Geoderma Regional 33 (2023) e00647

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Changes in soil organic carbon and soil aggregation due to deforestation for smallholder management in the Brazilian semi-arid region

Aldair de Souza Medeiros[a,b,*], Giordano Bruno Medeiros Gonzaga[c], Thamirys Suelle da Silva[c], Bruno de Souza Barreto[a], Thiago Cândido dos Santos[a], Paul Lineker Amaral de Melo[d], Tâmara Cláudia de Araújo Gomes[e], Stoécio Malta Ferreira Maia[f]

[a] *Postgraduate Program in Biodiversity and Biotechnology in the Amazon (Rede Bionorte), Federal University of Maranhão (UFMA), São Luís, Maranhão, Brazil*
[b] *Postgraduate Program in Biodiversity and Conservation (PPGBC), Federal University of Maranhão (UFMA), São Luís, Maranhão, Brazil*
[c] *Center of Agrarian Sciences, Federal University of Alagoas (UFAL), Rod. BR 104, km 85, 57100-000 Rio Largo, Alagoas, Brazil*
[d] *Department of Soil Science, Luiz de Queiroz College of Agriculture (ESALQ), University of São Paulo (USP), Avenida Paduas Dias, 11, 13418-900 Piracicaba, São Paulo, Brazil*
[e] *Brazilian Agricultural Research Corporation (Embrapa Tabuleiros Costeiros), Research and Development Execution Unit, Rod. BR 104, km 85, 57100-000 Rio Largo, Alagoas, Brazil*
[f] *Federal Institute of Education, Science and Technology of Alagoas (IFAL), Rua Lourival Alfredo, 176, 57160-000 Marechal Deodoro, Alagoas, Brazil*

A R T I C L E I N F O

Keywords:
Caatinga
CO_2 emissions
Conventional tillage
Multiple soil classes
Water-stable aggregate

A B S T R A C T

The Brazilian semi-arid region has currently approximately 33.3 million hectares occupied by agriculture, and the inadequate land use and management practices are still predominant, which have been associated with the soil degradation process. Therefore, the aims of this study were to evaluate the effect of conventional agricultural systems (cropland and pasture) on soil structure using water-stable aggregate and aggregation indexes, and to assess the impacts on soil organic carbon (SOC) stocks in different soil types and textures in the Brazilian semi-arid region. The study was carried out in the municipalities of Delmiro Gouveia, Inhapi and Pariconha, in the Brazilian semi-arid region of the state of Alagoas, Brazil. Arenosols, Acrisols and Regosols soil samples were collected at 0–10, 10–20 and 20–30 cm layers. The treatments analyzed were: Cropland with 4, 15 and 30 years and pasture with 10 years. As a reference, native vegetation (Caatinga) was used. Our results show that the maintenance of SOC and structure and soil physical quality in conventional agricultural systems in the Brazilian semi-arid region depend on soil type/texture and climate. In agricultural systems in Acrisols with sandy clay loam texture, a 5.4% non significant increase was observed in SOC stocks after 30 years of use compared to SOC stocks in the native vegetation area; while in soils with sandy texture (Arenosols and Regosols), the SOC stocks were reduced by 16.1% in comparison to areas under native vegetation. The analysis of water-stable aggregate in Acrisols showed great predominance of macroaggregates (>2.0 mm). On the other hand, in sandy soils (Arenosols and Regosols), great predominance of mesoaggregates was observed (<2.00 and > 0.25 mm).

1. Introduction

The Brazilian semi-arid region covers approximately 844.000 km^2, corresponding to 10% of the national territory (Brasil, 2020). However, it is an undeveloped region and the most populous semi-arid region in the world, with >27 million inhabitants (ASA, 2021), where agriculture is mainly conducted by smallholders, who adopt indiscriminate deforestation to produce predominantly subsistence crops (bean, maize, cassava), inadequate fallow periods and soil tillage, known as "conventional agricultural systems" (Medeiros et al., 2020). Therefore, conventional agricultural systems associated with the climatic characteristics of the Brazilian semi-arid region (high evapotranspiration and temperatures, reduced and irregular rainfall), greatly limiting soil fertility and agricultural production, resulting in the opening of new agriculture areas. The overgrazing is common in pasture area, with animals especially cattle. In addition, grazing in agricultural areas after harvests (Medeiros et al., 2021). There is also a substantial extraction of wood and timber to meet family demands (Maia et al., 2006; Santana

* Corresponding author at: Postgraduate Program in Biodiversity and Biotechnology in the Amazon (Rede Bionorte), Federal University of Maranhão (UFMA), São Luís, Maranhão, Brazil.
E-mail address: aldair.medeiros@ufma.br (A. de Souza Medeiros).

https://doi.org/10.1016/j.geodrs.2023.e00647
Received 22 March 2023; Received in revised form 1 May 2023; Accepted 5 May 2023
Available online 6 May 2023

et al., 2019), greatly contributing to the reduction of native vegetation, known as “Caatinga” – drought deciduous trees that lose their leaves during 8–9-months of long dry season and with many cactus species (Brasil, 2020). Therefore, inadequate land use (conventional agricultural systems) and climatic characteristics, have led to the process of environmental degradation and stagnation of productivity levels in the agriculture and livestock activity of the Brazilian semi-arid region.

The environmental degradation in this region has negative effects mainly on soil, leading to reduced water infiltration, increased erosion, nutrient loss, soil structure degradation and reduced soil organic carbon (SOC) and nitrogen contents (Maia et al., 2007; Guimarães et al., 2013; Medeiros et al., 2020). Soil structure is an important property that mediates many physical, chemical and biological processes and controls the soil organic matter (SOM) decomposition (Six et al., 2000; Sá et al., 2014; de Blécourt et al., 2019). Soil aggregate size distribution and stability are important indicators of structure and soil physical quality, generally reflecting the impact of land use and soil quality management and degradation of the managed area (Castro Filho et al., 2002; Plaza-Bonilla et al., 2013; Medeiros et al., 2018). For the Brazilian semi-arid region in Luvisol, Maia et al. (2006) found that the conversion of native vegetation to conventional agricultural systems with five years significantly reduced the SOC content; however, did not significantly change macroaggregation.

The conversion of native vegetation into conventional agricultural systems (cropland and pasture) causes considerable SOC changes. However, it depends on the cultivation system and agricultural practices adopted (Ogle et al., 2005; Medeiros et al., 2020, 2022). For example, Guo and Gifford (2002) estimated average world SOC losses of 42% and 59% after conversion of native vegetation and pastures into crop, respectively. Likewise, in the Brazilian semi-arid region, Medeiros et al. (2020) found SOC losses ranging from 2% to 26% over time of land use. In studies carried out on desertification areas with 20 years in Luvisol and Alfisol of the Brazilian semi-arid region, results point to mean SOC reduction of 58% (Martins et al., 2010; Sousa et al., 2012), while studies on management systems with 5 years in Luvisol present different results, such as SOC reductions between 7% and 33% in agroforestry areas (Maia et al., 2007) and organic systems with 2 years in Arenosols (Xavier et al., 2009). However, these values are very different from those found by Maia et al. (2013) for Ferralsols of the Cerrado biome of Brazil, where SOC reduction of 8% in low clay soils and increase of 10% in very clayey soils were found. Therefore, the loss of SOC in cropland and pasture areas has been attributed to reduced stabilization of SOM due to deteriorated aggregation, lower C inputs in croplands, erosion and mineralization promoted by increased soil temperature and aeration (Wiesmeier et al., 2019).

Long-term land use under grassland or forest or under conservation agriculture may improve SOC in certain soil types. Also, degradation of soil after conversion from native land (grassland, forest) to cropland and vice versa might happened faster or slower depending on soil type and duration of land use (Wiesmeier et al., 2019; Mamedov et al., 2021). In relation to the structure and soil physical quality, in tablelands of the Loess Plateau of China, Liu et al. (2014) found that the dominant aggregate size fractions under farmland were $<$ 0.5 mm, whereas the dominant aggregate size fractions under grassland and forestland were $>$ 0.5 mm. In addition, increase in clay content may positively or negatively affect soil aggregate stability, for example, in Mediterranean semi-arid agroecosystems, Plaza-Bonilla et al. (2013) in Typic Xerofluvent found the increase in the proportion of stable macroaggregates and the enrichment of C concentration within microaggregates are two main mechanisms of SOC protection when no-tillage is maintained over time. According to Mamedov et al. (2021), even one single tillage operation can significantly decrease the portion of water-stable macroaggregates ($>$250 mm) and 30–40% light fraction of SOC in grassland or long-term NT system; in addition, subsequent reestablishment of the grassland might take 5–6 years.

For the semi-arid region, studies evaluating SOC and soil aggregation in agroforestry, agroecological and intercropping systems, or in areas under degradation/desertification process, are obviously important and necessary. However, this land use do not represent conventional agricultural systems, mostly performed by smallholder that still predominate in the Brazilian semi-arid region and, therefore, do not allow evaluating their impacts on issues such as changes in SOC stocks and their contribution to greenhouse gas emissions, or structure and soil physical quality by assessing the stability of aggregates.

Therefore, our hypothesis is that the adoption of conventional agricultural systems conducted by smallholders under the Brazilian semi-arid conditions leads to the continuous degradation of soil physical quality and structure, negatively affecting soil aggregation and SOC stocks. Therefore, the aims of this study were to evaluate the effect of conventional agricultural systems (cropland and pasture) on soil physical quality using water-stable aggregate classes and aggregation indexes, and to assess the impacts on SOC stocks in three different soil types and varying in texture in the Brazilian semi-arid region.

2. Material and methods

2.1. Description of the study area

In order to evaluate the impacts of conventional agricultural systems on SOC and aggregation of three different soil types (Arenosols, Acrisols and Regosols), two representative agricultural systems (agriculture and pasture) of the Brazilian semi-arid region were assessed. Studies were conducted in the semi-arid region of the state of Alagoas (AL), northeastern Brazil (Fig. 1), in municipalities of Delmiro Gouveia (09° 29′ 004″ S; 37° 56′ 24.3″ W), Inhapi (09° 12′ 13.20″ S; 37° 44′ 11.44″ W) and Pariconha (09° 17′ 04.7″ S, 38° 02′ 43.4″ W). The climate of the semi-arid region is classified by Köppen as BSh type, representing hot and dry climate with annual mean temperature between 25 °C and 30 °C, with few variations, reaching up to 40 °C in the summer, air relative humidity generally $<$50%, mean annual rainfall of 586 mm distributed between April and July, with average monthly potential evapotranspiration of 215 mm and dry season from 8 to 9 months a year (Brasil, 2020).

In each municipality, a farm was selected with cropland and pasture areas close to the native vegetation area to represent the original soil conditions. These areas were selected considering the knowledge about land use and management practices adopted on the farm since conversion from native vegetation, and the cropland area had to occur within 0.2 km from the reference area with similar landscape, soil type and texture. In this study, eight land use systems in three different soil types were evaluated, classified according to IUSS Working Group WRB-FAO (2015).

All cropland areas were in production (non-experimental areas), under rainfed agricultural systems without management practices such as fertilizing (organic or inorganic), intercropping and crop rotation; Irrigation and crops were randomly chosen, depending on reasons such as seed availability, market price, etc. Crop residues are generally available for animal grazing. In general, 3–4 years of fallow were adopted in these areas, followed by mowing, burning of plant biomass and soil tillage, usually performed with animal traction plowing (conventional agricultural systems), with crops of 4–5 consecutive years.

In the municipality of Delmiro Gouveia, three land use systems in Arenosols were studied: Native vegetation area, with about 40 years of regeneration, steppe savanna comprising low trees and shrubs, which lose leaves in the dry period and with many cactus species (Brasil, 2020), and two agricultural areas measuring 3.0 and 2.5 ha, with 4 and 15 years of cultivation, respectively, alternated with maize, common bean and cassava. Soil management is based on conventional tillage with animal traction plowing and grazing of crop residues.

In the municipality of Inhapi, two land use systems in Acrisols were evaluated: Native vegetation area, with about 40 years of regeneration and agricultural area measuring 4.0 ha, with 30 years of cultivation

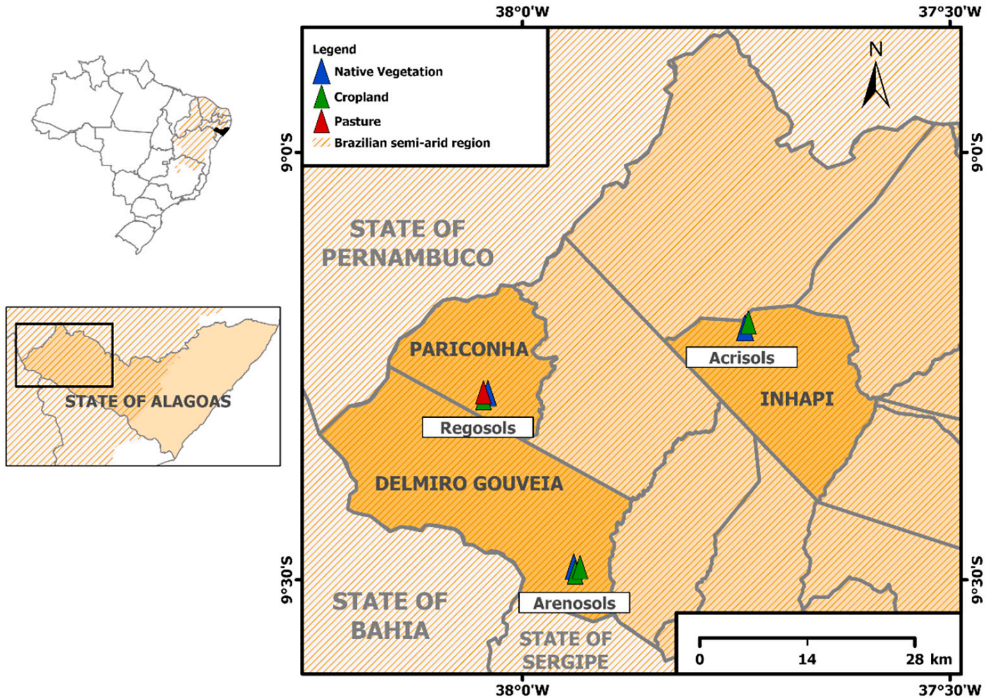

Fig. 1. Location of study areas in the semi-arid region of the state of Alagoas, Brazil.

alternated with maize, common bean and cassava, under conventional tillage and grazing of crop residues.

In the municipality of Pariconha, three land use systems in Regosols were evaluated: Native vegetation area, with about 40 years of regeneration, agricultural area measuring 2.0 ha, with 4 years of cultivation alternated with maize, common bean and cassava, under conventional tillage and grazing of crop residues, and pasture area with Pangola grass (*Digitaria Umfolozi*) measuring 6.0 ha. At the time of soil sampling, the area of pasture had been left for 10 years without any type of tillage, but previously, the area was cultivated for 30 years with maize and beans under the same practices (soil tillage, grazing of crop residues and fallow period), the same as those adopted in the other agricultural areas.

2.2. Soil sampling

Soil samples were collected from five points (5 replications) of each land use (native vegetation, cropland and pasture), which were randomly selected and arranged in a square of 100 × 100 m, having one pit at each corner and one in the center. However, collection points were always located in the same position of the relief and aiming to obtain the best spatial distribution within each land use. Soil samples were collected up to 30 cm in depth at 0–10, 10–20 and 20–30 cm layers. Samples were air-dried and sieved with 2-mm mesh to remove stones and root fragments before analysis. The main physical and chemical characteristics of soils are shown in Table 1.

2.3. Soil organic carbon and bulk density

Sub-samples were sieved through 100 mesh (0.149 mm) and ground to a fine powder before total carbon determination. Total carbon was measured by dry combustion in elemental analyzer (NCHS) model Flash 2000 (Thermo Scientific). Bulk density (BD) was measured in each sampled layer using the volumetric ring method (Teixeira et al., 2017). For each soil layer, SOC stock was calculated by multiplying C content (g g^{-1}) by BD (g cm^{-3}) and layer thickness (cm). Soil mass correction was performed for conventional systems (cropland and pasture), as described in Sisti et al. (2004). Soil under native vegetation was used as reference for soil mass correction.

2.4. Water-stable aggregate and aggregation indexes

Water-stable aggregate was evaluated according to procedure described by Teixeira et al. (2017). The analysis of aggregates was performed in duplicate, where 50 g of soil samples with diameter class <4.76 mm were weighed, transferred to Petri dishes, moistened with spray, and then placed in sieves with meshes of 4.76; 2.0; 1.0; 0.50 and 0.25 mm, being submitted to vertical stirring in Yodder's apparatus for 4 min. Subsequently, the material retained on each sieve was placed in aluminum cans and dried in an oven at 105 °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 mm), according to procedure described by Costa Junior et al. (2012).

Values obtained in sieves were used to calculate three aggregation indices, namely: mean weight diameter (MWD), geometric mean diameter (GMD), and aggregate stability index (ASI), which were determined according to Medeiros et al. (2018), obtained through Eqs. (1), (2) and (3):

$$MWD = \sum\nolimits_{i=1}^{n} (xi.wi) \tag{1}$$

where: wi = proportion of each class in relation to the total; xi = mean diameter of classes (mm).

$$GMD = exp\frac{\sum_{l=1}^{N} wp.logxi}{\sum_{l=1}^{N} wp} \tag{2}$$

where: wp = weight of aggregates of each class (g); xi = mean diameter of classes (mm).

$$ASI = \frac{WDS - wp25 - sand}{WDS - sand} \tag{3}$$

where: wp25 = dry weight of aggregates of class <0.25 mm; WDS = weight of each dried sample. For ASI calculation, sand correction was performed in each aggregate-size class because sand was not considered part of these aggregates (Plaza-Bonilla et al., 2013).

Table 1
Physical and chemical characterization in different soil types and land-use systems in the semi-arid region of Alagoas, Brazil.

Attributes[1]	Soil type / Texture								
	Arenosols / Loamy sand								
	0–10 cm			10–20 cm			20–30 cm		
	Native vegetation	Cropland 4 years	Cropland 15 years	Native vegetation	Cropland 4 years	Cropland 15 years	Native vegetation	Cropland 4 years	Cropland 15 years
Clay (%)	7.80	5.10	11.70	9.20	8.53	5.15	8.30	11.80	4.00
Sand (%)	87.60	91.42	88.16	90.09	85.80	84.95	87.47	74.41	83.90
Silt (%)	4.61	3.48	0.14	0.72	5.67	9.90	4.23	13.79	12.10
N ($g\ g^{-1}$)	0.14	0.11	0.15	0.11	0.09	0.11	0.24	0.08	0.11
C ($g\ g^{-1}$)	1.03	0.87	0.67	0.69	0.72	0.49	0.64	0.61	0.50
Ca^{+2} ($Cmol_c\ dm^{-3}$)	0.54	1.40	1.88	0.71	0.83	1.63	0.51	1.48	1.14
Mg^{+2} ($Cmol_c\ dm^{-3}$)	0.09	0.33	0.59	0.18	0.19	0.44	0.13	0.11	0.38
K^{+} ($Cmol_c\ dm^{-3}$)	0.17	0.27	0.30	0.14	0.19	0.28	0.14	0.18	0.26
Na^{+} ($Cmol_c\ dm^{-3}$)	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.02
P_{meh} ($mg\ kg^{-1}$)	14.80	12.40	7.20	6.80	6.80	5.20	5.00	4.40	4.20
CEC ($Cmol_c\ dm^{-3}$)	5.87	5.91	5.69	5.70	5.99	5.82	5.34	6.56	5.62
pH in H_2O	4.46	4.92	5.12	4.38	4.50	4.92	4.38	4.40	4.80

	Acrisols / Sandy clay loam								
	0–10 cm		–	10–20 cm		–	20–30 cm		–
	Native vegetation	Cropland 30 years		Native vegetation	Cropland 30 years		Native vegetation	Cropland 30 years	
Clay (%)	15.70	20.70		23.95	22.93		23.23	32.17	
Sand (%)	66.76	62.74		61.84	53.79		59.95	52.86	
Silt (%)	17.54	16.56		14.21	23.28		16.82	14.98	
N ($g\ g^{-1}$)	0.22	0.24		0.18	0.20		0.16	0.16	
C ($g\ g^{-1}$)	1.38	1.41		0.87	0.96		0.68	0.73	
Ca^{+2} ($Cmol_c\ dm^{-3}$)	3.21	2.61		2.33	1.66		2.18	2.13	
Mg^{+2} ($Cmol_c\ dm^{-3}$)	0.84	0.61		0.64	0.64		0.67	0.63	
K^{+} ($Cmol_c\ dm^{-3}$)	0.36	0.30		0.23	0.21		0.16	0.15	
Na^{+} ($Cmol_c\ dm^{-3}$)	0.02	0.02		0.02	0.02		0.02	0.02	
P_{meh} ($mg\ kg^{-1}$)	11.80	5.60		3.20	3.80		3.40	3.20	
CEC ($Cmol_c\ dm^{-3}$)	6.60	6.63		5.68	4.90		5.06	5.32	
pH in H_2O	5.94	5.22		5.86	5.52		5.76	5.66	

	Regosols / Loamy sand								
	0–10 cm			10–20 cm			20–30 cm		
	Native vegetation	Pasture	Cropland 4 years	Native vegetation	Pasture	Cropland 4 years	Native vegetation	Pasture	Cropland 4 years
Clay (%)	5.20	2.60	7.00	3.40	3.50	8.05	5.70	4.60	7.70
Sand (%)	89.35	87.00	80.44	87.72	83.66	75.18	87.40	81.87	72.87
Silt (%)	5.45	10.40	12.57	8.89	12.84	16.77	6.91	13.53	19.43
N ($g\ g^{-1}$)	0.16	0.14	0.20	0.18	0.18	0.25	0.12	0.18	0.10
C ($g\ g^{-1}$)	1.41	0.88	1.22	0.68	0.75	0.65	0.56	0.54	0.49
Ca^{+2} ($Cmol_c\ dm^{-3}$)	1.79	1.76	1.97	0.84	1.55	0.83	1.15	1.38	0.65
Mg^{+2} ($Cmol_c\ dm^{-3}$)	0.51	0.41	0.57	0.33	0.25	0.26	0.49	0.22	0.23
K^{+} ($Cmol_c\ dm^{-3}$)	0.18	0.29	0.19	0.20	0.25	0.12	0.13	0.26	0.12
Na^{+} ($Cmol_c\ dm^{-3}$)	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
P_{meh} ($mg\ kg^{-1}$)	6.40	4.40	6.80	4.00	4.20	5.00	3.80	3.80	3.60
CEC ($Cmol_c\ dm^{-3}$)	6.34	4.00	5.13	4.49	3.88	3.03	4.05	3.54	2.57
pH in H_2O	5.08	5.86	5.40	5.20	6.00	5.34	5.42	5.90	5.44

[1] According to procedure described by Teixeira et al. (2017).

2.5. Statistical analyses

Data were analyzed considering a completely randomized design, with eight treatments (land use systems) and three soil depths (0–10, 10–20 and 20–30 cm) within each soil type (Acrisols, Arenosols and Regosols) and five replicates. In all situations, data were submitted to normality analysis of residuals using the Shapiro-Wilk test ($p \leq 0.05$), analysis of variance (F test) and comparison of means (Tukey test at 0.05 significance level). The analysis of homogeneity of variances was performed and outliers were removed from the dataset.

Additionally, multivariate statistical analysis was used to determine relationships between SOC content, physical attributes and soil aggregation in the three soil types and their different layers. The attributes considered for soils were: SOC content, bulk density, macroaggregates, mesoaggregates, microaggregates, MWD, GWD, ASI, sand, silt, clay content. The data set, with normal distribution, was standardized ($\mu = 0$; $\sigma^2 = 1$) to provide the same significance to each variable. Subsequently, principal components analysis (PCA) was used to reduce the dimensionality of attributes in smaller number of new independent and interpretable variables (orthogonal principal components - PC). The Kaiser-Guttman method was used to retain the principal components that could be interpreted. This method retains components whose eigenvalue is >1. Only the first two principal components are presented because they capture most of the variance. In addition, confidence ellipses (95%) were constructed to separate the sampling units according to soil type and layer depth. Analysis was conducted using R Statistical Software (R Core Team, 2022), FactoMineR (Lê et al., 2008), and factorextra packages (Kassambara and Mundt, 2020).

3. Results

3.1. Soil organic carbon

The highest SOC content (Table 2) was found in superficial layers (0–10 cm), significantly reducing ($p \leq 0.05$) with depth in all land use systems and soil types evaluated (except for cropland with 15 years in Arenosols). In Arenosols, the highest SOC content was found in the native vegetation area, but with significant difference only from cropland with 15 years at 0–10 and 10–20 cm layers. For Regosols, significant interaction was found land use systems and soil depths, with the highest SOC contents recorded for the native vegetation area, but with significant difference only from the pasture system at the 0–10 cm layer. In Acrisols, cropland with 30 years presented SOC contents higher than those of native vegetation, however, without statistical difference ($p \geq 0.05$).

Fig. 2 shows SOC stock values in different land use systems and soil types. Regarding SOC stocks for the entire layer (0–30 cm), in Arenosols, conversion from native vegetation to agricultural systems with 4 and 15 years of cultivation reduced ($p \leq 0.05$), respectively, SOC stocks to 6.5% and 28.9%. In Regosols, significant SOC stock reductions ($p \leq 0.05$) of 17.2% and 11.7% were found due to conversion into pasture and cropland with 4 years, respectively. For Acrisols, which had higher clay content (23.1% on average), despite the increase in SOC stock of 5.4% in cropland with 30 years in relation to native vegetation, there was no statistical difference ($p \geq 0.05$). It is noteworthy that the decrease in SOC occurred mainly in the superficial layer in all soil types, except for Acrisols, and in the pasture system, no significant increase in SOC stocks was observed in lower layers, when compared to the reference area (native vegetation).

3.2. Soil bulk density, aggregate classes and soil aggregation indexes

Bulk density results showed low variation between land use systems and soil layers in the different soil types (Table 2). For the entire data set, values ranged from 1.37 to 1.61 g cm^{-3}. In Arenosols (loamy sand texture), the highest bulk density values were found in cropland with 15 years, differing ($p \leq 0.05$) only from native vegetation in the topsoil. In Regosols, the pasture system had the highest bulk density, regardless of soil layer, but it only differed ($p \leq 0.05$) from cropland with 4 years in the 0–10 cm layer. In Acrisols with sandy clay loam texture, no significant differences were found in bulk density values in the native vegetation and cropland with 30 years.

The distribution of water-stable aggregates in the different diameter classes (macroaggregates, mesoaggregates and microaggregates), land use systems and depths showed different trends among soil types under study (Fig. 3). Initially, it was observed that in Arenosols, there was predominance of mesoaggregates (<2.00 and > 0.25 mm) regardless of land use system, and the lowest percentages were found for cropland with 15 years, statistically differing from the other land use systems only in the topsoil. In Regosols (loamy sand texture), mesoaggregates also predominate, but without statistical difference between land use systems, with average values of com medias de 71.5%, 71.5% and 67.2% at 0–10, 10–20 and 20–30 cm layers, respectively. It is important to note that in the pasture system, macroaggregate values (diameter > 2.00 mm) were higher ($p \leq 0.05$) than the other land use systems in all soil layers. In Acrisols, there was an evident predominance of macroaggregates, with average values of 62%, 44% and 49% at 0–10, 10–20 and 20–30 cm layers, respectively. In addition, the results of the classes of aggregates do not differ statistically ($p \geq 0.05$) from the native vegetation and cropland with 30 years.

The mean MWD, GMD and ASI values in the different soil types of the semi-arid region of Alagoas, Brazil, are presented in Table 3. In Arenosols, significant difference ($p \leq 0.05$) was observed for MWD only in the superficial layer, in which cropland with 15 years had the highest values, differing only from cropland with 4 years. In Acrisols, there was no significant difference in MWD values in the evaluated land use systems, and the highest values were found in the superficial layer. In Regosols, the highest values were observed in the pasture system, statistically differing ($p \leq 0.05$) from the other land use systems for all soil depths.

GMD showed significance ($p \leq 0.05$) in Arenosols only in the superficial layer, where the highest values were found in cropland with 15 years, significantly differing only from native vegetation. In Acrisols and Regosols, no significant differences ($p \geq 0.05$) were found in GMD values of evaluated systems.

With regard to ASI, in Arenosols, the highest results were found in the native vegetation, differing ($p \leq 0.05$) from the other land use systems at 0–10 and 20–30 cm depths. In Acrisols, there was no statistically significant difference between results of systems under study. In Regosols, ASI results presented significant difference between land use systems only at the 20–30 cm layer, with the highest values being found for the pasture system.

3.3. Multivariate statistical analysis

PCA identified four components for all land use systems, and these components explained 80.92% of the total variation (Table 4). The first component (PC1) explained 54.90% of the total variation, which was

Table 2
Soil organic carbon content and soil bulk density in different soil types and land-use systems in the semi-arid region of Alagoas, Brazil.

Layer (cm)	Soil type / Land-use system							
	Arenosols / Loamy sand			Acrisols / Sandy clay loam		Regosols / Loamy sand		
	Native vegetation	Cropland 4 years	Cropland 15 years	Native vegetation	Cropland 30 years	Native vegetation	Pasture	Cropland 4 years
	Soil organic carbon (g g^{-1})							
0–10	1.03 (0.29) Aa	0.87 (0.08) ABa	0.67 (0.01) Ba	1.37 (0.22) Aa	1.41 (0.17) Aa	1.41 (0.38) Aa	0.88 (0.09) Ba	1.22 (0.22) Aa
10–20	0.68 (0.12) ABb	0.72 (0.21) Aab	0.49 (0.07) Ba	0.86 (0.13) Ab	0.96 (0.12) Ab	0.68 (0.19) Ab	0.75 (0.14) Aab	0.65 (0.20) Ab
20–30	0.64 (0.10) Ab	0.61 (0.14) Ab	0.50 (0.11) Aa	0.68 (0.05) Ab	0.72 (0.07) Ac	0.56 (0.13) Ab	0.54 (0.03) Ab	0.49 (0.11) Ab
	Soil bulk density (g cm^{-3})							
0–10	1.38 (0.05) Ba	1.41 (0.08) ABa	1.49 (0.05) Aa	1.45 (0.04) Aa	1.48 (0.08) Aa	1.51 (0.04) ABa	1.58 (0.04) Aa	1.47 (0.05) Ba
10–20	1.45 (0.05) Aa	1.41 (0.05) Aa	1.48 (0.06) Aa	1.45 (0.05) Aa	1.46 (0.04) Aa	1.52 (0.05) Aa	1.60 (0.09) Aa	1.50 (0.06) Aa
20–30	1.41 (0.02) Aa	1.42 (0.02) Aa	1.48 (0.08) Aa	1.43 (0.05) Aa	1.37 (0.05) Ab	1.53 (0.05) ABa	1.61 (0.07) Aa	1.52 (0.08) Ba

Values within parentheses represent the standard deviation of the mean (n = 5). Equal uppercase letters for land use systems and lowercase letters for layers, within the same soil type, do not differ by Tukey's test ($p \leq 0.05$).

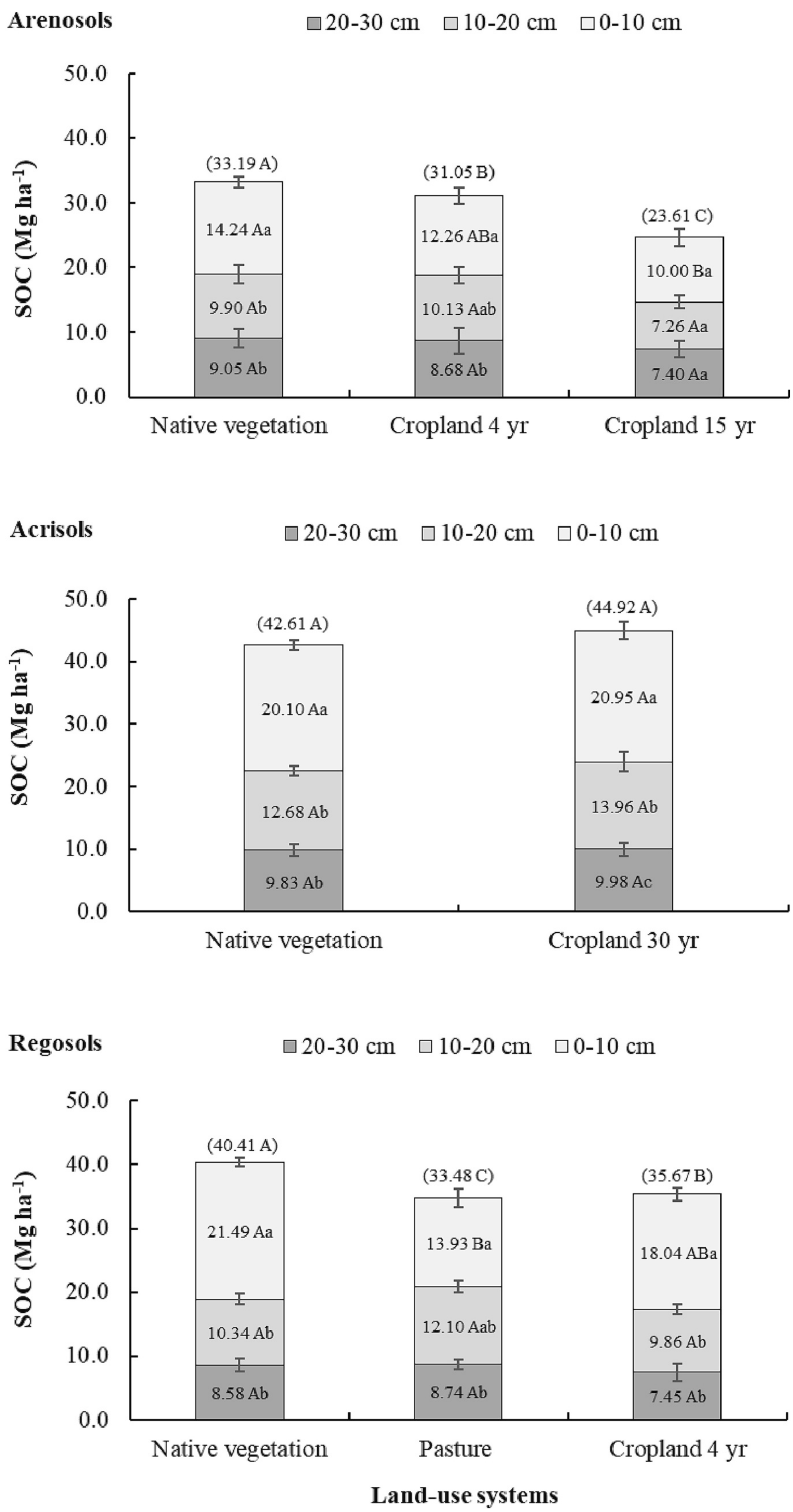

Fig. 2. SOC stocks for the 0–10, 10–20 and 20–30 cm layers in the different land-use systems and soil types in the semi-arid region of Alagoas state, Brazil. Values within parentheses are the SOC stocks in the 0–30 cm layer after correction using equivalent soil mass approach. Error bars show the standard deviation of the mean (n = 5). Equal uppercase letters for land use systems and lowercase letters for layers, within the same soil type, do not differ by Tukey test ($p \leq 0.05$).

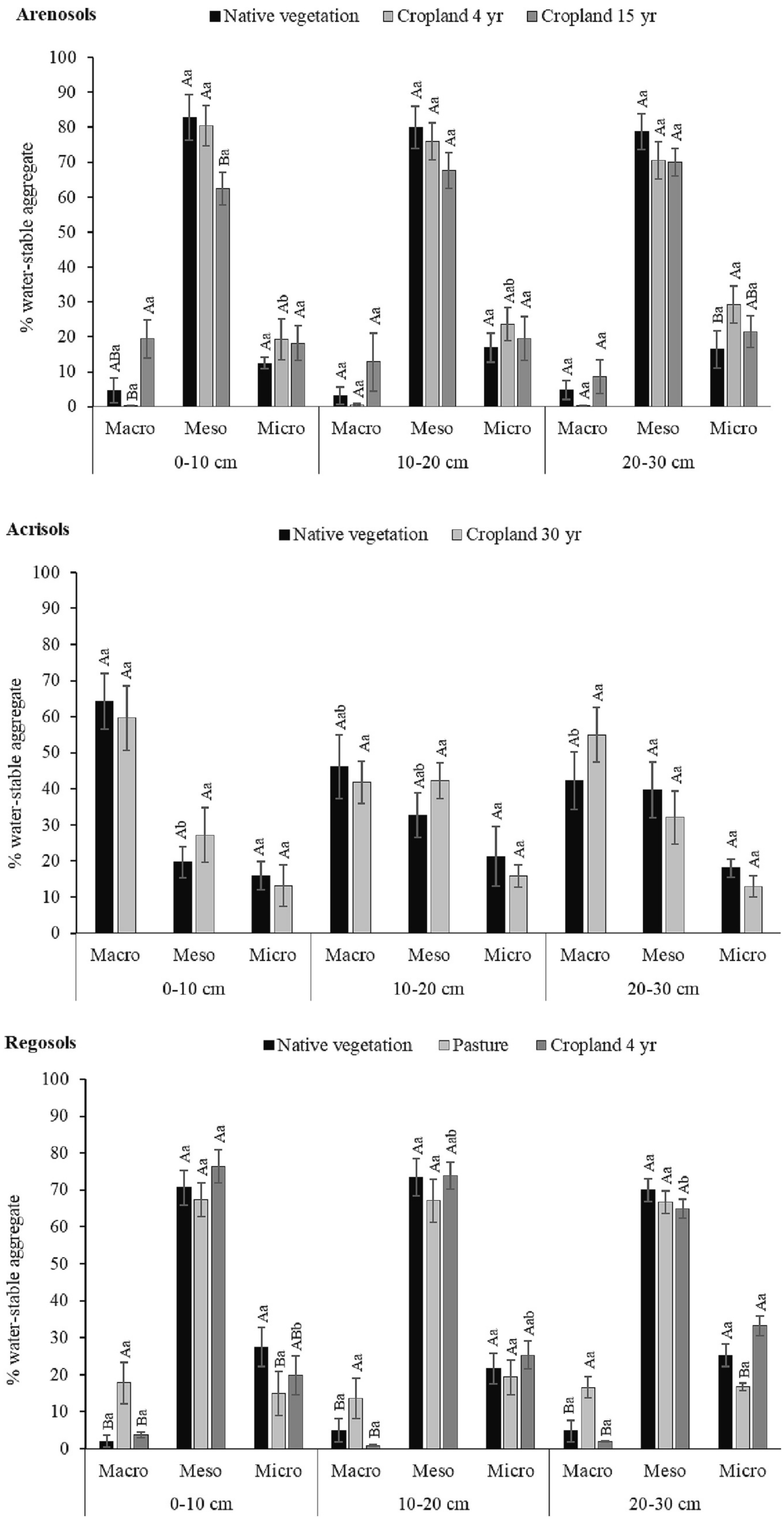

Fig. 3. Relative distribution of water-stable aggregates classes (%) macroaggregates (Macro), mesoaggregates (Meso) and microaggregates (Micro) for the 0–10, 10–20 and 20–30 cm layers under different land use systems in the Arenosols, Acrisols and Regosols. Error bars show the standard deviation of the mean ($n = 5$). Equal uppercase letters for land use systems and lowercase letters for layers, within the same soil type, do not differ by Tukey's test ($p \leq 0.05$).

Table 3
Mean values of the mean weight diameter, geometric mean diameter and aggregate stability index in different soil types and land use systems in the semi-arid region of Alagoas, Brazil.

Layer (cm)	Soil type / Land-use system							
	Arenosols / Loamy sand	Acrisols / Sandy clay loam			Regosols / Loamy sand			
	Native vegetation	Cropland 4 years	Cropland 15 years	Native vegetation	Cropland 30 years	Native vegetation	Pasture	Cropland 4 years
	Mean weight diameter (mm)							
0–10	0.70 (0.16) Ba	0.62 (0.09) Ba	1.09 (0.63) Aa	2.16 (0.23) Aa	2.09 (0.34) Aa	0.76 (0.10) Ba	1.20 (0.17) Aa	0.81 (0.04) Ba
10–20	0.67 (0.10) Aa	0.61 (0.14) Aa	0.88 (0.20) Aa	1.76 (0.33) Aab	1.73 (0.23) Aa	0.93 (0.24) Ba	1.20 (0.29) Aa	0.84 (0.00) Ba
20–30	0.74 (0.13) Aa	0.51 (0.05) Aa	0.83 (0.10) Aa	1.70 (0.29) Ab	1.99 (0.27) Aa	0.83 (0.04) Ba	1.19 (0.01) Aa	0.67 (0.00) Ba
	Geometric mean diameter (mm)							
0–10	1.38 (0.03) Ba	1.40 (0.06) ABa	1.46 (0.07) Aa	1.59 (0.02) Aa	1.57 (0.02) Aa	1.47 (0.04) Aa	1.47 (0.02) Aa	1.45 (0.01) Aa
10–20	1.40 (0.04) Aa	1.41 (0.06) Aa	1.45 (0.03) Aa	1.57 (0.03) Aab	1.54 (0.03) Aa	1.46 (0.03) Aa	1.50 (0.00) Aa	1.46 (0.05) Aa
20–30	1.40 (0.03) Aa	1.45 (0.03) Aa	1.44 (0.02) Aa	1.55 (0.03) Ab	1.56 (0.02) Aa	1.47 (0.01) Aa	1.49 (0.00) Aa	1.49 (0.04) Aa
	Aggregate stability index (%)							
0–10	86.80 (2.33) Aa	80.70 (5.85) ABa	75.34 (8.92) Ba	54.11 (8.75) Bb	67.89 (8.43) Aa	72.14 (9.14) Aa	78.69 (2.62) Aa	79.38 (5.26) Aa
10–20	82.58 (8.13) Aa	78.58 (10.18) Aa	77.37 (7.91) Aa	60.65 (12.92) Bab	72.06 (6.05) Aa	76.51 (5.92) Aa	75.77 (6.04) Aa	78.19 (0.00) Aa
20–30	82.68 (5.95) Aa	70.68 (5.32) Ba	76.58 (4.23) ABa	68.07 (4.22) Aa	70.32 (5.20) Aa	73.40 (3.49) Aa	79.26 (1.59) Aa	64.93 (0.00) Bb

Values within parentheses represent the standard deviation of the mean (n = 5). Equal uppercase letters for land use systems and lowercase letters for layers, within the same soil type, do not differ by Tukey test at the 0.05 significance level.

Table 4
Eigenvalues, percentage of variance, cumulative percentage of variance and correlation quotient between the original variables and the principal components.

	Principal component (PC)[1]			
	PC1	PC2	PC3	PC4
Eigenvalues (λ)	6.04	1.66	1.20	1.01
Percentage of variance (%)	54.90	15.07	10.95	9.16
Cumulative percentage of variance (%)	54.90	69.98	80.92	90.08
Variables	Correlation			
Soil organic carbon content (SOCc)	0.38	−0.21	0.02	0.75
Bulk density (BD)	−0.16	0.32	0.88	−0.13
Mean weight diameter (MWD)	0.91	−0.26	0.27	0.01
Geometric mean diameter (GMD)	0.91	0.26	0.15	0.08
Aggregate stability index (ASI)	−0.71	−0.58	0.08	−0.28
Macroaggregates (Macro)	0.93	−0.23	0.17	0.06
Mesoaggregates (Meso)	−0.96	−0.07	−0.08	−0.11
Microaggregates (Micro)	−0.20	0.92	−0.29	0.12
Clay	0.80	−0.21	−0.39	−0.18
Silt	0.69	0.30	0.05	−0.41
Sand	−0.88	−0.01	0.23	0.33

[1] PC1, PC2, PC3 and PC4 refer to the first, second, third and fourth components, respectively.

related to structure and soil physical quality, i.e., MWD, GMD, macroaggregates, clay and silt, with correlation coefficients (R) ≥0.69. The second component (PC2) explained 15.07% of the total variation and was related to variable microaggregates (R = 0.92). Soil bulk density (R = 0.88) was related to the third component (PC3), which explained 10.95% of the total variation. Finally, the fourth component (PC4) was related to SOC content (R = 0.75) and explained 9.16% of the total variation.

Fig. 4 illustrates the two-dimensional projections of the two main components (PC1 and PC2) to soil type and layers than explained 70% of the total variation. Our results show that SOC values, aggregate classes and aggregation indexes found in land use systems in Acrisols are different from those observed in Arenosols and Regosols, which are homogeneous with each other. In general, land use systems in Acrisols have higher SOC contents, macroaggregates, MWD, GMD, clay and silt, while in land use systems in Arenosols and Regosols, the lowest values of these variables were found. On the other hand, in the land use systems of Arenosols and Regosols, higher bulk density concentrations, mesoaggregates, microaggregates, ASI and sand were found, compared to land use systems in Acrisols (Fig. 4).

Although the studied variables showed distinction in the different land use systems between soil types, analyses made for the layers showed less pronounced variation. Therefore, there is no significant evidence that these variables are more homogeneously distributed among soil layers (Fig. 4). Thus, structure, soil physical quality, aggregation and SOC is markedly different between soil types with the highest values observed in Acrisols, which has sandy clay loam texture, while this pattern was not observed between layers (Tables 5 - Supplementary Material).

4. Discussion

In this study, the results showed that the conversion from native vegetation to smallholder management with soil conventional agricultural systems (animal traction plowing) in the Brazilian semi-arid region may show different responses in terms of bulk density, SOC dynamics and soil aggregation, what about other soil properties (CEC, N, Ca, Mg, K). Such differences are probably associated with soil texture, CEC, silt and clay content (Table 1), time since land-use change and input of organic residues, as observed by de Blécourt et al. (2019) in semi-arid region of southern Africa. However, the results from Brazilian semi-arid region might be different from the results for the same soil type from temperate or humid region (Wiesmeier et al., 2019; Mamedov et al., 2021).

The highest BD values were found in the pasture system in Regosols (Table 2). This effect is related to the pressure generated by the trampling of animals on the surface layer (0–10 cm), resulting in greater soil compaction. Convergent results were found by Santana et al. (2019), who also observed higher BD values in the superficial layer of the pasture area in sandy texture (Planosols and Leptosols) and clayey texture (Acrisols and Ferralsols) soils compared to cropland and native vegetation areas in the Brazilian semi-arid region. This information reinforces the degrading effect of animal trampling on the surface layer in pasture areas, regardless of soil type, resulting in soil compaction and reduced water infiltration and soil aeration.

In Acrisols soil with sandy clay loam texture and mean clay content of 23.1%, there was a slight increase (2.3 Mg ha^{-1}) in total SOC stock in

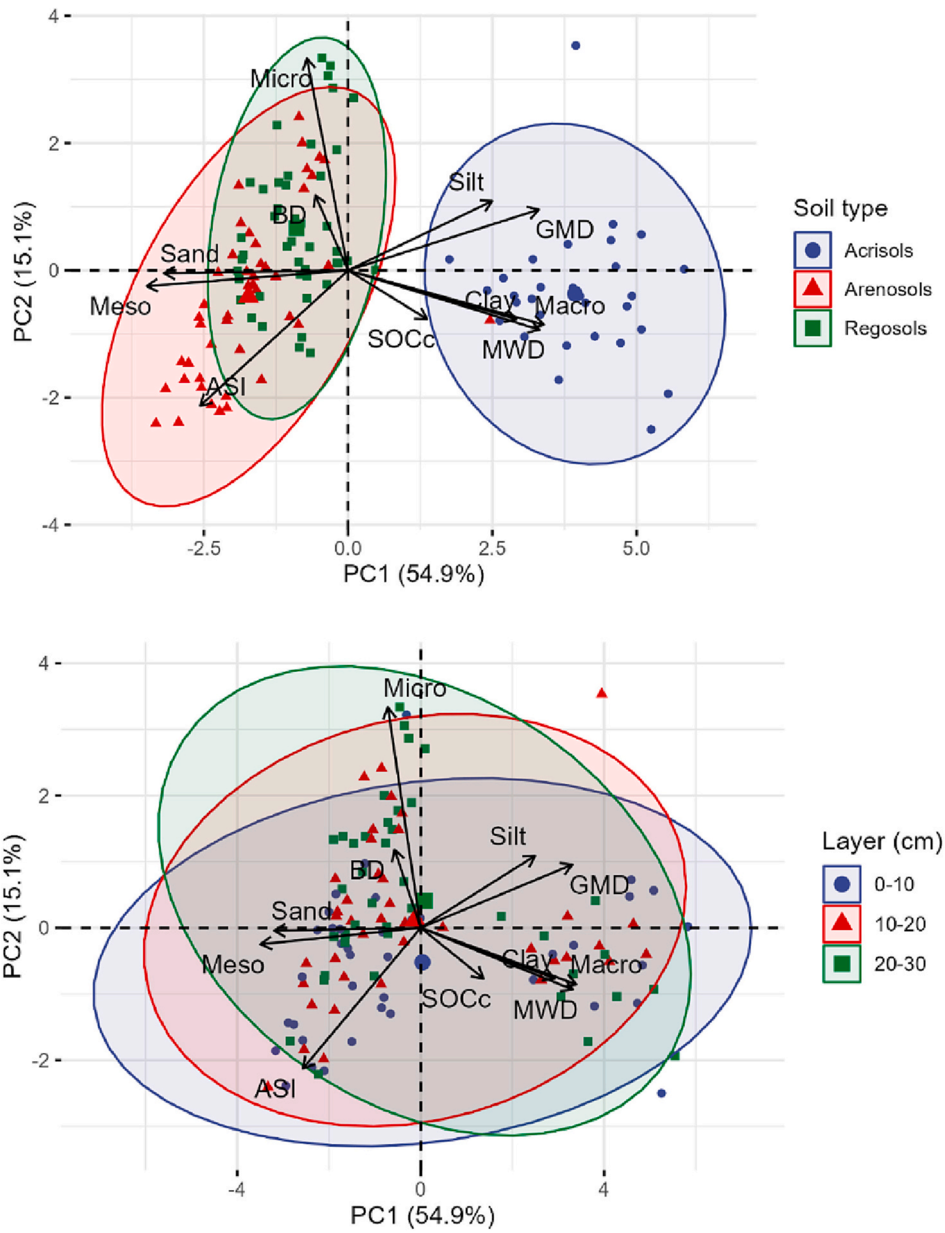

Fig. 4. Scores (points) and loadings (arrows) projections for the first two principal components of soil attributes by soil type and layers. BD: bulk density; MWD: mean weight diameter; GMD: geometric mean diameter; ASI: aggregate stability index; Macro: Macroaggregates; Meso: Mesoaggregates; and Micro: Microaggregates.

the agricultural system with 30 years of land use (Fig. 2), but not statistically significant ($p \geq 0.05$) when compared to native vegetation, and also high predominance of macroaggregate class (>2.0 mm) (Fig. 3). Conversely, soils with mostly loamy sand texture (Arenosols and Regosols) resulted in SOC reductions between 2.1 and 9.6 Mg ha^{-1} in agricultural systems, and with predominance of mesoaggregates (<2.00 and > 0.25 mm). Therefore, the results for Acrisols were unexpected, since the climatic conditions (high temperatures and evapotranspiration, low and unstable rainfall) and management conditions (conventional tillage, without use of any management practices) are favorable to SOC, nitrogen and soil structure loss (Ogle et al., 2005; Maia et al., 2007; Guimarães et al., 2013; Medeiros et al., 2020).

One of the aspects that may explain the maintenance or recovery of SOC stocks in cropland with 30 years in Acrisols (Fig. 4), is undoubtedly its higher clay content, usually soil with higher clay content are more stable (de Blécourt et al., 2019). It is widely known that clay minerals have the potential to form organomineral complexes that act to protect SOC, which is chemically stabilized and adsorbed by clay minerals with high negative charges, or by C physically protected from microbial mineralization through the formation of soil aggregates (Six et al., 2000; von Lutzow et al., 2006; Cavalcante et al., 2016; de Blécourt et al., 2019). In the Brazilian semi-arid region, Acrisols cover about 15% of the area and are typically clay accumulation soils, predominantly with low activity clay (Santos et al., 2011). Partial losses of bases and silica and soil reaction, predominantly in the moderately acidic to moderately alkaline range (pH 5.3–8.3) in Brazilian semi-arid region, in the case of Acrisols (Table 1), they allow the formation of both 1:1 clay minerals (kaolinite group) and 2:1 clay minerals (smectite group) (Araújo Filho et al., 2022). According to Lima et al. (2008), Acrisols can present varied mineralogy, with kaolinite often reported as the main constituent of the clay fraction. Therefore, these characteristics make Acrisols more chemically stabilized compared to Arenosols and Regosols (Fig. 4).

In addition, the time of land use probably exerted a strong influence on SOC maintenance in cropland with 30 years of land use (Fig. 2). In this sense, the Intergovernmental Panel on Climate Change (IPCC, 2006) adopts the period of 20 years as the standard for SOC stabilization after a change in land use or management. However, Medeiros et al. (2022) state that for the Brazilian semi-arid region, the new steady-state should not occur before 40 years of land use. However, the divergence of our results in relation to those of Medeiros et al. (2022) is probably related to the low representativeness (19%) of the Acrisols class in the total data set evaluated by the authors.

In relation to SOC decrease in Arenosols and Regosols (Fig. 2), other aspects that are characteristic of the Brazilian semi-arid region must have contributed to these results, namely: i) adoption of fallow periods, that is, areas are usually cultivated for 4 or 5 years and then left to fallow, ranging from 2 to 4 years; (ii) input of agricultural crop residues; and iii) time since land-use change. The Brazilian semi-arid region is characterized by the predominance of smallholders with very low level of rational management practices of natural resources (Medeiros et al., 2020). This combination has led smallholders to exploit a certain part of their farm until productivity reduction is observed, when the area is then abandoned (left to fallow), usually for no longer than 4 years, until it is used again for agriculture, livestock farming or both activities. This dynamics has been commonly associated with the degradation of the region (Martins et al., 2010; Sousa et al., 2012; Rodrigues et al., 2013; Ferreira et al., 2016; Santana et al., 2019), since in general, fallow periods are much shorter than the 10–15 years recommended by some authors, as the minimum period for the soil to recover its physical, chemical and biological properties (Tiessen et al., 1992; Medeiros et al., 2020). Moreover, it is certainly also related to the reduction of structure and soil physical quality, since both aggregate classes and aggregation indexes in conventional agricultural systems of these soils were significantly reduced (Table 3).

The second point refers to the input of residues from agricultural crops and or improper crop rotation, especially beans, which for being a legume, can provide more nitrogen to the soil, positively contributing to the maintenance of SOC and, consequently, soil structure (Bowles et al., 2014; Kontopoulou et al., 2015). The average contribution of shoot biomass in areas of native vegetation, annual crops, and pasture in the Brazilian semi-arid region is 6.0, 4.0, and 6.0 Mg ha^{-1} year^{-1} of dry mass, respectively (Sampaio and Costa, 2011). According to Medeiros et al. (2020), after conversion from native vegetation to agricultural system with annual crops (mainly maize and beans) in the Brazilian semi-arid region, SOM input is reduced to 2.5 Mg ha^{-1} year^{-1}, whereas decomposition of SOC present in the superficial soil layer will continue or even accelerated, until a new steady-state is reached (de Blécourt et al., 2019). However, it is important to point out that after harvest, the agricultural areas are made available for animal grazing (mainly cattle), which consume all possible biomass in a short period, leaving the soil uncovered for about 3–4 months a year, i.e., only the underground biomass remains, which has input of 1 Mg ha^{-1} year^{-1} (Sampaio and Costa, 2011). In pasture areas, due to inadequate management, such as, for example, lack of rotational management, irrigation and fertilization (organic or inorganic), shoot biomass is consumed by animals and the underground biomass that remains has input of 2 Mg ha^{-1} year^{-1} (Sampaio and Costa, 2011).

Finally, the time of land use can be also determinant for SOC dynamics. Thus, the long use time (30 years) of the agricultural system in Acrisols was probably decisive to promote the recovery and even a slight increase in SOC, while in Arenosols and Regosols, the agricultural areas that have at most 15 years of land use have not yet reached the new steady-state (IPCC, 2006; Medeiros et al., 2022), justifying SOC losses in these agricultural systems. For example, Maia et al. (2013) showed that there are significant differences when evaluating the conversion of Brazilian Cerrado into conventional tillage system in very clayey soils, considering the periods of 20 and 30 years.

The slight increase in SOC stocks in cropland with 30 years of land use in Acrisols was also accompanied by improved soil aggregation (Tables 3 and 4), which can be verified through ASI, which represents a measure of total soil aggregation, not considering the distribution by aggregate classes (Medeiros et al., 2018), and even through the increase of the water-stable aggregate classes of macro and mesoaggregates (Fig. 4). The relationship between SOC and aggregate formation/stabilization is already established in literature and, as described by Chen et al. (2017), it goes through the concept of the aggregate hierarchy model proposed by Tisdall and Oades (1979) and Hassink (1997), who stated that the addition of organic matter to soils first results in the formation of SOM associations with clay and silt particles. The formation of microaggregates (<0.25 mm) and macroaggregates begins if the SOM binding capacity of clay and silt fractions is saturated (Okolo et al., 2020). Therefore, in accordance with the concept of aggregate hierarchy, microaggregates are bound together to form macroaggregates by transient binding agents (i.e., microbial- and plant-derived polysaccharides) and temporary binding agents (i.e., roots and fungal hyphae) (Tisdall and Oades, 1979; Six et al., 2000).

The other agricultural systems in Arenosols (cropland with 4 and 15 years) and Regosols (pasture and cropland with 4 years), despite also having input of crop residues, including beans, and being also submitted to fallow periods, resulted in substantial SOC reductions. These results are similar to those found in other studies conducted in the Brazilian semi-arid region (Maia et al., 2007; Fracetto et al., 2012; Santana et al., 2019; Medeiros et al., 2020) and are certainly related to their high sand contents, which reduces the ability to form organomineral complexes and facilitates SOC loss via biological oxidation. There is; however, the time factor, which in these systems was much lower than cropland with 30 years, making it possible to question if in the long term it will be possible to recover at least in part the lost SOC. An indicator in this direction is the increase in the macroaggregate class observed in cropland with 15 years in Arenosols and pasture system in Regosols, which affected the MWD values (Fig. 4).

In other words, cropland with 15 years in Arenosols and pasture with 10 years in Regosols promoted significant ($p \leq 0.05$) increase in aggregation and stability when compared to native vegetation areas (reference area). Additionally, another aspect that must be considered is that in the areas under study, soil tillage is carried out using animal traction plowing (a practice that is still dominant in the Brazilian semi-arid), which is less intensive than the use of agricultural machinery (plowing and harrowing), causing less impact on soil aggregation. Therefore, it may be that in the long term, SOC stocks in these areas can be reestablished, a result similar to what was observed in cropland with 30 years in Acrisols (Medeiros et al., 2020).

It is, therefore, necessary to monitor whether this increase in soil aggregation in agricultural areas is accompanied by the increase in SOC contents. In Regosols, in the pasture system, it is verified that SOC stocks in 10–20 and 20–30 cm layers are higher than in the native vegetation area, which is probably due to the input of organic material from the grass root system; however, part of this increase is due to the substantial increase in soil bulk density (Table 2). This effect was confirmed by the sharpest reduction in SOC stock in the pasture area after soil mass correction (Fig. 2) using the native vegetation soil as reference (Sisti et al., 2004). Differently, in Arenosols, there is no evidence of SOC recovery in cropland with 15 years, since SOC levels and stocks are lower than in native vegetation and in cropland with 4 years, indicating that the SOC content continued to decrease between 4 and 15 years of land use. Therefore, further studies are needed to identify which process is governing this increase in aggregation.

Finally, our results evidence that, given the limitations imposed by soil conditions, climate and management adopted by smallholders, there is need for more effective public policies aimed at the implementation of more sustainable land use systems in the Brazilian semi-arid region, because the slight increase of SOC stock in the cropland with 30 years was not significant ($p \geq 0.05$) in comparison to native vegetation and does not represent what actually occurs in most cases, where SOC losses prevail. In addition, in Arenosols and Regosols, which together cover about 13.7% of this region (Medeiros et al., 2020), there were losses in SOC stocks ranging from 6.5% to 28.9%. Thus, most conventional land use systems in the Brazilian semi-arid region, especially in sandy soils, are increasing environmental degradation in this region (Fig. 4).

This context has contributed for the Brazilian semi-arid region to continue to be underdeveloped and to face difficulties to develop. All these factors also impact the food security issue and, additionally, do not contribute for Brazil to fulfill its Nationally Determined Contribution (NDC), or even global initiatives to mitigate GHG emissions, such as the "4 per mille" (Minasny et al., 2017).

5. Conclusions

Our results show that the maintenance of SOC and structure and soil physical quality in conventional agricultural systems in the Brazilian semi-arid region depend on soil type/texture and climate. In Acrisols, the cropland soil has higher clay content, leading to such difference of 5.4% in SOC stocks between cropland and native vegetation.; while in soils with sandy texture (Arenosols and Regosols), there was an average SOC decrease of 16.1% in comparison to areas under native vegetation.

The analysis of water-stable aggregate showed in Acrisols great predominance of macroaggregate classes (>2.0 mm); however, with no significant differences in the aggregate classes in native vegetation area and cropland with 30 years, but ASI indicated better aggregation condition in the agricultural system, which is probably associated with increase in SOC content. On the other hand, in sandy soils (Arenosols and Regosols), great predominance of mesoaggregates was observed (<2.00 and > 0.25 mm), which is explained by the known difficulty of sandy soils to form macroaggregates. However, the increase of macroaggregates and MWD in agricultural systems with longer land use times (i.e., pasture system and cropland with 15 years) is noteworthy.

Thus, further studies should be carried out, especially to improve the understanding of the role of soil type and texture, time in relation to SOC and the aggregation process in conventional agricultural systems under the Brazilian semi-arid conditions.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgments

This study was funded by the Research Support Foundation of the state of Alagoas (FAPEAL), the National Council for Scientific and Technological Development (CNPq) and the Foundation for the Support of Scientific and Technological Research and Development of Maranhão (FAPEMA - BPV-00350/22). We also thank the Federal Institute of Alagoas for providing the vehicle for field trips and farmers of the semi-arid region of Alagoas for their support during the collection of soil samples.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2023.e00647.

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