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RESEARCH ARTICLE
SOIL HEALTH IN TROPICAL AGROECOSYSTEM

Deforestation and conventional agriculture's impact on soil quality in five Brazilian semi-arid soils

Stoécio Malta Ferreira Maia[1], Aldair de Souza Medeiros[2,3] and Francisco Alisson da Silva Xavier[4]

[1]Federal Institute of Education, Science and Technology of Alagoas, Marechal Deodoro, Alagoas, Brazil, [2]Federal University of Piauí (UFPI), Bom Jesus, Piauí, Brazil, [3]Campus of Engineering and Agricultural Sciences, Federal University of Alagoas, Rio Largo, Alagoas, Brazil and [4]Brazilian Agricultural Research Corporation (Embrapa Fruticultura e Mandioca), Cruz das Almas, Bahia, Brazil

Corresponding author: Stoécio Malta Ferreira Maia; Email: stoecio.maia@ifal.edu.br

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Summary

This work aimed to evaluate the impact of conversion from native vegetation to pastures and agriculture on soil quality in the Brazilian semi-arid region and identify which soil attributes have the greatest potential as soil quality indicators. We collected soil samples at 0–10 and 10–20 cm layers from seven municipalities in the Brazilian semi-arid region. We determined the stocks of total soil organic carbon (TOC), total nitrogen (TN), carbon and nitrogen from microbial biomass (MB-C, MB-N), oxidizable fractions, humic substances, granulometry, soil bulk density (BD), pH, P, and cation exchange capacity (CEC). The evaluated systems were pasture, agriculture with different implementation times, and native forest (Caatinga biome). The results show that conventional cultivation and grazing systems lead to substantial losses of fundamental attributes needed to maintain soil quality. The study observed losses of MB-C, TOC, TN, and more recalcitrant fractions like fulvic acid and humin, along with a reduction in soil P and CEC. Soil physical, chemical, and biological attributes work as indicators of separation between environments; however, labile compartments showed greater potential as indicators of land use changes, being considered the main indicators in the soil quality assessment.

Keywords: soil organic matter; soil health; principal component analysis

Introduction

The Brazilian semi-arid region is the world's largest semi-arid (Sousa *et al.*, 2017), occupying approximately 1 million km^2 (IBGE, 2019), and occurring in ten Brazilian states (INSA, 2018). This region is characterized by high temperatures, low rainfall, reduced plant biomass production (Althoff *et al.*, 2018), a significant presence of poorly weathered soils, and a high surface runoff coefficient (Medeiros *et al.*, 2020). The native vegetation of the Brazilian semi-arid region is under increasing anthropic pressure, mainly due to the removal of firewood and the establishment of pastures and crops (Althoff *et al.*, 2018).

The Brazilian semi-arid currently has 58.4% of forest cover and 37.9% of the area used for agriculture or pasture, which represents approximately 50.6 million hectares. Additionally, estimates show that secondary forest vegetation under regeneration, originating from the fallow cycle of slash-and-burn agriculture or as regrowth from firewood production, accounts for

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approximately 13,1% of the Brazilian semi-arid region's forest cover area (MapBiomas, 2025). It is, therefore, a fragile ecosystem in terms of maintaining the quality of its natural resources, in particular soils, which in general are susceptible to significant losses of soil organic matter (SOM) and other soil attributes, such as CEC, P, K, labile and microbial carbon, and soil aeration (Sousa *et al.*, 2017). Thus, the definition and adoption of adequate soil management systems are essential for maintaining environmental sustainability in this region.

Despite the adverse edaphoclimatic conditions of the Brazilian semi-arid region, livestock and rainfed agriculture stand out among the main economic activities in the region, with areas of approximately 26.3 and 5.2 million hectares, respectively (MCTI, 2020). According to Medeiros *et al.* (2020), the agricultural model involves deforestation, biomass burning, and the application of conventional agriculture, which, after harvesting, frequently serves as animal grazing.

This exploitation model has led to significant losses of biodiversity and soil degradation in the region (Santos *et al.*, 2019). According to LAPIG (2023), approximately 14.8 million hectares of pastures in the Brazilian semi-arid region show some level of degradation. The land use change processes, overgrazing, and inadequate fallow periods result in not only an increase in desertification areas throughout the Brazilian semi-arid region (Perez-Marin *et al.*, 2012) but also losses in soil quality (Santos *et al.*, 2019).

Similar to Bunemann *et al.* (2018), we recognize that currently, the terms 'soil quality' and 'soil health' are equivalent and mean the persistent ability of soil to function as a vital ecosystem that sustains plants, animals, and humans, including soil biota/biodiversity, related soil functions, and soil-based ecosystem services (Bunemann *et al.*, 2018; Brito Neto *et al.*, 2023).Therefore, the complexity and variability of this concept have led to the widespread acceptance that there is no single method to assign a soil quality index. Thus, the adoption of physical, chemical, and biological soil indicators has been proposed, which should be related to soil functions, such as the availability of water and nutrients, maintenance of an adequate biological habitat, and the ability to resist management-induced degradation (Doran and Parkin, 1994; Karlen *et al.*, 2001).

In this sense, SOM is considered a determining factor of soil quality, as its functions are closely associated with soil properties (Vezzani and Mielniczuk, 2009). Therefore, studies suggest that we can base the assessment of soil quality in agricultural and pasture systems in the Brazilian semi-arid region on the analysis of SOM carbon fractions, which are more sensitive to land use changes and can serve as indicators of land use change (Sousa *et al.*, 2012; Oliveira *et al.*, 2015; 2016; Santos *et al.*, 2019).

Thus, this study is based on the hypothesis that the adoption of conventional crop systems leads to a loss of soil quality in the semi-arid region of Brazil, which may vary depending on the type of soil. Therefore, we aimed to evaluate the impact of converting native vegetation into agricultural systems on the quality of soils in the Brazilian semi-arid region, as well as identify which other attributes, in addition to SOM, have potential as soil quality indicators.

Materials and methods

Description of the study area

This study was carried out in seven municipalities in three states of the Brazilian semi-arid region (Figure 1). The semi-arid region of Brazil is centred on the Northeast of the country and in the North of the state of Minas Gerais, representing 12% of Brazilian territory (Brasil, 2020). This region has an average annual temperature ranging between 25 °C and 30 °C, a relative air humidity of 50% (Brasil, 2020), and an average rainfall of 800 mm (Medeiros *et al.*, 2020), generally restricted to 3–4 months of the year. The Caatinga vegetation is heterogeneous and characterized by the presence of low-height forests and shrubs, which lose leaves in the dry period and with many species of Cactaceae (Brasil, 2020).

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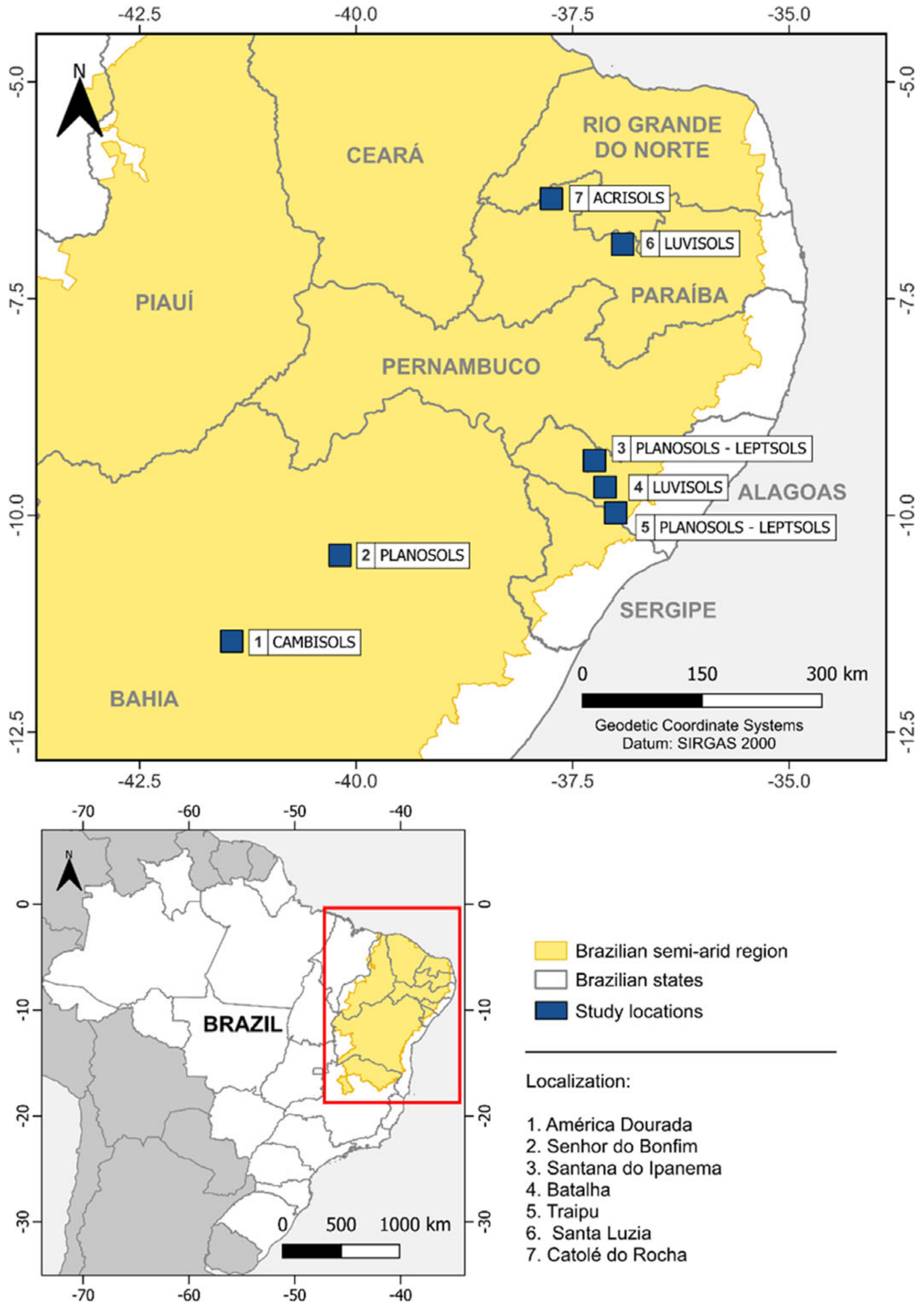

Figure 1. Location of study areas in the semi-arid region of the Brazil.

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The study areas were in five different soil types: Acrisols, Cambisols, Leptosols, Luvisols, and Planosols, which represent approximately 70.6% of the Brazilian semi-arid region (Cunha *et al.*, 2010). Different classification levels mean very different types of soil. Based on the first level, Acrisols are acidic soils with a layer below that is high in clay and low in base saturation. The Cambisols are young soils with minimal horizon development, showing the beginning stages of soil formation processes. Leptosols are shallow soils with limited depth, often over brittle rock or gravel. Luvisols have a subsurface horizon rich in clay and are known for high base saturation. Planosols have a distinct top-soil layer over a dense, compacted subsurface horizon, often leading to waterlogging.

Soil sampling and analysis

Areas of conventional agriculture were selected, which are generally cultivated for four to five years and then left fallow for two to four years. In the sampled areas, there were no records of fertilization or liming. Animal grazing usually makes the straw biomass of post-harvest crops available, resulting in the constant removal of nutrients and SOM. We used two criteria in the farm selection process: (i) the owner or land manager must possess knowledge about the land use and management practices implemented on the farm since its conversion from native forest (NF); and (ii) agricultural and pasture areas should be no more than 0.2 km away from NF areas, with similar topography, soil type, and texture. NF areas were used as references for the comparative study with managed areas. The description of the areas under study can be found in Table 1.

Soil samples were collected at 0–10 and 10–20 cm layers in three mini trenches in each of the following situations: NF, crops, and pasture, totalling 264 samples, which were air-dried, homogenized, and passed through a 2.0 mm sieve to remove root fragments and gravel. We collected the samples between February and April, during the rainy season in the region.

Soil bulk density (BD) was determined using the volumetric ring method, and granulometry analysis was performed using the pipette method (EMBRAPA, 1997). For the chemical soil characterization, the following parameters were determined: pH in water, available P, exchangeable K^+ and Na^+ extracted by Mehlich 1, exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} using 1 mol L^{-1} KCl extractor; and potential acidity ($H^+ + Al^{3+}$) (calcium acetate extractor and SMP buffer solution) (EMBRAPA, 1997). With values obtained in analyses, the following calculations were performed: sum of bases (SB), cation exchange capacity (CEC) at pH 7.0, base saturation index (V%), and saturation index by exchangeable aluminium (m%) (EMBRAPA, 1997).

The total organic soil C and N contents (TOC and TN) were determined by dry combustion in the elemental analyser model Flash 2000 (Organic Elemental Analyzer, CNHS Analyzer). Microbial C and N levels (MB-C and MB-N) were determined by the irradiation-extraction method (Islam and Weil, 1998; Ferreira *et al.*, 1999). MB-C was quantified using wet oxidation (Yeomans and Bremner, 1988), and MB-N was quantified using sulphuric digestion followed by Kjeldahl distillation (Tedesco *et al.*, 1995).

We obtained oxidizable C fractions using different H_2SO_4 concentrations, which separated TOC into four fractions with different liability degrees (Chan *et al.* 2001). C content was quantified by wet organic matter oxidation, without external heating, using 0.167 mol/L $K_2Cr_2O_7$ in sulphuric medium (Yeomans and Bremner, 1988). Fraction 1 was considered to represent labile organic carbon (Lab-C) in the soil. Therefore, we calculated the non-labile organic C (nLab-C) by subtracting the TOC from the Lab-C contents.

The fractionation of humic substances (HS) was carried out according to the differential solubility technique in an acid or alkaline medium of corresponding fractions, separating fulvic acid (FA), humic acid (HA), and humin (HUM) fractions according to concepts of humic fractions established by the International Humic Substance Society (IHSS) (Swift, 1996). C determination in humic fractions was carried out according to the methodology proposed by Yeomans and Bremner (1988). We calculated the TOC and C stocks of humic fractions, indices,

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Table 1. Location and description of study areas in the Brazilian semi-arid region

Location	Land use	Land use time (years)*	Acronym	Description	Soil type	Crops
Santana do Ipanema – AL	Caatinga		SI_1NF	Dense forest. Used as pasture during the dry period.	Planosols	
09° 21′ 14″ S e 37º 16′ 31″ W	Agriculture	47	SI_1A47	Soil tillage with mechanized plowing.		Maize/bean
	Caatinga		SI_2NF	Open forest. Used as pasture during the dry period.	Leptosols	
	Agriculture	2	SI_2A2	Soil tillage with mechanized plowing.		Maize/bean
		38	SI_2A38			
Batalha – AL	Caatinga		BaNF	Open forest. Used as pasture during the dry period.	Luvisols	
09° 40′ 40″ S e 37° 07′ 29″ W	Agriculture	11	BaA11	Soil tillage with heavy mechanized harrowing.		Maize/bean
Traipu – AL	Caatinga		Tr_1NF	Dense forest. Used as pasture during the dry period.	Planosols	
09° 58′ 14″ S e 37º 00′ 12″ W	Pasture	10	Tr_1P10	Pasture well managed with no signs of degradation.		Pangola grass *(Digitaria eriantha)*
		20	Tr_1P20			
	Caatinga		Tr_2NF	Dense forest. Used as pasture during the dry period.	Leptosols	
	Pasture	4	Tr_2P4	Pasture well managed with no signs of degradation.		Pangola grass *(Digitaria eriantha)*
Catolé do Rocha – PB 06° 20′ 28″ S e 37° 44′ 59″ W	Caatinga		CR_1NF	Open forest. Used as pasture during the dry period.	Acrisols	
	Agriculture	12	CR_1A12	Soil tillage with mechanized plowing.		Maize/bean
		15	CR_1A15			
	Caatinga		CR_2NF	Open forest. Used as pasture during the dry period.		
	Pasture	6	CR_2P6	Pasture moderately degraded.		Native pasture
	Agriculture	50	CR_2A50	Soil tillage with mechanized plowing. Used as pasture after harvest.		Maize/bean
	Caatinga		CR_3NF	Open forest. Used as pasture during the dry period.		
	Pasture	30	CR_3P30	Pasture moderately degraded.		Native pasture
	Agriculture	40	CR_3A40	Soil tillage with mechanized plowing. Used as pasture after harvest.		Maize/bean
Santa Luzia – PB 06° 52′ 2″ S e 36° 55′ 16″ W	Caatinga		SL_1NF	Open forest. Used as pasture during the dry period.	Luvisols	
	Agriculture	19	SL_1A19	Soil tillage with mechanized plowing. Used as pasture after harvest.		Maize/bean
		38	SL_1A38			
	Agriculture	90	SL_1A90			
	Caatinga		SL_2NF	Open forest. Used as pasture during the dry period.		
	Agriculture	20	SL_2A20	Soil tillage with mechanized plowing. Used as pasture after harvest.		Maize/bean
		30	SL_2A30			

(*Continued*)

Table 1. (*Continued*)

Location	Land use	Land use time (years)*	Acronym	Description	Soil type	Crops
América Dourado – BA 11° 26′ 7″ S e 41° 25′ 54″ W	Caatinga		AD$_1$NF	Dense forest. Used as pasture during the dry period.	Cambisols	
	Agriculture	5	AD$_1$A5	Soil tillage with mechanized plowing. Used as pasture after harvest.		Maize/bean/castor bean
		15	AD$_1$A15			
		20	AD$_1$A20			
		30	AD$_1$A30			
		35	AD$_1$A35			
		40	AD$_1$A40			
	Caatinga		AD$_2$NF	Dense forest. Used as pasture during the dry period.		
	Agriculture	33	AD$_2$A33	Soil tillage with mechanized plowing. Used as pasture after harvest.		Maize/bean/castor bean
		46	AD$_2$A46			
Senhor do Bonfim – BA 10° 27′ 41″ S e 40° 11′ 22″ W	Caatinga		SB$_1$NF	Dense forest. Used as pasture during the dry period.	Planosols	
	Agriculture	10	SB$_1$A10	Soil tillage with mechanized plowing. Used as pasture after harvest.		Maize/bean
		15	SB$_1$A15			
	Caatinga		SB$_2$NF	Dense forest. Used as pasture during the dry period.		
	Agriculture	8	SB$_2$A8	Soil tillage with mechanized plowing. Used as pasture after harvest.		Maize/bean
		18	SB$_2$A18			

*Time since the conversion of native forest to conventional cultivation system and/or pasture.

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the humification degree (HA + FA + HUM)/TOC (Guimarães *et al.*, 2013), the structural stability indicator of SOM, which is the HUM/(FA + HA) ratio (Canellas *et al.*, 2005), and the condensation index of soil soluble organic matter (HA/FA) (Benites *et al.*, 2003).

TOC, TN, MB-C, MB-N, C stocks of oxidizable fractions and humic substances were calculated by multiplying the C and N content (dag kg^{-1}), soil BD (g cm^{-3}), and soil layer thickness (cm). To minimize discrepancies generated by soil BD induced by management practices, stocks were corrected based on soil equivalent mass, according to the method proposed by Sisti *et al.* (2004).

Data analysis and statistics

Data were standardized ($X^{-} = 0.0$ and $s^2 = 1.0$) and submitted to principal component analysis (PCA), considering only variables that presented factor loading values above 0.60 (Araújo *et al.*, 2013). Variables with low variance explanation associated with principal components (PCs) ($|r| < 0.60$) were removed from the database, and a new analysis was performed. PCA was performed using mean data (for each variable) aggregated by land use type (NF, agriculture, and pasture) and soil type. Kaiser (1958) set the rules that PCs must have eigenvalues greater than one ($\lambda > 1.0$) and that the total variance for each PC must be greater than 10% (Govaerts *et al.*, 2007) and that the variance accumulated by PCs must be ≥70% (Rencher, 2002). These rules were used to divide variables into two groups, in both layers and for all soil classes that were being studied. Data were also submitted to descriptive statistical analysis, and maximum, minimum, mean, coefficient of variation (CV), and Shapiro-Wilk normality test (S-W) were calculated for all variables used in PCA. Data were grouped for NF, agriculture, and pasture systems. All analyses were performed using the R software (R CORE TEAM, 2018).

Results

Impact of land use on soil quality

In the Brazilian semi-arid region, our dataset consists of 14 NF areas, 25 agricultural areas, and five pasture areas spread across five soil classes. The descriptive analysis of this dataset (Table 2) showed that the mean data for most soil attributes in managed areas (agricultural and pastures) were lower than those seen in natural vegetation (Table S1). It is noteworthy that, in general, the impacts of agricultural systems were more pronounced than in pastures, which is evidenced, for example, in losses of variables such as TOC, TN, MB-C, MB-N, FA, HUM, and Lab-C, where the average losses in agricultural systems in relation to native vegetation were 19, 24, 52, 32, 32, 26, and 30%, while in pasture areas, reductions were 13, 11, 21, 11, 8, 11, and 9%. These results are confirmed by specific data from the other analyses (Figures 2 and 3), which considered the analysis of each study site.

We also observed significant changes in the total P content, showing reductions of 48 and 42% in agricultural areas and pasture, respectively, and a decrease of 19 and 27% in CEC in both areas. Finally, the normality test (Table 2) showed that most variables had a normal distribution, indicating that even when aggregating data from different conditions, such as type of soil, management, and climate, variables have a normal distribution and thus can be used in probabilistic and modelling studies with greater security.

Of the 230 values observed in Figure 2, only 68 showed an increase in relation to NF; that is, 69.6% of the data point to losses, and the rest of the data (30.4%) show gains in soil attributes. Among types of soil, Planosols were the class that presented the highest number of attributes with a reduction (91.4%) in relation to the NF. Only MB-C, FA, and P in the pasture areas showed an increase when compared to their respective native vegetation areas.

Differently, Cambisols were the soil class where the negative impacts of agricultural systems were smaller, since there were losses of 56.2% and gains of 43.8%. However, we observed that

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Table 2. Descriptive statistical analysis (maximum. minimum. mean. coefficient of variation) and Shapiro-Wilk normality test (S-W) for the data grouped by land use type (NF: native forest; Agri: agriculture; past: pasture)

		TOC	TN	MB-C	MB-N	FA	HA	HUM	Lab-C	nLab-C	Clay	Sand	Silt	BD	pH (in H_2O)	P	CEC
		Mg ha^{-1}									g dm^{-3}			g cm^{-3}		Cmolc dm^{-3}	
NF	Min	31.53	2.22	0.08	0.07	1.07	0.33	7.78	3.29	28.23	64.50	172.37	73.50	1.14	5.41	0.04	7.14
	Max	68.01	6.49	4.57	0.65	6.66	6.95	35.48	14.16	61.15	344.40	860.00	557.13	1.58	7.83	3.63	52.93
	Mean	52.75	4.41	0.90	0.19	3.19	4.38	22.68	8.58	44.16	192.24	625.82	180.90	1.38	6.43	0.52	16.97
	CV (%)	19.45	26.57	126.90	80.16	52.42	50.65	43.94	36.92	20.91	40.47	31.88	79.51	9.74	10.28	179.75	71.12
	S-W	0.93^{ns}	0.98^{ns}	0.66**	0.71**	0.92^{ns}	0.91^{ns}	0.89^{ns}	0.96^{ns}	0.97^{ns}	0.96^{ns}	0.83*	0.75**	0.95^{ns}	0.97^{ns}	0.52**	0.74**
Agri	Min	15.31	1.56	0.07	0.04	0.40	0.48	3.93	2.35	11.97	47.00	297.90	14.50	1.22	5.39	0.06	4.84
	Max	76.14	5.64	1.05	0.43	4.60	4.86	37.76	11.57	68.25	346.15	914.00	550.95	1.59	8.17	2.16	35.87
	Mean	42.86	3.35	0.43	0.13	2.18	2.54	16.68	6.00	36.87	148.82	626.97	223.32	1.40	6.65	0.27	13.79
	CV (%)	35.40	28.52	69.70	74.47	51.54	51.73	63.89	39.86	37.60	53.07	35.71	81.69	8.26	13.57	152.85	64.90
	S-W	0.97^{ns}	0.97^{ns}	0.91*	0.79**	0.95^{ns}	0.96^{ns}	0.89*	0.95^{ns}	0.98^{ns}	0.93^{ns}	0.83**	0.84**	0.93^{ns}	0.91*	0.43**	0.86**
Past	Min	35.42	3.05	0.43	0.11	2.01	3.68	14.38	3.88	26.26	114.58	315.00	16.50	1.28	5.58	0.08	10.32
	Max	69.06	5.43	1.03	0.26	3.89	7.08	25.29	9.16	60.02	211.50	799.00	472.50	1.52	6.78	0.54	13.90
	Mean	45.79	3.91	0.71	0.17	2.95	5.33	20.15	7.85	37.94	165.42	629.50	204.10	1.42	6.45	0.30	12.39
	CV (%)	29.52	24.06	38.62	40.56	26.02	25.81	21.78	28.60	33.96	26.37	30.50	86.37	6.85	7.97	56.45	10.58
	S-W	0.79^{ns}	0.89^{ns}	0.87^{ns}	0.83^{ns}	0.93^{ns}	0.97^{ns}	0.96^{ns}	0.67**	0.80^{ns}	0.87^{ns}	0.88^{ns}	0.95^{ns}	0.92^{ns}	0.75*	0.98^{ns}	0.92^{ns}

TOC: total organic C; TN: total N; MB-C: microbial biomass C; MB-N: microbial biomass N; FA: fulvic acids; HA: humic acids; HUM: humin; Lab-C: labile C; nLab-C: non-labile C; BD: soil bulk density; pH: soil pH; CEC: cation exchange capacity. ns: no significant difference. *: significant at 5%. **: significant at 1%.

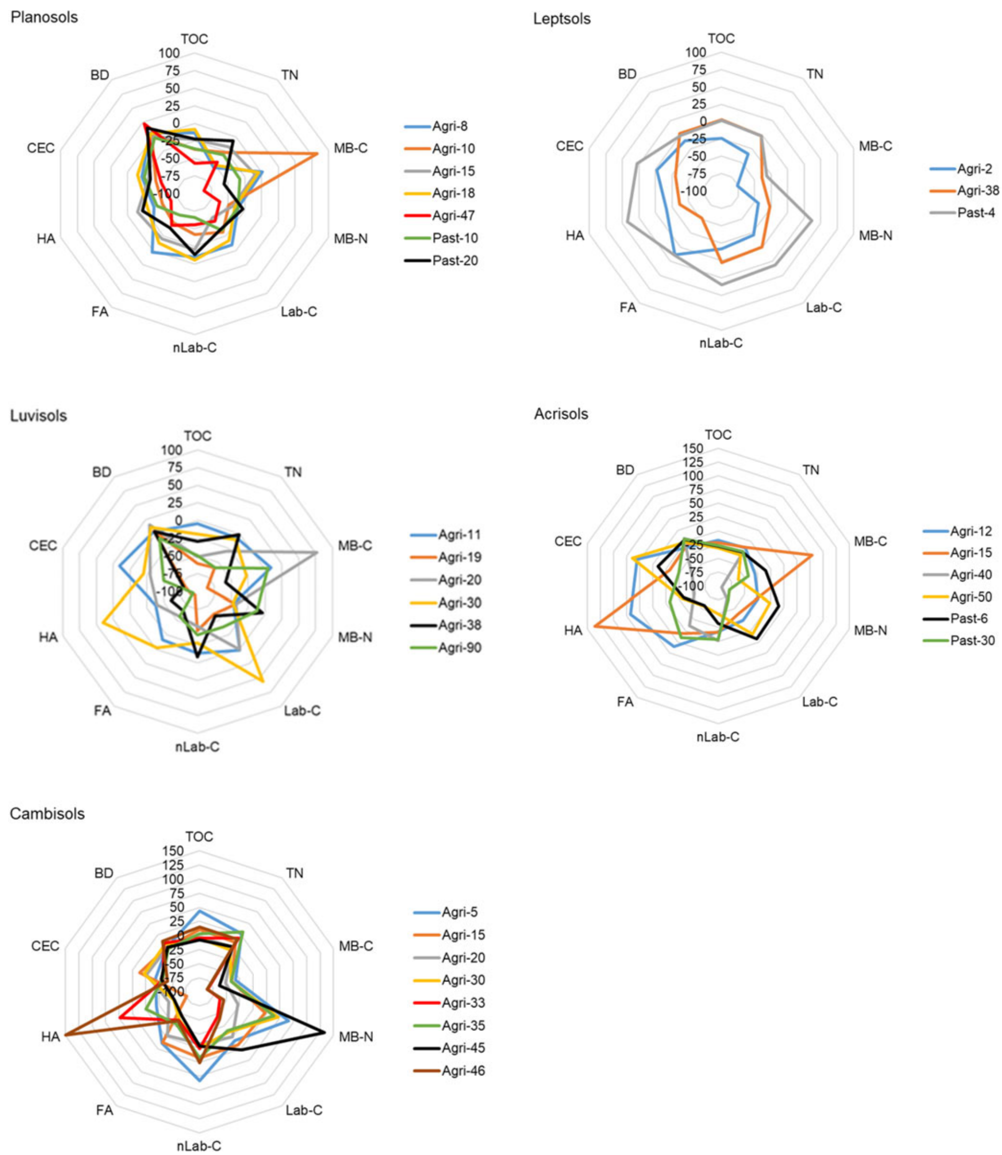

Figure 2. Percentage of gains or losses of soil properties as a function of land use change (LUC) from native forest to pasture or conventional agriculture in different types of soil for 0–20 cm soil layer in the semi-arid region of Northeastern Brazil.

agricultural areas with a short duration of use (5 and 15 years) accounted for a significant portion of the positive results (42.8%).

In the other soil classes, losses in attributes were 66.7, 71.7, and 80.0%, respectively, for Leptosols, Acrisols, and Luvisols. The Leptosols have only three areas of study, which limits the analysis. In any case, it was evident that agricultural systems negatively impacted the soil in a much more accentuated way than in the pasture area. Similar to Cambisols, Luvisols showed improvement in most soil attributes in the agricultural area with the shortest time of use (11 years); however, in areas with the longest time of use (19–90 years), soil degradation predominated through a reduction in its attribute values. Finally, in Acrisols, where there were

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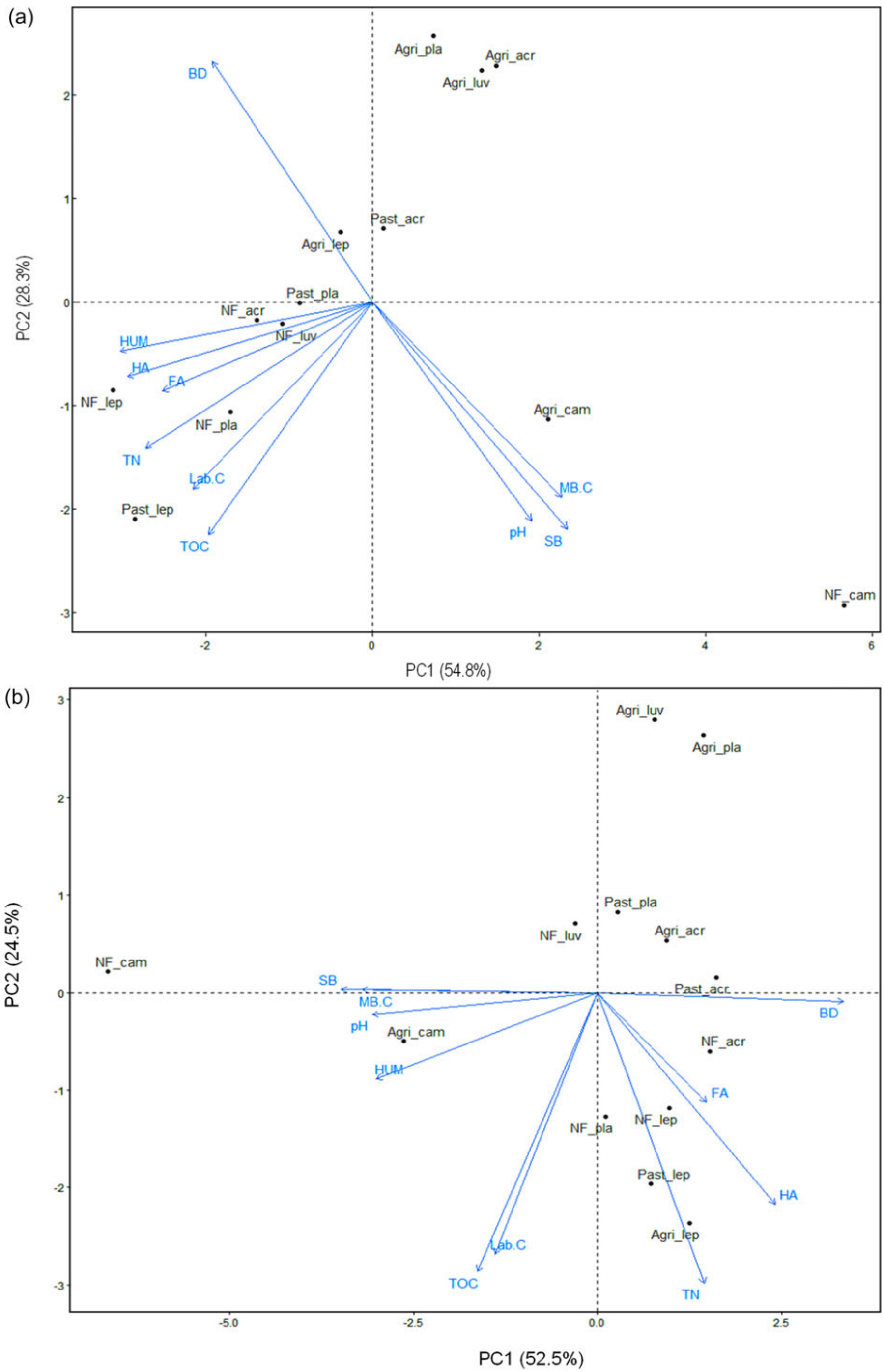

Figure 3. Biplot of principal components PC1 and PC2 of the PCA for physical, chemical, and biological indicators of soil quality at 0–10 cm (a) and 10–20 cm (b) depths under different use, management and types of soil. NF: native forest; Agr: intensive agriculture systems; Past: pasture systems; acr: Acrisols; cam: Cambisols; lep: Leptosols; luv: Luvisols; pla: Planosols. (e.g., Agr_acr: area of conventional agriculture under Acrisols).

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Table 3. Percentage of variance and contribution of soil quality indicators to the principal components (PC) 1 and 2 in the 0–10 and 10–20 cm depths

	0–10 cm		10–20 cm	
	PC1	PC2	PC1	PC2
Variance (%)	55	28	52	24
Eigenvectors*	% contribution to the PC			
TOC	6.6	16.8	4.0	26.3
TN	12.8	6.6	3.1	28.6
MB-C	8.9	11.8	15.4	0.0
Lab-C	8.0	10.9	2.9	23.1
FA	10.9	2.5	3.3	4.1
HA	14.9	1.7	8.8	15.2
HUM	15.8	0.7	13.6	2.5
BD	6.3	17.9	16.8	0.0
pH	6.2	14.9	14.0	0.2
SB	9.4	16.0	18.1	0.0

*TOC: total organic C; TN: total N; MB-C: microbial biomass C; Lab-C: labile C; FA: fulvic acids; HA: humic acids; HUM: humin; BD: soil bulk density; pH: soil pH; SB: sum of soil bases.

losses in 71.3% of soil attributes, positive results also occurred in younger areas, pasture (6 years), and agriculture (12 and 15 years). In the 30-year pasture, the reduction was observed in all attributes, while in agricultural areas, only in the 50-year crop, improvement was observed in Lab-C, P and CEC (Figure 2).

Therefore, the analysis of average data (Table 2), as well as the type of soil (Figure 2) allowed the identification of two clear responses of soil attributes to the adoption of conventional agriculture and pasture systems in the semi-arid region of Brazil. The first and most important is that these systems predominantly lead to significant losses in soil attributes; the second is that the time of use seems to be a determining factor in promoting soil degradation.

Thus, these findings show that conventional land use models in the Brazilian semi-arid region, which are characterized by agricultural crops with little or no use of technology such as fertilization, liming, crop rotation, etc., soil tillage, inadequate fallow periods, grazing of agricultural residues, and overgrazing in the case of pastures, have contributed to soil degradation in the region, compromising soil quality and the sustainability of agricultural production in the medium and long term (Medeiros *et al.*, 2022). It is important to point out that an 'indirect' effect of this situation is the increase in deforestation in the semi-arid region, as farmers abandon degraded areas or areas that have reduced their productive potential and move into new areas.

PCA

The impact of land use change was evaluated using PCA (Table 3). The first two principal components accounted for over 70% of the total variance, a proportion deemed sufficient for this analytical approach based on the criteria established by Kaiser (1958). The PCA integrated the analysis of various land uses (e.g., NF, pasture, agriculture) and soil classes assessed in this study.

The biplot diagram distinctly illustrated reductions in soil quality within the surface layer (Figure 3a) following the conversion of NF to conventional agriculture. This is evidenced by the positioning of agricultural areas in the upper quadrant of the diagram, markedly distant from the corresponding NF areas. The variables contributing most significantly to this differentiation were those associated with organic matter (e.g., TOC, TN, Lab-C, and humic substances), as they exhibited the strongest correlations with NF areas. The Planosols, Luvisols, and Acrisols soil classes were particularly sensitive to the transition from forest to agriculture, experiencing the

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most substantial declines in soil quality, predominantly due to the loss of TOC, MB-C, Lab-C, and SB. Collectively, these variables accounted for approximately 55% of the variance in PC2 (Table 3).

The soil BD exhibited a strong correlation with agricultural areas (Figure 3a), indicating that the transition to conventional agriculture leads to an increase in this indicator. In the 0–10 cm soil layer, pasture areas reflected an intermediate level of soil quality degradation following the conversion from native vegetation, except for the Leptosols, where the pasture area (Past_lep) demonstrated a high degree of similarity with the corresponding native vegetation area (NF_lep) concerning indicators associated with SOM. The separation between the Agr_cam and NF_cam areas along PC1 (Figure 3a) indicates that Cambisols experience some decline in quality when utilized for agriculture; however, they appear to be more resilient compared to other soil classes. This resilience may be attributed to higher inherent soil fertility, as suggested by strong correlations with variables such as pH, CEC, SB, and MB-C.

Similar to the surface layer, the degradation of soil quality following the conversion from NF to conventional agriculture was also evident at a depth of 10–20 cm (Figure 3b). However, this effect was more pronounced in Planosols and Luvisols. In contrast, the soil quality levels in Acrisols and Leptosols under NF, pasture, and agricultural use were relatively similar, as indicated by the proximity of NF, Past, and Agr areas in both principal components (Figure 3b). The Leptosols class diverged from the others, particularly in PC2, due to higher stocks of TOC, Lab-C, and TN. Similar to the 0–10 cm depth, Cambisols differed markedly from the other soil classes in the PC1 analysis at the 10–20 cm depth (Figure 3b), showing strong positive correlations with variables such as SB, pH, MB-C, and HUM. In this class, the decline in soil quality due to conversion from NF to agriculture was evident, as reflected by the separation between NF_cam and Agr_cam along PC1. The variable BD accounted for approximately 17% of the variance in PC1 (Table 3), showing a stronger correlation with agriculture and pasture areas.

Discussion

Overall, our results showed that the conversion from native vegetation to conventional agricultural systems in the semi-arid region of Brazil led to a reduction in physical, chemical, and biological soil attributes, including SOC stocks and SOM compartments, and the greatest losses were found in agricultural areas, mainly those with longer periods of land use. In pasture and agriculture areas with less time for land use, losses were smaller, and even gains in SOM stocks, CEC, and P were observed, which is similar to other studies in tropical regions (Pegoraro *et al.*, 2018; Santos *et al.*, 2019).

Frequent soil tillage, a common practice in conventional cultivation systems, has the potential to reduce structural stability due to increased aggregate rupture (Guimarães *et al.*, 2013). Additionally, it can contribute to increase the soil aeration and soil/plant residue contact, which in turn stimulates the microbial oxidation of organic materials previously protected in soil aggregates. This, in turn, can lead to a reduction in SOM. This reduction may jeopardize even the C stocks of the most recalcitrant SOM fractions, given the challenges faced by soil mineral particles in forming stable aggregates, which are responsible for the physical protection of SOM (Oliveira *et al.*, 2016). Furthermore, conventional cultivation increases the risk of soil erosion, which in turn results in nutrient losses, greater soil exposure, litter removal, and increased SOM mineralization (Trindade *et al.*, 2011).

Our results corroborate those found by Santos *et al.* (2019), who evaluated oxidizable C fractions, TOC, and HS stocks in Luvisols with different uses in the Brazilian semi-arid region and observed that the cultivation system with corn had lower C values in oxidizable fractions and non-labile C, TOC, and C of HS fractions when compared to the area with native vegetation in the 0–5 cm layer. According to these authors, less stable C fractions can quickly change into more complex molecules with a high molecular weight. However, the change from native vegetation to

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conventional agriculture made soil C and SOM maintenance less stable. Thus, the loss of more recalcitrant organic material negatively affects soil quality, since this material with greater resistance to oxidation contributes to improving the soil's physical properties, such as the structure and stability of aggregates (Fultz *et al.*, 2013).

The lower losses and even the maintenance of soil quality observed in agricultural areas with less time of land use in Luvisols (BaA11), Acrisols (CR1A12 and CR1A15), and Cambisols (AD1A5 and AD1A15) are indicative that improvements in some attributes could be observed in the first years after the conversion of native vegetation, which is probably due to the input of organic matter produced during deforestation (Maia *et al.*, 2007). However, areas with longer periods of use showed that such improvement is not sustainable in the medium and long term; that is, the management practices adopted in agricultural systems and pastures, added to the adverse climatic conditions of the Brazilian semi-arid region, prevent such improvements from being maintained and, in practice, should lead to soil degradation.

Therefore, more rational systems should be adopted, such as agroforestry systems, consortiums and crop rotation, adequate fallow periods, agroecological systems, respect for the support capacity of pastures, elimination of the practice of grazing agricultural residues, etc. Studies (Guimarães *et al.*, 2013; Maia *et al.*, 2006; Brito Neto *et al.*, 2023) indicate that we can achieve sustainable management in the semi-arid region by correctly adopting and implementing the aforementioned practices or systems.

In all evaluated soil classes, PCA contributed to highlighting the separation between NF areas and agricultural systems. It was also evident that such losses were more pronounced at the 0–10 cm layer, especially in SOM-related indicators. Intensive farming led to a loss of both total C and N stocks as well as the active (Lab-C) and passive (humic substances) SOM compartments. This may have been because of intensive management practices like burning biomass, plowing, and harrowing often, as previously mentioned.

Planosols, Luvisols, and Acrisols classes were the most sensitive to loss of soil quality with conversion to agriculture; therefore, they need more attention in the process of land use change. Alternative cropping systems to the current ones are crucial for restoring the productive capacity of these soils. Soil BD was the soil physical quality indicator most sensitive to management. In general, the values of this indicator increased after the establishment of intensive agriculture areas, possibly in response to the intense soil mechanization, low return of organic matter, and low soil cover level. The increase in soil density can imply a series of other impacts on the soil, such as a decrease in aeration, hydraulic conductivity, and water retention capacity, which enhances water erosion and increases the soil's resistance to root penetration. It is important to highlight that the physical degradation of soils presents a high difficulty of recovery, as it generally requires the use of agricultural implements, which can cause further degradation, in addition to time to recover the chemical and biological attributes that are impacted by physical degradation.

The results showed that the establishment of pasture after the conversion of native vegetation also causes a loss in soil quality, albeit at levels lower than those observed in conventional agriculture. The indicators associated with SOM in the Leptosols demonstrated similar levels of soil quality in pasture and NF areas, indicating that good pasture practices can maintain soil productivity in this type of soil. In Cambisols, however, the higher level of natural soil chemical fertility seems to be a resilience factor during the conversion from NF to agriculture. Although PCA indicates the separation between the agriculture area and native vegetation in PC1 at both depths, the indicators point to these areas as those with the highest chemical fertility in relation to the others. However, the resilience imposed by natural soil fertility cannot be a decisive factor for the maintenance of conventional agricultural systems, since the loss of quality indicators is occurring over time in this type of soil.

In the 10–20 cm layer, responses were similar to those in the superficial layer. In Planosols and Luvisols, the impacts of converting NF into conventional agriculture were more evident, highlighting the need for alternative production systems for these types of soil. At this depth,

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Leptosols present higher levels of SOM-associated indicators, providing a certain similarity between areas of NF, pasture, and agriculture. However, inadequate management practices, such as biomass slashing and burning and mechanization in conventional agriculture, can accelerate the loss of soil organic C stocks, resulting in soil quality loss in the medium to long term.

This loss of soil quality has certainly contributed to the stagnation of agricultural and livestock production in the Brazilian semi-arid region, since, according to IBGE data (2022), productivity levels in the region, in addition to not showing consistent gains in recent decades, are much lower than other regions of the country. For example, bean, cassava, and maize crops had average yields between 2011 and 2020 of 358.5, 8,325.1, and 790.4 kg ha^{-1}, respectively. The other regions (except for the northern region) presented averages of 1,691.2, 19,556.7, and 5771.1 kg ha^{-1}, respectively; that is, productivity levels were between 2.3 and 7.3 times higher than in the semi-arid region. In pasture areas, the situation is similar, since according to LAPIG data (2022), the Caatinga has 14.5% of the area with pasture in Brazil; however, pasture classified as severely degraded in this biome corresponds to 21.3% of pasture in this condition in the country, which means approximately 5.5 million hectares of pasture with a high degradation level.

Conclusions

Our research demonstrates that conventional agricultural practices frequently lead to considerable degradation of essential soil properties, hence compromising the sustainability of farming systems. The adverse effects on croplands surpassed those in pasture regions, as clearly demonstrated by the disparities in TN, microbial carbon and nitrogen, humic substance fractions, and labile carbon. Substantial disparities existed among soil types. Planosols exhibited the biggest alterations, with a 91.4% drop in their characteristics, while Cambisols experienced a 56.2% decrease.

The findings indicated that SOM is the main attribute for assessing soil quality, as both organic carbon levels and labile fractions such as microbial carbon and nitrogen, labile carbon; and even the humic substance fractions, exhibited heightened sensitivity to alterations in land use and management practices in the Brazilian semi-arid region. Alongside SOM, soil density and phosphorus show significant sensitivity to alterations in land use and soil management practices.

The results indicate that these soils presently or potentially may encounter challenges concerning structure and aggregate stability, infiltration and water retention, nutrient availability, and cycling, all of which are influenced by diminished microbial activity and reduced soil fertility.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0014479725000055

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