to carbon sequestration mechanisms. The incorporation of carbon into soil aggregates helps transform these aggregates into forms that are less susceptible to decomposition, with a longer residence time in the soil. This transformation is vital for establishing a sustainable method of long-term carbon sequestration, effectively capturing atmospheric carbon and integrating it into the soil (Ferreira et al., 2018; Medeiros et al., 2023).

On the other hand, reduced organic matter inputs in the soil are identified as a key factor leading to decreased soil aggregation and SOC (Kabiri et al., 2015), which significantly contributes to degradation trends in semi-arid areas (Bird et al., 2007; Wiesmeier et al., 2012; Bai et al., 2020). Medeiros et al. (2021) found that the conversion of native vegetation (NV) to grasslands in the Brazilian semi-arid areas results in less organic matter inputs into the soil, consequently leading to losses of SOC, ranging from 12.0% to 16.0% at a depth of 0–100 cm.

Furthermore, Bieluczyk et al. (2025) demonstrated that the conversion of NV to grasslands combined with overgrazing and soil trampling by livestock, compacted and reduced soil aggregation, and depleted SOC by 14.70 Mg C/hm (0–20 cm). Nonetheless, well-managed (improved) pastures, when combined with grazing exclusion, can provide more organic inputs than low-productive/degraded pastures; however, well-managed pastures generally maintain lower SOC levels and fewer stable aggregates (0–10 cm) compared with semi-arid native forests (Bieluczyk et al., 2025; Lima et al., 2025).

Medeiros et al. (2023) emphasized that enhancing SOM inputs and maintaining stable soil aggregates are essential for protecting SOC from rapid decomposition. Nature-based Solutions (NbS) contribute to the preservation or enhancement of soil structure by increasing the amount of organic matter inputs and minimizing soil disturbance (Maia et al., 2007; Medeiros et al., 2023).

Tonucci et al. (2023) also confirmed that in semi-arid environments, the adoption of NbS such as integrated systems under no-tillage that deposit organic matter on the soil, increases the formation of stable aggregates by providing binding agents, enhancing microbial activity, improving soil structure, and facilitating the incorporation of organic carbon into more stable forms, thereby being an alternative of enhancing long-term carbon sequestration and avoiding losses to the atmosphere. Long-term no-tillage practices in Brazil have been shown to gradually restore SOC stocks, surpassing those found in NV; whereas conventional tillage leads to substantial SOC losses ranging from 38.0% to 46.0% (100 cm depth) compared with SOC stocks in NV (Sá et al., 2025). Thiengo et al. (2024) observed that no-tillage combined with short-term silvopastoral systems (2 a) significantly improved soil structure, compared with conventional tillage, which reduced soil aggregation stability. Additionally, converting low-productivity pastures into integrated systems also showed strong potential to enhance soil structure and SOC, as this conversion has restored SOC to levels comparable to those found in native Cerrado–Caatinga forests (0–30 cm), resulting in carbon accruals of approximately 4.31 Mg/(hm a) (Freitas et al., 2022). Furthermore, dos Santos et al. (2025) found that integrated livestock-forestry (ILF) systems with different grasses (e.g., massai and buffel) enhanced soil quality following forest conversion.

Despite these insights, important gaps remain for the Brazilian semi-arid areas, as limited studies have compared the effects of soil aggregation and SOC across various land use systems and tillage practices on soil physical properties. Thus, this study was conducted to assess how different land uses in the Brazilian semi-arid areas affect soil physical quality and structural degradation, particularly concerning SOC and soil aggregation. We hypothesize that the degraded pasture will exhibit the lowest soil aggregation indices and SOC, while ILF under no-tillage will preserve stable aggregates and SOC stocks compared with NV. This study aims to evaluate the impact of converting NV (dense Caatinga) into two types of pastures (degraded and improved) and two ILF systems (under no-tillage and conventional tillage) on SOC content and the physical quality of soil by analyzing water-stable aggregate (WSA) classes and aggregation indices. By comparing soil parameters, the work offers practical insights into how NbS and management practices influence soil aggregation, SOC protection, and long-term carbon sequestration potential, supporting policy decisions aimed at restoring degraded lands and enhancing agricultural productivity in semi-arid agricultural areas. 2 Materials and methods

2.1 Study area

This study was conducted at the Semi-Arid Experimental Station of the Brazilian Agricultural Research Corporation (EMBRAPA), located in Nossa Senhora da Glória Municipality, Sergipe State, Brazil (10°13′S, 37°25′W). This region has a semi-arid climate, classified as hot semi-arid climate (BSh) according to Köppen' s classification (Alvares et al., 2013). It is characterized by an annual precipitation of 710.000 mm, which is distributed irregularly throughout the year. The average maximum and minimum temperatures are 32°C and 20°C, respectively (Alvares et al., 2013). High potential evapotranspiration (PET) coupled with strong rainfall seasonality results in prolonged soil moisture deficits that limit plant water availability and enhance evapotranspiration losses, typical conditions of semi-arid environments. The soil in this region is classified as Eutrophic Red-Yellow Podzol (Santos et al., 2025).

ILF systems and pasture areas close to the NV were evaluated. We selected these areas based on the knowledge of land use and management strategies implemented since the conversion from

NV, and to represent the region's dominant management practices (conventional tillage and no-tillage) and vegetation types (Caatinga forest and pastures). In this study, five land use systems were evaluated, including NV, an ILF system with Gliricidia Gliricidia sepium (Jacq.) Kunth ex Walp.)+ Urochloa Urochloa decumbens (Stapf) R.D. Webster) under no-tillage (ILFug), another ILF system with Gliricidia +forage cactus (Opuntia cochenillifera (Linnaeus) Miller) under convention tillage (ILFcg), improved pasture (ImpP), and degraded pasture (DegP).

The NV served as the reference for assessing the effects of land use change on the soil (Fig. 1 [Figure 1: see original paper]).

The ILFug system is managed under no-tillage, with G. sepium planted at a spacing of 1.5 m, while U. decumbens is cultivated in the interrows, spaced 5.0 m apart. Importantly, the decumbens is not subjected to cutting, allowing it to grow undisturbed, and its biomass is retained in situ . This system has been in place for the past 8 a and involves the routine pruning of sepium , with its biomass used as a cover crop on the soil. In the ILFcg system, the G. sepium plants are spaced 1.0 m apart, and forage cactus is cultivated in two lines between the 3.0 m interrows. The forage cactus cutting is performed every 2 a. This system has been established for 10 a and is managed with conventional tillage practices. Every 2 a, the soil is tilled, followed by the cultivation of sorghum in May in the interrow spaces between G. sepium and forage cactus.

The cut of sorghum is done after approximately 110 d, and if there is sufficient rainfall, a second cut is made after regrowth. After being cut, both the forage cactus and the sorghum are used for animal foraging. Both ILF systems are managed without grazing cattle, and no fertilizers are applied; however, herbicides are utilized for weed control. The ImpP represents a sustainably managed grassland system, incorporating species improvement practices as described by Eggleston et al. (2006). This system consists of a mix of three grass species: buffel grass Cenchrus ciliaris L.), aruana grass (Panicum maximum cv. Mombasa), and corrente grass Urochloa mosambicensis (Hack.) Dandy). In contrast, the DegP represents a moderately degraded grassland where no management interventions are implemented. This area consists of aruana grass. Both pastures have unrestricted cattle grazing throughout the year and have been established and maintained for 15 a.

2.2 Soil sampling

Five replications of disturbed soil samples were collected up to 100 cm in depth at 0–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm layers from the five different land use systems (i.e., five replicates per depth per land use), resulting in a total of 150 samples. Disturbed samples (soil collected with its original structure preserved) were collected with a garden spade or by slicing the exposed face of the trench in the desired layer, and the soil from that layer was placed into labeled bags for laboratory analysis, including SOC content, pH, granulometry, nutrients, and WSA.

Additionally, undisturbed soil samples were obtained using Kopeck rings to evaluate soil bulk density (BD). The soil samples were randomly collected from each land use system to accurately represent the entire area.

2.3 Data analysis

2.3.1 Soil physical and chemical characterization Soil particle-size distribution (sand, silt, and clay) was determined using the pipette method after chemical dispersion with sodium hexametaphosphate. Soil pH was measured in water at a 1.0:2.5 soil-to-solution ratio. Exchangeable calcium (Ca), magnesium (Mg), and aluminium (Al) ions were extracted using 1 mol/L potassium chloride (KCl) and exchangeable potassium (K), phosphorus (P), and sodium (Na) were extracted with Mehlich-1 solution (Teixeira et al., 2017).

SOC content and BD Disturbed soil samples were air-dried, homogenized, and sieved through a 2.000 mm mesh to remove stone fragments and roots prior to analysis. Total organic carbon (TOC) content was measured using the dry combustion method with an elemental analyzer (TOC-Shimadzu; Shimadzu Corporation, Kyoto, Japan) equipped with the SSM-5000A solid sample module.

The undisturbed soil samples were dried in an oven at 105°C for 48 h and weighed. BD was calculated using the volumetric ring method, which consists of dividing the soil dry mass by the volume of the Kopeck ring (Teixeira et al., 2017).

Location (a) and landscape (b) of the study area and timeline (b) for five land use systems. NV, native vegetation; ILFug, integrated livestock-forestry (ILF) with Gliricidia Gliricidia sepium (Jacq.) Kunth ex Walp.)+ Urochloa Urochloa decumbens (Stapf) R.D. Webster) under no-tillage; ILFcg, ILF with Gliricidia sepium)+forage cactus (Opuntia cochenillifera (Linnaeus) Miller; phase 1) or with Gliricidia G. sepium)+forage cactus+sorghum (phase 2) under convention tillage; ImpP, improved pasture; DegP, degraded pasture.

To be continue Soil physical and chemical characterization of five land use systems ILFug ILFcg

Note: NV, native vegetation; ILFug, integrated livestock-forestry (ILF) with Gliricidia Gliricidia sepium (Jacq.) Kunth ex Walp.)+ Urochloa Urochloa decumbens (Stapf) R.D. Webster) under no-tillage; ILFcg, ILF with Gliricidia G. sepium)+forage cactus (Opuntia cochenillifera (Linnaeus) Miller; phase 1) or with Gliricidia G. sepium)+forage cactus+sorghum (phase 2) under convention tillage; ImpP, improved pasture; DegP, degraded pasture; CEC, cation exchange capacity; Na, sodium; P, phosphorus; K, potassium; Ca , calcium ion; Mg , magnesium ion; Al , aluminium ion.

Continue

50–70 324.48 224.32 451.20 5.6 210.3 <1.0 90.0 1.1 8.2 3.5 14.0 73.0 1.0

70–100 363.42 267.62 368.97 6.0 289.3 <1.0 101.0 0.8 10.5 2.9 15.8 79.7 0.7

2.3.3 Soil degree of compactness (SDC)

The maximum bulk density (BD) was calculated considering SOM and clay content as key input parameters (Marcolin and Klein, 2011). These factors significantly influence BD , with an inverse relationship observed between them. Furthermore, both BD and BD data were utilized to calculate SDC. This calculation aimed to normalize the BD limits based on soil texture and other relevant parameters. The formulae used are as follows (Marcolin and Klein, 2011): clay, 100%, where SOC is the organic carbon content (g/kg); 1.724 is the coefficient, which can convert SOC to SOM; and clay is the particle size fraction of clay (g/kg).

Soil structural stability index (SSI) According to Pieri (1992) and Reynolds et al. (2009), we calculated the SSI to evaluate the risk of soil structural degradation. This methodology is proposed as a measure of the susceptibility of the soil to structural degradation.

SOC 1.724 100%, where silt is the particle size fraction of silt (g/kg). SSI<5.0% indicates great susceptibility to loss of structure and erosion; 5.0%<SSI<7.0% indicates instability and risk of loss of structure; 7.0%<SSI<9.0% indicates low risk of soil structural degradation; and SSI>9.0% represents no immediate risk of loss of structure.

WSA and aggregation indices WSA was determined by the wet-sieving method, as described by Teixeira et al. (2017). The analysis of aggregates was performed in duplicate, where 50 g of air-dried soil samples placed on the uppermost layer of stacked sieves of 2.000, 0.250, and 0.053 mm, were submitted to vertical stirring for 15 min. Subsequently, the material retained on each sieve was backwashed into pre-weighed Al containers and dried in an oven at 60°C for 48 h. After drying, the mass of aggregates retained on each sieve was obtained. Finally, aggregates were grouped into three classes: macroaggregates (2.000 mm), mesoaggregates (0.250–2.000 mm), and microaggregates (0.053–0.250 mm) (Costa Junior et al., 2012).

After obtaining the mass of aggregates, the sand correction was performed in each aggregate size class because sand was not considered part of those aggregates (Plaza-Bonilla et al., 2013).

Utilizing this data, three aggregation indices were calculated: mean weight diameter (MWD), geometric mean diameter (GMD), and aggregate stability index (ASI) (Medeiros et al., 2018).

1 MWD

where is the proportion of aggregate size class to the total (%); is the mean diameter of class (mm); and is the number of classes. where is the weight of aggregates of class (g/kg).

25 WDS

where is the dry weight of microaggregate class (0.250 mm) (g/kg); WDS is the weight of each dried sample (g/kg); and sand is the particle size fraction of sand (g/kg).

The aggregate sensitivity index (SI) was calculated using the methodology proposed by Bolinder et al. (1999). This index is based on the principle of relative comparison between treatments, indicating whether the managed soil has lost or gained structural quality. where MWD is the mean weight diameter of the managed system, including ILFug, ILFcg, ImpP, and DegP (mm); and MWD the mean weight diameter of the NV (mm). 2.4 Experimental design and statistical analysis The data were tested for the main analysis of variance (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 <0.050). The statistical analysis was performed on the basis of 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 (<0.050). In cases where one or more ANOVA assumptions were not met, the non-parametric Friedman test was applied. When the Friedman test was significant, pairwise comparisons were performed using the Siegel-Castellan post hoc test with Bonferroni correction. All statistical analyses were conducted using R v.4.2.2 software (R Core Team, Vienna, Austria). Pearson' s correlation coefficient was calculated to assess the relationship among the soil parameters studied.

3.1 SOC and BD

The highest SOC content was observed at the upper soil layer (0-10 cm) and significantly decreased (<0.050) with depth across all land use systems. However, at the 50-70 and 70-100 cm layers, there was no statistically significant difference in SOC content among the treatments >0.050). The highest SOC content was found in the ILFug system, with values of 20.76, 13.05, 8.17, 7.40, 5.46, and 4.46 g/kg for the 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm layers, respectively. The conversion of NV to ILFcg, ImpP, and DegP resulted in the largest losses at the 0-10 cm layer, reducing the SOC content by 8.12, 9.07, and 8.65 g/kg, which corresponds to losses of 41.3%, 46.1%, and 44.0%, respectively (Fig. 2a [Figure 2: see original paper]). The lowest SOC content was observed at the 70-100 cm layer of ImpP with 2.31 g/kg.

Soil organic carbon (SOC) content (a) and bulk density (BD; b) at the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm soil layers in different land use systems.

Indicates significant difference at <0.050 level compared with NV in the same soil layer by Friedman' s non-parametric test for SOC and by Tukey' s test for BD.

Regarding BD, results showed low variation across different land use systems. Significant differences were found only at the 70-100 cm soil layer (<0.050). At this layer, the highest BD of 1.65 g/cm was found in the ImpP, while the lowest BD of 1.23 g/cm was observed in the ILFcg system (<0.050). Across the soil profile, the BD values varied as follows: for NV, values ranged from 1.31 to 1.52 g/cm ; for ILFug, from 1.27 to 1.46 g/cm ; for ILFcg, from 1.24 to 1.42 ; for ImpP, from 1.39 to 1.66 g/cm ; and for DegP, from 1.38 to 1.47 g/cm . The ImpP consistently showed the highest BD values across all soil layers, with values of 1.39, 1.49, 1.55, 1.57, 1.47, and 1.66 g/cm for the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers, respectively (Fig. 2b).

3.2 SDC

The SDC is a pedotransfer function that utilizes soil texture and SOC content to normalize the limits of BD. Overall, SDC values ranged from 72.4% to 85.7 % in NV, 74.3% to 94.6% in pastures (ImpP and DegP), and 73.6% to 85.4% in the integrated systems (ILFug and ILFcg) (Fig. 3 [Figure 3: see original paper]). At all soil layers, there were no significant differences (>0.050) in SDC values among land use systems. The NV had the lowest SDC values at the 0-10 and 10-20 cm layers, with the conversion of NV to DegP representing the greatest increase in the SDC by 1.9% at the 0-10 cm layer, while the NV-ImpP conversion led to the highest increase of 4.3% at the 10-20 cm layer. At the 20-30, 50-70, and 70-100 cm layers, the ILFcg showed the lowest SDC values, with 78.7%, 77.4%, and 76.8%, respectively. In the comparison of integrated systems with pastures, integrated systems showed the lowest SDC values across all soil layers except the 30-50 cm layers.

Soil degree of compactness (SDC) at the 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm soil layers in different land use systems in the Brazilian semi-arid areas. Error bars show the standard deviation (SD; Means followed by the same letter between land use systems for the same soil layer do not differ by Tukey' s test >0.050).

3.3 SSI

The ILFug had higher SSI values throughout the soil profile (<0.050). A decreasing trend in SSI values in depth was observed (Fig. 4 [Figure 4: see original paper]). Conversion from NV to ILFcg, ImpP, and DegP consistently resulted in reductions of SSI at the 0-10, 10-20, and 20-30 cm layers. The NV had the lowest SSI at the 50-70 cm layer, with a value of 1.45 (<0.050).

3.4 Distribution of WSA classes

The distribution of WSA showed different trends with depth across the land use systems <0.050) (Table S1). There is a predominance of macroaggregates (>2.000 mm) at topsoil (0-10 cm layer) regardless of the land use, with the highest proportion of this size class found in NV (78.7%), while the lowest was observed in the ILFcg system (59.0%) (Fig. 5 [Figure 5: see original paper]). The ImpP showed a different response when compared with other land use systems, increasing the predominance of

Soil structural stability index (SSI) at the 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm soil layers in different land use systems in the Brazilian semi-arid areas. Error bars show the SD (=5). Different lowercase letters represent significant difference at <0.050 level between different land use systems at the same soil layer by Tukey’ s test.

Distribution of water-stable aggregate (WSA) classes in different land use systems in the Brazilian semi-arid areas. (a), NV; (b), ILFug; (c), ILFcg; (d), ImpP; (e), DegP. Error bars represent the SD (macroaggregates at the 70-100 cm layer, with this size class representing 78.8% of the total WSA <0.050), while the percentages of mesoaggregates (0.250-2.000 mm) and microaggregates (0.053-0.250 mm) were 5.8% and 15.4%, respectively. Differences in the proportion of mesoaggregates between land use systems were only found at the 20-30, 50-70, and 70-100 cm layers (Table S1), where the ImpP showed the lowest values at 26.8%, 15.9%, and 5.8%, respectively. However, the low proportion of mesoaggregates in ImpP at the 20-30, 50-70, and 70-100 cm layers was compensated by a higher proportion of macroaggregates. In general, microaggregates represented the smallest proportion of the WSA across all soil layers and land use systems. The exception was at the 50-70 and 70-100 cm layers of ImpP, where the microaggregate class accounted for 19.2% and 15.4% of WSA, respectively. At the 10-20 cm layer, no statistical differences were observed among the land use systems concerning the three classes of aggregates (>0.050). All land use systems presented a higher proportion of macro than micro WSA.

3.5 Soil aggregation indices

No significant differences in MWD between land use systems were observed at the 10-20 cm

layer (>0.050). At the 0-10 cm layer, the NV presented the highest MWD at

4.120 mm (Fig. 6a [Figure 6: see original paper]), while the lowest MWD was found in the ILFcg (3.284 mm). Across all soil layers and land use systems, the MWD values ranged from 2.097 to 4.120 mm.

The GMD was also affected by land use change (<0.050). Across all land use systems, the GMD ranged from 1.662 mm at the 0-10 cm layer of NV to 1.115 mm at the 70-100 cm layer of ILFcg. No statistical differences in the GMD among land use systems were observed at the 10-20 and 30-50 cm layers (Fig. 6b). At the 0-10 cm layer, the NV had the highest GMD (1.662 mm), significantly differing from the other land use systems (<0.050), with values of 1.419, 1.378, and 1.368 mm for the ImpP, ILFcg and DegP, respectively (Fig. 6b). Conversely, at the 70-100 cm layer, the ImpP had the highest GMD (1.536 mm), followed by ILFug, NV, DegP, and ILFcg, with values of 1.312, 1.200, 1.194, and 1.115, respectively. The DegP exhibited the lowest GMD values in all soil layers except the 70-100 cm layer, where ILFcg had the lowest GMD of 1.115 Regarding the ASI, the highest value (89.1%) was found at the 0-10 cm layer of NV, while the lowest (70.3%) was observed at the 20-30 and 30-50 cm layers of DegP (Fig. 6c). Statistical differences among land use systems were observed at the 0-10 and 30-50 cm soil layers <0.05). Although the ImpP exhibited the highest MWD and GMD at the 70-100 cm layer, its ASI was the lowest at 80.4%.

Mean values of the mean weight diameter (MWD; a), geometric mean diameter (GMD; b), and aggregate stability index (ASI; c) in different land use systems in the Brazilian semi-arid areas. Error bars represent the SD =5). Different uppercase letters for land use systems and lowercase letters for soil layers signify significant difference at <0.050 level by Tukey’ s test.

A SI value greater than 1.00 indicated that the structural quality and stability of soil aggregates have improved compared with the reference area (NV). At the topsoil layer (0-10 cm) all land use systems had SI values lower than 1.00, indicating loss of structural quality compared with NV (Fig. 7 [Figure 7: see original paper]), with the ILFcg system showing the lowest SI (0.77), suggesting a significant decline in soil structural quality. At all soil layers, the DegP had a SI under 1.00, with values of 0.80, 0.88, 0.94, 0.93, 0.77, and 0.89, respectively for the 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm

layers, respectively. The ILFcg showed similar results, except for the 30-50 cm layer, which had a SI of 1.06. In contrast, the ImpP and ILFug system showed SI values above 1.00 at the 10-20, 20-30, 30-50, 50-70, and 70-100 cm layers, indicating that these land use systems have improved soil structural quality compared with NV (Fig. 7). When comparing only the pastures and integrated systems, the ILFug had the highest SI at all soil layers, with values ranging from 0.87 to 1.28, except for the 70-100 cm layer, where ImpP had the greatest SI of 1.40.

Sensitivity index (SI) of different land use systems in the Brazilian semi-arid areas compared with NV 3.6 Correlation between soil physical properties and

SOC content The correlations among soil parameters indicated that the SOC content significantly correlated with nearly all other attributes (Fig. 8 [Figure 8: see original paper]). The SOC content had significant positive correlations with macroaggregates, MWD, GMD, ASI, SSI, and sand. In contrast, SOC content was negatively correlated with clay, BD, and SDC. Regarding the mineral fractions, the soil, sand, and clay did not have significant correlations with soil aggregation. However, the silt fraction showed a significant positive correlation with macroaggregates (=0.43; <0.010) and a negative correlation with microaggregates (= -0.38; <0.010). The strongest correlation among the WSA classes and aggregation indices was observed between macroaggregates and MWD (=0.99; <0.001). The correlation revealed that the main factor negatively affecting the ASI was the presence of microaggregates (= -0.91; <0.001). SDC was significantly correlated with all soil mineral fractions (clay, silt, and sand).

4 Discussion

Key findings revealed that land use and management strongly influence soil aggregate stability and the distribution of SOC across the soil profile. The ILFug under no-tillage consistently showed the highest SOC contents, along with the most favorable aggregation indices across most soil layers. In contrast, the DegP and ILFcg showed patterns indicative of structural degradation (higher BD for DegP and reduced macroaggregate proportion for ILFcg).

4.1 SOC, BD, and SDC

In all land use systems, it was clear that SOC significantly affected the stability of soil aggregates.

Almost all soil’ s parameters studied were positively and significantly correlated with SOC

Pearson’ s correlation coefficient matrix of the soil parameters for the combined land use systems. indicate significant correlations at <0.050, <0.010, and <0.001 levels, respectively. Macro, macroaggregate; meso, mesoaggregate; micro, microaggregate. content, demonstrating that SOM is a primary agent in binding soil particles together, influencing the variation in particle size distribution and aggregation indices. According to Blanco-Canqui and Lal (2004), SOC promotes soil aggregation, while aggregates subsequently store SOC, reducing SOM decomposition rate. All land use systems showed a decreasing trend in SOC content with depth. At the 50–70 and 70–100 cm layers, there was no difference (>0.050) among land use systems. Previous studies indicated higher SOC content in topsoil, without difference in deeper soil layers across various land use systems in semi-arid areas (Álvaro-Fuentes et al., 2009; Kabiri et al., 2015).

Greater SOC content was observed in the ILFug system across all soil layers. This system is managed under no-tillage, where crop residues are left on the soil surface, which leads to a slower process of decomposition and incorporation of these residues into the soil, resulting in a lower susceptibility of the soil to physical disruption (Álvaro-Fuentes et al., 2009). Moreover, the decumbens forage is commonly used in integrated systems because it efficiently accumulates carbon in the soil through aboveground biomass and roots (Cavalcante et al., 2019; Neto et al., 2021).

U. decumbens produces substantial amounts of biomass and has more slow-decomposing recalcitrant compounds, improving soil conservation by extending soil coverage, reducing temperature exposure, and increasing carbon inputs. Consequently, the slower decomposition rate of crop residues results in the accumulation of SOC in the soil. Moreover, Lal (2003) stated that SOC content can be maintained or increased in comparison with NV in semi-arid soils when crop residues are maintained on the soil. Furthermore, G. sepium , a leguminous plant, effectively distributes litter in integrated systems and decomposes quickly due to its low carbon/nitrogen (C/N) ratio (Apolinário et al., 2015). Rapid decomposition enhances fulvic acid levels in SOM, making it more mobile and contributing to SOC increases in shorter periods (Assunção et al., 2019; Junior et al., 2020). This may explain the higher SOC content in the ILFug system, despite

the shorter cultivation period of 8 a. The conversion of NV to ILFcg system resulted in decreased SOC content. One possible explanation for these reductions is the practice of soil tillage every 2 a. Soil tillage can fragment soil aggregates, disrupt soil structure, and expose SOM to higher levels of oxidation, reducing the SOC (Medeiros et al., 2022). In addition, limited soil coverage and low biomass production from cactus forage increase soil surface temperatures and SOM decomposition (Rigon and Calonego, 2020; Neto et al., 2021).

The ImpP and DegP exhibited similar SOC content, however, Fonte et al. (2014) observed a 20.0% increase in SOC in well-managed pastures compared with degraded pastures in the deforested Amazon Basin of Colombia. These findings indicated that, despite improved pastures being better managed, their capacity to maintain SOC content is still limited, particularly in the semi-arid areas, as observed by Medeiros et al. (2021). Considering the soil profile (0–100 cm), the conversion of NV to ImpP and DegP resulted in SOC losses of 28.9% and 28.3%, respectively. Medeiros et al. (2021) also observed losses in SOC with the conversion of NV to grasslands in the Brazilian semi-arid areas at a 0–100 cm depth, with these losses ranging from 12.0% to 16.0%. The low SOC content in these pastures is followed by soil compaction, as indicated by elevated BD (Fig. 2b). Continuous grazing can lead to cattle trampling, which may increase soil compaction (Costa et al., 2009; Don et al., 2011; Valbrun et al., 2018). Similar findings were reported by Santana et al. (2019) and Medeiros et al. (2023), who observed higher BD in the superficial layer of pasture areas compared with other land uses in the Brazilian semi-arid areas. The continuous grazing of pasture areas increases BD and mechanical stress, leading to the disruption of soil aggregates (Wiesmeier et al., 2012), which in turn, can lead to significant losses of SOC, particularly in areas with high evaporation rates where precipitation is scarce and irregularly distributed (Xie and Wittig, 2004). However, despite the similar SOC content in both pasture areas, the highest MWD, GMD, ASI, SI, and increased amount of macroaggregates in ImpP, indicated that improved pasture management contributes to greater soil aggregate stability and better structural quality. Conversely, the ILFug and ILFcg had the lowest BD. In ILFug, the lowest BD can be explained by the higher SOC content, which contributes to greater SOM in the soil. On the other hand, the low BD observed in ILFcg is due to the soil tillage practiced in conventional management (Barros et al., 2013; Valbrun et al., 2018). Disturbances in soil structure caused by compaction (DegP/ImpP) or tillage (ILFcg) can lead to rapid nutrient recycling, surface crusting, and decreased availability of water and air to roots (Bronick and Lal, 2005).

Soil compaction impacts important ecological characteristics, such as water and air flow, as well as root growth and functionality, consequently affecting plant growth and productivity (Reichert et al., 2009). The higher SDC values observed in the ImpP/DegP are likely a result of continuous grazing and low vegetative cover in the DegP. According to Fonte et al. (2014), soil compaction is mainly caused by overgrazing and is a clear feature of pasture decline and structure degradation. Cherubin et al. (2016) also observed increased SDC in pastures with continuous cattle trampling associated with SOC depletion, leading to reduced soil porosity and lower hydraulic conductivity of water in the soil. Increased SDC reduces soil aeration, leading to strong correlations between SDC and BD (Cherubin et al., 2016). In this study, a significant correlation was observed between SDC and BD (=0.81; <0.001). Conversely, the ILFcg system showed the lowest SDC across almost all soil layers. This can be attributed to the fact that this system is the only one subjected to tillage. According to Cherubin et al. (2016), tillage operations involve the mechanical disruption of the soil, which helps to break up compacted layers, creating large pores that can lead to reduced soil compaction. Nonetheless, this reduction in soil compaction occurs only in short-term tillage; over time, continuous tillage practices can lead to soil structural degradation (Centurion et al., 2007).

4.2 SSI

The SSI refers to the correlation between SOM and the surface area of clay and silt. This index is

used for the assessment of the soil's vulnerability to structural degradation (Pieri, 1992). The highest SSI values observed in ILFug indicated the potential of this system to enhance soil quality and minimize the vulnerability to structural degradation.

A correlation between the decline in SOC with depth and lower SSI values across all land use systems was observed. While erosion is not probable in deeper soil layers, the decline in SOC content and SSI may affect factors such as aggregate stability and soil compaction, which can subsequently contribute to erosion in more superficial layers. In tropical sandy soils, soil structure and aggregation predominantly depend on organic bonds due to the low clay content, where the lack of nutrients and reduced surface area of minerals adsorbents are insufficient to maintain soil structure (Pieri, 1992; Blair, 2000; Cherubin et al., 2016). Conversely, Wiesmeier et al. (2015) noted that in semi-arid climates, the reduced input of carbon significantly influences soil aggregation and soil carbon storage capacity, which largely depend on clay mineralogy. Since the studied soil is a podzol with adequate clay content to support its structure, the processes involved in aggregation and carbon storage can be linked to several factors beyond clay mineralogy, including the activity of both organic and inorganic agents and the presence of ferrum (Fe) and aluminum (Al) oxides, and calcium (Ca) flocculants. As a result, we can say that in this case, the SSI partially indicates the capacity of the soil for SOC storage, considering the amount of clay and silt that is available for organo-mineral interactions.

4.3 Distribution of WSA classes

The NV (dense Caatinga) presented the highest proportion of macroaggregates at the 0–10 cm layer (78.7%). A greater proportion of macroaggregates was also observed in topsoil layers by Garcia-Franco et al. (2015), in a 20-a afforestation area in the southeast semi-arid area of Spain.

The accumulation of litter in forested areas contributes to soil aggregation by enhancing SOM replenishment, which, in turn, supports beneficial microbial activities (Blanco-Canqui and Lal, 2004; Okolo et al., 2020).

On average, the ILFcg system showed the lowest proportion of macroaggregates, likely due to soil tillage, carried out every 2 a. Several authors have reported a lower proportion of macroaggregates in areas under conventional tillage (Hajabbasi and Hemmat, 2000; Álvaro-Fuentes et al., 2008; Plaza-Bonilla et al., 2013; Kabiri et al., 2015; Okolo et al., 2020).

According to Six et al. (2000), systems under conventional tillage frequently show a reduced proportion of macroaggregates due to an increased rate of macroaggregate turnover (formation and degradation). Ponyane et al. (2025), through a factor analysis, observed a significant correlation between conventional tillage practices and the formation of mesoaggregates and microaggregate soil fractions. Their findings indicated that the management of soil through conventional tillage not only alters its structure but also influences the distribution and stability of these smaller size aggregates. Additionally, insufficient residue cover from the cactus forage on the soil surface does not protect the integrity of soil aggregates, which may also be a primary factor contributing to the reduced proportion of macroaggregates observed in the DegP. Moreover, in semi-arid grazed pastures, a small input of organic matter and continuous trampling, associated with degradation processes, can hinder the biologically induced formation of macroaggregates (Wiesmeier et al., 2012).

The lower proportion of macroaggregates resulted in an increased proportion of mesoaggregates in the ILFcg system at almost all soil layers. Hajabbasi and Hemmat (2000) also reported an increased proportion of mesoaggregates (<0.250 mm) under conventional tillage in the semi-arid areas of Iran. The hierarchical aggregation theory proposes that macroaggregates are initially formed through the accumulation of microaggregates and mesoaggregates and, over time, the occluded organic matter within macroaggregates is decomposed, forming microaggregates and mesoaggregates inside (Bronick and Lal, 2005). Soil tillage, eventually disrupts macroaggregates, releasing microaggregates and mesoaggregates in the soil.

Conversely, in the ILFug, the adoption of no-tillage practices, while also preventing the disruption of soil aggregates, enhances microbial activity in the soil surface (Madejón et al., 2009; Plaza-Bonilha et al., 2013), leading to greater production of organic binding by-products during the decomposition of fresh organic inputs and contributing for the formation and stability of macroaggregates (Abiven et al., 2009; Plaza-Bonilla et al., 2013). Furthermore, Plaza-Bonilla et al. (2013) indicated that the proportion of macroaggregates in topsoil tends to increase over time with no-tillage practices.

Regarding the correlation between WSA classes with clay and silt mineral fractions, only silt showed significant correlations with WSA distribution. This correlation was positive for the percentage of macroaggregates (=0.43; <0.010) and negative for the percentage of microaggregates (= -0.38; <0.010). The presence of clay and silt minerals can enhance mineral–mineral and SOM–mineral interactions, leading to the formation and stabilization of macroaggregates through physicochemical processes (Bronick and Lal, 2005; Fernández-Ugalde et al., 2011). Moreover, the formation and stabilization of macroaggregates can be driven not only by organic matter dynamics in semi-arid soils but also by other mechanisms, such as the interaction of clay and silt with soil aggregation (Fernández-Ugalde et al., 2011). Although not significant, this study showed an inverse correlation between clay and macroaggregates (= -0.22; >0.050). Clay particles are often linked to aggregation through rearrangement and flocculation; however, expansive clay can disrupt soil aggregates (Bronick and Lal, 2005). Clay swelling occurs when clay absorbs water and expands due to changes in soil moisture. Wet/dry cycles are a predominant factor disrupting soil macroaggregates in semi-arid areas (Blankinship et al., 2016), potentially explaining the weak and negative correlation between WSA and clay. The increase in clay content does not necessarily indicate enhanced aggregate stability. Although clay is a crucial component in soil aggregation, it is important to distinguish the different effects of various clay minerals on soil aggregation (Cruz, 2017). Further research on the mineralogical composition of different WSA classes is necessary to provide a clearer understanding the interaction of clay and soil aggregation.

The distribution of macroaggregates was directly correlated with SOC content (=0.28; <0.050). A direct correlation between the WSA size class distribution and SOC was also reported in several studies (Hajabbasi and Hemmat, 2000; Blanco-Canqui and Lal, 2004; Jastrow and Miller, 2018). Jastrow and Miller (2018) found a similar correlation degree between SOC and macroaggregates in a chronosequence prairie restorations on chernozems (=0.43).

4.4 Soil aggregation indices

Each aggregation index indicates a distinct characteristic of the soil. The MWD indicates the quality of soil aggregation and its physical stability. The GMD estimates the predominant class of WSA. The ASI measures soil resistance to disaggregation. Lastly, the SI is based on the principle of relative comparison between treatments, indicating whether the managed soil has lost or gained structural quality compared with the reference (NV).

The ILFug showed greater MWD in all soil layers compared with ILFcg. This can be attributed to the management (ILFug=no-tillage and ILFcg=conventional tillage) and the greater SOC content in the ILFug system, since in this study the SOC content had a positive and significant correlation with MWD (=0.47; <0.001), indicating that increases in SOM can also improve soil structure and aggregation (Kabiri et al., 2015). These findings corroborated with Hernanz et al. (2002) and Álvaro-Fuentes et al. (2007), who also found in the semi-arid areas in central Spain, greater values of MWD under no-tillage compared with conventional tillage, also attributing this fact to greater SOC content under no-tillage. Additionally, aggregate formation and stability are related to root biomass. The roots of U. decumbens in the ILFug system can better contribute to an increase in soil aggregation compared with forage cactus in the ILFcg system, as these plants have a perennial growth pattern and continuously renew their root systems (Luna et al., 2019;

Junior et al., 2020). The ILFug showed the highest ASI at the 10–20, 20–30, 30–50, and 70–100 cm layers, while NV showed the highest ASI at the 0–10 and 50–70 cm layers, corroborating other studies that aggregates in integrated systems under no-tillage and forests exhibit greater stability compared with aggregates from other land uses (Six et al., 2000; Álvaro-Fuentes et al., 2008). Increased amounts of crop residues retained on the soil surface in forests and integrated systems under no-tillage enhance SOC levels and provide better habitats for soil microorganisms, resulting in larger and more stable soil aggregates (Hernanz et al., 2002), due to improved cohesion among soil mineral particles and an increase in the hydrophobicity of the aggregates (Chenu et al., 2000; Álvaro-Fuentes et al., 2008). This is further supported by the positive correlation between SOC and ASI (=0.26; <0.050), suggesting that increases in SOM can improve soil aggregation and structural quality. Several studies have demonstrated that increases in crop residues on the soil under no-tillage are correlated with enhanced aggregate stability in semi-arid Mediterranean soils (Álvaro-Fuentes et al., 2008; Fernández-Ugalde et al., 2011). Moreover, G. sepium plays a crucial role in enhanced aggregate stability. Roots of leguminous plants are associated with increased aggregation and greater WSA than those of non-leguminous plants

(Bronick and Lal, 2005).

The ImpP increased all aggregation indices compared with DegP, a pattern also observed by Fonte et al. (2014), who reported greater soil aggregation in well-managed pastures relative to degraded ones. Well-managed pastures often have stronger and deeper root systems that aerate soils and promote the binding of soil particles and soil biological activity, improving soil aggregation (Fonte et al., 2014). Since soil aggregate formation is mostly driven by biotic factors, such as plant roots, microorganisms, and earthworms, lower organic inputs in degraded pastures result in decreased soil aggregation (Fonte et al., 2014).

The results of MWD and ASI at the 70–100 cm soil layer had an opposite pattern compared with other soil layers. In this layer, the ImpP showed a higher proportion of macroaggregates, which contributed to greater MWD values, although simultaneously having the lowest ASI.

According to Gale et al. (2000) and Álvaro-Fuentes et al. (2007), the macroaggregates primarily formed in the rhizosphere at depth, are less stable compared with those formed in topsoil through plant senescence processes. Therefore, our findings supported this concept, with the elevated MWD values observed in the ImpP linked to a higher macroaggregate proportion, despite the lower ASI.

The SI values indicated that overall soil aggregation and structural quality have improved in the ILFug system and ImpP. This can be attributed to the protection offered by plant residues, protecting the soil from erosion. Additionally, the incorporation of organic matter into the soil and microbial activity releases compounds that promote the formation and stabilization of soil aggregates. Furthermore, the hairy root system is also crucial in enhancing soil aggregation (Lima et al., 2017). These results corroborated with Cruz (2017), who also found higher values of SI in well-managed pastures and integrated systems compared with NV. The lowest SI values found in the ILFcg system and DegP reflect the harmful effect of soil tillage and degradation processes on aggregate stability.

All these findings highlighted that both land use systems and soil management practices are essential for the formation and stability of soil aggregates in semi-arid areas, where soil quality is vital for sustainable agricultural productivity. Additionally, by improving aggregate stability and SOC, NbS strengthens climate change mitigation and adaptation and aligns with several Sustainable Development Goals (SDGs).

4.5 Recommendations

Improved and degraded pastures exhibited similar SOC content, indicating that despite improved pastures being better managed, their capacity to maintain SOC content in semi-arid areas is still limited.

However, the increase in macroaggregates, aggregate stability, and aggregation indices observed in improved pastures emphasized the critical role of management in preserving soil structure in semi-arid grasslands, which may also signal a potential for long-term carbon stock recovery, as structural improvements create conditions more favorable for carbon stabilization and sequestration.

Considering all the factors discussed, adopting NbS positively impacted SOC, SOM dynamics, and overall soil physical quality, especially in integrated systems under no-tillage. NbS that promotes soil aggregation is essential for sustainable agriculture in semi-arid areas. These practices not only improve soil aggregation but also enhance carbon sequestration, reducing carbon losses to the atmosphere. Therefore, both farmers and policymakers should recognize these benefits and prioritize the expansion of NbS in semi-arid areas, where water scarcity and high temperatures often exacerbate soil degradation. Restoring degraded areas not only helps to mitigate carbon emissions but also enhances the resilience of local ecosystems against climate change.

The findings have significant practical and policy implications. Promoting ILF under no-tillage and pasture restoration practices can enhance sustainable land management, improve carbon sequestration, and strengthen ecosystem resilience, especially in the semi-arid areas with water-limited and high-temperature conditions. However, the implementation of NbS faces important practical barriers, including technical complexity and restricted access to finance and extension services, which can discourage smallholders from adopting these practices despite their long-term benefits. Therefore, we recommend that policymakers encourage broader implementation of NbS and design targeted incentive mechanisms and training for smallholders.

Such measures would increase agricultural productivity over time while promoting ecosystem conservation.

5 Conclusions

By evaluating WSA classes and aggregation indices across the soil profile following conversion from NV to pastures and ILF systems under different tillage regimes, this study provided field-based evidence to support NbS and management practices that can preserve soil structure, enhance SOC protection, and guide policy and restoration efforts in the Brazilian semi-arid agricultural areas. At the topsoil layer (0–10 cm), all managed systems showed a lower SI compared with the NV, indicating a decline in soil structural quality. Nonetheless, the ImpP and ILFug system showed higher SI values at the 10–20, 20–30, 30–50, 50–70, and 70–100 cm layers, suggesting that these land uses have improved soil structural quality in comparison with NV. The ILFug system maintained the highest SOC contents throughout the soil profile, whereas the conversion of NV to ILFcg, ImpP, and DegP resulted in SOC losses.

The results demonstrated that implementing ILF systems under no-tillage (ILFug) as a NbS significantly enhanced SOC content and improved the stability of soil aggregates and structural stability in semi-arid environments, indicating a high potential for SOC protection and reduced susceptibility to degradation. In contrast, the ILFcg system under conventional tillage and the DegP showed the lowest aggregation indices, compared with NV; ILFug under no tillage and ImpP reflected the adverse impacts of conventional tillage and degradation on soil structure.

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

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Appendix

Table S1 Distribution of water-stable aggregate (WSA) classes in different land use systems in the Brazilian semi-arid areas Land use system Size class WSA (%) 0-10 cm 10-20 cm 20-30 cm 30-50 cm 50-70 cm 70-100 cm Macro 78.7$±8.461.4±17.445.9±13.844.3±13.361.4±17.837.4±10.615.7±7.624.6±12.936.6±11.838.4±13.230.2±17.050 Note: NV, native vegetation; ILFug, integrated livestock-forestry (ILF) with Gliricidia Gliricidia sepium (Jacq.) Kunth ex Walp.)+ Urochloa Urochloa decumbens (Stapf) R.D. Webster) under no-tillage; ILFcg, ILF with Gliricidia G. sepium)+forage cactus Opuntia cochenillifera (Linnaeus) Miller; phase 1) or with Gliricidia G. sepium)+forage cactus+sorghum (phase 2) under convention tillage; ImpP, improved pasture; DegP, degraded pasture; macro, macroaggregate; meso, mesoaggregate; micro, microaggregate.

Mean±SD; =5. Different uppercase letters for land use systems and lowercase letters for soil layers signify significance difference at <0.050 level by Tukey' s test.

Note: Figure translations are in progress. See original paper for figures.

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