Scientific Article

EFFECTS OF DEGRADATION ON SOIL ATTRIBUTES UNDER CAATINGA IN THE BRAZILIAN SEMI-ARID

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ABSTRACT – Anthropic activities in their various aspects have promoted soil degradation in the Brazilian semi-arid region (SAB). As a result, significant losses in productivity and in the ability of soils to fulfill their ecological functions have been reported. The present study investigated the effects of degradation on soil attributes and properties under dense (CAD) and sparse (CAE) shrubby Caatinga in Campina Grande, PB, Brazil. Samples from the 0-20 cm layer of soil were investigated via physical (particle size distribution and soil density), chemical (acidity, electrical conductivity, macronutrients, soil organic matter) and microbiological attributes (microbial biomass carbon (C-BMS), basal respiration of the soil (RBS) and metabolic quotient (qCO_2) Data were submitted to the Mann-Whitney Test and Principal Component Analysis (PCA). Anthropic actions on the CAE promoted the exposure of the saprolitic layer on the surface. This layer has imperfect drainage, low levels of nutrients and organic matter and high sodicity, which contributes to the slow regeneration of vegetation. Carbon stock and microbial activity are significantly lower in CAE compared to CAD. Degradation resulted in losses of supporting ecosystem services (nutrient cycling and primary production) and regulation (erosion control and climate regulation). The results can be used to understand the dynamics of landscapes of low complexity (high degradation) in the SAB and serve as a framework to find strategies to restore the productive capacity of extensive degraded and/or desertified areas in the SAB.

Keywords: Ecosystem Services; Desertification; Carbon Stock.

EFEITOS DA DEGRADAÇÃO NOS ATRIBUTOS DE SOLOS SOB CAATINGA NO SEMIÁRIDO BRASILEIRO

RESUMO – As atividades antrópicas em seus diversos aspectos têm promovido a degradação dos solos no Semiárido brasileiro (SAB). Como consequência, têm sido reportadas perdas significativas de produtividade e da capacidade dos solos em cumprir suas funções ecológicas. O objetivo desta pesquisa foi avaliar os efeitos da degradação nos atributos e propriedades de solos sob Caatinga arbustiva densa (CAD) e esparsa (CAE) em Campina Grande, PB, Brasil. Amostras da camada de 0-20 cm do solo foram analisadas quanto aos atributos físicos (granulometria e densidade do solo), químicos (acidez, condutividade elétrica, macronutrientes, matéria orgânica) e microbiológicos (carbono da biomassa microbiana (C-BMS), respiração basal do solo (RBS) e quociente metabólico (qCO_2). Os dados foram submetidos ao Teste de Mann-Whitney e à Análise de Componentes Principais (ACP). As ações antrópicas na CAE promoveram a exposição da camada saprolítica em superfície. Esta camada possui drenagem imperfeita, baixos teores de nutrientes e de matéria orgânica e elevada sodicidade, o que contribui para a lenta regeneração da vegetação. O estoque de carbono e a atividade microbiana são significativamente mais baixos na CAE em relação à CAD. A degradação acarretou em perdas de serviços ecossistêmicos de suporte (ciclagem de nutrientes e produção primária) e de regulação (controle da erosão e regulação do clima). Os resultados podem ser utilizados para compreensão da dinâmica de paisagens de baixa complexidade (elevada degradação) no SAB, bem como para adoção de estratégias de restabelecimento da capacidade produtiva de extensas áreas degradadas e/ou desertificadas no SAB.

Palavras-Chave: Serviços ecossistêmicos; Desertificação; Estoque de carbono.

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1. INTRODUCTION

The Brazilian Semi-arid (SAB), a region with 1,182,697 km^2 (Sudene, 2017), represents almost 14% of the national territory and 76% of the Northeast region. It is a region traditionally subject to droughts, where erosive processes have been intensified due to extensive livestock farming, rudimentary agriculture, and vegetal extractivism (CGEE, 2016).

Studies evaluating the effects of land use change on C (carbon) and N (nitrogen) dynamics (Althoff et al., 2018), energy and water flows (Silva et al., 2017), nutrient cycling (Moura et al., 2016), microbial abundance (Neves et al., 2021), physical and chemical soil quality (Mota et al., 2014) and microclimate (Silva et al., 2021) have been conducted in different SAB regions. Numerous studies have also shown the effects of degradation on the soil attributes of the SAB. Most of these studies have assessed these changes in the first soil layers (Mora and Lázaro, 2014; Araújo Filho et al., 2017; Althoff et al., 2018) and, to a lesser extent, in depths greater than 40 cm and/or in subsurface pedogenetic horizons (Neves et al., 2021; Silva et al., 2021; Menezes et al., 2021).

Recently, some studies have sought to understand the relationships between biophysical variables and the flow of water and C in areas with different stages of degradation in the Caatinga (Borges et al., 2020; Oliveira et al., 2021). These studies showed that the degradation of the Caatinga can modify the local microclimate by reducing atmospheric C sequestration and increasing greenhouse gas emissions.

Despite the importance of these studies, combined with the fact that soil properties and attributes can be safely used to assess soil quality (Maurya et al., 2020). Research that seeks to evaluate the physical, chemical and biological attributes of soils under Caatinga in different stages of regeneration has been neglected (Silva et al., 2021).

Thus, in this research we seek to evaluate the physical, chemical and biological attributes of soil layers exposed on the surface by land degradation, where even after interventions and actions towards reforestation, it still has a slow capacity for vegetation regeneration. This scenario is similar to that observed for other regions in the SAB, where extensive heavily degraded areas have truncated soils, with subsurface horizons of high unavailability for agricultural use exposed on the surface (CGEE, 2016; Macedo et al., 2021).

In this context, this integrated study of soil attributes can contribute to the understanding of the effects of human actions on the dynamics and stock of nutrients in soils at different stages of degradation, as well as elucidate the mechanisms involved in the recovery of fertility and ecosystem services of these soils with the restoration of vegetation. Certainly, this knowledge will also contribute to strategic actions aimed at reincorporating extensive areas of degraded soils in the SAB into agricultural activities, increasing the resilience and food security of family agroecosystems in the face of climatic adversities in the region.

The objective of this research was to evaluate physical, chemical and microbiological attributes of soils in two areas of Caatinga (dense shrubby Caatinga - CAD; sparse shrubby Caatinga - CAE) subjected to anthropic pressures in the SAB.

2. MATERIAL AND METHODS

2.1 Study area

The research was carried out at the Experimental Station Prof. Ignácio Salcedo, belonging to the Instituto Nacional do Semiárido (INSA), municipality of Campina Grande, state of Paraíba, Brazil. An area under dense shrubby Caatinga (CAD) and another under sparse shrubby Caatinga (CAE) was studied (Figure 1).

The CAD site (7º16'47.76"S and 35º58'29.21"W; 480 m) corresponds to a legal reserve area with approximately 300 ha of dense preserved vegetation in different stages of regeneration, primarily consisting of shrubs and tree species typical of the Caatinga biome. The species commonly found in the area are umburana (*Spondias tuberosa Arruda*), pereiro (*Aspidosperma pyrifolium Mart*), imburana (*Comminphora leptophloeos* (*Mart*) J. B. Gillet), mandacaru (*Cereus jamacaru DC*.), facheiro (*Pilosocereus pachycladus Ritter*), marmeleiro (*Croton sonderianus Müll. Arg*), umburana (*Amburana cearensis* (*Fr All*) A. C. C. Smith), catingueira (*Poincianella bracteosa* (*Tul*.) L. P. Queiroz), mororó (*Bauhinia cheilantha* (*bong*.) *steud*), jurema branca (*Mimosa verrucosa*), jurema preta (*Mimosa tenuiflora* (*Wild*.) *Poir*), jurema unha-

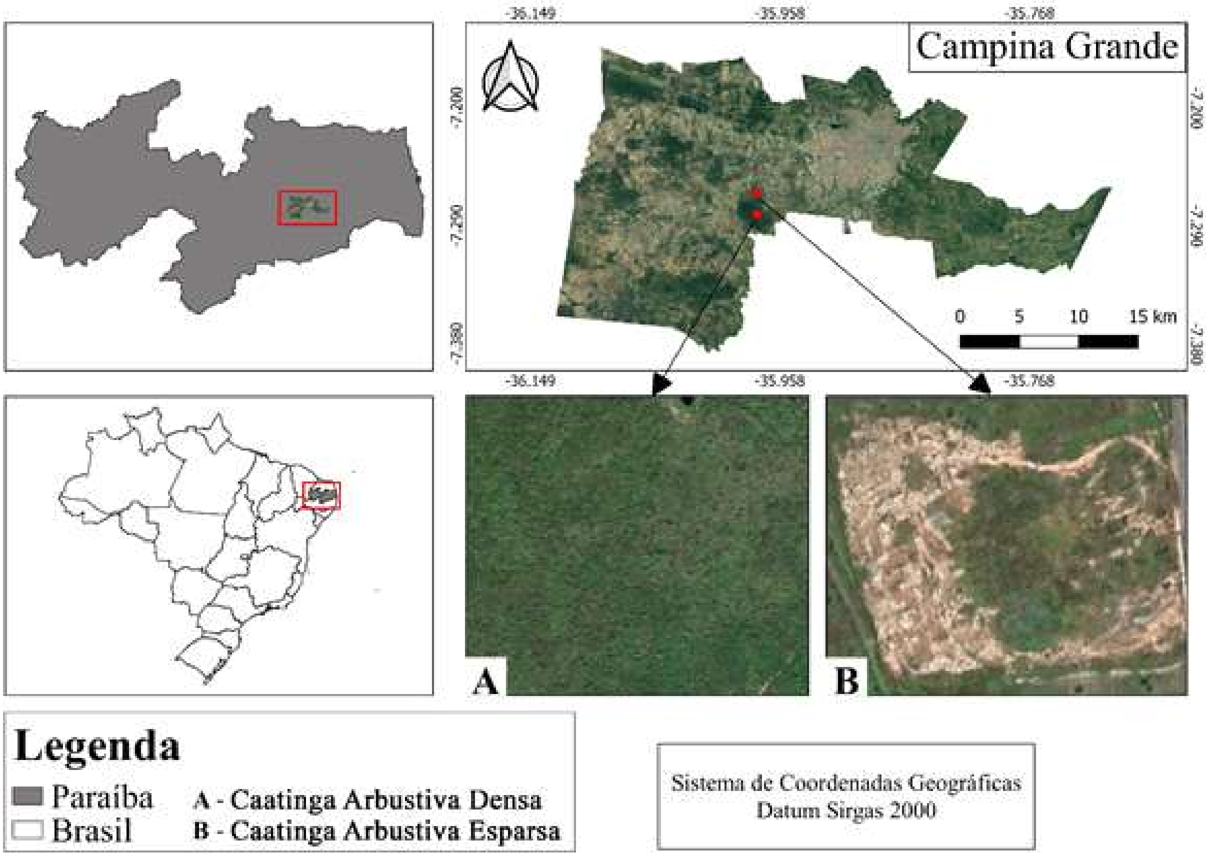

Figure 1 – Location of study areas.
Figura 1 – *Localização das áreas de estudo.*

de-gato (*Mimosa* sp.) and joão mole (*Guapira* sp.). The local vegetation is classified as dense shrubby Caatinga (Rizzini, 1997).

The CAE site (7º14'59.78"S and 35º56'49.70"W; 500 m) corresponds to a borrow area where the surface horizon of the soil was removed to supply material for the construction of a nearby road. This process caused the exposure of the saprolitic layer (horizon C) on the surface, which presents characteristics of the source material and ample occurrence of partially weathered minerals. As part of the recovery process of this degraded area, in 2018, reforestation was carried out with adapted and native species in the region, such as white jurema (*Mimosa verrucosa*), jurema preta (*Mimosa tenuiflora* (*Wild.*) *Poir*), guandu (*Cajanus cajan*), cunhã (*Clitoria ternatea*), crotalaria (*Crotalarea juncea*), marmeleiro (*Croton sonderianus Müll. Arg*) and pereiro (*Aspidosperma pyrifolium Mart*). This configuration results in a phytophysiognomy consisting of a low shrub stratum, with a maximum height of 3 m, being classified as a sparse shrubby Caatinga (Rizzini, 1997).

The climate is semi-arid with low altitude and latitude (BSh) according to the Köppen classification (Alvares et al., 2013). The average annual temperature is 23.3°C and the average annual rainfall is 503 mm. The native vegetation is the hyperxerophytic Caatinga, characterized as a dry xerophytic forest with sparsely distributed shrubs and small trees (less than 7 meters in height), and patches of grass that develop only during the rainy season (January to September).

The relief varies from gently undulating to undulating with elevations of flat tops, composed of slopes of tens of meters with dry and open valleys (Brasil, 1972). Leptsols predominate in the area, formed from the weathering of cataclastic leuco-gneiss with biotite (Brazil, 1972).

2.2 Soil collection and analysis

Soils were collected in August 2020. Year in which annual precipitation was 551.2 mm, with a rainy season between March and July (494.2 mm), corresponding to 89% of annual precipitation. In this rainy period, rainfall was 270.6 mm in March and April and 223.6 mm between May and July.

The experimental design used was completely randomized. The sampling was performed in two homogeneous areas of 1000 m^2, with five collection points (experimental units), and at each point five simple deformed soil samples were collected (0-20 cm), which constituted a composite sample that was dried in air and passed through a 2 mm sieve (TFSA). At each collection point five undisturbed samples were also collected in 100 cm^3 volumetric rings to perform soil density (Ds) analysis. The deformed samples were morphologically described according to Santos et al. (2015). Additional features such as rock volume and percentage of aggregates were evaluated according to Schoeneberger et al. (2012).

Sample preparation and physical and chemical analyses of the soils were performed at the INSA Soils and Mineralogy Laboratory according to methodologies proposed by Embrapa (Teixeira et al. 2017). Particle size analysis and water dispersed clay were performed by the pipette method, using NaOH and H_2O as dispersants, respectively. Ds was obtained by the volumetric cylinder method.

The pH was determined in water (1:2.5 - TFSA:H_2O) and the electrical conductivity (CE) was obtained using a direct reading conductivity meter (1:5.0 - TFSA:H_2O). The exchangeable contents of Ca^{2+}, Mg^{2+} and Al^{3+} were extracted with KCl 1 mol L^{-1}, while P, K^+ and Na^+ were extracted with Mehlich 1 solution (HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}). Potential acidity (H + Al) was extracted with 0.5 mol L^{-1} calcium acetate pH 7.0. Ca^{2+} and Mg^{2+} were determined by complexometry, Al^{3+} by titration, K^+ and Na^+ by flame photometry and P by colorimetry. The total organic carbon (COT) was determined by the method proposed by Yeomans and Bremner (1988). COT contents were converted to soil organic matter (MOS) from multiplication by the factor 1.724 (Machado et al., 2003). Total carbon (CT) was obtained via dry combustion in a CHNS elemental analyzer. Organic carbon stock (EstC) was calculated according to the following equation (Du et al., 2017):

$$EstC = COT \times Ds \times E \times (1-R)$$

Where: EstC (Mg ha^{-1}) represents the concentration of organic carbon (g kg^{-1}), Ds is the density of the soil (kg dm^{-3}), E is the thickness of the evaluated layer (cm) and R is the content volumetric (%) of rock fragments > 2 mm in the soil.

With the results, the following indices were obtained: degree of flocculation (GF), base sum (SB), effective and total cation exchange capacity (CTCef), base saturation (V%), aluminum saturation (m%) and percentage of sodium saturation (PST) (Teixeira et al. 2017). Soil analysis results were interpreted according to Sobral et al. (2015).

The analyzes of the microbiological attributes were carried out at the Laboratory of Environmental Microbiology of INSA, evaluating the microbial biomass from the quantification of carbon (C-BMS), by the chloroform-fumigation-extraction (CEF) method (Vance et al., 1987) and the activity microbial growth by basal soil respiration (RBS) (Jenkinson and Powlson, 1976). The metabolic quotient (qCO_2) values, which express the ratio between basal respiration and soil microbial biomass per unit of time, were calculated by dividing CBM by RBS.

2.3 Data analysis

The data obtained were submitted to the nonparametric Mann-Whitney test ($p < 0.05$). In addition, principal component analyzes (PCA) were performed in order to reduce the large number of variables to a more significant set. The R software (version 4.1.0) was used for such analyzes (CoreTeam, 2017).

3. RESULTS

3.1 Morphology and physical attributes

The morphological and physical attributes of the studied areas are shown in Table 1. The soil under CAD is dark yellowish-brown and under CAE it is dark gray. Mottles occur only on the ground under CAE. Very friable medium/large subangular blocks predominate in the area under CAD, while extremely hard/firm massive structure was identified in CAE. Roots of varying sizes are common or abundant only in soil under CAD.

Table 1 – Morphological and physical attributes of the 0-20 cm layer of soils under sparse (CAE) and dense (CAD) shrubby Caatinga in the Brazilian semi-arid region. Experimental Station of the Instituto Nacional do Semiárido (INSA), municipality of Campina Grande, PB, Brazil.

Tabela 1 *– Atributos morfológicos e físicos da camada de 0-20 cm de solos sob Caatinga arbustiva esparsa (CAE) e densa (CAD) no Semiárido brasileiro. Estação Experimental do Instituto Nacional do Semiárido (INSA), município de Campina Grande, PB, Brasil.*

Área	Cor		Estr(1)	Consi(2)	Raízes(3)	Areia	Silte	Argila	ADA	Ds	GF
	Matriz	Mosqueado				---- $g\ kg^{-1}$ ----				$kg\ dm^{-3}$	%
CAE	10YR 4/6	7,5YR 4/1; 2,5YR 5/8	ma	ed, ef, np, npe	po, fi/mfi	781a(4)	119a	100b	60,0ns	1,17b	34,3ns
CAD	10YR 3/3	-	f, m/g, bs	s, mf, p, pe	ab (mf, fi); co (me, gr)	724a	66b	210a	64,0	1,58a	68,3

(1) Structure: f: weak; m: medium; g: coarse; bs: subangular blocky; ma: massive; (2) Consistence: s: loose; ed: extremely hard; mf: very friable; ef: extremely firm; np: non-plastic; p: plastic; npe: non-sticky; pe: sticky; Matriz: soil colour (matrix); Mosqueado; colour of mottles; Areia: sand, Silte: silt; Argila: clay, ADA: clay dispersed in water, Ds: soil bulk, GF: flocculation degree (4) Averages followed by different letters in the column differ by the Mann-Whitney test at 5% significance ($p<0,05$); ns Not significant.

(1) Estrutura: f: fraca; m: media; g: grande; bs: blocos subangulares; ma: maciça; (2) Consistência: s: solta; ed: extremamente dura; mf: muito friável; ef: extremamente firme; np: não plástica; p: plástica; npe: não pegajosa; pe: pegajosa; (3) po: poucas; co: comuns; ab: abundantes; mfi: muito finas; fi: finas; me: médias; gr: grossas. ADA: argila dispersa em água; Ds: densidade do solo; GF: grau de floculação. (4) Médias seguidas por diferentes letras na coluna diferem ao nível de 5% ($p<0.05$) pelo teste de Mann-Whitney; ns Não significativo.

The soil under CAE is sandy loam, while the soil under CAD is sandy loam (Table 1). There is no significant difference in sand, ADA and GF contents between the evaluated soils. Silt contents are significantly higher in CAE, while clay contents are significantly higher in CAD ($p < 0.05$). Silt contents are significantly higher under CAE, while Ds is significantly higher under CAD.

3.2 Chemical Attributes

The chemical attributes of the studied areas are presented in Table 2. Soil under CAE is practically neutral, while soil under CAD is moderately acidic. The low content of Ca^{2+} in the soil of CAE is significantly lower than the content considered high in the CAD (CAE: 0.5; CAD: 3.3 $cmol_c\ kg^{-1}$; $p < 0.05$). The average Mg^{2+} content in CAE is significantly lower than in CAD (CAE: 1.0; CAD: 1.9 $cmol_c\ kg^{-1}$; $p < 0.05$). Both soils have high K^+ contents, although significantly higher in CAD (CAE: 1.2; CAD: 7.9 $cmol_c\ kg^{-1}$; $p < 0.05$). Al^{3+} and P contents are low in both evaluated soils, although P is significantly higher in CAD.

CTCef is high in both soils, being significantly higher in CAD (Table 2). The base saturation (V%) is high and significantly higher in the soil

Table 2 – Chemical attributes, soil organic matter (MOS), total organic carbon (COT), carbon stock (EstC) and total carbon (CT) of soils in soils under sparse (CAE) and dense shrubby (CAD) soils in the Brazilian semi-arid region. Experimental Station of the Instituto Nacional do Semiárido (INSA), municipality of Campina Grande, PB, Brazil.

Tabela 2 *– Atributos químicos, teores de matéria orgânica solo (MOS), carbono orgânico total (COT), estoque de carbono (EstC) e carbono total (CT) de solos sob Caatinga arbustiva esparsa (CAE) e densa (CAD) no Semiárido brasileiro. Estação Experimental do Instituto Nacional do Semiárido (INSA), município de Campina Grande, PB, Brasil.*

Área	pH	CE	P	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	H +Al	SB
	H_2O	$dS\ m^{-1}$	$mg\ kg^{-1}$	---- $cmol_c\ kg^{-1}$ ----						
CAE	7,1a(1)	0,067b	1,5b	0,5b	1,0b	1,2b	2,0a	0,0b	1,0b	4,7b
CAD	5,7b	0,303a	9,7a	3,3a	1,9a	7,9a	0,9b	0,6a	7,5a	14,0a
	CTCef	**T**	**V**	**m**	**PST**	**MOS**	**COT**	**EstC**	**CT**	
	$cmol_c\ kg^{-1}$	---- % ----					$g\ kg^{-1}$	$Mg\ ha^{-1}$	$g\ kg^{-1}$	
CAE	4,7b	5,7b	-82,5a	0,0b	35,1a	0,6b(1)	3,6b	2,1b	6,4b	
CAD	14,6a	21,5a	65,1b	4,1a	4,2b	8,0a	46,2a	19,2a	100,1a	

(1) Average followed by different letters in the column differ by the Mann-Whitney test at 5% significance ($p < 0,05$). CE: electric conductivity; SB: sum of bases; CTCef: effective cation exchange capacity; T: cation exchange capacity at pH 7.0; V%: base saturation; m%: aluminum saturation; PST: sodium saturation percentage; MOS: soil organic matter; COT: total organic carbon; EstC: organic carbon stock; CT: total carbon.

(1) Médias seguidas por diferentes letras na coluna diferem ao nível de 5% ($p<0.05$) pelo teste de Mann-Whitney. CE: condutividade elétrica; SB: soma de bases: CTCef: capacidade de troca de cations efetiva; T: capacidade de troca de cátions à pH 7,0; V% saturação por bases; m: saturação por alumínio; PST: percentagem de saturação por sódio; MOS: matéria orgânica do solo; COT: carbon orgânico total; EstC: estoque de carbon orgânico; CT: carbono total.

Table 3 – Microbiological attributes of soils under sparse (CAE) and dense (CAD) shrubby Caatinga in the Brazilian semi-arid region. Experimental Station of the Instituto Nacional do Semiárido (INSA), municipality of Campina Grande, PB, Brazil.
Tabela 3 *– Atributos microbiológicos de solos sob Caatinga arbustiva esparsa (CAE) e densa (CAD) no Semiárido brasileiro. Estação Experimental do Instituto Nacional do Semiárido (INSA), município de Campina Grande, PB, Brasil.*

Área	C-BMS	RBS	qCO_2[1]
	mg kg^{-1}	mg $kg^{-1}h^{-1}$	mg g^{-1}
CAE	190,2[ns]	0,34b[2]	2,0b
CAD	150,4	0,91a	5,7a

[1] Soil analyzes performed according to the methodology described by Vance et al., (1987) and Jenkinson & Powlson (1976); [2] Averages followed by different letters in the column differ by the Mann-Whitney test at 5% significance ($p<0.05$); [ns] Not significant. C-BMS: carbon from soil microbial biomass; RBS: basal soil respiration; qCO_2: metabolic quotient.
[1] Análises de solo realizadas conforme procedimento descrito em Vance et al., (1987) e Jenkinson & Powlson (1976); [2] Médias seguidas por diferentes letras na coluna diferem ao nível de 5% (p<0.05) pelo teste de Mann-Whitney; [ns] Não significativo. C-BMS: carbono da biomassa microbiana; RBS: respiração basal do solo; qCO_2: coeficiente metabólico.

under CAE (CAE: 82.6; CAD: 64.9%; $p < 0.05$), while the aluminum saturation is low in both soils and significantly higher under CAD. Electrical conductivity (EC) is low in both soils and significantly higher in CAD. The PST in the CAE is high and significantly higher than the levels considered low for the CAD (CAE: 34.5; CAD: 4.3%; $p < 0.05$).

The COT (CAE: 3.6; CAD: 46.2 g kg^{-1}; $p < 0.05$) and CT (CAE: 6.4; CAD: 100.1%; $p < 0.05$) contents are significantly higher in CAD. Therefore, EstC is also significantly higher in soil under CAD (CAE: 2.1; CAD: 19.2 Mg ha^{-1}; $p < 0.05$).

3.3 Microbiological attributes

No significant difference was observed in microbial biomass carbon content (C-BMS) for the evaluated soils (Table 3). On the other hand, RBS

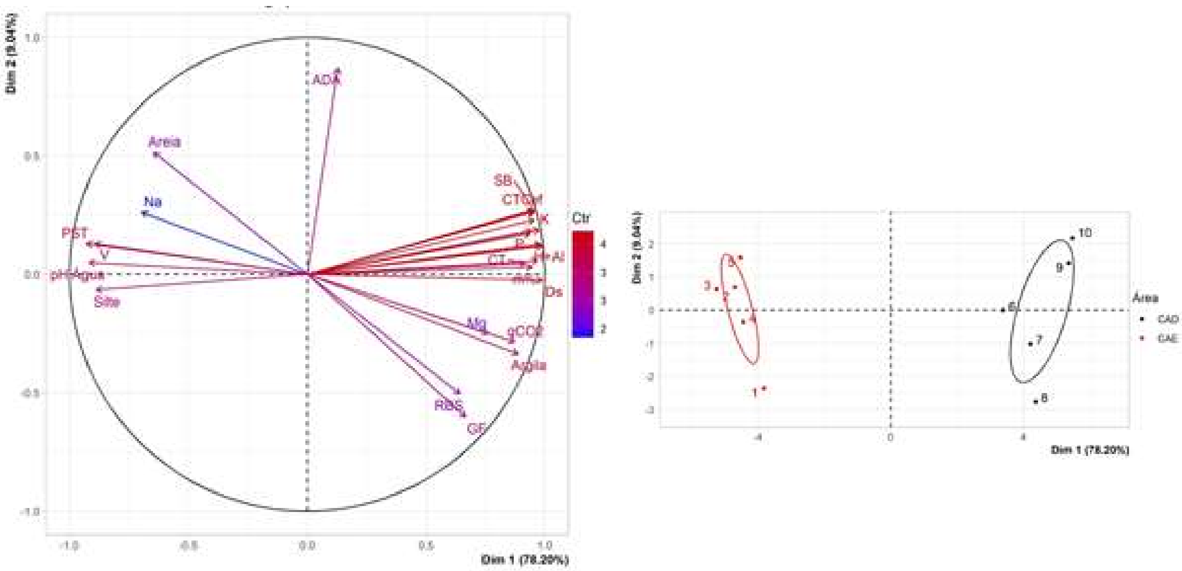

Figure 2 – Principal Component Analysis (PCA) of physical, chemical and microbiological attributes of soils under sparse (CAE) and dense (CAD) shrubby Caatinga in the Brazilian semi-arid region. Experimental Station of the Instituto Nacional do Semiárido (INSA), municipality of Campina Grande, PB, Brazil. CAE: 1-5; CAD: 6-10. Active acidity (pH_{H2O}), Potential acidity (H+Al), electric conductivity (CE), available levels of P, exchangeable levels of Ca^{2+}, Mg^{2+} e Al^{3+}, extractable contents of K^+ e Na^+, total carbon (CT), total organic carbon (COT), soil carbon stock (EstC), soil organic matter (MOS), effective cation exchange capacity (CTCef), cation exchange capacity at pH 7.0 (T), sum of bases (SB), base saturation (V%), aluminum saturation (m%), sodium saturation percentage (PST), granulometry (sand, silt and clay), clay dispersed in water (ADA), soil density (Ds), flocculation degree (GF), carbon from soil microbial biomass (C-BMS), basal soil respiration (RBS) e metabolic quotient (qCO_2).
Figura 2 *– Análise de Componentes Principais (ACP) de atributos físicos, químicos e microbiológicos de solos sob Caatinga arbustiva esparsa (CAE) e densa (CAD) no Semiárido brasileiro. Estação Experimental do Instituto Nacional do Semiárido (INSA), município de Campina Grande, PB, Brasil. CAE: 1-5; CAD: 6-10. Acidez ativa (pH_{H2O}), acidez potencial (H+Al), condutividade elétrica (CE), teores disponíveis de P, teores trocáveis de Ca^{2+}, Mg^{2+} e Al^{3+}, teores extraíveis de K^+ e Na^+, carbono total (CT), carbono orgânico total (COT), estoque de carbono no solo (EstC), matéria orgânica do solo (MOS), capacidade de troca de cátions efetiva (CTCef), capacidade de troca de cátions a pH 7,0 (T), soma de bases (SB), saturação por bases (V%), saturação por alumínio (m%), percentagem de saturação por sódio (PST), granulometria (areia, silte e argila), argila dispersa em água (ADA), densidade do solo (Ds), grau de floculação (GF), carbono da biomassa microbiana do solo (C-BMS), respiração basal do solo (RBS) e quociente metabólico (qCO_2).*

(CAE: 0.34; CAD: 0.91 mg g^{-1} h^{-1}; $p < 0.05$) and qCO_2 (CAE: 2.0; CAD: 5.7 mg g^{-1} h^{-1}; $p < 0.05$) are significantly higher in CAD.

3.4 Principal Component Analysis

The analysis of principal components of the physical, chemical and microbiological attributes of soils is presented in Figure 2. The two main components explained 87.6% of the data variability, with 78.5% and 8.9% being attributed to PCA1 and PCA2, respectively. The positive dimension of PCA1 is constituted by the attributes argila, ADA, GF, Ds, CE, Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, P, H+Al, SB, T, CTCef, COT, EstC, MOS, CT, m%, qCO_2 e RBS, while the negative dimension is composed of areia, silte, pH, V, Na^+ and PST. On the other hand, the positive dimension of PCA 2 is composed of the attributes pH, V, PST, Ca^{2+}, Al^{3+}, Na^+, areia, ADA, SB, T, SB, m%, CTCef, K^+, P, H+Al, CE, COT, Estc, MOS, CT, while the negative dimension consists of silte, m%, Ds, Mg^{2+}, RBS, qCO_2, argila e GF.

4. DISCUSSION

4.1 Degradation and physical attributes of soils

Our results showed that the removal of the Caatinga followed by the removal of the surface layer of the soil significantly altered soil properties. Such practices intensified the erosive processes in the area currently under sparse shrubby Caatinga (the authors observations), which resulted in the loss of the soil surface horizon (horizon A) and the exposure of the saprolite surface (horizon Crn). The occurrence of ≥ 50% of rock structure, < 50% of soil aggregates and massive structure confirm the occurrence of saprolite (Juilleret et al., 2016).

No variability was found in the sand contents, given the predominance of quartz in the soil source material and the low precipitation rates in the region. The higher levels of silt in CAE reflect the incipient pedogenesis of the saprolytic layer. The high silt/clay ratio confirms the moderate weathering in the saprolite, delaying the transformation and/or dissolution of plagioclases and micas that remain in the soils at silt particle size (Santos et al., 2018).

Studies have shown that seasonality and different land use systems alter Ds in semi-arid regions (Mora and Lazaro, 2014; Silva et al., 2021). In this research, Ds reflects the higher temperature on the surface of degraded soils, since it is more exposed (Oliveira et al., 2021), which contributes to the reduction of MOS from the oxidation of carbon with a consequent increase in Ds. In addition, in the soil under CAD there is a greater contribution of litter and roots, which contributes to an increase in MOS and a reduction in Ds.

4.2 Degradation and chemical attributes of soils

The more acidic reaction of soils in CAD is mainly due to the ionization of H^+ ions from carboxylic and phenolic acids, and notably from tertiary alcohols from organic matter (Silva and Mendonça, 2007). On the other hand, the practically neutral condition of the saprolite reflects its origin from gneisses and amphibolites, which release considerable amounts of basic reaction cations (Santos et al., 2017; Câmara et al., 2021).

Soils under CAE have a eutrophic character (V > 50%). However, in these soils Na^+ ions predominate in the exchange complex, while K^+, Ca^{2+} e Mg^{2+} are dominant in soils under CAD. This fact confirms that the removal of the surface layer of soils and the consequent exposure of the saprolite on the surface reduces soil fertility, which corresponds to 75% of the Ca^{2+} and K^+ contents and 47% of the Mg^{2+} contents. This lower availability of nutrients, together with the greater compactness of the saprolite, contributes to the slow regeneration of vegetation in the area.

Degradation promoted an increase in surface Na^+ contents. Surprisingly, these contents are much higher than the average values found in natric horizons in the SAB (Brasil, 1972; Oliveira Filho et al., 2020). These levels confirmed the sodium character (PST ≥ 15%) of the saprolite, whose origin is mainly credited to the weathering of plagioclases (dos Santos et al., 2018). In semi-arid regions, where the potential for evapotranspiration exceeds precipitation, Na^+ tends to predominate in the exchange (sodification) complex (Araújo Filho et al., 2017), which can lead to colloidal dispersion and reduced soil permeability, making regeneration difficult from degraded areas.

Significant carbon losses in degraded soils in the Brazilian semi-arid region have been reported (Neves et al., 2021; Santos et al., 2022). Our results confirm these observations, where the exposure of saprolite on the surface represents a reduction of 93.6% in CT and 87.8% in EstC, when compared to the surface layer of soil under CAD. Although the Caatinga vegetation in both areas acts as a carbon sink (Oliveira et al., 2021), our results indicate that only soils under CAD store carbon at levels reported for other areas of the Caatinga biome, even in amounts greater than found in Caatinga preserved under similar soils (Althoff et al., 2018).

Thus, considering that Leptsols sequester an average of 65 Mg ha^{-1} of total carbon, which corresponds to between 70 and 80% of the total carbon stock of ecosystems with Caatinga vegetation (Menezes et al., 2021), our results prove that degradation compromises atmospheric carbon sequestration, with direct impacts on the carbon cycle and the provision of ecosystem services, notably those related to regional climate regulation.

4.3 Degradation and microbiological attributes of soils

Soil microbiological attributes can be significantly altered with changes in land use, management practices and soil degradation (Kaschuk et al., 2010; Araújo Filho et al., 2018). The C-BMS values found for CAD and CAE are similar to those found for soils under different uses in the Caatinga (72 and 385 mg C kg^{-1}) (Kachuck et al., 2010).

The highest RBS observed in the CAD area indicates high biological activity and decomposition of organic matter, with a consequent high level of productivity in the ecosystem (Silva et al., 2007). A study carried out in agroforestry systems found greater RBS in the surface layer of the soil, associated with a greater amount of organic residues in this layer (Pezarico et al., 2013), corroborating the results of our study, where the CAD presented a greater amount of MOS.

The highest values of qCO_2 in soil under CAD reflect the release of CO_2 throughout the process of mineralization of organic matter. Higher values of qCO_2 were observed in forests and significantly decreased in soil under cultivation (Dinesh et al., 2003). According to the authors, these high values suggest that soil microorganisms in forests need high energy compared to cultivated sites. Higher values of qCO_2 in an area of native Caatinga when compared to cultivated areas are indicative that the microbial biomass in areas without cultivation has greater metabolic activity.

On the other hand, the significantly lower qCO_2 in CAE may indicate an economy in the use of energy by microorganisms in the saprolitic layer, which have become more efficient in the use of ecosystem resources, releasing less CO_2 into the atmosphere and incorporating more carbon contents to microbial tissues. This fact indicates a stable system, but not necessarily with a high level of productivity.

4.4. Degradation and density of vegetation cover

PCA clearly individualized the topsoil under CAD and the saprolite of the CAE area. In this way, we show that the slow regeneration of the Caatinga vegetation is taking place in a saprolitic layer with: (i) imperfect drainage, inferred by the occurrence of gray mottling (7.5YR 4/1) indicative of oxidation-reduction processes (gleization); (ii) low clay content, which implies a lower amount of clay minerals responsible for the high cation exchange capacity in saprolites in the SAB (Santos et al., 2017); (iii) low levels of organic matter and carbon, with adverse implications for the phenomena of nutrient adsorption and water absorption; (iv) high sodicity; and (v) reduced microbiological activity, which can compromise the mineralization of organic compounds and, therefore, the release of nutrients to plants.

On the other hand, soils under CAD have higher levels of nutrients and organic matter, with carbon stocks at levels similar or superior to other areas with preserved Caatinga vegetation. This explains the higher stage of vegetation regeneration in these soils, presenting higher primary production and significant contribution to atmospheric carbon sequestration (Oliveira et al., 2021). These conditions allow the characterization of this area as highly complex, given its capacity to maintain important ecosystem services for the semi-arid region, such as nutrient cycling, primary production (support services), erosion control and climate regulation (regulation services) (Araújo et al., 2021).

5. CONCLUSIONS

The removal of native vegetation followed by degradation causes the removal of the surface horizon of the soils and promotes the exposure on the surface of a saprolitic layer with high compactness, low nutrient and organic matter contents and high sodium contents.

Degradation significantly reduces the carbon stock and biological activity of the soil, resulting in an increase in carbon emissions into the atmosphere and savings in energy use by microorganisms, with adverse implications for the mineralization of organic matter and the release of nutrients.

Ecosystem services related to climate regulation and nutrient cycling are compromised with degradation. This adverse scenario increases the vulnerability of these areas to extreme weather events and the process of desertification, the latter due to regressive changes in soils, vegetation and water regime, leading to local biological deterioration, with direct implications for both the regeneration of Caatinga, as for the establishment of its productive capacity.

AUTHOR CONTRIBUTIONS

Conceptualization: Lambais ÉO, Macedo RS, Moro L, Lambais GR; Performed the analysis: Macedo RS, Moro L, Lambais ÉO, Lambais GR; Analysis of results: Macedo RS, Lambais ÉO, Lambais GR; Statistical analysis: Moro L; Writing-original draft: Macedo RS; Writing-review & editing: Moro L, Lambais ÉO, Lambais GR; Supervision and coordination of research; Bakker AP.

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