FEDERAL UNIVERSITY OF ALAGOAS
ENGINEERING AND AGRICULTURAL SCIENCES CAMPUS
POSTGRADUATE PROGRAM IN AGRONOMY
AREA OF CONCENTRATION: PLANT PRODUCTION

HANDERSON BRANDÃO MELO DE LIMA

IMPACT OF LAND-USE CHANGE ON CARBON STOCKS, ORGANIC MATTER DYNAMICS, AND SOIL AGGREGATION UNDER INTEGRATED SYSTEMS AND GRASSLANDS IN THE SEMI-ARID OF SERGIPE, BRAZIL

Rio Largo - AL
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Dissertation presented to obtain the degree of master in Agronomy. Area: Plant Production, CECA/UFAL.

Advisor: Prof. Dr. Stoécio Malta Ferreira Maia

Rio Largo - AL

2025

Catalogação na Fonte
Universidade Federal de Alagoas
Biblioteca Campus de Engenharias e Ciências Agrárias
Bibliotecário Responsável: Erisson Rodrigues de Santana - CRB4 - 1512

L732i Lima, Handerson Brandão Melo de.

Impacto da mudança no uso da terra nos estoques de carbono, dinâmica da matéria orgânica e agregação do solo sob sistemas integrados e pastagens no semiárido de Sergipe, Brasil. / Handerson Brandão Melo de Lima. – 2025.

85f.: il.

Orientador(a): Stoécio Malta Ferreira Maia

Dissertação (Mestrado em Agronomia) – Programa de Pós -Graduação em Agronomia, Área de concentração: Produção Vegetal, Campus de Engenharias e Ciências Agrárias, Universidade Federal de Alagoas. Rio Largo, 2025.

Inclui bibliografia.

1. Caatinga. 2. Soluções baseadas na natureza. 3. Qualidade do solo. 4. mudanças climáticas. 5. Plantio direto. I. Título.

CDU: 581.9: 633.2.03(813.7)

APPROVAL SHEET

HANDERSON BRANDÃO MELO DE LIMA

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Prof. Dr. Leidivan Almeida Frazão - UFMG

To my daughter Maria Eduarda Ferreira Brandão

I DEDICATE

ACKNOWLEDGMENTS

I would like to express my gratitude to:

My parents, Joselilde Brandão de Melo e José Brandão dos Santos Júnior, who have guided me in life.

My advisor, Stoécio Malta Ferreira Maia for the opportunity, guidance, patience, and encouragement.

My daughter, Maria Eduarda Ferreira Brandão, your words of support and belief in me have been a constant source of strength.

The Federal Institute of Alagoas (IFAL), Marechal Deodoro Campus, for providing me with the opportunity to conduct my research on campus.

My colleagues, Crislâny Canuto dos Santos, Thamirys Suelle da Silva, and José Lucas Pereira da Silva, for their camaraderie and assistance throughout this process. The conversations, shared challenges, and moments of laughter have made this experience even more enriching.

The Federal University of Alagoas (UFAL), the Postgraduate Program in Agronomy – Plant Production.

The NbS Programme of the Research Centre for Greenhouse Gas Innovation (RCGI) affiliated with the University of São Paulo USP/Esalq, that involves the restoration of native vegetation, expansion of integrated agricultural systems, and restoration of pasture areas. The RCGI's mission is both urgent and pivotal: to significantly reduce greenhouse gas emissions across the nation, thereby making a crucial contribution toward achieving Brazil's Nationally Determined Contributions (NDC) to global climate action.

Lastly, to everyone who, in one way or another, contributed to this journey, my deepest appreciation. This work would not have been possible without your support.

THANK YOU ALL.

ABSTRACT

In Brazil, the semi-arid region is one of the most climatically challenged areas, experiencing irregular and low rainfall, with long periods of drought, high temperatures, and intense solar radiation, and is characterized by a unique biome known as Caatinga, which native vegetation is recognized as a unique regional vegetation; however, it is also linked to broader classifications as one of the tropical dry deciduous forests. and has undergone significant degradation due to deforestation for agriculture, livestock, and the use of firewood. In this context, nature-based solutions (NbS) that prioritize soil health are crucial due to the susceptibility of the semi-arid region to degradation. This study aimed to evaluate the impact of converting native vegetation (dense Caatinga) into two grasslands and two integrated livestock-forestry systems on soil organic carbon (SOC) stocks, soil organic matter (SOM) pools (particulate organic matter (POM) and mineral-associated organic matter (MAOM)), and soil physical quality through Water-stable Aggregate (WSA) classes and aggregation indices. The study was conducted at the Semi-arid Experimental Station of the Brazilian Agricultural Research Corporation (EMBRAPA), located in the municipality of Nossa Senhora da Glória, Sergipe, Brazil. Soil samples were collected at 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers in 5 different land uses: native vegetation (NV), integrated livestock-forestry system under no-tillage with gliricidia (*Gliricidia sepium*) + *Urochloa* (*Urochloa decumbens*) (ILFug), an integrated livestock-forestry system under conventional tillage with gliricidia + forage cactus (*Opuntia cochenillifera*) (ILFcg), improved pasture (ImpP), and degraded pasture (DegP). The ILFug system showed the highest stocks of MAOM, at all soil depths, and that led to increases in the SOC stocks, thus placing this system with the greatest SOC stocks. The ILFug system also showed the greatest aggregate stability index (ASI) in 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 90.4%, respectively. The NV-DegP conversion represented a decline in soil quality, showing the most significant reductions in the POM fraction of SOM. Almost all parameters studied were significantly correlated with SOC, demonstrating that 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 stocks; however, the ImpP showed a higher ASI and increased amount of macroaggregates (> 2.00 mm), highlighting the adverse impacts of degradation processes in soil structure. By promoting practices that enhance SOC stocks, C sequestration, reduce greenhouse gas emissions, and improve ecosystem resilience, NbS provides a sustainable approach to mitigating the impacts of climate change, while supporting local communities in the Brazilian semi-arid region.

Keywords: Caatinga; nature-based solutions; soil quality; climate change; no-tillage.

RESUMO

No Brasil, a região semiárida é uma das áreas que sofrem os maiores desafios climáticos, caracterizada por precipitações irregulares e escassas, longos períodos de seca, altas temperaturas e intensa radiação solar. Esta região abriga um bioma único, conhecido como Caatinga, cuja vegetação nativa é reconhecida como uma vegetação regional distinta, mas que também pode ser classificada de forma mais ampla como uma das florestas tropicais secas e decíduas. No entanto, esse bioma tem sofrido degradação significativa devido ao desmatamento para a agricultura, pecuária e extração de lenha. Nesse contexto, as soluções baseadas na natureza (NBS), que priorizam a saúde do solo, são essenciais devido à susceptibilidade da região semiárida à degradação. Este estudo teve como objetivo avaliar o impacto da conversão da vegetação nativa (Caatinga densa) em duas pastagens e dois sistemas integrados de pecuária-floresta sobre os estoques de carbono orgânico do solo (COS), nos compartimentos da matéria orgânica do solo (MOS), incluindo a matéria orgânica particulada (MOP) e a matéria orgânica associada aos minerais (MOAM), e na qualidade física do solo, por meio da avaliação das classes de agregados estáveis em água (AEA) e de índices de agregação. O estudo foi conduzido na Estação Experimental do Semiárido da Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), localizada no município de Nossa Senhora da Glória, Sergipe, Brasil. A coleta de amostras de solo foi realizada nas camadas de 0-10, 10-20, 20-30, 30-50, 50-70 e 70-100 cm, em cinco diferentes usos da terra: vegetação nativa (NV), sistema de integração pecuária-floresta sob plantio direto com gliricídia (*Gliricidia sepium*) + *Urochloa* (*Urochloa decumbens*) (ILFug), sistema de integração pecuária-floresta sob preparo convencional com gliricídia + palma forrageira (*Opuntia cochenillifera*) (ILFcg), pastagem melhorada (ImpP) e pastagem degradada (DegP). O sistema ILFug apresentou os maiores estoques de MOAM em todas as profundidades do solo, resultando em aumentos nos estoques de COS, tornando-se o sistema com os maiores estoques de COS. Além disso, o sistema ILFug apresentou o maior índice de estabilidade de agregados (IEA) em quase todas as camadas do solo, com exceção das camadas de 0-10 cm e 50-70 cm, onde a NV apresentou os valores mais elevados, de 89,1% e 90,4%, respectivamente. A conversão de NV para DegP resultou em uma redução na qualidade do solo, com as maiores perdas na fração MOP da MOS. Quase todos os parâmetros estudados apresentaram correlação significativa com o COS, destacando o papel fundamental da MOS na junção entre as partículas do solo e na influência sobre a variação dos AEA e dos índices de agregação. Embora o ImpP e DegP tenham apresentado estoques de COS semelhantes, o ImpP apresentou um IEA mais elevado e uma maior proporção de macroagregados (>2,00 mm), evidenciando os impactos negativos dos processos de degradação na estrutura do solo. Ao incentivar práticas que aumentem os estoques de COS, promovam o sequestro de carbono, reduzam as emissões de gases de efeito estufa e melhorem a resiliência dos ecossistemas, as SBN oferecem uma abordagem sustentável para mitigar os impactos das mudanças climáticas, ao mesmo tempo em que beneficiam as comunidades locais da região semiárida brasileira.

Palavras-chave: Caatinga; soluções baseadas na natureza; qualidade do solo; mudança climática; plantio direto.

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1 GENERAL INTRODUCTION

The semi-arid region of Brazil, predominantly located in the northeastern part of the country, encompasses a unique biome known as Caatinga, which is distinguished by its diverse array of thorny vegetation, resilient cacti, and a pronounced pattern of dry seasons, with rainfall averaging between 300 to 800 millimeters annually (ARAÚJO; TABARELLI, 2002; MAIA et al., 2007). The Caatinga occupies approximately 11% (around 800,000 Km²) of the national territory and is crucial for maintaining ecological functions such as biodiversity, carbon (C) cycling, and soil health (SANTOS et al., 2011b). Research reveals that intact Caatinga vegetation plays a crucial role in sustaining soil organic matter (SOM) levels, enhancing the stocks of soil organic carbon (SOC), and fostering C sequestration (GIONGO et al., 2011; MENEZES et al., 2021) . Medeiros et al., (2021) found that the conversion of native vegetation to grasslands in the Brazilian semi-arid region results in less organic matter inputs into the soil, consequently leading to losses of SOC, ranging from 12% to 16% at a depth of 0-100 cm.

However, unsustainable land use practices, including extensive deforestation for agriculture, overgrazing by livestock, and the use of firewood for fuel, have led to significant degradation of this fragile biome (NOBRE, 2005; SOUSA et al., 2012; TOMASELLA et al., 2018). These activities contribute to soil erosion and nutrient depletion, exacerbating desertification and jeopardizing the ecological balance of the region. Consequently, efforts to promote sustainable land management and conservation in the Caatinga are essential to protect its unique biodiversity and ensure the resilience of this important biome against climate change.

In this context, nature-based solutions (NbS) have gained significant attention as an effective strategy for improving soil health and resilience. NbS encompasses a range of practices designed to enhance soil quality, sequester atmospheric C, and restore degraded ecosystems (GIRARDIN et al., 2021; SOTERRONI et al., 2023). Examples of these solutions include integrated livestock-forestry systems (ILF), which strategically combine pastures with forestry practices to optimize land use; improved pastures, which are cultivated with specific grass species to increase forage quality and biomass; and sustainable land management as no-tillage, that minimize soil disturbance. NbS not only helps mitigate the impacts of climate change by reducing greenhouse gas (GHG) emissions but also supports the sustainability of local agricultural systems (LAL, 2004; MAIA et al., 2007; COTRUFO et al., 2019). Moreover, the correlation between elevated GHG emissions and climate change has established C storage in SOM as a feasible approach for sequestering atmospheric CO_2 (COTRUFO et al., 2019).

Understanding the composition and stability of SOM is vital for assessing its influence on C dynamics, especially in semi-arid regions where organic matter inputs are often limited by climatic conditions (MEDEIROS; SOARES; MAIA, 2022). A widely used approach to studying the different pools of organic matter and their respective contributions to soil health is the physical fractionation of SOM (CAMBARDELLA; ELLIOTT, 1992).

SOM is primarily divided into two main fractions: particulate organic matter (POM) and mineral-associated organic matter (MAOM) (KUNDE et al., 2018; LAVALLEE, SOONG; COTRUFO, 2020). POM consists of relatively undecomposed organic materials and tends to be more readily available for microbial decomposition and nutrient cycling (SIX et al., 2002; LAVALLEE, SOONG; COTRUFO, 2020). In contrast, MAOM is characterized by smaller organic molecules that become stabilized through interactions with soil minerals, resulting in a more durable form of C storage (SIX et al., 2002; COTRUFO; LAVALLEE, 2022). The balance between these two fractions is essential for effective C sequestration in soils, as POM is a short-term nutrient source, providing essential elements to plants and microorganisms, while MAOM contributes significantly to long-term C storage and soil structure, enhancing soil resilience against erosion and degradation (MAIA et al., 2007). Sousa et al. (2012) conducted a study in the Brazilian semi-arid region and found that the frequent droughts experienced in this area led to an increased residence time for the POM fraction, which accounted for approximately 45% of total SOC, highlighting the importance of managing organic matter inputs in these environments to optimize SOC stocks.

Declines in SOC stocks, combined with high temperatures and low moisture availability in the semi-arid, can lead to soil particle detachment, as SOM is one of the main cementing agents promoting soil aggregation (FERNÁNDEZ-UGALDE et al., 2011; KABIRI; RAIESI; GHAZAVI, 2015), which is essential for soil health, due to the susceptibility of the semi-arid region to erosion and degradation (MAIA et al., 2007; MEDEIROS et al., 2020, 2023). A thorough understanding of the distribution of aggregates in the soil and how they interact with SOC is essential for developing sustainable management strategies. The incorporation of C into soil aggregates enhances their structural stability, resulting in a longer C residence time in the soil (FERREIRA et al., 2018; MEDEIROS et al., 2023). Medeiros et al. (2023) emphasized that enhancing SOM inputs and maintaining stable soil aggregates are essential for protecting SOC from rapid decomposition. NbS can enhance the formation of MAOM in semi-arid soils, by promoting the accumulation of organic matter in stable aggregates, helping to increase SOC levels, improving soil resilience to environmental stressors (MEDEIROS; SOARES; MAIA, 2022a). Considering these aspects, this study was conducted to assess how the conversion of native vegetation to two pastures (improved and degraded), and two ILF systems, one under no-tillage and one under conventional tillage, affect SOM dynamics, and soil physical quality in the Brazilian semi-arid region, particularly in relation to SOC stocks and soil aggregation. Through assessments of SOC stocks, POM and MAOM fractions, water-stable aggregates, and aggregation indices, this work highlights the potential of NbS to enhance soil aggregation and C sequestration. The findings provide valuable insights into sustainable land management practices that not only combat land degradation and climate change but also contribute to the resilience of semi-arid ecosystems under increasing environmental pressures.

2 OBJECTIVES

2.1 General

To evaluate the impact of converting native vegetation (dense Caatinga) to improved pastures, degraded pastures, and two integrated livestock-forestry systems under no-tillage and conventional tillage on the soil organic carbon stocks, soil organic matter pools, soil aggregation, and physical quality in the semi-arid of Sergipe, Brazil.

2.2 Specific

To quantify carbon stocks and their distribution in the soil profile to a depth of 1 meter in the different land uses;

To provide a sensitive measurement of the rate of change in soil carbon dynamics through carbon management index and annual soil organic carbon change rate;

To assess the SOM dynamics through the physical fractionation of soil organic matter into particulate organic matter (POM) and mineral-associated organic matter (MAOM);

To evaluate soil aggregate stability in the soil profile and generate aggregation indices;

To assess the risk of structural degradation of the soil and soil degree of compactness;

3 LITERATURE REVIEW

3.1 Semi-arid region of Brazil and the Caatinga biome

The semi-arid region of Brazil, predominantly located in the northeastern states, is one of the most climatically challenged areas in the country, experiencing irregular and low rainfall, with long periods of drought, high temperatures, and intense solar radiation (ARAÚJO; TABARELLI, 2002; GIULIETTI et al., 2004; SILVA et al., 2011). This area is one of the most densely populated semi-arid regions in the world. Due to climatic challenges, along with historical, geographical, and political factors, it is home to the poorest segment of the population in the country (SILVA et al., 2010). A significant portion of the population in this region is engaged in agropastoral activities, relying on the natural resources available on their properties and in their surrounding areas for their livelihood. These activities are heavily dependent on rainfall, and due to climate challenges and frequent drought cycles, they often contribute to substantial environmental degradation (SILVA et al., 2010). The irregularity and low levels of rainfall, highlight the importance of constructing water reservoirs to ensure the availability of water for human and animal consumption, as well as for food production. The region experienced severe droughts from 2011 to 2017, impacting over 80% of its municipalities. In 2012, the area faced the most devastating drought in three decades, dramatically impacting the livelihoods and economies of approximately 30 million people (MARENGO et al., 2017). By 2016, the consequences of this environmental crisis had become more evident, with 24% of the municipalities in the semi-arid region reporting the emergence or expansion of desertified areas (MARENGO et al., 2017).

The Caatinga biome, exclusive to Brazil, represents the most extensive semi-arid region in South America, covering an area of approximately 800,000 km², and is home to a variety of drought-resistant species that have adapted to the harsh environmental conditions, including succulents, deciduous shrubs, and trees (FIGUEIRÔA et al., 2006; MAIA et al., 2007; MEDEIROS; SOARES; MAIA, 2022). The Caatinga native vegetation is recognized as a unique regional vegetation; however, it is also linked to broader classifications (GARIGLIO et al., 2010). On an international scale, it is classified as one of the tropical dry deciduous forests (RODAL; JARENKOW; OLIVEIRA-FILHO, 2006).

Located between the Equator and the Tropic of Capricorn, the Caatinga biome has year-round sunlight. Most of its terrain is at low altitudes, with only a few areas in Bahia state exceeding 2,000 meters (GAROGLIO et al., 2010), resulting in consistently high temperatures, averaging between 25°C and 30°C, with minimal variation throughout the year. Consequently, light and temperature are not the main limiting factors to plant growth, and have little impact on environmental variability (SAMPAIO, 2003). However, intense high temperatures, along with irregular rainfall, lead to increased evapotranspiration, which reduces soil moisture and the amount of water stored in reservoirs (SILVA et al., 2010). Regarding soil classes, there is a rich diversity of soils with unique and distinct properties, ranging from sandy to clayey soils (SANTANA et al., 2019), being the biome with the most soil variability in Brazil (CARIGLIO et al., 2010). The most representative soils in the region are Ferralsols (21.0% of the total area), Leptsols (19.2%), Acrisols (14.7%), Luvisols (13.3%), Arenosols (9.3%), Planosols (9.1%), and Regosols (4.4%) (MENEZES et al., 2012; SANTOS et al., 2023). Over 80% of the area faces some soil limitations for agricultural use, primarily due to low fertility and shallow soil profiles (MENEZES et al., 2012; SILVA, 2000).

The Caatinga biodiversity is vital for ecosystem functioning, particularly regarding C cycling and soil health. Studies show that intact native Caatinga vegetation maintains SOM levels and promotes C sequestration (GIONGO et al., 2011; MENEZES et al., 2021), and covers an area of about 450,000 km² (CARIGLIO et al., 2010). However, this region has undergone significant degradation due to deforestation for agriculture, livestock, and the use of firewood. The conversion of native vegetation into grasslands and conventional agriculture can reduce SOC stocks by 23 % and 34%, respectively (MENEZES et al., 2021), reducing soil fertility and exacerbating the effects of desertification. Studie by Giulietti et al. (2004) have highlighted the importance of conserving native vegetation to maintain soil health and ecosystem services in the Caatinga. These land-use changes have resulted in landscapes characterized by diverse grasslands, agricultural fields, and forests, ranging from disturbed, or open forests to dense forest fragments (MENEZES et al., 2012, 2021).

Efforts to mitigate environmental degradation and promote sustainable land use in the Caatinga biome have increased significantly in recent years. Programs focused on agroecological practices and the implementation of integrated systems have shown potential for improving soil health and increasing C sequestration (TONUCCI et al., 2023). These approaches not only benefit the soil physical and chemical properties but also contribute to the socio-economic well-being of local communities by improving agricultural productivity and resilience to climatic variability.

The Caatinga biome is not only a significant biological hotspot but also a crucial area for examining the effects of climate change on semi-arid ecosystems. As global temperatures rise and rainfall patterns become increasingly unpredictable, the preservation of Caatinga natural resources and the implementation of more conservationist management in the Brazilian semi-arid will be important for maintaining ecological balance and supporting the livelihoods of millions of people in the region (LEAL et al., 2005).

3.2 Soil organic carbon stocks in semiarid regions

SOC stocks represent one of the most important indicators of soil health and play a key role in the global C cycle. In semiarid regions, the dynamics of SOC are influenced by factors such as low precipitation, high temperatures, and the seasonal variability of biomass production (MEDEIROS et al., 2021; SANTOS et al., 2011a). Studies indicate that SOC stocks in these semi-arid environments, including the Caatinga, are generally lower than those in more humid regions due to the limited input of organic matter and its rapid mineralization (MAIA et al., 2007; SANTOS et al., 2023).

Conversion of native Caatinga vegetation into conventional agriculture or pastures often results in a significant loss of SOC. However, management practices, such as agroforestry systems and no-till agriculture, can mitigate these losses and even enhance C sequestration (SILVA et al., 2019; SANTOS et al., 2019). According to Lima et al. (2020), preserving the native Caatinga vegetation is essential for protecting soil structure, improving microbial activity, and increasing SOC levels in the semi-arid region of Brazil. Menezes et al. (2021) reported SOC stocks in the Caatinga biome ranging from 56.38 to 136.71 Mg C ha^{-1} down to a depth of 1 m, with variations attributed to differences in land-use systems. The average SOC stocks in preserved Caatinga were 89.86 Mg ha^{-1}; however, in restored native vegetation, SOC stocks were reduced by 27%, while in pasture and conventional agriculture, the losses were 23% and 34%, respectively.

Marengo (2008) emphasized that declining SOC stocks can lead to reduced soil fertility, impaired water retention, and decreased microbial activity. This not only affects agricultural productivity but also contributes to the desertification process, which is a major concern in semi-arid areas worldwide (SOLOMON; LEHMANN; ZECH, 2000). Therefore, restoring SOC levels through sustainable land management practices is a priority for maintaining soil health and combating land degradation (MAIA et al., 2007; MEDEIROS; SOARES; MAIA, 2022).

Lei et al. (2019) demonstrated that land-use changes in semi-arid regions, particularly the conversion to agriculture and grasslands, lead to a significant decline in SOC stocks. They found that these reductions in SOC stocks could be up to 50%, depending on the management practices employed. This underscores the importance of sustainable land management to preserve the remaining native vegetation and restore degraded areas. Over 8 million hectares of Caatinga native vegetation have been converted to activities linked to agriculture and livestock, which now account for 38.1% of the biome area (MAPBIOMAS, 2021; MENEZES et al., 2021). In addition, Tonucci et al. (2023) emphasized the role of agroforestry systems and reforestation as effective strategies for restoring SOC in the Brazilian semi-arid region.

One promising strategy for improving SOC stocks in semi-arid regions is the adoption of conservational agriculture techniques, such as no-till farming and cover cropping (FRIEDRICH; DERPSCH; KASSAM, 2012). These practices help to protect the soil surface, reduce erosion, and increase organic matter inputs (SANTOS et al., 2019a). Sampaio; Costa (2012) found that integrating these practices into agricultural systems in the Caatinga biome increases SOC levels over time. Moreover, the use of organic amendments, such as manure or compost can further enhance SOC sequestration in these regions (YEASMIN et al., 2022).

3.3 Soil organic matter

Soil organic matter (SOM) is an invaluable renewable natural resource that plays a crucial role in maintaining the health and functionality of ecosystems. Additionally, SOM helps regulate climate by sequestering carbon dioxide (CO_2), thereby mitigating the effects of climate change. The SOM also influences water cycles by improving soil structure and water retention, reducing runoff, and promoting groundwater recharge (COTRUFO; LAVALLEE, 2022). Furthermore, SOM is crucial for regenerating soil fertility, as it supplies essential nutrients for plants and supports the microbial communities that contribute to nutrient cycling (SMITH et al., 2015). Moreover, soil organic matter is key to supporting the diverse range of organisms that inhabit the soil, fostering biodiversity that is critical to ecosystem resilience and productivity (SMITH et al., 2015).

Understanding the composition and stability of SOM is essential for assessing its role in C dynamics, particularly in semi-arid regions where organic matter inputs are often limited (MEDEIROS; SOARES; MAIA, 2022a). The physical fractionation of SOM is a common method for studying the various pools of organic matter and their respective contributions to soil health (CAMBARDELLA; ELLIOTT, 1992a). The two main fractions of SOM are POM and MAOM (KUNDE et al., 2018; LAVALLEE; SOONG; COTRUFO, 2020). POM consists of relatively undecomposed organic material, such as plant residues, and is more readily available for microbial decomposition (LAVALLEE; SOONG; COTRUFO, 2020; SIX et al., 2002). MAOM, on the other hand, is composed of smaller organic molecules that are stabilized through interactions with soil minerals, making it more resistant to degradation (COTRUFO; LAVALLEE, 2022; SIX et al., 2002). The balance between these fractions is critical for long-term C sequestration, as POM provides a short-term source of nutrients, while MAOM contributes to the stable storage of C over longer periods (MAIA et al., 2007).

In semi-arid soils, the dynamics of SOM fractions are influenced by the limited supply of organic inputs and the rapid decomposition of POM due to high temperatures (NETO et al., 2021; MAIA et al., 2007; MEDEIROS; SOARES; MAIA, 2022). Maia et al. (2007) highlight the importance of MAOM in maintaining SOC stocks in these environments, as it represents the more stable fraction of SOM that is less vulnerable to decomposition under harsh climatic conditions. The formation and stabilization of MAOM are closely linked to soil aggregation, which protects organic matter from microbial attack and physical disturbance (COTRUFO; LAVALLEE, 2022; LAVALLEE; SOONG; COTRUFO, 2020).

Sustainable land management practices, such as integrated systems and reduced tillage, can enhance the formation of MAOM in semi-arid soils, by promoting the accumulation of organic matter in stable aggregates, helping to increase SOC levels and improve soil resilience to environmental stressors (MEDEIROS; SOARES; MAIA, 2022a). Neto et al. (2021) has shown that these land-use practices that increase organic inputs into the soil can enhance both POM and MAOM fractions. These strategies connect short-term C availability with long-term storage, establishing a pathway for sustainable land management in the semi-arid region. This is particularly important in the context of climate change, where the preservation of SOM is critical for maintaining the productivity and sustainability of agricultural systems in semi-arid regions.

3.4 Nature-based solutions as a tool to mitigate climate change and improve soil quality

NbS are strategies that utilize natural processes to tackle environmental, social, and economic challenges. These include actions such as ecosystem restoration, sustainable land management, and conservation practices that aim to provide ecological benefits while enhancing resilience against climate-related stressors (GIRARDIN et al., 2021; SOTERRONI et al., 2023).

The NbS have a significant global mitigation potential, estimated at around 10 gigatonnes of carbon dioxide ($GtCO_2$) per year. This large volume accounts for approximately 27% of the total annual greenhouse gas emissions currently produced worldwide (GIRARDIN et al., 2021). By harnessing natural processes and ecosystems, NbS can effectively reduce C emissions, contributing to climate change mitigation strategies. studies by Girardin et al. (2021) and Soterroni et al. (2023) underscores the critical role that these solutions can play in addressing the urgent need for emission reductions on a global scale. The Brazilian semiarid region, encompassing the Caatinga biome, faces significant environmental challenges associated with climate change and the greenhouse effect. As environmental awareness grows, there is an increasing focus on NbS to address these environmental issues (ALVES; DJORDJEVIĆ; JAVADI, 2022).

Integrated systems, particularly those that combine crops, livestock, and forestry, are examples of NbS that provide sustainable solutions for improving soil health and C sequestration in semiarid regions (MAIA et al., 2007). These systems take advantage of the complementary interactions among different plant species and livestock to optimize resource use and ecological benefits. Tonucci et al. (2023) found that integrated systems in the semi-arid can increase SOC by 24% compared to native vegetation; while the conversion of native vegetation into agriculture and pastures caused reductions of 12% in SOC stocks in the first years, increasing to reductions of 29% over 15 years. These results highlight the potential of integrated systems as one of the key strategies for low-carbon agriculture under semi-arid conditions.

In the Caatinga, integrated systems are crucial for mitigating the adverse effects of land degradation and enhancing SOC stocks. Herrera et al. (2021) and Camelo et al. (2021) explored the implementation of silvopastoral practices involving species such as *Gliricidia sepium, Opuntia spp.* and *Urochloa spp*. These species are well-adapted to the semiarid climate and provide multiple ecosystem services, including nitrogen fixation, soil shading, and organic matter input (BEEDY et al., 2010; CAMELO et al., 2021; HERRERA et al., 2021). The incorporation of gliricidia in integrated systems, for instance, not only improves soil fertility through nitrogen fixation but also enhances soil structure by providing organic residues that contribute to aggregate formation (BEEDY et al., 2010; MAFONGOYA et al., 2006; MAKUMBA, 2003). *Opuntia spp.*, commonly known as forage cactus, plays a crucial role in integrated systems within the Caatinga (CAMELO et al., 2021). These cactus species are highly drought-resistant and serve as both forage for livestock and as a source of organic matter for the soil. Camelo et al. (2021) demonstrated that integrated systems based on forage cactus and gliricidia improve water use efficiency and reduce soil erosion while contributing to SOC accumulation through the deposition of decomposing plant tissues. *Urochloa* grasses are also integral to integrated systems in semi-arid regions, providing high-quality forage for livestock and contributing to ground cover, reducing soil erosion, and enhancing water infiltration. Herrera et al. (2021) and Lima et al. (2020) found that the inclusion of *Urochloa* in integrated systems leads to improved soil structure and increased SOC levels. The extensive root systems of *Urochloa* facilitate the incorporation of organic matter into deeper soil layers, promoting long-term C storage and enhancing soil fertility. However, the establishment of planted pastures, usually with exotic species, has led to a reduction in native vegetation, especially in areas with greater water availability (GARIGLIO et al., 2010).

The examples discussed illustrate how NbS can enhance resilience in local communities while restoring the ecosystem. As Brazil faces the challenges of climate change and environmental degradation, adopting NbS will be crucial for building a sustainable future (SOTERRONI et al., 2023). In conclusion, integrating NbS into climate adaptation strategies can help mitigate the greenhouse effect and promote sustainable development in the Brazilian semiarid region by diversifying agricultural production and strengthening the resilience of the ecosystem to climate variability.

3.5 Soil aggregation

Soil aggregation is a fundamental process that influences various soil properties, including structure, porosity, water infiltration, and resistance to erosion (MEDEIROS et al., 2023). Aggregates are formed through the binding of individual soil particles by organic matter, root exudates, microbial activity, and the presence of clay minerals (COTRUFO; LAVALLEE, 2022).

In the context of the semi-arid, soil aggregation is particularly important due to the susceptibility of the region to erosion and degradation (MAIA et al., 2007). High temperatures and low moisture availability can exacerbate soil particle detachment, leading to the loss of fertile topsoil and a decline in SOC stocks and aggregate stability (WIESMEIER et al., 2019). Medeiros et al. (2023) emphasized that maintaining stable soil aggregates is essential for protecting SOC from rapid decomposition and physical loss. They found that practices promoting aggregate stability, such as no-tillage, can significantly enhance SOC retention in semi-arid soils. Corroborating this affirmation, Álvaro-Fuentes et al. (2009) found a greater proportion of macroaggregates (> 2.00 mm) in no-tillage compared with conventional tillage areas in the semi-arid region of Spain, with values of 37 % and 16 %, respectively.

Organic matter is a key driver of soil aggregation in environments and its more labile fractions contribute to the formation of macroaggregates, which are less prone to erosion and provide habitats for soil microorganisms (SIX; ELLIOTT; PAUSTIAN, 2000). According to Tonucci et al. (2023), the addition of organic residues in the soil increases the formation of stable aggregates by providing binding agents and enhancing microbial activity. This not only improves soil structure but also facilitates the incorporation of organic carbon into more stable forms, thereby enhancing long-term C sequestration.

Microbial activity is another critical factor influencing soil aggregation. Soil microorganisms, including fungi and bacteria, produce extracellular polymers that act as glue, binding soil particles together (BLÉCOURT et al., 2019; MEDEIROS et al., 2023; SIX; ELLIOTT; PAUSTIAN, 2000). Zhang et al. (2014) found a greater positive correlation ($r = 0.76$; $p < 0.05$) between a higher proportion of > 1 mm aggregates and microbial biomass carbon, compared to aggregates of less size, confirming the influence of microorganisms among different aggregate classes. Blécourt et al. (2019) highlighted the role of mycorrhizal fungi in promoting aggregate stability in semi-arid regions. These fungi enhance plant root systems, leading to increased root exudation and organic matter input, which in turn supports the formation of stable aggregates (BLÉCOURT et al., 2019; MEDEIROS et al., 2023; SIX; ELLIOTT; PAUSTIAN, 2000). Soil management practices that enhance aggregation are vital for sustainable agriculture in semi-arid regions. Techniques such as cover cropping and agroforestry, help maintain or improve soil structure by increasing organic matter inputs and reducing soil disturbance (MEDEIROS et al., 2023; MAIA et al., 2007).

Furthermore, the physical properties of soil minerals influence aggregation processes. Clay minerals, for example, play a role in stabilizing aggregates by binding with organic molecules and other soil particles (BLÉCOURT et al., 2019; MEDEIROS et al., 2023; LÜTZOW et al., 2006). At larger scales, when examining soils that share similar textures, research indicates that higher stocks of SOM are associated with increased aggregate stability (BISSONNAIS et al., 2018). This means that soils with greater amounts of organic matter tend to form stronger aggregates, which can enhance soil structure and resilience (COTRUFO; LAVALLEE, 2022). Medeiros et al. (2023) found that in Arenosols, native vegetation promotes aggregate stability, compared to other land uses, with an aggregate stability index (ASI) ranging from 82% to 86%, which consequently leads to enhanced SOC retention in semi-arid soils. Nonetheless, in Acrisols, grasslands showed greater ASI compared to native vegetation and conventional agriculture areas, with values ranging from 75 % to 79% up to 0-30 cm depth. They also observed that soils with mostly loamy sand texture resulted in SOC reductions between 2.1 and 9.6 Mg C ha^{-1} in agricultural systems, which led to a predominance of mesoaggregates (<2.00 and > 0.25 mm).

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CHAPTER I

SOIL CARBON AND ORGANIC MATTER FRACTIONS UNDER INTEGRATED SYSTEMS AND GRASSLANDS IN THE BRAZILIAN SEMI-ARID REGION

ABSTRACT

In Brazil, the semi-arid regions are predominantly situated in the northeastern part of the country. This area is characterized by a unique biome known as Caatinga, and has undergone significant degradation due to deforestation for agriculture, livestock, and the use of firewood. In this context, nature-based solutions (NbS) that prioritize environmental sustainability in semi-arid regions are crucial. Thus, this study aimed to evaluate the impact of the conversion from native vegetation (dense Caatinga) to two grasslands and two integrated livestock-forestry systems; to test the hypothesis that NbS increase soil organic carbon (SOC) stocks and soil organic matter (SOM) pools, establishing a pathway for sustainable land management in semi-arid regions. Soil samples were collected in 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers in 5 different land uses: native vegetation (NV), integrated livestock-forestry system with gliricidia (*Gliricidia sepium*) + *Urochloa* (*Urochloa decumbens*) (ILFug), an integrated livestock-forestry system with gliricidia + forage cactus (*Opuntia cochenillifera*) (ILFcg), improved pasture (ImpP), and degraded pasture (DegP). SOC stocks, SOM pools and soil carbon indices were analyzed. The ILFug system showed the highest stocks of mineral-associated organic matter, at all soil depths, and that led to increases in the SOC stocks, thus placing this system with the greatest SOC stocks. The NV-DegP conversion represented a decline in soil quality, showing the most significant reductions in the particulate organic matter (POM) fraction of SOM. None of the land uses presented carbon management index values higher than the NV. This effect is related to the higher POM values in the NV. The ILFug system showed the best soil stability index indicating the potential that NbS has to enhance soil quality and minimize the vulnerability to structural degradation. The importance of NbS extends beyond agricultural productivity. By promoting practices that enhance carbon sequestration, reduce greenhouse gas emissions, and improve ecosystem resilience, NbS provides a sustainable approach to mitigating the impacts of climate change, while supporting local communities in the semi-arid.

Keywords: soil organic carbon; Caatinga; nature-based solutions; soil quality; climate change.

RESUMO

No Brasil, as regiões semiáridas estão predominantemente localizadas na região nordeste do país. Essa área é caracterizada por um bioma único, conhecido como Caatinga, que vem sofrendo com degradação significativa devido ao desmatamento para agricultura, pecuária e uso de lenha. Nesse contexto, as soluções baseadas na natureza (SBN) que priorizam a sustentabilidade ambiental em regiões semiáridas são cruciais. Assim, este estudo teve como objetivo avaliar o impacto da conversão de vegetação nativa (Caatinga densa) para dois tipos de pastagens e dois sistemas integrados de pecuária-floresta, a fim de testar a hipótese de que SBN aumentam os estoques de carbono orgânico do solo (COS) e as frações da matéria orgânica do solo (MOS), estabelecendo um caminho para o manejo sustentável em regiões semiáridas. Amostras de solo foram coletadas nas camadas de 0-10, 10-20, 20-30, 30-50, 50-70 e 70-100 cm em cinco diferentes usos do solo: vegetação nativa (NV), sistema integrado de pecuária-floresta com gliricídia (*Gliricidia sepium*) + *Urochloa* (*Urochloa decumbens*) (ILFug), sistema integrado de pecuária-floresta com gliricídia + palma forrageira (*Opuntia cochenillifera*) (ILFcg), pastagem melhorada (ImpP) e pastagem degradada (DegP). Foram analisados os estoques de COS, as frações da MOSe índices de carbono do solo. O sistema ILFug apresentou os maiores estoques de matéria orgânica associada a minerais (MOAM) em todas as profundidades do solo, o que levou a aumentos nos estoques de COS, posicionando este sistema commaior estoque de COS. A conversão de NV para DegP representou um declínio na qualidade do solo, com as reduções mais significativas na fração de matéria orgânica particulada (MOP) da MOS. Nenhum dos usos do solo apresentou valores de índice de manejo de carbono (IMC) superiores aos da VN, efeito relacionado aos maiores valores de MOP na VN. O sistema ILFug apresentou o melhor índice de estabilidade do solo, indicando o potencial das SBN para melhorar a qualidade do solo e minimizar a vulnerabilidade à degradação estrutural. A importância das SBN vai além da produtividade agrícola. Ao promover práticas que aumentam o sequestro de carbono, reduzem as emissões de gases de efeito estufa e melhoram a resiliência dos ecossistemas, as SBN fornecem uma abordagem sustentável para mitigar os impactos das mudanças climáticas, ao mesmo tempo em que apoia as comunidades locais no semiárido.

Palavras-chave: carbono orgânico do solo; Caatinga; soluções baseadas na natureza; qualidade do solo; mudanças climáticas.

1 INTRODUCTION

In Brazil, the semi-arid regions are predominantly situated in the northeastern part of the country. This area is characterized by a unique biome known as Caatinga, which consists of thorny shrubs, cacti drought-resistant trees, dry seasons, and limited rainfall (ARAÚJO; TABARELLI, 2002; MAIA et al., 2007). The Caatinga covers approximately 800,000 km², representing around 11% of the national territory (SANTOS et al., 2011b), and its biodiversity is vital for ecosystem functioning, particularly regarding carbon (C) cycling and soil health. Studies show that intact Caatinga vegetation maintains soil organic matter (SOM) levels and promotes C sequestration, resulting in greater soil organic carbon (SOC) stocks (GIONGO et al., 2011; MENEZES et al., 2021).

However, this region has undergone significant degradation due to deforestation for agriculture, livestock, and the use of firewood. Nobre (2005) and Sousa et al. (2012) and Tomasella et al. (2018) highlight an increasing trend of desertification in the Brazilian semi-arid region, which presents significant challenges for biodiversity, as the Caatinga biome demonstrates limited capacity to adapt to climatic changes over time. Nevertheless, the degradation process can be restrained by exploring agricultural methods and practices that prioritize environmental sustainability in semi-arid regions.

In this context, nature-based solutions (NbS) have shown potential to combat desertification and improve SOC, including actions such as ecosystem restoration, sustainable land management, and conservation practices that aim to provide ecological benefits while enhancing resilience against climate-related stressors (GIRARDIN et al., 2021; SOTERRONI et al., 2023). Integrated systems illustrate NbS that leverage the synergistic interactions among different plant species to improve soil health and SOM.

Lal (2004) says that many farmers in semi-arid regions of developing countries are small landholders with limited resources who practice subsistence agriculture, which usually includes NbS. In this situation, it is crucial to handle SOM correctly in order to keep the environmental and economic aspects of food production (MAIA et al., 2007). Moreover, the correlation between elevated greenhouse gas (GHG) emissions and climate change has established C storage in SOM as a feasible approach for sequestering atmospheric CO_2 (COTRUFO et al., 2019).

Consequently, understanding the composition and stability of SOM is essential for assessing its role in C dynamics, particularly in semi-arid regions where organic matter inputs are often limited (MEDEIROS; SOARES; MAIA, 2022). The physical fractionation of SOM is a common method for studying the various pools of organic matter and their respective contributions to soil health (CAMBARDELLA; ELLIOTT, 1992). The two main fractions of SOM are particulate organic matter (POM) and mineral-associated organic matter (MAOM) (KUNDE et al., 2018; LAVALLEE; SOONG; COTRUFO, 2020). The POM consists of relatively undecomposed organic material, such as plant residues, and is more readily available for microbial decomposition (LAVALLEE; SOONG; COTRUFO, 2020; SIX et al., 2002), and the MAOM, on the other hand, is composed of smaller organic molecules that are stabilized through interactions with soil minerals, making it more resistant to decomposition (COTRUFO; LAVALLEE, 2022; SIX et al., 2002). The balance between these fractions is critical for long-term C sequestration, as POM provides a short-term source of nutrients, while MAOM contributes to the stable storage of C over longer periods (MAIA et al., 2007). Sousa et al. (2012) found that in the Brazilian semi-arid region, frequent droughts lead to a longer residence time of the POM fraction, which accounted for approximately 45% of SOC.

NbS can enhance the formation of MAOM in semi-arid soils, by promoting the accumulation of organic matter in stable aggregates, helping to increase SOC levels, and improve soil resilience to environmental stressors (MEDEIROS; SOARES; MAIA, 2022). Research by Neto et al. (2021) has shown that these land-use practices that increase organic inputs into the soil, can enhance both POM and MAOM fractions. Considering these aspects, this study was conducted to determine whether NbS increase SOC stocks and SOM pools, establishing a pathway for sustainable land management in the Brazilian semi-arid region. Thus, this study aimed to evaluate the impact of the conversion from native vegetation to two grasslands and two integrated livestock-forestry systems on the SOC stocks and SOM pools.

2 MATERIAL AND METHODS

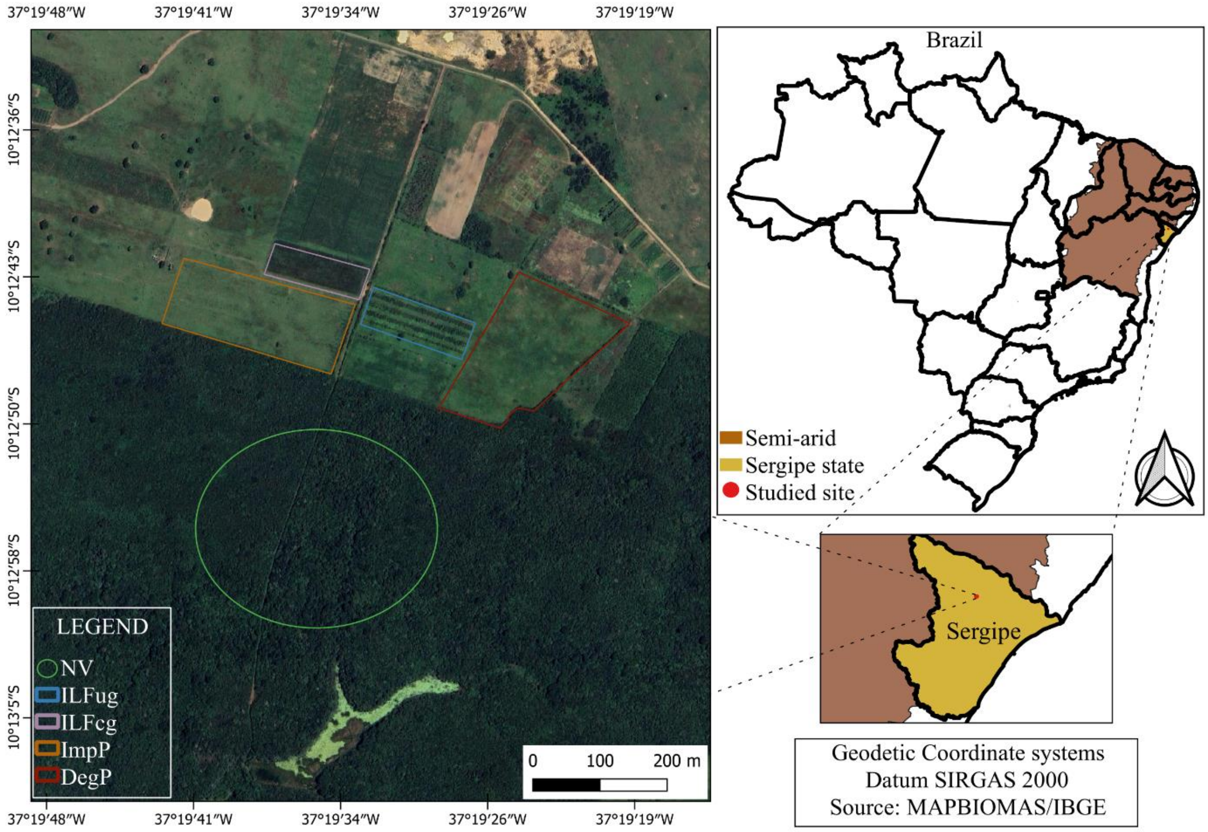
2.1 Site description

The study was carried out at the Semi-Arid Experimental Station of the Brazilian Agricultural Research Corporation (EMBRAPA, 2024), in the municipality of Nossa Senhora da Glória, Sergipe, Brazil (10° 13’S, 37° 25’W). The climate of the region is classified as semi-arid BSh according to Köppen’s classification, characterized by annual precipitation of 710 millimeters with great irregularity in its distribution, and average maximum and minimum temperatures of 32 °C and 20 °C, respectively (FRANCISCO et al., 2015). The soil is a Eutrophic Red-yellow Podzol.

2.2 Soil sampling and analysis

Disturbed soil samples were collected in 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers in five different land uses (Fig. 1): native vegetation (NV), integrated livestock-forestry system with gliricidia (*Gliricidia sepium*) + *Urochloa* (*Urochloa decumbens*) (ILFug), an integrated livestock-forestry system with gliricidia + forage cactus (*Opuntia cochenillifera*) (ILFcg), improved pasture (ImpP), and degraded pasture (DegP). In addition, undisturbed soil samples were collected using Kopeck rings for the assessment of soil bulk density (BD).

Figure 1 - Map of the semi-arid region of Brazil with the delineation of Sergipe state, and the areas of native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the municipality of Nossa Senhora da Glória.



Source: Author (2025)

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

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

Table 1 - Physical and chemical characterization of studied soils at 0-100 cm layer.

Attributes	Land uses				
	NV	ImpP	DegP	ILFug	ILFcg
Clay (g kg^{-1})	243.77	318.58	317.86	296.69	347.41
Silt (g kg^{-1})	305.93	242.52	260.04	254.22	222.47
Sand (g kg^{-1})	449.24	458.21	451.46	449.08	439.19
pH in H_2O	5.32	5.83	5.38	5.21	5.16
CEC ($Cmol_c$ dm^{-3})	14.34	11.96	11.25	10.48	10.77
Na (mg dm^{-3})	70.06	239.11	128.17	57.56	74.33
P (mg dm^{-3})	2.03	2.17	1.67	13.78	1.61
K (mg dm^{-3})	238.89	102.67	118.56	91.28	56.39
Ca^{2+} ($Cmol_c$ dm^{-3})	2.02	2.22	1.46	2.71	1.69
Mg^{2+} ($Cmol_c$ dm^{-3})	7.44	5.47	5.22	2.82	3.65
Al^{3+} ($Cmol_c$ dm^{-3})	0.30	0.09	0.17	0.12	0.33
H^+ + Al^{3+} ($Cmol_c$ dm^{-3})	3.96	2.96	3.71	4.47	4.96
V (%)	68.44	72.00	61.50	56.28	51.94
m (%)	4.00	1.33	3.22	2.17	7.06

Source: Author (2025)

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

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

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

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

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

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

$$CMI=CPIxLIx100 \quad (2)$$

Where CPI is the C pool index and LI is the C lability index.

The CPI and LI were calculated as follows (Equation 3 and, respectively):

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

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

Where C-POM and C-MAOM are the labile and non-labile C fractions for each land use.

The structural stability index (SSI) was calculated (Equation 5) to evaluate the risk of soil structural degradation, according to Pieri (1992) and Reynolds et al. (2009). This methodology is proposed as a measure of the susceptibility of the soil to structural decline.

$$SSI\ (\%) = \frac{SOC\ (g\ kg^{-1})\ x\ 1{,}724}{Silt\ (g\ kg^{-1}) + Clay\ (g\ kg^{-1})}\ x\ 100 \quad (5)$$

Where SOC is the organic carbon content (g kg^{-1}); 1.724 is the factor to convert SOC to SOM; silt and clay are particle size fractions (g kg^{-1}). SSI < 5% indicates great susceptibility to loss of structure and erosion; 5% < SSI < 7% indicates instability and risk of loss of structure; 7% < SSI < 9% indicates low risk of soil structural decline and SSI > 9% no immediate risk of loss of structure.

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

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

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

2.3 Statistical analysis

The data were subjected to normality and homogeneity analysis using the Shapiro-Wilk test ($p>0.05$). When the ANOVA assumptions were not met, the data was transformed using the Box-Cox transformation. ANOVA was used to test the significance between the treatments in the study, at each soil depth (0-10, 10-20, 20-30, 30-50, 50-70 and 70-100), and in the accumulated layers (0-30, 0-50 and 0-100 cm). When significant, Tukey test ($p<0.05$) was used to compare the means of the treatments. All statistical analyses were performed using Minitab Program and OriginPro software (MINITAB, 2023; ORIGINLAB CORPORATION, 2024).

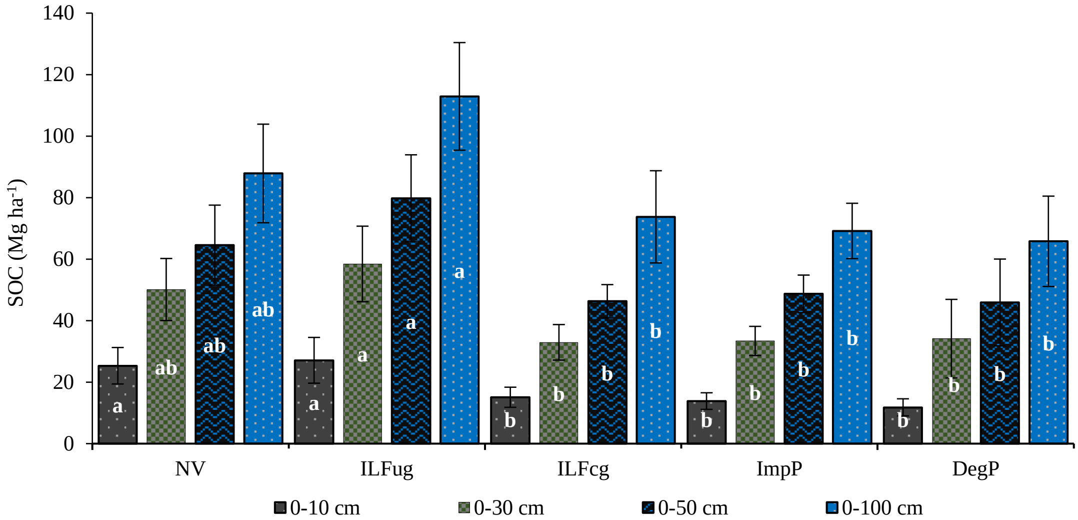
3 RESULTS

3.1 Soil carbon stocks

The SOC stock changes varied according to the land use, where representative reductions in the SOC stocks were observed in the ILFcg, ImpP, and DegP treatments when compared to NV in all layers (Fig. 2). The SOC losses were higher in the surface layer (0-10 cm), where the stocks were reduced by 40.5, 45.4 and 53.4 % in the ILFcg, ImpP and DegP, respectively ($p < 0.05$). The NV-DegP conversion generally resulted in greater losses, reducing the SOC by 13.5, 16.0, 18.6, and 22.1 Mg ha^{-1} for the 0-10, 0-30, 0-50, and 0-100 cm layers, being significant in the 0-10 cm layer ($p < 0.05$).

Otherwise, no reductions were observed in SOC stocks after NV-ILFug conversion for the 0-10, 0-30, 0-50, and 0-100 layers. Although these changes were not statistically significant ($p > 0.05$), the NV-ILFug conversion increased SOC stocks in the 0-10, 0-30, 0-50, and 0-100 layers by 6.5, 13.3, 18.4 and 21.8 % (i.e. 1.8, 8.3, 15.2 and 25.1 Mg C ha^{-1}), respectively (Fig. 2).

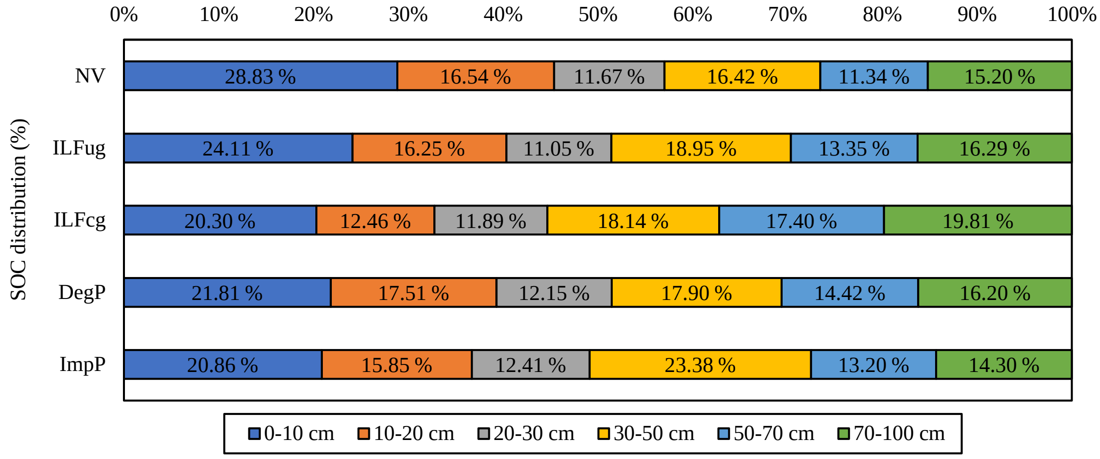
Figure 2 - Soil organic carbon (SOC) stocks in 0-10, 0-30, 0-50 and 0-100 cm soil layers under native vegetation (NV), integrated ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP), in the Brazilian semi-arid region.



Error bars show the standard deviation (n = 5). Means followed by the same letter between the land uses for the same layer do not differ by Tukey's test ($p < 0.05$).
Source: Author (2025)

SOC distribution was similar across the soil profile for all land-use systems, with stocks being well distributed among the 0-10, 10-20, 20-30, 30-50 50-70, and 70-100 cm layers (Fig. 3). The superficial layer (0-10 cm) held the largest percentage of the total SOC for all land uses, accounting for 28.8, 24.1, 20.3, 21.8 and 20.8 % for the NV, ILFug, ILFcg, DegP, and ImpP respectively. The ILFcg and ImpP were the only ones to show less than 50 % of C allocation within the first 0-30 cm layers, with values of 44.6 and 49.12 % respectively. In contrast, the NV, ILFug, and DegP had higher values of 57.4, 51.4, and 51.47 %, respectively.

Figure 3 - Soil organic carbon (SOC) distribution (%) in 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm soil layers under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region.



Source: Author (2025)

Table 2 shows the rates of SOC change calculated using the classical method. The conversion from NV to ILFcg, ImpP, and DegP results in a decrease in SOC stocks across all layers. In contrast, converting NV to ILFug increases SOC stocks by 0.22, 1.04, 1.91, and 3.13 Mg ha^{-1} year^{-1} for the 0-10, 0-30, 0-50, and 0-100 cm layers, respectively. The NV-ILFcg showed the highest losses of SOC for the 0-10, 0-30, and 0-50 cm layers, with values of 1.03, 1.72, and 1.82 Mg C ha^{-1} year^{-1}. In the 0-100 cm layer, the NV-DegP conversion results in the greatest loss of SOC, at 1.47 Mg ha^{-1} year^{-1}.

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

Land-use change	Years of cultivation	Soil layer (cm)			
		0-10	0-30	0-50	0-100
		Rates of SOC change (Mg ha^{-1} year^{-1})			
NV/ILFug	8	0.22 ± 0.92	1.04 ± 1.88	1.91 ± 2.17	3.13 ± 2.89
NV/ILFcg	10	-1.03 ± 0.32	-1.72 ± 0.54	-1.82 ± 0.58	-1.41 ± 1.59
NV/ImpP	15	-0.77 ± 0.17	-1.11 ± 0.37	-1.06 ± 0.47	-1.25 ± 0.79
NV/DegP	15	-0.90 ± 0.18	-1.06 ± 0.31	-1.24 ± 0.87	-1.47 ± 0.85

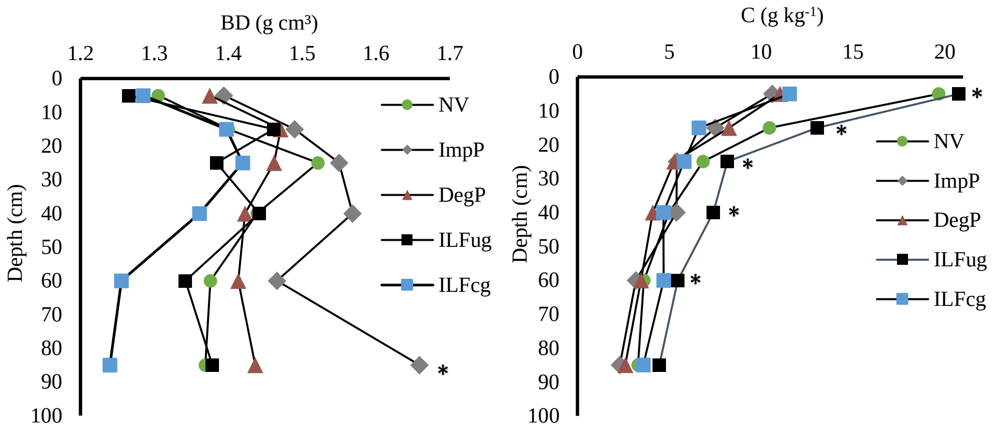
Source: Author (2025)

3.2 Soil carbon content and bulk density

The highest C content was observed in the upper soil layers (0-10 cm) and significantly decreased ($p < 0.05$) with depth across all land uses. In the 70-100 cm layer, however, there was no statistically significant difference in soil C among the treatments ($p > 0.05$). The highest C content was found in the ILFug system, with values of 20.7, 13.0, 8.1, 7.40, 5.4 and 4.4 g kg^{-1} for the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers, respectively. The conversion of NV to ILFcg, ImpP, and DegP resulted in the largest losses at the 0-10 cm layer, reducing the C content by 8.1, 9.1, and 8.6 g kg^{-1}, which corresponds to losses of 41.3%, 46.1%, and 44.0%, respectively (Fig. 4).

Regarding soil bulk density, results showed low variation across different land uses (Fig. 4). Significant differences were found only at the 70-100 soil layer ($P < 0.05$). In this layer, the highest BD of 1.65 g cm^3 was found in the ImpP while the lowest BD of 1.23 g cm^3 was observed in the ILFcg system ($p < 0.05$). Across the soil profile, the BD values varied as follows: for NV, values ranged from 1.31 to 1.52 g cm^3; for ILFug, from 1.27 to 1.46 g cm^3; for ILFcg, from 1.24 to 1.42 g cm^3; for ImpP, from 1.37 to 1.66 g cm^3; and for DegP, from 1.38 to 1.47 g cm^3. The ImpP consistently showed the highest BD values across most soil layers, with values of 1.39, 1.49, 1.55, 1.57, 1.47, and 1.66 g cm^3 for the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers (Fig. 4).

Figure 4 - Soil carbon (C) content and bulk density (BD) in 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm soil layers under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region.

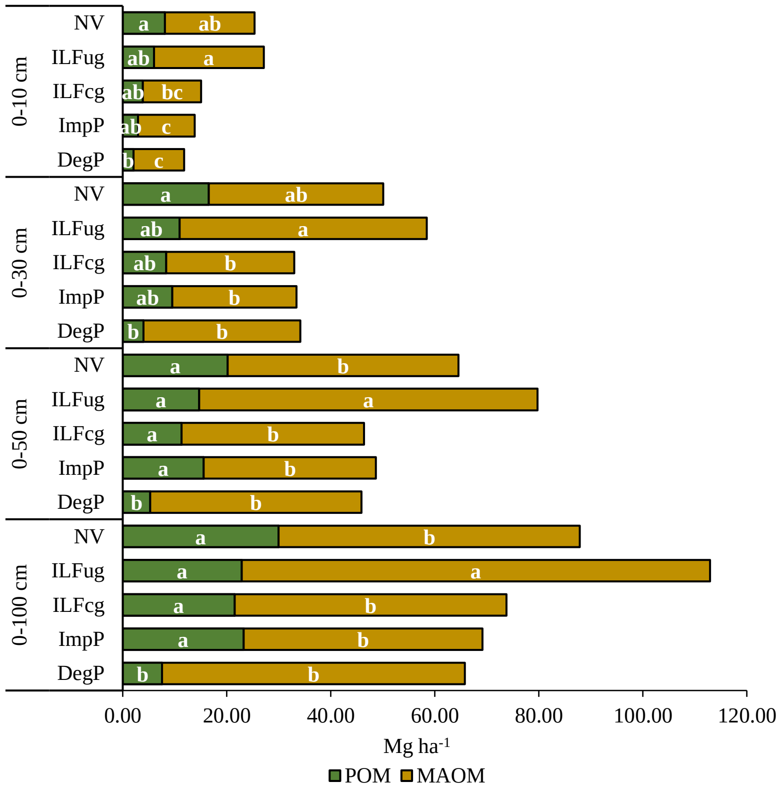


* Indicates significant difference by Tukey's test ($p < 0.05$) for C and BD in the same soil layer.
Source: Author (2025)

3.3 Carbon stock of particulate and mineral-associated organic matter fractions

Across the soil profile, the NV exhibited the highest POM stocks compared to other land-use systems, though significant difference was observed only in the NV-DegP conversion ($p < 0.05$). The most substantial loss of POM occurred during this conversion, reducing POM by 74.5%, 75.8%, 73.8% and 74.7% in the 0-10, 0-30, 0-50, and 0-100 cm layers, respectively (Fig. 5). When comparing only the integrated systems and pastures, the ILFug system showed higher POM values in the 0-10 and 0-30 cm layers (6.0 and 10.9 Mg ha^{-1}, respectively), while the ImpP showed higher values in the 0-50 and 0-100 cm layers, with 15.6 and 23.2 Mg ha^{-1}, respectively (Fig. 5). In the DegP area, the lowest POM values were observed across all layers, with values of 2.0, 4.0, 5.2 and 7.57 Mg ha^{-1}, for the 0-10, 0-30, 0-50 and 0-100 cm layers, respectively.

Figure 5 - Particulate organic matter (POM) and mineral associated organic matter (MAOM) stocks in 0-10, 0-30, 0-50 and 0-100 cm soil layers under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region.

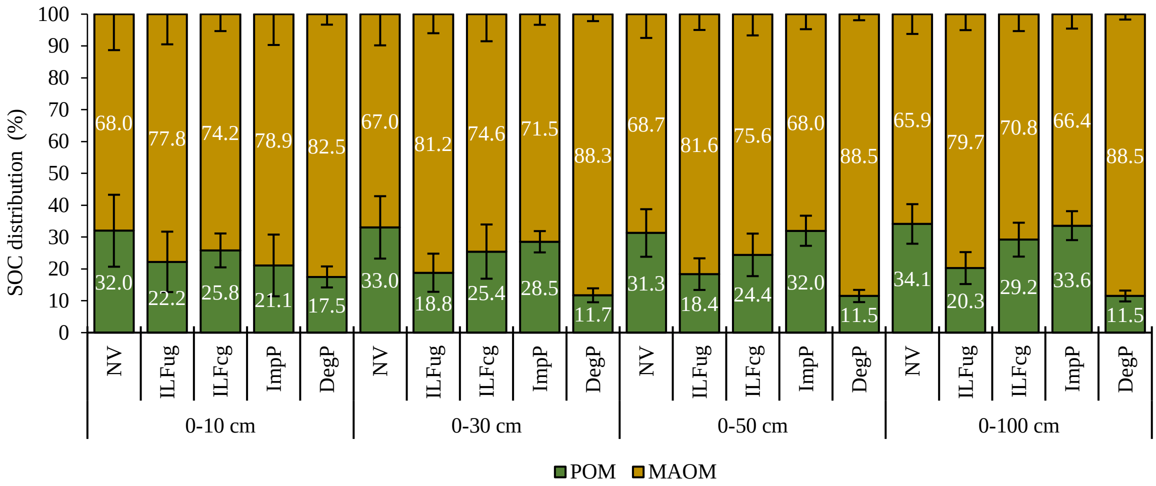


Means followed by the same letter between the land uses for the same layer do not differ by Tukey's test ($P < 0.05$).
Source: Author (2025)

Regarding MAOM, the ILFug system had the highest stocks with significant differences across the soil profile ($p < 0.05$), showing values of 21.0, 47.4, 65.1, and 90.0 Mg ha^{-1}, for the 0-10, 0-30, 0-50 and 0-100 cm layers, respectively. This represents increases of 18.2, 29.3, 31.8 and 35.7 % when compared to NV (Fig. 5). Among the other systems, significant differences in MAOM were only noted in the 0-10 cm layer, where NV, ILFcg, ImpP, and DegP showed values of 17.2, 11.2, 10.9 and 9.7 Mg ha^{-1}, respectively (Fig. 5). The ImpP showed the lowest MAOM values in the 0-30 cm (23.9 Mg ha^{-1}), 0-50 cm (33.1 Mg ha^{-1}), and 0-100 cm (Mg ha^{-1}) layers. Notably, in the 0-10 cm layer, DegP had the lowest value with 9.7 Mg ha^{-1}, followed by ImpP with 10.9 Mg ha^{-1}.

A quantitative evaluation of SOM fractions revealed that the MAOM compartment accounted for the largest portion of SOC across all land-use systems, with an average contribution ranging from 65.9 to 88.5 % (Fig. 6). The NV had the highest contribution of POM to SOC in all soil layers, with values ranging from 31.3 (0-50 cm layer) to 33.6 % (0-100 cm layer). In contrast, in the DegP was observed the lowest contributions of POM to SOC, with values of 17.5, 11.7, 11.5 and 11.5 % for the 0-10, 0-30, 0-50, and 0-100 cm layers, respectively.

Figure 6 - Particulate organic matter (POM) and mineral-associated organic matter (MAOM) distribution (%) in 0-10, 0-30, 0-50 and 0-100 cm soil layers under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region.



Error bars show the standard deviation (n = 5).
Source: Author (2025)

3.4 Carbon management index

CPI values increased with soil depth in the land-use systems (Table. 3). Significant differences in CPI were observed among the land uses for all soil layers ($p < 0.05$). The ILFug system showed the highest CPI values ($p < 0.05$) across the soil profile, with values of 1.07, 1.17, 1.24, and 1,29 for the 0-10, 0-30, 0-50, and 0-100 cm layers, respectively. This represents increases of 46.7, 41.8, 42.7 and 41.8 % compared to the CPI of DegP. No significant differences in CPI were found between ILFcg, ImpP, and DegP throughout the soil profile ($p > 0.05$).

The L values were highest in the ILFcg system for the 0-10 cm and 0-30 cm layers, although no significant differences were detected between land uses ($p > 0.05$). The highest L values were observed in NV for the 0-50 and 0-100 cm layers. DegP showed the lowest L values across the soil profile (Table 3), and the NV-DegP conversion resulted in decreases of 74.6, 84.4, 77.5 and 79.6 % for the 0-10, 0-30, 0-50, and 0-100 cm layers, respectively ($p < 0.05$).

The LI showed significant differences between land uses in the 0-30 cm, 0-50 cm, and 0-100 cm soil layers ($p < 0.05$), with the ImpP system having the highest LI values of 0.45, 0.83, and 0.81 for these layers, respectively. In the superficial layer (0-10 cm), no significant differences were observed between treatments ($p > 0.05$), although the ILFcg system (highest LI) showed an increase of 45.8 % when compared to DegP, which had the lowest LI values across the soil profile ($p < 0.05$).

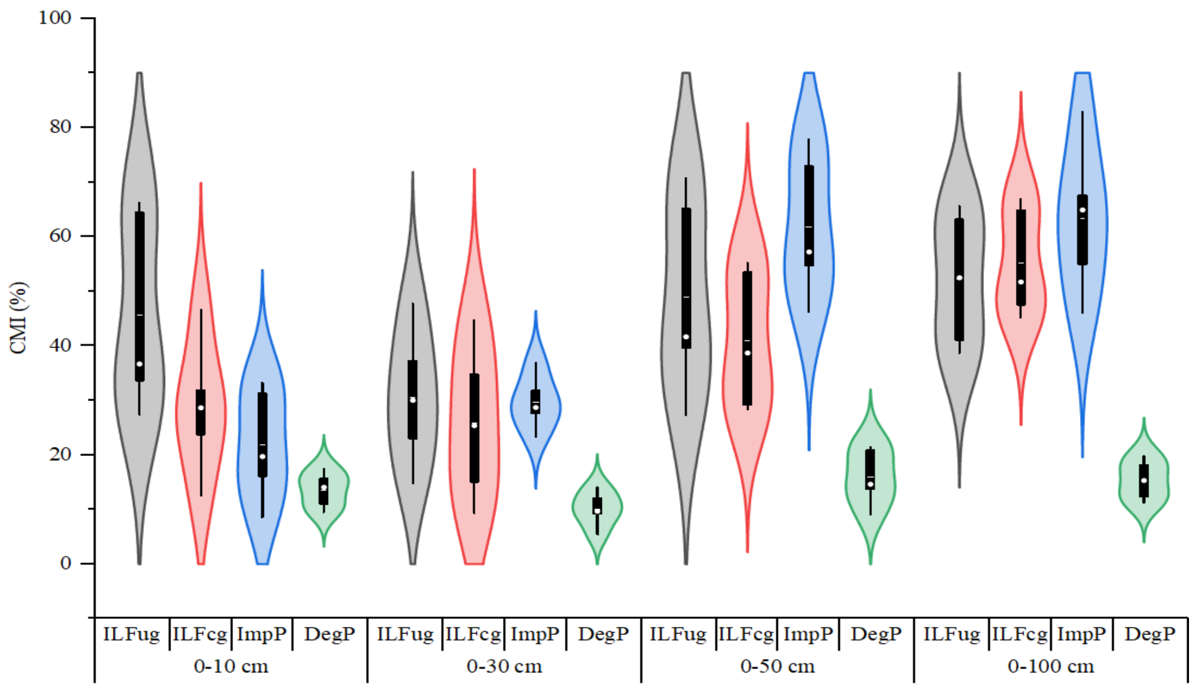
Table 3 - Carbon pool index (CPI), lability (L) and lability index (LI) in 0-10, 0–30, 0–50 and 0–100 cm soil layers under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region.

Soil layer (cm)	Land-use	CPI	L	LI
0-10	NV	-	0.71a	-
	ILFug	1.07a	0.33a	0.46a
	ILFcg	0.60ab	0.98a	0.48a
	ImpP	0.55b	0.30a	0.42a
	DegP	0.57b	0.18a	0.26a
0-30	NV	-	0.90a	-
	ILFug	1.17a	0.24a	0.26ab
	ILFcg	0.66b	0.34a	0.38a
	ImpP	0.67b	0.41a	0.45a
	DegP	0.68b	0.14a	0.15b
0-50	NV	-	0.58a	-
	ILFug	1.24a	0.23ab	0.40bc
	ILFcg	0.72b	0.34a	0.58ab
	ImpP	0.75b	0.48a	0.83a
	DegP	0.71b	0.13b	0.22c
0-100	NV	-	0.64a	-
	ILFug	1.29a	0.27ab	0.42b
	ILFcg	0.84b	0.43ab	0.68a
	ImpP	0.79b	0.52ab	0.81a
	DegP	0.75b	0.13b	0.21b

Mean values followed by the same letter within the same soil layer do not differ by Tukey's test ($p < 0.05$).
Source: Author (2025).

In all soil layers, there was a decrease in the CMI values for the integrated systems and pastures compared to NV (Fig. 7). However, evaluating only the managed systems, the highest CMI values for the 0-10 and 0-30 cm layers were observed in the in ILFug, with percentages of 45.6 % and 30.5 %, respectively. For the 0-50 and 0-100 cm layers, the ImpP showed the highest values, measuring 61.7 and 63.2 %, respectively. Conversely, the DegP had the lowest CMI values across all layers ($p < 0.05$), with values of 13.5, 10.0, 15.9 and 15.3 % for the 0-10, 0-30, 0-50 and 0-100 cm layers, respectively. This indicates decreases of 37.8, 66.0, 74.1 and 75.7 % when compared to ImpP for the same layers.

Figure 7 - Carbon management index (CMI) in 0-10, 0-30, 0-50 and 0-100 cm soil layers under ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region.

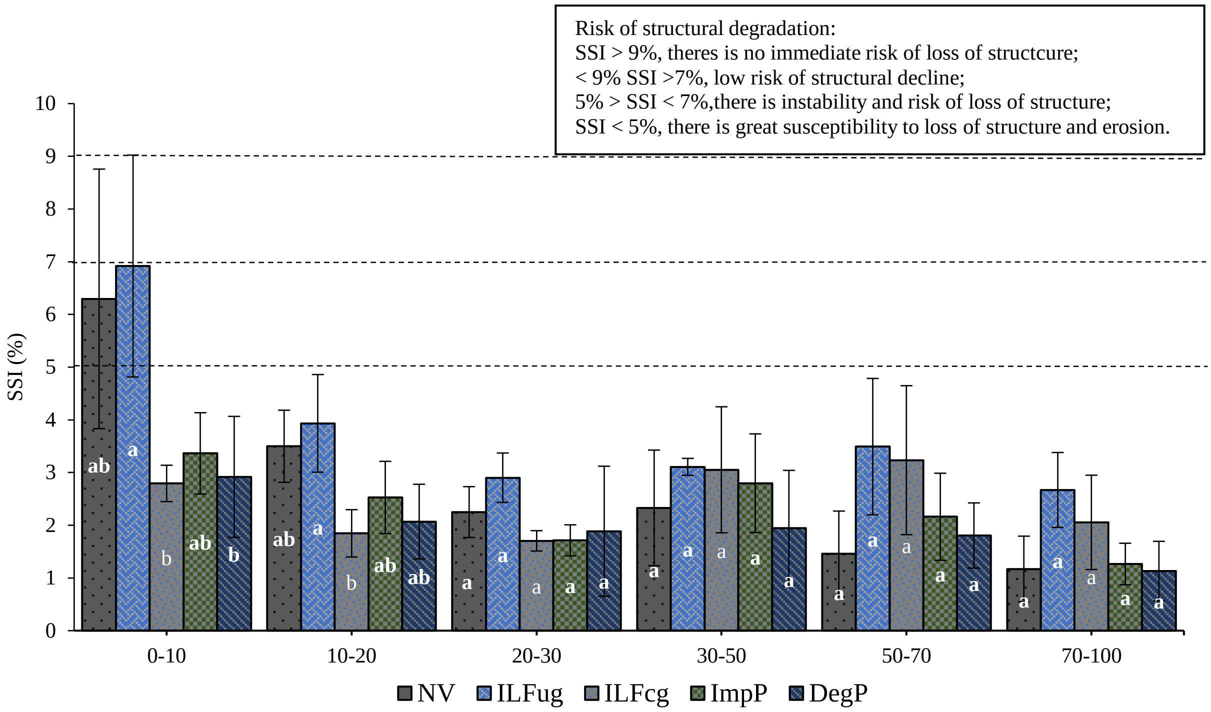


In the boxplot, the line inside the box indicates the mean, the circle indicates the median. The violin plot represents a Kernel's distribution of the data.
Source: Author (2025)

3.5 Soil structural stability index

The ILFug had higher SSI values throughout the soil profile ($p < 0.05$). A decreasing trend in SSI values in depth was observed (Fig. 8). Conversion from NV to ILFcg, ImpP, and DegP consistently resulted in reductions of SSI in the 0-10, 10-20, and 20-30 cm layers. The NV had the lowest SSI in the 50-70 cm layer, with a value of 1.45. However, there was no significant difference ($p > 0.05$) when compared to the other land uses.

Figure 8 – Soil structural stability index (SSI) in 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm soil layers under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region.



Error bars show the standard deviation (n = 5). Means followed by the same letter between the land uses for the same layer do not differ by Tukey's test (P < 0.05).
Source: Autor (2025)

4 DISCUSSION

4.1 Soil carbon stocks

The 87.8 Mg ha^{-1} stock of SOC found in this study for the NV was similar to the average 89.8 Mg ha^{-1} SOC stocks at 1 m depth under dense Caatinga in the main soil classes of this biome observed by Menezes et al. (2021). Nonetheless, the ILFug system showed the highest SOC stocks. This highlights the significance of conservation management, and the potential of integrated systems to stock C in the soil, which can help mitigate climate change. This potential will clearly depend on aspects such as the species involved, the design of the integrated system, and the type of soil management. In the Brazilian semi-arid, the *Urochloa* forage has been used in integrated systems due to its efficiency in accumulating C in the soil, mostly due to its production of biomass and roots (CAVALCANTE et al., 2019; NETO et al., 2021). The *Urochloa* not only produces a large amount of biomass, but also contains higher levels of recalcitrant compounds that decompose more slowly, ensuring longer-lasting soil coverage, reducing exposure to temperature, and enhancing C inputs to the soil. Neto et al. (2021) also found greater SOC stocks under systems intercropped with forage. They noted that integrated/silvopastoral systems help moderate the amplitude of temperature at the soil surface, favoring the microbial activity of the soil (ARAÚJO; TABARELLI, 2002; GIULIETTI et al., 2004; NETO et al., 2011; SILVA et al., 2011).

Additionally, the gliricidia which is a leguminous plant, provides a litter that is well-distributed throughout the soil in integrated systems and decomposes quickly due to its C/N ratio (APOLINÁRIO et al., 2015). This rapid decomposition can lead to higher levels of fulvic acid in the SOM, which is more mobile than other fractions of SOM and contributes more significantly to SOC over shorter periods (ASSUNÇÃO et al., 2019; JUNIOR et al., 2020). These findings support our hypothesis that greater C inputs from crop residue combined with no-till management in integrated systems positively affect SOC stocks. This highlights the critical role of land management practices like NbS in maintaining and improving SOC stocks, particularly in the semi-arid regions of Brazil. Integrated systems, especially those involving *Urochloa* and gliricidia, demonstrated significant potential for increasing SOC and the MAOM, offering a feasible strategy for mitigating climate change impacts.

Adopting an integrated system does not guarantee the sustainability of the system (NETO et al., 2021). Conservation agriculture management includes practices such as no-tillage (as practiced in the ILFug system), crop rotation, and maintaining crop residues on the soil surface (DERPSCH et al., 2014). According to this, the NV-ILFcg conversion resulted in decreases on SOC stocks in all layers. What could explain these reductions is that in this area, every 2 years, the soil is tilled. The reductions in the SOC stocks in the ILFcg system are associated with conventional soil tillage, which can lead to the fragmentation of soil aggregates, which disrupts soil structure and exposes SOM to increased levels of oxidation (MEDEIROS; SANTOS; MAIA, 2022).

The fact that cactus forage produces lower amounts of biomass both aboveground and belowground compared to species like *Urochloa*, which are used in the ILFug system, is another trait that could explain the SOC reductions in the ILFcg system. Moreover, the limited biomass production combined with the sparse soil coverage provided by cactus forage leave the soil more exposed to solar radiation, increasing soil surface temperatures and accelerating SOM decomposition (NETO et al., 2021; RIGON; CALONEGO, 2020). The edaphoclimatic conditions of the semi-arid region also favor this decomposition process (MEDEIROS; SANTOS; MAIA, 2022; SANTANA et al., 2019).

The conversion of NV to ImpP and DegP resulted in reductions of 21.2 % and 25.1 %, respectively in the 0-100 cm layer. Since this reduction also occurs in deeper layers, it is important to include sub-superficial soil layers in studies on the impacts of land-use change on SOC dynamics, as these changes are not restricted to surface layers (SANTOS et al., 2023; LOCATELLI et al., 2022). These results suggest that, although improved pastures are better managed, their ability to preserve SOC stocks is still limited, particularly in the Brazilian semi-arid region, as observed by (MEDEIROS et al., 2021). They reported SOC losses ranging from 12% to 16% in the same soil layer when native vegetation was converted to grasslands in the Brazilian semi-arid region. The similarity in SOC losses between ImpP and DegP highlights that improving pasture management alone, without more substantial changes, is insufficient to address the challenges imposed by the semi-arid environment. This contrasts with results observed in other regions, where well-managed pastures have demonstrated greater efficiency in SOC retention. Maia et al. (2009), for example, reported a 9% decrease in SOC resulting from the conversion of native vegetation to degraded grasslands, along with a 19 % increase to improved grasslands in the Cerrado (Brazilian savannah) biome. To mitigate these losses in the semi-arid region, it is essential to invest in more integrated and diversified practices, such as pasture rotation including leguminous plants and the adoption of integrated systems, especially under no-tillage conditions. These practices help maintain soil cover, reduce compaction, and enhance SOC stocks through increased biomass diversification.

The classical approach to measuring changes in SOC rates considers how time affects SOC dynamics (DENG et al., 2018; MAIA et al., 2013; MEDEIROS et al., 2020). The NV-ILFug conversion showed that a more conservation-oriented land use allows the maintenance of C over time, playing a crucial role in C sequestration, converting NV areas into systems that sequester SOC. It points out the encouragement of improved practices and conservationist soil management in the semi-arid region of Brazil. In addition to providing various environmental benefits, these improvements could also help the country in reducing GHG emissions. These approaches not only benefit the soil physical and chemical properties but also contribute to the socio-economic well-being of local communities by improving agricultural productivity and resilience to climatic variability.

4.2 Carbon stock of particulate and mineral-associated organic matter

In addition to the quantitative assessment of C stocks, evaluating the SOM compartments with different lability is also crucial in studies related to the effect of management practices on SOM dynamics. Despite having a smaller contribution to SOC than

MAOM (Fig. 5), POM is still important because it serves as a bond for the more stable fraction (FIGUEIREDO; RESCK; CARNEIRO, 2010; MEDEIROS; SOARES; MAIA, 2022), and is a highly sensitive indicator of how management affects SOC.

The NV showed the highest stocks of POM across the soil profile. Santos et al. (2019) also found that native vegetation had greater stocks of the labile fraction of SOM. They attributed the elevated levels of POM in native vegetation to the growth of dominant perennial species, which produce large quantities of residues continuously. Our findings confirm the hypothesis that the POM fraction is more sensitive to soil management (BLAIR; LEFROY; LISLE, 1995; MAIA et al., 2007). This study indicates that the conversion of NV-DegP represents a decline in soil quality, showing the most significant reductions in POM. The conversion from NV–ImpP resulted in a greater loss of POM compared to integrated systems (ILFug/ILFcg) in the 0–10 cm layer; however, in the 0 - 50 cm, and 0 - 100 cm layers, the ImpP showed the highest POM stocks of the managed systems. This could be due to the higher input of belowground biomass present in the deeper layers of well-managed pasture areas, which can contribute to mitigating the negative impact on POM stocks observed in the subsurface. Nevertheless, this increase in the POM did not increase SOC stocks.

The MAOM is the most recalcitrant and stable fraction of SOM, primarily composed of root exudates and products of microbial decomposition that form organo-mineral complexes, which hinder decomposition (SANTOS et al., 2011a). As a result, MAOM is less sensitive to different types of management practices (MEDEIROS; SOARES; MAIA, 2022). The ILFug showed the greatest stocks of MAOM at all soil depths, and that led to increases in the SOC stocks. The roots of gliricidia and *Urochloa* can contribute to an increase in organic matter in deeper soils, as these plants have a perennial growth pattern and continuously renew their root systems (JUNIOR et al., 2020; LUNA et al., 2019), which may result in the accumulation of MAOM in depth. According to Santos et al. (2019), POM can swiftly turn into more complex recalcitrant molecules (i.e. MAOM), from the stacking of organic compounds. This change in the lability of SOM can be affected by pH, nutrient availability, and interactions with low molecular weight organic compounds released by roots, all of which influence biogeochemical cycling and soil quality (MOSQUERA et al., 2012; SANTOS et al., 2019b). This result is highly positive for soil quality, as the more recalcitrant organic matter (which has greater resistance to decomposition) contributes to the improvement of soil physical properties, such as aggregate stability, and has a lower turnover rate, contributing to both climate change mitigation and the sustainability of agricultural systems in the semi-arid region. (MAIA et al., 2007; MEDEIROS; SOARES; MAIA, 2022; NETO et al., 2021).

The results obtained for the MAOM fraction corroborate with other studies, indicating that the MAOM has high stability and can be increased through C inputs from no-tillage practices and crop residues, particularly in integrated systems with forage grasses (NETO et al., 2021). The higher stocks of SOC and MAOM in the ILFug and NV can be explained by the constant input of organic residues to the soil, along with the lack of conventional soil management practices, which favor the maintenance of SOM (MEDEIROS; SOARES; MAIA, 2022; SANTOS et al., 2011a).

4.3 Bulk density

The pastures (DegP/ImpP) in the 0–10 cm layer had higher BD (Fig. 4). This can be attributed to the fact that pasture areas were the only locations where cattle could graze throughout the year. Continuous grazing can lead to cattle trampling, which may increase soil compaction (COSTA et al., 2009; DON; SCHUMACHER; FREIBAUER, 2011; VALBRUN et al., 2018). Similar findings were reported by Medeiros et al. (2023) and Santana et al. (2019), who observed higher BD in the superficial layer of pasture areas compared to other land uses in the Brazilian semi-arid region.

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. In contrast, the low BD observed in ILFcg is due to conventional soil management practices, such as plowing (BARROS et al., 2013; VALBRUN et al., 2018).

4.4 Carbon management index

The carbon management index (CMI) is an index that takes into account the total C stock and its lability, providing a sensitive measurement of the rate of change in soil C dynamics compared to a more stable reference soil (VN=100 %) (BLAIR; LEFROY; LISLE, 1995; SANTOS et al., 2023; MAIA et al., 2007). None of the treatments presented CMI values higher than 100 % across the soil profile. This effect is related to the higher POM values in the NV, which highlights the challenges in surpassing the reference soil conditions.

The DegP presented the lowest CMI values in all soil layers, which suggests that the soil environment in this area is showing signs of degradation and that there is no trend of recovery over time since this area has been in place for 15 years. According to Medeiros et al., (2021), who derived SOC stock change factors for grassland management in the Brazilian semi-arid, the conversion of native vegetation to native and planted grasslands starts to show recovery of SOC stocks (4%) after 30 years. Consistent with the POM stocks, the ImpP had also the greatest CMI values for the 0-50 and 0-100 cm layers when comparing only the managed systems. This fact can probably be explained by the higher input of grassroots biomass from the 3 different grasses, which plays an important role in the stabilization of SOM (CONCEIÇÃO et al., 2014; MEDEIROS; SOARES; MAIA, 2022). Additionally, through the actions of mycorrhiza and root hairs, especially in deeper soil layers and chemical interactions with metal ions (i.e. Ca^{2+}), the root system also contributes to the physicochemical preservation of SOM (MEDEIROS; SOARES; MAIA, 2022; RASSE; RUMPEL; DIGNAC, 2005). These findings reinforce the critical role of diverse and well-managed grass species in the restoration of degraded areas particularly in semi-arid regions where land degradation threatens agricultural productivity and ecosystem resilience.

4.5 Structural stability index

The structural stability index (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 vulnerability to structural degradation (PIERI, 1992). Therefore, it is intrinsically linked to MAOM, which is the fraction of SOM associated with silt and clay and, consequently, to the processes of C stabilization within the organo-mineral complex of the soil. The highest SSI values observed for ILFug indicate 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 uses was observed. While erosion is not probable in deeper soil layers, the decline in SOC stocks 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 (BLAIR, 2000; CHERUBIN et al., 2016; PIERI, 1992). Conversely, Wiesmeier et al. (2015) state that due to reduced C input in semi-arid climates, the aggregation and soil carbon storage capacity largely depend on clay mineralogy. Since the studied soil is a podzol with sufficient clay content to support soil structure, aggregation and C storage capacity can be associated with multiple different processes. These processes can include the activity of organic and inorganic agents, iron and aluminum oxides, and calcium (flocculants). As a result, we can say that in this case, the SSI partially indicates the capacity of the soil for SOC storage, taking into account the amount of clay and silt that is available for organomineral interactions.

5 CONCLUSION

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

The disparity in the carbon management index between the DegP and ImpP underscores the significance of adopting management strategies aimed at restoring soil quality. Improved pastures can act as a key tool for reversing degradation trends, by integrating conservation principles into pasture management. However, it is noteworthy that even after 15 years, SOC stocks in ImpP remain similar to those in DegP. This suggests that while improved pastures can act as a tool to reverse degradation trends, their effectiveness may be limited under semi-arid conditions if not complemented with additional strategies such as, pasture rotation with leguminous plants and the adoption of integrated systems, especially under no-tillage.

Among all land uses studied, the integrated livestock-forest system (ILFug) demonstrated the capacity as a nature-based solution (NbS) to sustain and increase organic carbon pools in the soil. This finding highlights the potential of NbS as a viable and sustainable soil management strategy for semi-arid regions. This positive outcome can be attributed to key features of the system, such as the inclusion of a leguminous species, the design of the system, and the adoption of no-tillage. However, successfully promoting the adoption of NbS requires the development of policies that ensure adequate financial incentives for local communities, particularly for smallholders with limited resources who depend on agricultural and livestock activities as their primary means of livelihood. The importance of NbS extends beyond agricultural productivity. By promoting practices that enhance carbon sequestration, reduce greenhouse gas emissions, and improve ecosystem resilience, the NbS provide a sustainable approach to mitigating the impacts of climate change while supporting local communities.

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CHAPTER II

SOIL ORGANIC CARBON AND AGGREGATE STABILITY IN AREAS CONVERTED FROM CAATINGA TO INTEGRATED SYSTEMS AND GRASSLANDS IN THE BRAZILIAN SEMI-ARID REGION

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 physical quality of the soil is crucial to the development of sustainable agriculture. In this biome, soil aggregation is critical due to the susceptibility of the semi-arid region to erosion and degradation. This study aimed to evaluate the impact of converting native vegetation (dense Caatinga) into two grasslands and two integrated livestock-forestry systems on soil organic carbon (SOC) content and soil physical quality through Water-stable Aggregate (WSA) classes and aggregation indices. The study was conducted at the Semi-arid Experimental Station of the Brazilian Agricultural Research Corporation (EMBRAPA), located in the municipality of Nossa Senhora da Glória, Sergipe, Brazil. Soil samples were collected at 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers. The land uses analyzed were: native vegetation (NV), an integrated livestock-forestry system with gliricidia (*Gliricidia sepium*) + *Urochloa* (*Urochloa decumbens*) (ILFug) under no-tillage, another integrated livestock-forestry system with gliricidia + forage cactus (*Opuntia cochenillifera*) (ILFcg), improved pasture (ImpP), and degraded pasture (DegP). Almost all parameters studied were significantly correlated with SOC content, demonstrating that soil organic matter is a primary agent in binding soil particles together, influencing the variation in WSA and aggregation indices. ImpP and DegP exhibited similar SOC content. However, the ImpP showed a higher aggregate stability index (ASI) and increased amount of macroaggregates (> 2.00 mm), highlighting the adverse impacts of degradation processes in soil structure. The highest SOC content was found in the ILFug system, with values of 20.7, 13.0, 8.1, 7.40, 5.4 and 4.4 g kg^{-1} for the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers, respectively. There is a predominance of macroaggregates in topsoil (0-10 cm layer) regardless of the 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 in 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 90.4%, respectively. This study demonstrates that implementing integrated systems under no-tillage as a nature-based solution can enhance SOC content, stability of soil aggregates and structural stability in semi-arid environments.

Keywords: integrated livestock-forestry; no-tillage; water-stable aggregates; nature-based solutions.

RESUMO

A agregação do solo é um processo fundamental que influencia várias propriedades do solo, incluindo estrutura, porosidade, infiltração de água e resistência à erosão. No bioma Caatinga, preservar a qualidade física do solo é crucial para o desenvolvimento de uma agricultura sustentável. Nesse bioma, a agregação do solo é essencial devido à suscetibilidade da região semiárida à erosão e degradação. Este estudo teve como objetivo avaliar o impacto da conversão de vegetação nativa (Caatinga densa) em duas pastagens e dois sistemas de integração pecuária-floresta nos teores de carbono orgânico do solo (COS) e na qualidade física do solo por meio de classes de agregados estáveis em água e índices de agregação. O estudo foi realizado na Estação Experimental do Semiárido da Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), localizada no município de Nossa Senhora da Glória, Sergipe, Brasil. Amostras de solo foram coletadas nas camadas de 0-10, 10-20, 20-30, 30-50, 50-70 e 70-100 cm. Os usos do solo analisados foram: vegetação nativa (VN), um sistema de integraão pecuária-floresta com gliricídia (*Gliricidia sepium*) + *Urochloa* (*Urochloa decumbens*) (ILFug) sob plantio direto, outro sistema de integração pecuária-floresta com gliricídia + palma forrageira (*Opuntia cochenillifera*) (ILFcg), pastagem melhorada (ImpP) e pastagem degradada (DegP). Quase todos os parâmetros estudados mostraram correlação significativa com o teor de COS, demonstrando que a matéria orgânica do solo é um agente primário na união das partículas do solo, influenciando a variação nas classes de agregados e dos índices de agregação. ImpP e DegP exibiram teores semelhantes de COS. No entanto, o ImpP apresentou maior índice de estabilidade de agregados (IEA) e maior quantidade de macroagregados (> 2,00 mm), destacando os impactos adversos dos processos de degradação na estrutura do solo. O maior teor de COS foi encontrado no sistema ILFug, com valores de 20,7, 13,0, 8,1, 7,40, 5,4 e 4,4 g kg^{-1} para as camadas de 0-10, 10-20, 20-30, 30-50, 50-70 e 70-100 cm, respectivamente. Houve uma predominância de macroagregados na camada superficial do solo (camada de 0-10 cm) independentemente do uso do solo, com a maior proporção encontrada na VN (78,7%), enquanto a menor foi observada no sistema ILFcg (59,0%). O sistema ILFug também apresentou o maior IEA na maioria das camadas do solo. A exceção foram as camadas de 0-10 e 50-70 cm, onde a VN apresentou os maiores valores de 89,1% e 90,4%, respectivamente. Este estudo demonstrou que a implementação de sistemas integrados sob plantio direto, como uma solução baseada na natureza, pode melhorar o teor de COS, a estabilidade dos agregados do solo e a estabilidade estrutural em ambientes semiáridos.

Palavras-chave: integração pecuária-floresta; plantio direto; agregados estáveis em água; soluções baseadas na natureza.

1 INTRODUCTION

Soil aggregation is a fundamental process that influences various soil properties, including structure, porosity, water infiltration, and resistance to erosion (BRONICK; 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; LAL, 2005; COTRUFO; LAVALLEE, 2022). The aggregates are frequently divided by size, such as, macroaggregates (> 2 mm) mesoaggregates (< 2 and > 0.25 mm) and microaggregates (< 0.25 or > 0.053 mm). The distribution and stability of soil aggregates are crucial indicators of soil structure and overall physical quality (CASTRO FILHO et al., 2002; MEDEIROS et al., 2023; PLAZA-BONILLA et al., 2013), providing valuable insights into the impact of land use practices and soil management strategies on soil health.

In the Caatinga biome, preserving the physical quality of the soil 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 region to erosion and degradation (MAIA et al., 2007; MEDEIROS et al., 2020, 2023). High temperatures and low moisture availability in semi-arid regions 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 regions 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, promoting the aggregation of soil particles into micro, meso, and macroaggregates, which results in a better soil structure, enhancing aeration and drainage, and improving the ability of the soil to retain water (FERREIRA et al., 2018; THAPA et al., 2018; TIVET et al., 2013). In turn, stable soil aggregates protect SOC from microbial decomposition by creating physical barriers that isolate SOM within aggregates (SIX et al., 2002; PLAZA-BONILLA et al., 2013). Furthermore, according to Okolo et al. (2020), soil aggregation is fundamental to carbon (C) sequestration mechanisms. The incorporation of C into soil aggregates helps transform them 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 C sequestration, effectively capturing atmospheric C and integrating it into the soil (FERREIRA et al., 2018; MEDEIROS et al., 2023).

Conversely, reductions of organic matter inputs in the soil are reported as a crucial factor responsible for decreasing soil aggregation and SOC(KABIRI; RAIESI; GHAZAVI, 2015).

Several studies have documented an increasing trend of degradation in semi-arid regions (BAI et al., 2020; BIRD et al., 2007; WIESMEIER et al., 2012). Medeiros et al., (2021) found that the conversion of native vegetation to grasslands in the Brazilian semi-arid region results in less organic matter inputs into the soil, consequently leading to losses of SOC, ranging from 12% to 16% at a depth of 0-100 cm.

Medeiros et al. (2023) emphasized that enhancing SOM inputs and maintaining stable soil aggregates are essential for protecting SOC from rapid decomposition. They found that nature-based solutions (NbS) such as cover cropping, and integrated systems under no-tillage can significantly enhance SOC retention in semi-arid soils. NbS contribute to the preservation or enhancement of soil structure by increasing the amount of organic matter inputs and minimizing soil disturbance (MEDEIROS et al., 2023; MAIA et al., 2007). 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 and enhancing microbial activity, improving soil structure and, facilitating the incorporation of organic C into more stable forms, thereby been an alternative of enhancing long-term C sequestration and avoiding losses to the atmosphere. This study was conducted to assess how various land uses in the Brazilian semi-arid region affect soil physical quality and structural degradation, particularly in relation to SOC and soil aggregation. This study aims to evaluate the impact of converting native vegetation (dense Caatinga), into two types of grasslands and two integrated livestock-forestry systems, one under no-tillage and one under conventional tillage, on SOC content and the physical quality of soil by analyzing water-stable aggregate (WSA) classes and aggregation indices.

2 MATERIAL AND METHODS

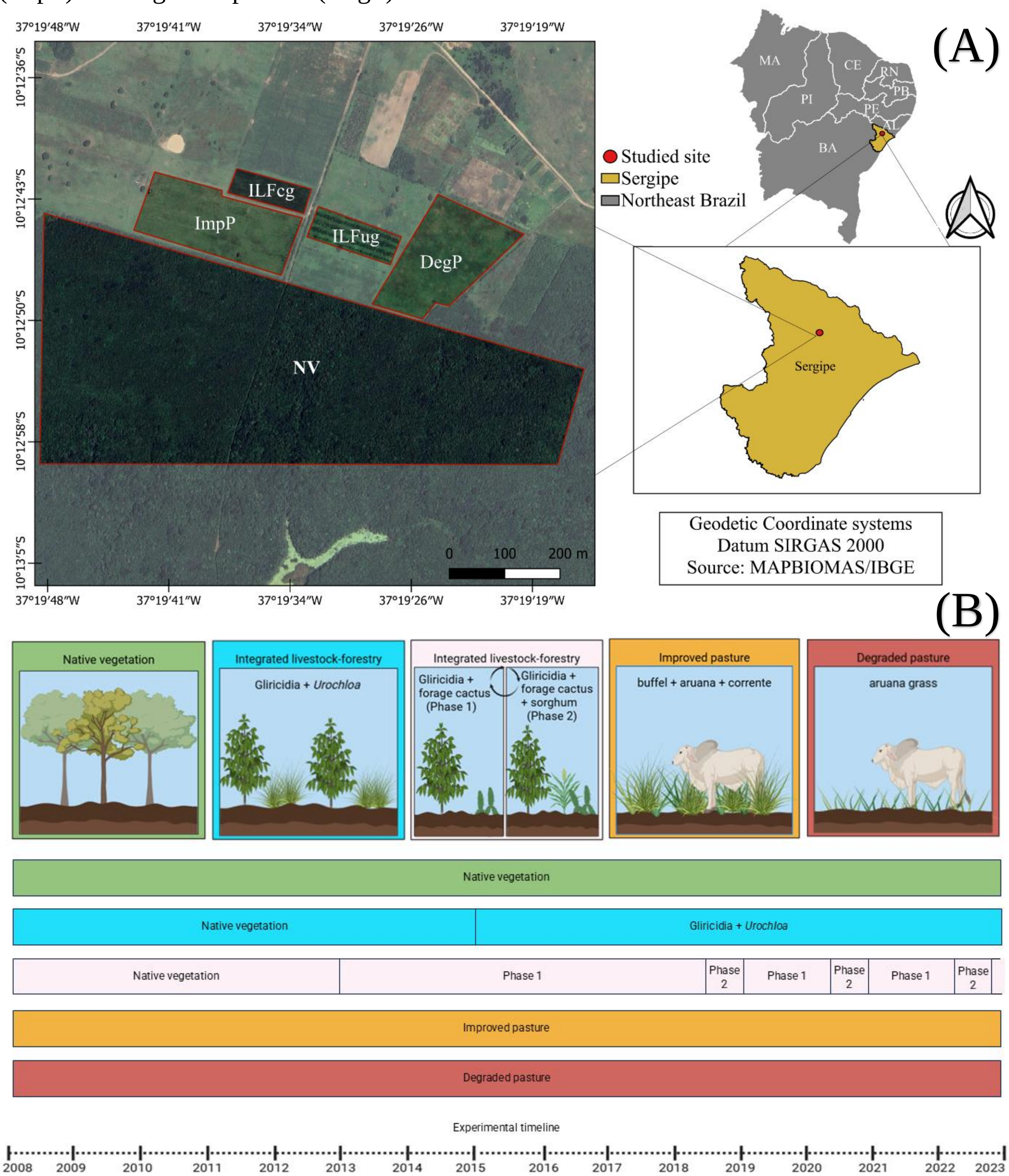
2.1 Site description

The study was conducted at the Semi-Arid Experimental Station of the Brazilian Agricultural Research Corporation (EMBRAPA), located in the municipality of Nossa Senhora da Glória, Sergipe, Brazil (10° 13’S, 37° 25’W). This region has a semi-arid climate, classified as BSh according to Köppen’s classification. It is characterized by an annual precipitation of 710 millimeters, which is distributed irregularly throughout the year. The average maximum and minimum temperatures are 32 °C and 20 °C, respectively (FRANCISCO et al., 2015) . The soil in this area is classified as Eutrophic Red-Yellow Podzol.

Integrated livestock-forestry systems and pasture areas close to the native vegetation were evaluated. The selection of these areas was based on the knowledge of land use and management strategies implemented since the conversion from native vegetation. In this study, five land use systems were evaluated. These land uses include: native vegetation (NV), an integrated livestock-forestry system with gliricidia (*Gliricidia sepium*) + *Urochloa* (*Urochloa decumbens*) (ILFug), another integrated livestock-forestry system with gliricidia + forage cactus (*Opuntia cochenillifera*) (ILFcg), improved pasture (ImpP), and degraded pasture (DegP).

The native vegetation (NV) served as the reference for assessing the effects of land-use change on the soil (Fig. 1). The ILFug sytem is managed under no-till, with gliricidia planted at a spacing of 1.5 meters, while *Urochloa* is cultivated in the interrows that are spaced 5 meters apart. This system has been in place for the past eight years and involves the routine pruning of gliricidia, with its biomass used as cover crop on the soil. In the the ILFcg system the gliricidia are spaced 1 meter apart, and forage cactus is cultivated in two lines between the 3 meters interrows. The forage cactus cutting is performed every 2 years. This system has been established for 10 years and is managed with conventional tillage practices. Every 2 years, the soil is tilled, followed by the cultivation of sorghum in May, in the interrow spaces between gliricidia and forage cactus. The cut of sorghum is done after approximately 110 days, and if there is sufficient rainfall, a second cut is made after regrowth. Both 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*), aruana grass (*Panicum maximum* cv.), and corrente grass (*Urochloa mosambicensis*). 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 years.

Figure 1 - Location of study area (A) and land use timeline (B) for native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP).



Source: Author (2025)

2.2 Soil sampling

Five replications of disturbed soil samples were collected up to 1 m in depth at 0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm layers from the five different land uses. Additionally, undisturbed soil samples were obtained using Kopeck rings to evaluate soil bulk density (BD). The soil samples were randomly collected at each land use to accurately represent the entire area. Table 1 provides details on the chemical and physical properties of the soil.

Table 1 - Soil physical and chemical characterization under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP).

	Depth	Sand	Silt	Clay	pH	Na	P	K	Ca^{2+}	Mg^{2+}	$H^+ + Al^{3+}$	CEC	V	m
	cm	-------------- g kg ------------			H_2O	--------mg dm^{-3}-------			-----------$Cmol_c$ dm^{-3}--------				-------%------	
NV	0-10	497.60	339.10	163.30	4.7	22.0	4.3	277.7	2.9	2.6	5.6	11.9	51.7	4.3
	10-20	514.59	319.54	165.87	4.8	24.7	2.3	373.7	2.0	2.9	5.1	11.0	53.3	7.0
	20-30	467.48	361.62	176.00	5.3	35.0	1.7	235.0	1.9	4.9	3.8	11.4	63.7	8.3
	30-50	389.52	287.95	275.90	5.5	61.3	1.3	212.7	2.1	7.6	3.4	13.9	75.0	3.0
	50-70	410.62	279.09	285.57	5.7	127.0	1.0	168.0	1.9	13.1	3.1	19.1	82.7	1.0
	70-100	421.70	252.71	271.65	5.9	150.3	1.5	166.3	1.3	13.6	2.7	18.7	84.3	0.3
ImpP	0-10	571.95	307.27	137.40	4.9	45.3	7.0	174.3	2.5	1.7	3.8	8.7	56.0	4.3
	10-20	531.94	329.83	138.23	5.3	48.7	2.0	102.7	2.4	2.1	3.3	8.3	60.7	1.3
	20-30	548.49	211.64	210.27	5.6	103.3	1.0	72.7	2.0	3.3	3.0	8.9	66.3	1.7
	30-50	364.22	201.31	388.05	6.0	289.3	1.0	78.7	2.5	7.9	3.1	14.9	79.0	0.7
	50-70	348.42	192.42	362.00	6.3	407.0	1.0	83.3	2.1	8.9	2.6	15.7	83.0	0.0
	70-100	354.65	234.22	332.40	6.9	541.0	1.0	104.3	1.7	8.9	1.9	15.2	87.0	0.0
DegP	0-10	576.56	248.28	175.17	4.8	49.7	3.7	243.7	2.1	2.2	4.2	9.4	53.7	4.3
	10-20	558.53	275.18	166.30	5.0	38.0	1.0	105.3	1.9	1.5	4.2	8.1	46.7	6.0
	20-30	490.78	293.39	164.30	5.2	50.3	1.0	86.0	1.7	2.8	3.7	8.6	52.7	5.0
	30-50	491.52	251.48	353.50	5.7	131.3	1.0	85.3	1.2	6.0	3.7	11.7	63.3	2.3
	50-70	390.99	278.03	451.20	5.6	210.3	<1	90.0	1.1	8.2	3.5	14.0	73.0	1.0
	70-100	363.42	323.86	368.97	6.0	289.3	<1	101.0	0.8	10.5	2.9	15.8	79.7	0.7
ILFug	0-10	551.38	272.99	175.63	5.1	44.7	65.7	151.7	5.0	2.5	5.1	13.2	60.7	1.3
	10-20	554.46	262.97	182.57	4.9	31.3	6.0	79.3	3.4	1.4	5.1	10.2	50.0	2.7
	20-30	515.07	250.97	233.97	5.1	33.3	5.0	75.3	2.6	1.5	4.7	9.1	48.0	4.7
	30-50	441.93	230.77	327.30	5.3	55.0	3.0	84.3	2.3	2.7	4.0	9.5	57.0	1.7
	50-70	319.28	236.46	444.27	5.3	72.7	2.0	86.0	1.7	3.6	4.0	9.9	58.0	1.7
	70-100	312.40	271.17	416.43	5.5	108.3	1.0	71.0	1.2	5.2	3.9	10.9	64.0	1.0
ILFcg	0-10	608.60	211.80	179.60	4.6	35.3	4.3	77.0	1.9	1.3	6.1	9.6	36.7	12.3
	10-20	569.44	180.26	250.30	4.9	38.0	1.3	137.7	2.0	1.4	5.4	9.4	41.7	15.7
	20-30	550.61	193.36	256.03	5.0	35.3	1.0	41.0	2.0	1.8	5.2	9.2	43.7	9.3
	30-50	361.80	146.73	491.47	5.3	83.7	1.0	27.7	1.5	4.4	4.8	11.1	56.0	2.7
	50-70	269.08	271.52	459.40	5.5	112.7	1.0	24.7	1.5	5.4	4.4	11.8	62.3	1.7
	70-100	275.63	276.74	447.63	5.7	141.0	1.0	30.3	1.4	7.7	3.8	13.6	71.3	0.7

Source: Author (2025)

2.3 Soil organic carbon and bulk density

Disturbed soil samples were air-dried, homogenized, and sieved through a 2.0 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) 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. Bulk density (BD, g/cm^{-3}) was calculated using the volumetric ring method, which consists of dividing the soil dry mass by the volume of the Kopeck ring (DONAGEMMA et al., 2011).

The maximum bulk density (BD_{max} in $g\ cm^{-3}$) was calculated using Equation 1, which considers SOM and clay content as key input parameters (MARCOLIN; KLEIN, 2011). These factors significantly influence BD_{max}, with an inverse relationship observed between them. Furthermore, both BD and BD_{max} data were utilized to calculate the soil degree of compactness (SDC). This calculation aims to normalize the BD limits based on soil texture and other relevant parameters, as outlined in Equation 2.

$$BD_{max} = 2,03133855-0,00320878 \text{ x } \left(SOC\left(g\ kg^{-1}\right) \text{ x } 1,724\right)-0,00076508 \text{ x clay } (g\ kg^{-1}) \quad (1)$$

$$SDC\ (\%) = \frac{BD\ \left(g\ cm^{-3}\right)}{BD_{max}\ \left(g\ cm^{-3}\right)} \text{ x } 100 \quad (2)$$

2.4 Water-stable aggregates and aggregation indices

WSA were determined by the wet-sieving method, as described by Teixeira et al. (2017). The analysis of aggregates was performed in duplicate, where were weighed 50 g of air-dried soil samples with a diameter class < 8 mm, transferred to Petri dishes, moistened with spray, and then evenly placed on the uppermost layer of stacked sieves of 2, 0.25 and 0.053 mm. The stacked sieves were placed into a Yodder's apparatus with the water level adjusted to completely cover the samples and submitted to vertical stirring for 15 minutes.

Subsequently, the material retained on each sieve was backwashed into pre-weighed aluminum 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 (diameter class > 2.00 mm), mesoaggregates (diameter classes between < 2.00 and > 0.25 mm), and microaggregates (diameter class < 0.25 and > 0.053mm), according to procedure described by Costa Junior et al. (2012).

After obtaining the mass of aggregates, the presence of individual mineral particles (sand) were determined using a solution of 1.0 mol L^{-1} sodium hydroxide (NaOH), added to the aluminum containers, ensuring that the samples were fully submerged for 15 minutes. The material was then transferred to the respective sieves, back-washed into the aluminum containers and dried in an oven at 105°C for 24 h, allowing for the determination of the dry mass of the individual particles. 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), according to Medeiros et al. (2018), obtained through Equations (3), (4) and (5):

$$MWD = \sum_{i=1}^{n} (xi.wi) \quad (3)$$

Where wi is the proportion of each class in relation to the total and xi is the mean diameter of classes (mm).

$$GMD = \frac{\sum_{l=1}^{N} wp.logxi}{\sum_{l=1}^{N} wp} \quad (4)$$

where wp is the weight of aggregates of each class (g) and xi = mean diameter of classes (mm).

$$ASI = \frac{WDS\text{-}wp25\text{-}sand}{WDS\text{-}sand} \quad (5)$$

where wp25 is the dry weight of aggregates of class < 0.25 mm and WDS is the weight of each dried sample.

The aggregate sensitivity index (SI) was calculated using the methodology proposed by Bolinder et al. (1999), and based on Equation 6. This index is based on the principle of relative comparison between treatments, indicating whether the managed soil has lost or gained structural quality.

$$SI = \frac{MWD_t}{MWD_{nv}} \quad (6)$$

Where MWD_t is the mean weight diameter of the managed system and MWD_{nv} is the mean weight diameter of the native vegetation.

2.5 Statistical analysis

The data were analyzed for normality and homogeneity using the Shapiro-Wilk test ($p > 0.05$). In cases where the assumptions for ANOVA were not satisfied, the data underwent Box-Cox transformation. ANOVA was employed to evaluate the significance among the treatments at each soil depth (0-10, 10-20, 20-30, 30-50, 50-70, and 70-100 cm). When significant results were obtained, Tukey test ($p < 0.05$) was used to compare the means of the treatments. All statistical analyses were conducted using Minitab and OriginPro software. (MINITAB, 2023; ORIGINLAB CORPORATION, 2024).

3 RESULTS

3.1 Soil organic carbon content and bulk density

The highest SOC content was observed in the upper soil layers (0-10 cm) and significantly decreased ($p < 0.05$) with depth across all land uses. However, in the 70-100 cm layer, there was no statistically significant difference in SOC content among the treatments ($p > 0.05$). The highest SOC content was found in the ILFug system, with values of 20.7, 13.0, 8.1, 7.4, 5.4 and 4.4 g kg^{-1} for the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers, respectively. 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 8.1, 9.1, and 8.6 g kg^{-1}, which corresponds to losses of 41.3%, 46.1%, and 44.0%, respectively (Table 2). The lowest SOC content was observed in the 70-100cm layer of ImpP with 2.31 g kg^{-1}.

Regarding BD, results showed low variation across different land uses (Table 2). Significant differences were found only at the 70-100 soil layer ($p < 0.05$). In this layer, the highest BD of 1.65 g cm^3 was found in the ImpP while the lowest BD of 1.23 g cm^3 was observed in the ILFcg system ($p < 0.05$). Across the soil profile, the BD values varied as follows: for NV, values ranged from 1.31 to 1.52 g cm^3; for ILFug, from 1.27 to 1.46 g cm^3; for ILFcg, from 1.24 to 1.42 g cm^3; for ImpP, from 1.37 to 1.66 g cm^3; and for DegP, from 1.38 to 1.47 g cm^3. 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^3 for the 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers, respectively (Table 2).

Table 2 - Bulk density (BD) and soil organic carbon (SOC) content in 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm soil layers under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP).

Layer (cm)	Land-use system				
	Bulk density (g/cm³)				
	NV	ImpP	DegP	ILFug	ILFcg
0-10	1.31 (0.08) Aa	1.39 (0.19) Aa	1.38 (0.09) Aa	1.27 (0.20) Aa	1.29 (0.12) Aa
10-20	1.40 (0.07) Aa	1.49 (0.07) Aa	1.47 (0.13) Aa	1.46 (0.13) Aa	1.40 (0.06) Aa
20-30	1.52 (0.12) Aa	1.55 (0.07) Aa	1.46 (0.07) Aa	1.38 (0.12) Aa	1.42 (0.12) Aa
30-50	1.44 (0.13) Aa	1.57 (0.16) Aa	1.42 (0.22) Aa	1.44 (0.13) Aa	1.36 (0.22) Aa
50-70	1.38 (0.20) Aa	1.47 (0.13) Aa	1.41 (0.17) Aa	1.34 (0.20) Aa	1.26 (0.13) Aa
70-100	1.37 (0.09) ABa	1.66 (0.13) Ba	1.44 (0.20) ABa	1.38 (0.25) ABa	1.24 (0.08) Aa
	C content (g kg^{-1})				
	VN	ImpP	DegP	ILFug	ILFcg
0-10	19.67 (5.47) Aa	10.60 (2.06) Ba	11.02 (4.92) Ba	20.76 (5.70) Aa	11.55 (2.51) ABa
10-20	10.44 (2.12) ABb	7.51 (1.27) Bb	8.25 (3.34) Bab	13.05 (3.32) Ab	6.61 (1.23) Bb
20-30	6.84 (2.14) ABbc	5.41 (0.63) Bbc	5.27 (1.30) Bbc	8.17 (1.60) Abc	5.80 (0.70) Aab
30-50	4.99 (1.23) ABc	5.39 (0.90) ABbc	4.10 (0.87) Bbc	7.40 (1.06) Ac	4.68 (2.22) Bb
50-70	3.61 (1.13) ABc	3.18 (1.18) Bcd	3.46 (0.77) ABbc	5.46 (1.08) Ac	4.70 (1.33) ABb
70-100	3.30 (1.65) Ac	2.31 (0.35) Ad	2.60 (1.17) Ab	4.46 (0.85) Ac	3.58 (1.53) Ab

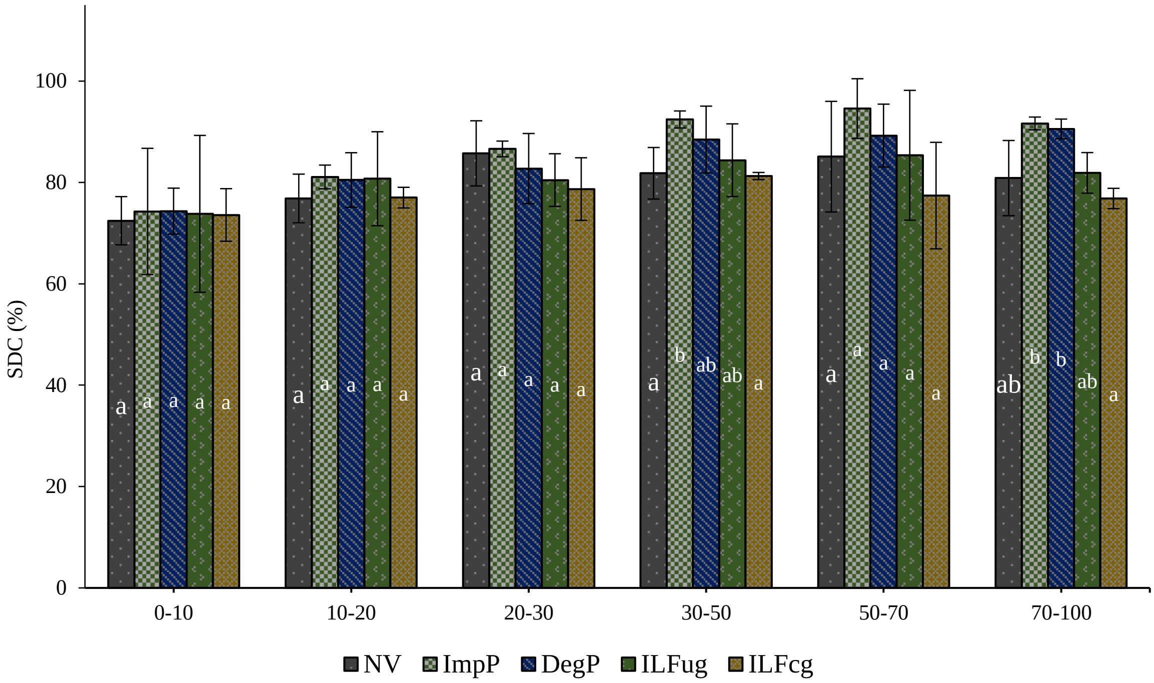
Values within parenthesis show the standard deviation (n = 5). Equals uppercase letters for land-use system and lowercase letters for layers do not differ by Tukey's test ($p < 0.05$).

Source: Author (2025)

3.2 Soil degree of compactness

The SDC is a pedotransfer function that utilizes soil texture and SOC content to normalize the limits of BD. Overall, SDC values range from 72.4 % to 85.7 % under NV, 74.3 % to 94.6 % under pastures and 73.6 % to 85.4 % in the integrated systems (Fig. 2). In the 0-10, 10-20, 20-30 and 50-70 cm layers, there were no significant differences ($p > 0.05$) in SDC values between land uses. The NV had the lowest SDC values in the 0-10 and 10-20 cm, with the conversion of NV to ImpP/DegP representing the greater increase in the SDC by 1.9% in the 0-10 cm layer, while the NV-ImpP conversion led to the highest increase of 4.3% in the 10-20 cm layer. In the 20-30, 30-50, 50-70 and 70-100 cm layers, the ILFcg showed the lowest SDC values, with 78.7, 81.3, 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.

Figure 2 - Soil Degree of Compactness (SDC) in 0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm soil layers under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP) in the Brazilian semi-arid region.



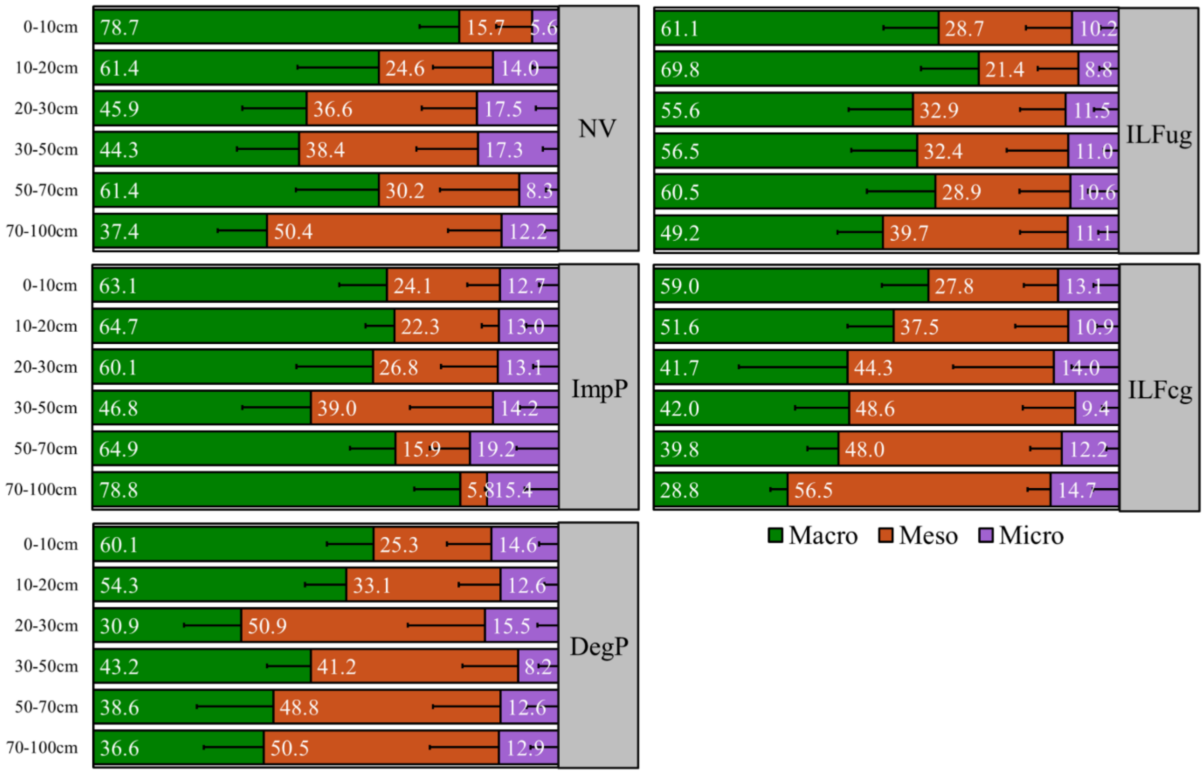
Error bars show the standard deviation (n = 5). Means followed by the same letter between the land uses for the same layer do not differ by Tukey's test (P < 0.05).
Source: Author (2025)

3.3 Distribution of water-stable aggregate classes

The distribution of WSA showed different trends with depth across the land-use systems ($p < 0.05$) (Appendix 1). There is a predominance of macroaggregates (> 2.00 mm) in 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. 3). The ImpP showed a different response when compared to other land uses, increasing the predominance of macroaggregates in the 70-100 cm layer, with this size class representing 78.8% of the total WSA ($p < 0.05$), while the percentages of mesoaggregates (< 2.00 and > 0.25 mm) and microaggregates (< 0.25 and > 0.053 mm) were 5.8% and 15.4%, respectively. For the other land uses, a greater proportion of mesoaggregates was observed in the 70-100 cm layer, with no statistical differences observed, and average values of 50.4, 50.5, 39.7 and 56.6 % for the NV, DegP, ILFug and ILFcg, respectively ($p > 0.05$). Differences in the proportion of mesoaggregates between land uses were only found in the 50-70 and 70-100 cm layers

(Appendix 1), where the ImpP showed the lowest values at 15.9% and 5.8%, respectively. However, it was compensated by a higher proportion of macroaggregates. In general, microaggregates represented the smallest proportion of the WSA across all soil layers and land uses. The exception was in the 50-70 and 70-100 cm layers of ImpP, where this class accounted for 19.2% and 15.4% of WSA, respectively. In the 10-20 and 20-30 cm layers, no statistical differences were observed among the land-use systems concerning the three classes of aggregates ($p > 0.05$). All land uses presented a higher proportion of macro than micro WSA.

Figure 3 - Distribution of Water-stable Aggregate (WSA) classes (%), macroaggregates (Macro), mesoaggregates (Meso) and microaggregates (Micro) under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP).

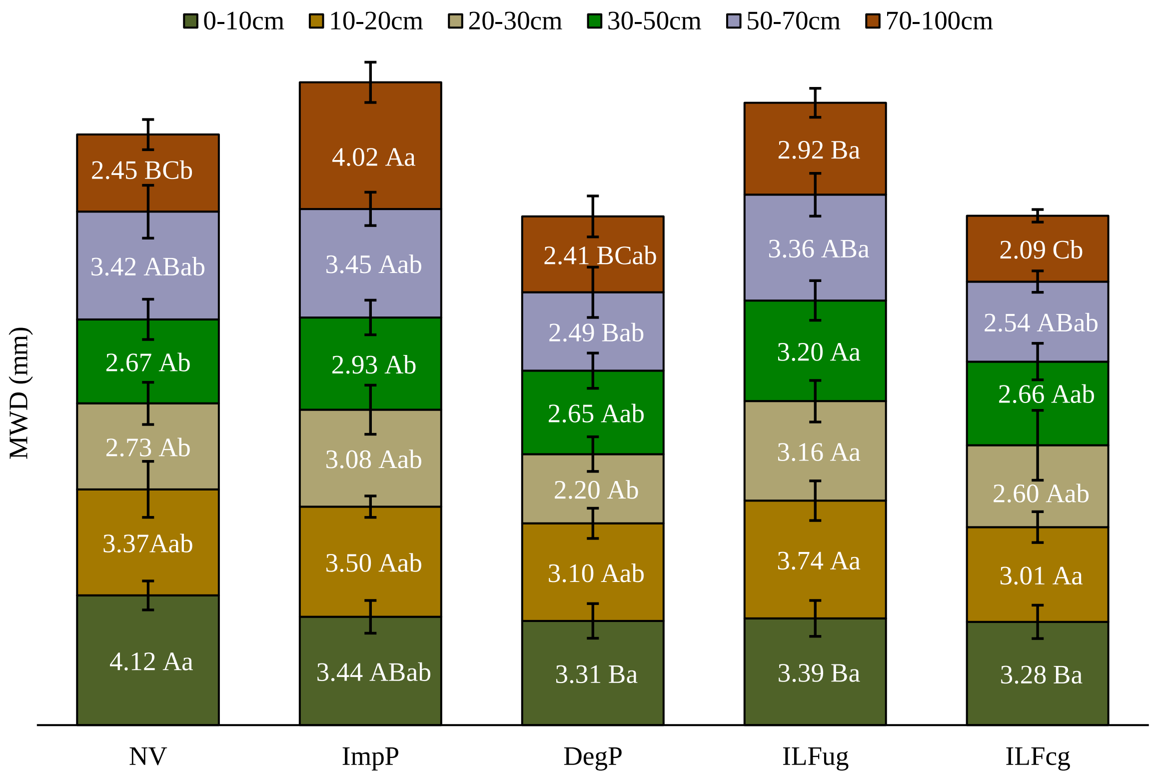


Error bars represent the standard deviation (n=5).
Source: Author (2025)

3.4 Soil aggregation indices MWD, GMD, ASI and SI

Significant differences in MWD between land uses were observed in the 0-10, 50-70, and 70-100 cm layers ($p < 0.05$). In the 0-10 cm layer, the NV presented the highest MWD at 4.12 mm (Fig. 4), while the lowest MWD was found in the ILFcg (3.28 mm). In the 50-70 cm layer, the highest MWD was observed in the ImpP (3.45 mm), followed by NV, ILFug, ILFcg and DegP, with values of 3.42, 3.36, 2.54, and 2.49 mm, respectively. A similar pattern was observed in the 70-100 cm layer, where ImpP also had the greatest MWD of 4.02 mm, followed by ILFug, NV, DegP, and ILFcg with values of 2.92, 2.45, 2.41, and 2.09 mm, respectively. Notably, the ILFug was the only system that did not present statistical differences in MWD across soil layers ($p > 0.05$), with values ranging from 2.92 mm in the 70-100 cm layer to 3.74 mm in the 10-20 cm layer. Across all soil layers and land uses, the MWD values ranged from 4.02 to 2.09 mm.

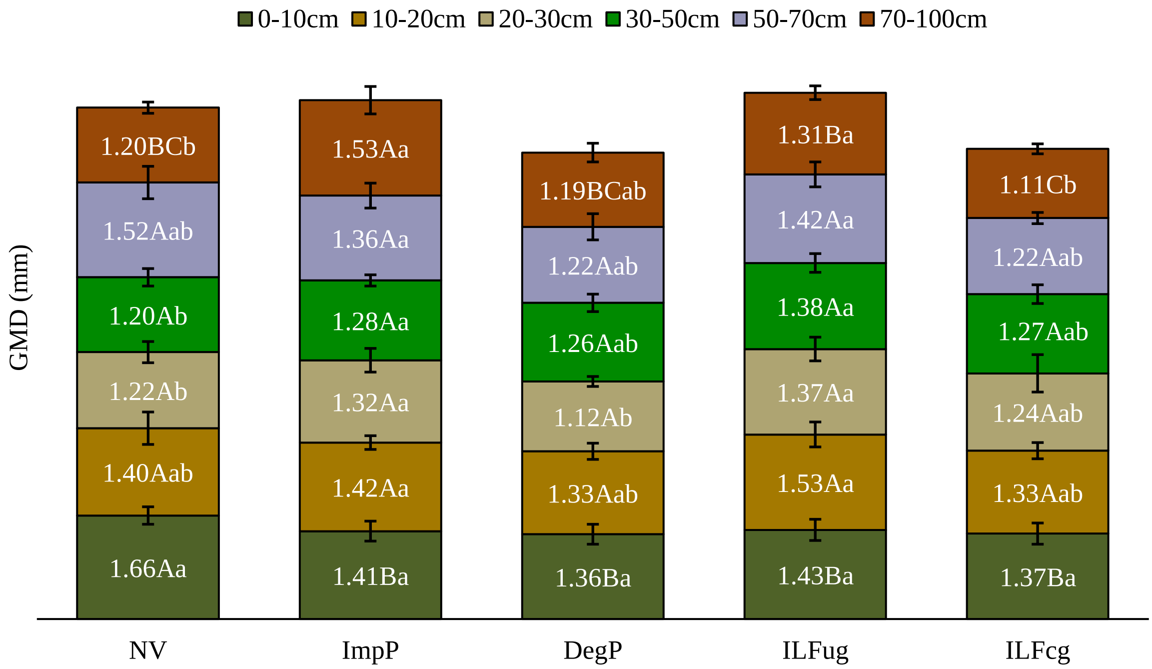
Figure 4 - Mean values of the Mean Weight Diameter (MWD) under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP).



Error bars represent the standard deviation (n=5). Equals uppercase letters for land use system and lowercase letters for layers do not differ by Tukey's test ($p < 0.05$).
Source: Author (2025)

The GMD was also affected by land-use change ($p < 0.05$). Across all land uses, the GMD ranged from 1.66 mm in the 0-10 cm layer of NV to 1.11 mm at the 70-100 cm layer of ILFcg. Statistical differences in the GMD between land uses were observed in the 0-10 and 70-100 cm layers (Fig. 5). In the 0-10 cm layers, the NV had the highest GMD (1.66 mm), significantly differing from the other land use systems ($p < 0.05$), with values of 1.43, 1.41, 1.37 and 1.36 mm for the ILFug, ImpP, ILFcg and DegP, respectively (Fig. 5). This indicates that NV has larger soil aggregates in the topsoil. Conversely, in the 70-100 cm layer, the ImpP had the highest GMD (1.53 mm), followed by ILFug, NV, DegP and ILFcg, with values of 1.31, 1.20, 1.19 and 1.11, respectively. The DegP exhibited the lowest GMD values in all soil layers except 70-100 cm, where ILFcg had the lowest GMD of 1.11 mm. In both ImpP and ILFug, the GMD values did not differ statistically within their respective layers, ranging from 1.28 to 1.53 mm for ImpP and 1.31 to 1.53 mm for ILFug ($p > 0.05$). This higher GMD value of 1.53 mm for ImpP was found in the 70-100 cm layer, while in the ILFug was found in the 10-20 cm layer, indicating differences in aggregate distribution with depth.

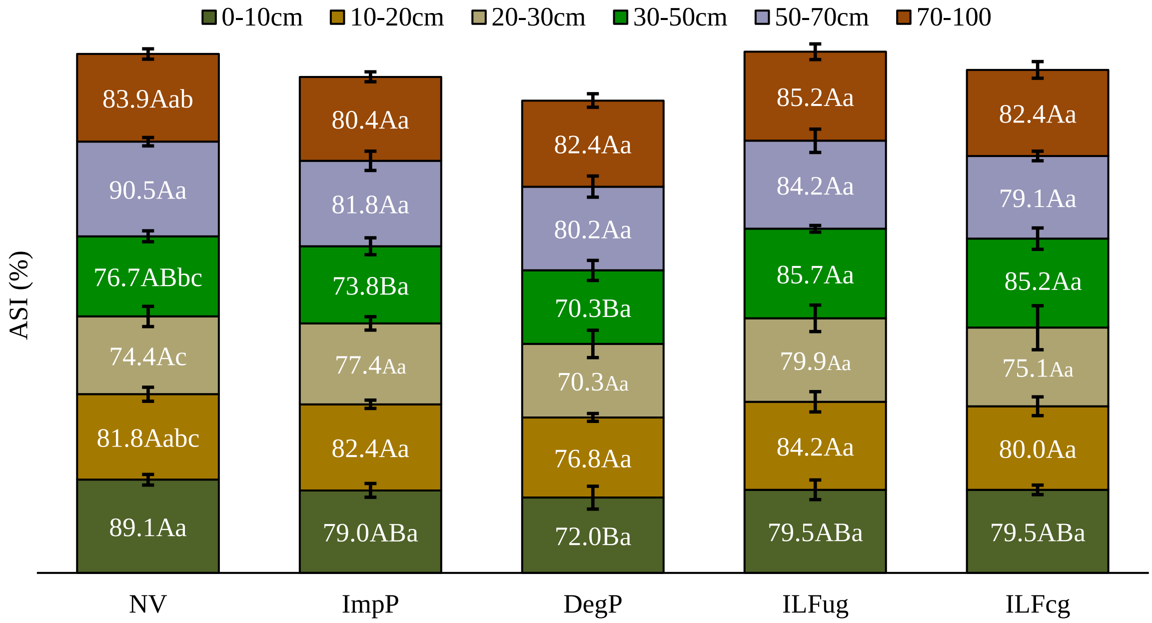
Figure 5 - Mean values of the Geometric Mean Diameter (GMD) under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP).



Error bars represent the standard deviation (n=5). Equals uppercase letters for land use system and lowercase letters for layers do not differ by Tukey's test ($p < 0.05$).
Source: Author (2025)

Regarding the ASI, the highest value (89.1%) was found in the 0-10 cm layer of NV, while the lowest was observed in the 20-30 and 30-50 cm layers of DegP (Fig. 6). Statistical differences between land uses were observed in the 0-10 and 30-50 cm soil layers ($p < 0.05$). Nevertheless, no trend in ASI was observed with depth. In the 0-10 cm layer, the DegP presented the lowest ASI (72.0%), differing from the other land-use systems ($p < 0.05$). In the 30-50 cm layer, the DegP also had the lowest ASI (70.3%), differing from ILFug and ILFcg which had the highest ASI values of 85.7% and 85.2%, respectively. Although the ImpP exhibited the highest MWD and GMD in the 70-100 cm layer, its ASI was the lowest at 80.4%. However, no differences were observed among land uses in this layer ($p > 0.05$).

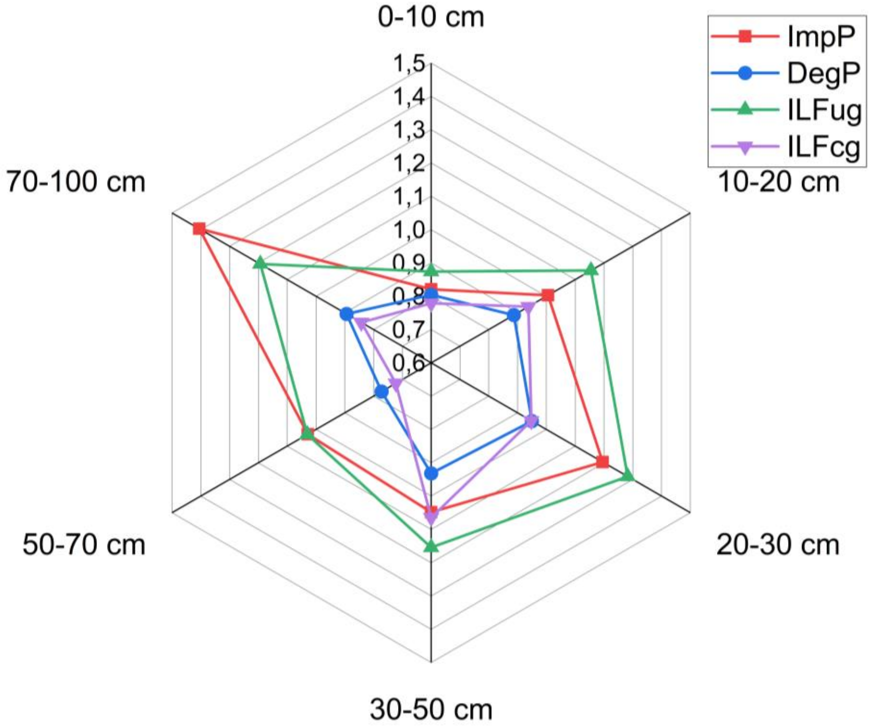
Figure 6 - Mean values of the aggregate stability index (ASI) under native vegetation (NV), ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP).



Error bars represent the standard deviation (n=5). Equals uppercase letters for land use system and lowercase letters for layers do not differ by Tukey's test ($p < 0.05$).
Source: Autor (2025)

A SI value greater than 1 indicates that the structural quality and stability of soil aggregates have improved compared to the reference area (NV). In the topsoil layer (0-10 cm) all land uses had SI values lower than 1, indicating loss of structural quality compared to NV (Fig. 7), with the ILFcg system showing the lowest SI (0.77), suggesting a significant decline in soil structural quality. In all soil layers, the DegP had a SI under 1, with values of 0.80, 0.88, 0.94, 0.93, 0.77 and 0.89. 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 in the 10-20, 20-30, 30-50, 50-70 and 70-100 cm layers, indicating that these land uses have improved soil structural quality compared to NV (Fig. 7). When comparing only the pastures and integrated systems, the ILFug had the highest SI in 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.

Figure 7 - Sensibility index (SI) under ILF of *Urochloa* + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP).

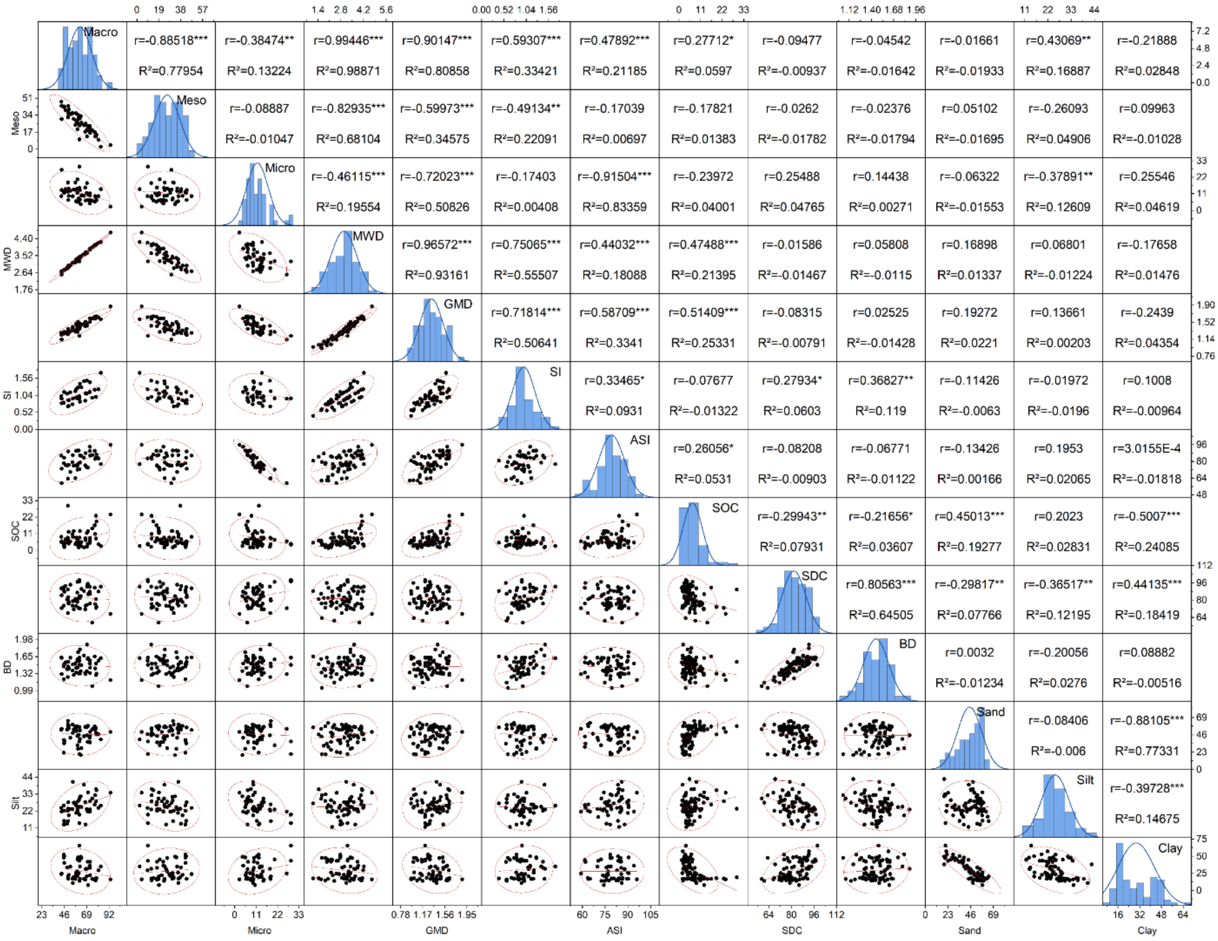


Source: Author (2025)

3.5 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). The SOC content had significant positive correlations with macroaggregates, MWD, GMD, ASI and sand. In contrast, SOC content was negatively correlated with Clay, BD and SDC. Regarding the mineral fractions of the soil, sand, and clay did not have significant correlations with soil aggregation. However, the silt fraction showed a significant positive correlation with macroaggregates ($r = 0.43$; $p < 0.01$) and a negative correlation with microaggregates ($r = -0.37$; $p < 0.01$). The strongest correlation among the WSA classes and aggregation indices was observed between macroaggregates and MWD ($R^2 = 0.98$; $r = 0.99$; $p < 0.001$). The correlation revealed that the main factor negatively affecting the ASI is the presence of microaggregates ($R^2 = 0.83$; $r = -0.91$; $p < 0.001$). SDC was significantly correlated with all soil mineral fractions (clay, silt, sand).

Figure 8 - Pearson's correlation coefficient matrix and regression of the studied parameters for the combined land-use systems.



***, ** and * indicate significant correlations of $p < 0.001$, $p < 0.01$ and $p < 0.05$, respectively. r indicates Pearson's coefficient.

Source: Author (2025)

4 DISCUSSION

4.1 Soil organic carbon content, bulk density and degree of compactness

In all land uses, it was clear that SOC significantly affects the stability of soil aggregates (Fig. 8). Almost all parameters were positively and significantly correlated with SOC 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; Lal (2004), SOC promotes soil aggregation, while aggregates subsequently store SOC, reducing SOM decomposition rate. All land uses showed a decreasing trend in SOC content with depth. In the 70-100 cm layers, there was no difference ($p > 0.05$) between land uses. Previous studies indicate higher SOC content in topsoil, without difference in deeper soil layers across various land-use systems in semi-arid regions (ÁLVARO-FUENTES et al., 2009; KABIRI; RAIESI; GHAZAVI, 2015).

Greater SOC content was observed in the ILFug system across all soil layers. This system is 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 *Urochloa* forage is commonly used in integrated systems because it efficiently accumulates C in the soil through biomass and roots (CAVALCANTE et al., 2019; NETO et al., 2021). *Urochloa* produces substantial amounts of biomass and has more slow-decomposing recalcitrant compounds, improving soil protection by extending soil coverage, reducing temperature exposure, and increasing C inputs. Consequently, this slower decomposition rate of crop residues, results in the accumulation of SOC in the soil. Moreover, Lal (2003) says that SOC content can be maintained or increased in comparison to native vegetation in semi-arid soils when crop residues are maintained on the soil. Moreover, gliricidia, a leguminous plant, effectively distributes litter in integrated systems and decomposes quickly due to its high 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 years.

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 years. Soil tillage can fragment soil aggregates, disrupt soil structure, and expose SOM to higher levels of oxidation, reducing the SOC (MEDEIROS; SOARES; MAIA, 2022a). In addition, limited soil coverage and low biomass production from cactus forage increase soil surface temperatures and SOM decomposition (NETO et al., 2021; RIGON; CALONEGO, 2020).

ImpP and DegP exhibited similar SOC content. In contrast, Fonte et al. (2014) observed a 20% increase in SOC in well-managed pastures compared to degraded pastures in the deforested Amazon Basin of Colombia. These findings indicate that, despite improved pastures being better managed, their capacity to maintain SOC content is still limited, particularly in the semi-arid regions, 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 region at a 0-100 cm depth, with these losses ranging from 12% to 16%. The low SOC content in these pastures is followed by soil compaction caused by animal trampling, as indicated by elevated BD (Table 2). Continuous grazing can lead to cattle trampling, which may increase soil compaction (COSTA et al., 2009; DON; SCHUMACHER;

FREIBAUER, 2011; VALBRUN et al., 2018). Similar findings were reported by Medeiros et al. (2023) and Santana et al. (2019), who observed higher BD in the superficial layer of pasture areas compared to other land uses in the Brazilian semi-arid region. The continuous grazing of pasture areas increases BD and mechanical stress, leading to disruption of soil aggregates (WIESMEIER et al., 2012), which in turn, can lead to significant losses of SOC, particularly in regions with high evaporation rates where precipitation is scarce and irregularly distributed (XIE; WITTIG, 2004). However, despite the similar SOC content in both pasture areas, the lowest MWD, GMD, ASI, SI, and decreased amount of macroaggregates in DegP, indicate the adverse impacts of soil degradation processes.

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. In contrast, the low BD observed in ILFcg is due to 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; LAL, 2005).

Soil compaction impacts important ecological characteristics, such as water and air flow, 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 (R^2= 0.64; r = 0.80; $p < 0.001$). 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 Distribution of water-stable aggregate classes

The NV (dense Caatinga) presented the highest proportion of macroaggregates in 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-year afforestation area in the southeast semi-arid region 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; 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 years. Several authors have reported a lower proportion of macroaggregates in areas under conventional tillage (ÁLVARO-FUENTES et al., 2008; HAJABBASI; HEMMAT, 2000; PLAZA-BONILLA et al., 2013; KABIRI; RAIESI; GHAZAVI, 2015; OKOLO et al., 2020). According to Six; Elliott; Paustian (2000), systems under conventional tillage frequently show a reduced proportion of macroaggregates due to an increased rate of macroaggregate turnover (formation and degradation). Additionally, insufficient residue cover from the cactus forage on the soil surface does not protect the integrity of soil aggregates. This lack of protection 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 in almost all soil layers. Hajabbasi; Hemmat (2000) also reported an increased proportion of mesoaggregates (< 0.25 mm) under conventional tillage in the semi-arid region of Iran. The hierarchical aggregation theory proposes that macroaggregates are initially formed through the accumulation of micro and mesoaggregates and, over time, the occluded organic matter within macroaggregates is decomposed, forming micro and mesoaggregates inside (BRONICK; LAL, 2005). Soil tillage, eventually disrupts macroaggregates, releasing micro and mesoaggregates in the soil.

Conversely, in the ILFug, the adoption of no-till practices, while also preventing the disruption of soil aggregates, enhances microbial activity in the soil surface (MADEJÓN et al., 2009; PLAZA-BONILLA et al., 2013),which leads to greater production of organic binding by-products during the decomposition of fresh organic inputs, contributing for the formation and stability of macroaggregates (ABIVEN; MENASSERI; CHENU, 2009; PLAZA-BONILLA et al., 2013). Furthermore, Plaza-Bonilla et al. (2013) indicate 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 ($r = 0.43$; $p < 0.01$) and negative for the percentage of microaggregates ($r = -0.37$; $p < 0.01$). 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; LAL, 2005; FERNÁNDEZ-UGALDE et al., 2011). Furthermore, according to Fernández-Ugalde et al. (2011), 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. Although not significant, this study showed an inverse correlation between clay and macroaggregates ($r = -0.21$; $p > 0.05$). Clay particles are often linked to aggregation through rearrangement and flocculation; however, swelling clay can disrupt soil aggregates (BRONICK; 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 regions (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 of this interaction.

The distribution of macroaggregates was directly correlated with SOC content ($r = 0.26$; $p < 0.05$). A direct correlation between the WSA size class distribution and SOC was also reported in several studies (BLANCO-CANQUI; LAL, 2004; HAJABBASI; HEMMAT, 2000; JASTROW; MILLER, 2018). Jastrow; Miller (2018) found a similar correlation between SOC and macroaggregates ($r = 0.28$).

4.3 Soil aggregation indices MWD, GMD, ASI and SI

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 to the reference (NV).

The ILFug showed greater MWD in all soil layers compared to ILFcg. This can be attributed to the management (ILFug = no-tillage, 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 ($r = 0.47$; $p < 0.001$), indicating that increases in SOM can also improve soil structure and aggregation (KABIRI; RAIESI; GHAZAVI, 2015). These findings corroborate with Álvaro-Fuentes et al. (2007) and Hernanz et al. (2002), who also found in the semi-arid of Central Spain, greater values of MWD under no-tillage compared to 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 *Urochloa* in the ILFug system can better contribute to an increase in soil aggregation compared to forage cactus in the ILFcg system, as these plants have a perennial growth pattern and continuously renew their root systems (JUNIOR et al., 2020; LUNA et al., 2019).

The ILFug and NV showed the highest ASI across soil profile, corroborating other studies indicating that aggregates in integrated systems under no-tillage and forests exhibit greater stability compared to aggregates from other land uses (ÁLVARO-FUENTES et al., 2008; SIX; ELLIOTT; PAUSTIAN, 2000). Increased amounts of crop residues retained on the soil surface in these land uses 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 (ÁLVARO-FUENTES et al., 2008; CHENU; LE BISSONNAIS; ARROUAYS, 2000). This is further supported by the positive correlation between SOC and ASI ($r = 0.26$; $p < 0.05$), 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, gliricidia plays a crucial role in this enhanced aggregate stability. Roots of leguminous plants are associated with increased aggregation, and greater WSA than those of non-leguminous plants (BRONICK; LAL, 2005).

The ImpP increased all aggregation indices compared to DegP. Fonte et al. (2014) also found greater soil aggregation in well-managed pastures compared to degraded pastures. Well-managed pastures often have stronger and deeper root systems that aerate soils, enmesh soil particles, and promote 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 dynamics of MWD and ASI in the 70-100 cm soil layer had an opposite pattern compared to 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; Cambardella; Bailey (2000) and Álvaro-Fuentes et al. (2007), these macroaggregates, primarily formed in the rhizosphere at depth, are less stable compared to those formed in topsoil through plant senescence processes. Therefore, our findings support 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, release 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 corroborate with Cruz (2017) who also found higher values of SI in well-managed pastures and integrated systems compared to a native vegetation. The lowest SI values found in the ILFcg system and DegP, reflects the harmful effect of soil tillage and degradation processes on aggregate stability.

5 CONCLUSION

This study demonstrates that implementing integrated livestock-forest systems under no-tillage as a NbS can enhance SOC content, stability of soil aggregates and structural stability in semi-arid environments. In these regions, where irregularly distributed rainfall, high temperatures and consequently wet/dry cycles are some of the most limiting factors for soil structure, the distribution and stability of soil aggregates are critical due to the susceptibility of the semi-arid to erosion and degradation. In contrast, the ILFcg system and DegP showed the lowest aggregation indices, reflecting the adverse impacts of conventional tillage and degradation on soil structure.

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 regions is still limited. However, the increase in macroaggregates, aggregate stability and aggregation indices observed in improved pastures emphasizes the critical role of management in preserving soil structure in semi-arid grasslands. Soil aggregation is essential for maintaining soil health, as it improves various soil properties, including structure, porosity, water infiltration, and resistance to erosion, especially in semi-arid regions where environmental pressures and land-use changes present significant challenges to soil sustainability.

NbS that promote soil aggregation are essential for sustainable agriculture in semi-arid regions. These practices not only improve soil aggregation but also enhance C sequestration, reducing C losses to the atmosphere.

6 FINAL REMARKS

Considering all the factors discussed, adopting NbS positively impacted SOC, SOM dynamics, and overall soil physical quality, especially in integrated systems under no-tillage. Therefore, both farmers and policymakers should recognize these benefits and prioritize the expansion of NbS in semi-arid regions, where water scarcity and high temperatures often exacerbate soil degradation. Restoring these degraded areas not only helps to mitigate C emissions but also enhances the resilience of local ecosystems against climate change.

However, to enhance and expand the benefits of NbS, policymakers should consider implementing legislation that actively encourages farmers to adopt these sustainable practices, providing targeted financial assistance, such as low-interest loans, to help cover the costs of transitioning degraded and conventional agriculture areas to NbS that increase SOC and C sequestration. Additionally, offering hands-on technical training programs can equip farmers with the necessary skills and knowledge to effectively implement these NbS, such as no-tillage, cover cropping, agroforestry, and regenerative agriculture. Furthermore, establishing market mechanisms that recognize and reward the value of C sequestration and improved soil health could create new economic incentives. For example, introducing carbon credit programs could allow farmers to monetize their efforts in reducing GHG emissions, thereby contributing to climate mitigation.

These initiatives not only enhance agricultural resilience to challenges posed by a semi-arid climate but also contribute significantly to global environmental goals by improving soil health and biodiversity, fostering a more sustainable agricultural system that benefits both farmers and the environment.

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Appendix 1 - Distribution of Water-stable Aggregate (WSA) classes (%) macroaggregates (Macro), mesoaggregates (Meso) and microaggregates (Micro) under native vegetation (NV), ILF of Urochloa + gliricidia (ILFug), ILF of cactus forage + gliricidia (ILFcg), Improved pasture (ImpP) and degraded pasture (DegP). Error bars represent the standard deviation (n = 5). Equals uppercase letters for land use system and lowercase letters for layers do not differ by Tukey's test ($p < 0.05$).

Land use		Depth (cm)					
	Size Class (%)	0-10	10-20	20-30	30-50	50-70	70-100
NV	Macro	78.7 (8.4) Aa	61.4 (17.4) Aab	45.9 (13.8) Abc	44.3 (13.3) Abc	61.4 (17.8) ABabc	37.4 (10.6) BCc
	Meso	15.7 (7.6) Ac	24.6 (12.9) Abc	36.6 (11.8) Aab	38.8 (13.2) Aab	30.2 (17.0) ABabc	50.4 (11.4) Aa
	Micro	5.6 (1.9) Bc	14.0 (5.5) Aa	17.5 (4.7) Aa	17.3 (3.2) Aa	8.3 (2.6) Abc	12.2 (2.7) Aabc
ImpP	Macro	63.1 (10.3) ABab	64.7 (6.1) Aab	60.1 (16.4) Aab	46.8 (14.6) Ab	64.9 (9.7) Aab	78.8 (9.8) Aa
	Meso	24.1 (6.9) Aab	22.3 (3.7) Aab	26.8 (12.2) Aab	39.0 (17.8) Aa	15.9 (8.55) Bb	5.8 (0.5) Bb
	Micro	12.7 (4.3) ABa	13.0 (2.7) Aa	13.1 (4.2) Aa	14.2 (3.15) ABa	19.2 (9.17) Aa	15.4 (4.8) Aa
DegP	Macro	60.1 (9.9) Ba	54.3 (8.8) Aa	30.9 (11.9) Ab	43.2 (8.6) Aab	38.6 (16.4) Bab	36.6 (12.8) BCab
	Meso	25.3 (9.4) Ab	33.1 (8.9) Aab	50.9 (16.1) Aa	41.2 (10.9) Aab	48.8 (14.4) Aab	50.5 (14.82) Aab
	Micro	14.6 (4.3) Aa	12.6 (3.14) Aa	15.5 (4.5) Aa	8.2 (4.14) Ba	12.6 (6.9) Aa	12.9 (6.10) Aa
ILFug	Macro	61.1 (11.8) Bab	69.8 (12.3) Aa	55.6 (13.8) Aab	56.5 (14.1) Aab	60.5 (144.7) ABab	49.2 (9.7) Bb
	Meso	28.7 (9.8) Aa	21.4 (8.7) Aa	32.9 (9.8) Aa	32.4 (13.2) Aa	28.9 (10.8) ABa	39.7 (10.2) Aa
	Micro	10.2 (4.0) ABa	8.8 (4.3) Aa	11.5 (5.4) Aa	11.0 (3.3) ABa	10.6 (6.7) Aa	11.1 (4.5) Aa
ILFcg	Macro	59.0 (9.9) Ba	51.6 (9.8) Aa	41.7 (23.4) Aab	42.0 (11.6) Aab	39.8 (6.7) Bab	28.8 (3.6) Cb
	Meso	27.8 (7.2) Ac	37.5 (11.3) Abc	44.3 (21.6) Aabc	48.6 (11.3) Aab	48.0 (6.8) Aab	56.5 (4.9) Aa
	Micro	13.1 (5.5) Aa	10.9 (4.7) Aa	14.0 (10.2) Aa	9.4 (3.6) Ba	12.2 (2.7) Aa	14.7 (5.6) Aa