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Carbon and nitrogen in degraded Brazilian semi-arid soils undergoing desertification

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ABSTRACT

Although the effects of grazing exclusions on the recovery of soil properties have been extensively reported, few studies have addressed the different soil organic matter (SOM) fractions in desertification threatened areas from tropical regions. The objective of this work was to evaluate the effect of overgrazing (Og) and grazing exclusion (Exc) on SOM content and its pools in a desertification nucleus of the Brazilian semi-arid region. Six experimental plots with two treatments (Exc and Og) were studied. Soils from Exc plots showed higher total organic carbon (TOC: 4–37%) and total N (TN: 1–29%) contents when compared to soils from Og plots. At the Exc plots, the OC (organic carbon) contents in the light, labile and humin fractions were 38, 29 and 36% greater, respectively. The N contents at the Exc areas were greater in the light and humin fractions. The Carbon Management Index (CMI) was also greater in all Exc areas, ranging from 16 to 49%. Despite the low CMI values (<100) found for both treatments, indicative of highly degraded soils, Exc increased CMI in ~20%. Although the period of seven years seems to be insufficient for large TOC and TN accumulations, the results indicate that exclusion may be an important management strategy for the recovery of desertified lands in Brazilian semi-arid regions.

1. Introduction

The Brazilian semi-arid region is characterized by high temperatures, low rainfall, slightly weathered soils, and low phytomass production (Maia et al., 2008). Under these conditions, a sustainable production system requires efficient soil management practices, because the regenerative capacity of soil is low. However, good soil management practices are not adopted by the subsistence agriculture carried out in the region. Usually the subsistence systems in the semi-arid region lacks on nutrient input and soil cover, and works with slash and burn system, presenting high rate of runoff during the rainy season (Oliveira et al., 2004). Overgrazing and continued grazing predominate in stock-raising while farming is carried out in the traditional slash and burn system (Maia et al., 2007). Overgrazing also contributes to soil degradation by: (i) reducing vegetation cover, which increases erosion risks, (ii) increasing soil compaction through trampling, which causes less soil porosity and higher soil bulk densities and (iii) reducing water infiltration rates (Pei et al., 2008).

These factors make these regions extremely fragile, both from the environmental and the socio-economic viewpoints (Sharma et al., 2005). As a consequence of this scenario, in the past decades, large areas of the Brazilian semi-arid region were degraded, and in some cases, affected by an advanced stage of desertification.

In Brazil, areas prone to desertification cover 980,711 km^2, distributed in eight states from Northeast Brazil and one from southeast (Costa et al., 2009). Of the 900,000 km^2 within the semi-arid region, 99,000 km^2 are in an advanced stage of desertification (Gomes et al., 2007). Degraded areas cover approximately 13% of the Northeast Brazil (IBGE, 1997). Ceará state has 14% of its area prone to desertification, with Irauçuba remaining as one of the most affected areas in Brazil (Brasil, 1998).

Although soil degradation in Brazilian semi-arid regions is recognized as a major problem, research efforts still need to evaluate physical, chemical, and biological aspects as a whole, especially in studies concerning recovery and/or regeneration under grazing exclusion conditions (Mekuria et al., 2007). Recently, this management technique, where grazing and farming are excluded from degrading areas, has been considered as a valid alternative for restoring lands that are not yet completely degraded (Mekuria et al., 2007; Pei et al., 2008; Lipper et al., 2010).

Previous studies indicate that exclusion promotes not only the recovery of soil fertility, but also the recovery of soil biomass, plant communities, soil fauna, and water storage capacity. Although the effects of exclusions on the recovery and/or regeneration of important soil properties (TOC, N, P, K, Ca, pH and bulk density) have been

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extensively reported (Aerts et al., 2004; Su et al., 2004; Valone and Sauter, 2005; Descheemaeker et al., 2006; Mekuria et al., 2007; Pei et al., 2008) some recent studies have obtained inconclusive results (Raiesi and Asadi, 2006; Shrestha and Stahl, 2008).

To assess the effects of grazing exclusion over time one can use the same parameters used to detect changes caused by management practices and land use. Larson and Piece (1994) proposed a set of chemical, physical and biological soil parameters, which if followed over time, are able to detect changes in soil quality due to management. The soil organic matter (SOM), given by the total organic carbon content (TOC) and/or total nitrogen (TN), are one of the main indicators of soil quality (Dalal and Mayer, 1986; Mielniczuk, 1999; Sharma et al., 2005). This is due to the response of SOM content to management practices (Dalal and Mayer, 1986) and also due to its essential role in determining the physical, chemical and biological characteristics of a soil and therefore in determining its quality (Silva and Mendonça, 2007). In fact, indices that assess SOM changes, such as Carbon Management Index (CMI), have been used as a monitoring tool for both soil degradation and ecosystem farm yields (Wendling et al., 2008). The decrease in the SOM contents over time is often due to bad soil management practices, which may lead to unsustainable cultivation both from the economic and environmental aspects (Mielniczuk, 1999). Additionally, changes in soil organic C and N content are not only crucial to assessing soil quality and ecosystem productivity, but also to understanding the impacts of C and N cycling rates and storage on global climate change (Zhao et al., 2009).

Several studies have found increases in C and N contents in exclusion areas when compared to continuous grazing areas (Derner et al., 1997; Schuman et al., 1999; Reeder et al., 2004; Su et al., 2004; Mekuria et al., 2007). However, few studies have addressed the evaluation of different SOM fractions in desertification threatened areas from tropical regions. We hypothesize that exclusion in the semi-arid region of Ceará (Brazil) may improve soil properties in overgrazed areas by increasing C and N contents and consequently contribute to greater SOM input. The objective of this work was to evaluate the effect of overgrazing and 7-year exclusion on SOM content and also on C and N soil pools and to evaluate whether these highly degraded areas are still able to regenerate/recover.

2. Material and methods

2.1. Study area

This study was carried out in an experimental area located in the rural district of Irauçuba (Fig. 1a), a degradation/desertification nucleus of the Brazilian semi-arid region (MCT/Brasil, 2001) in the state of Ceará (Soares et al., 1995). The region has a mean annual temperature of 26.3 °C, a mean rainfall of 530 mm which is concentrated mostly in three months (between March and May; Fig. 2b) and a potential evapotranspiration of 1582 mm yr^{-1} (Krol et al., 2006). Fig. 2a presents the average annual precipitation of the last 30 years in Irauçuba and evidences the harsh semiarid environment of the study area.

The soil survey map of NE Brazil (Brasil, 1973; Lustosa, 2004) indicates eight soil association in the Irauçuba district (Fig. 1b), with the predominance of Lixisols, Luvisols, Leptosols, and Planosols (WRB, 2006). Sales (2003) identified the association of Planosols and Luvisols in the exclusion plots of the present study and Caatinga (seasonal xerophilous thorn woodland/shrubland) as the main vegetation unit. The soils are slightly weathered, with high activity-clay, high base and sodium saturation. The classification of the studied profiles, according to the World Reference Base for Soil Resources (WRB, 2006), along with their location, topographic position and chemical and physical characteristics are given in Table 1. All routine analytical chemical and physical measurements for soil classification were obtained using standard procedures (Embrapa, 1997).

The soil use and management history are similar for all 6 areas since all have been subjected to extensive livestock system for more than 20 years (Irauçuba local farmers, personal communication).

2.2. Field work

Six experimental areas were investigated (Table 1). Each experimental area was submitted to two treatments: (i) grazing exclusion (Exc); the area was fenced off (for 7 years) to prevent grazing by bovine, ovine, caprine, equine, donkeys, and mules for the evaluation of the natural regeneration processes and (ii) overgrazed areas (Og); areas of free access by animals used to evaluate the influence of overgrazing over time. The adopted management system is based on free-grazing by cattle during the rainy season and free-grazing by sheep and goats during all year (feeding mostly on the amount of pasture left by cattle). The dominant native grass at the study area is *Aristida setifolia* and *Stylosantes humilis* (Sales and Oliveira, 2005). Previous studies indicate that the recommended livestock capacity for the study area is 13,960 animal units (AU) (Araújo Filho et al., 2002). However a recent survey (IBGE, 2006) indicates that the total livestock population of Irauçuba is of 23,600 AU (69% above the recommended carrying capacity), which evidences an overgrazing situation.

Two natural vegetation areas (Forest 1 and Forest 2) situated adjacent to the studied sites were also sampled and used as control sites. Forest 1 was used as a control plot for areas 1, 2, 3, and 5, and Forest 2 was used as a control for areas 4 and 6. These combinations were chosen considering the proximity of the areas and similar soil characteristics.

Sampling was performed in triplicate in each studied area, where 3 subsamples were collected and homogenized in order to obtain composite samples. Three composite samples were prepared for each treatment. The treatments were compared for changes in SOM and its C and N pools content. In each sampling site, measures of A horizon thickness were performed in mini-trenches (40 cm × 40 cm × 40 cm).

2.3. Chemical analysis

The soil samples were air dried and sieved through a 2 mm sieve to obtain the fine earth. A fraction of the samples was ground in a mortar and sieved with a 0.2 mm sieve before laboratory analysis.

The total organic carbon content (TOC) was determined by wet oxidation using potassium dichromate in acidic medium with an external heat source (Yeomans and Bremner, 1988). Test of soil carbonate content was, previously, carried on, presenting negative result. Total nitrogen (TN) was determined in soil samples digested with sulfuric acid and analyzed by Kjeldahl distillation (Bremner, 1996). The TOC and TN stocks were calculated from the bulk density values (Fig. 3) according to Eqs. (1)–(3).

$$\text{Soil mass}\,(\text{kg ha}^{-1}) = \text{depth}\,(\text{m}) \times 100\,\text{m} \times 100\,\text{m} \times \text{bulk density}\,(\text{g cm}^{-3}) \quad (1)$$

$$\text{C stock}\,(\text{kg ha}^{-1}) = \frac{\text{C content}\,(\text{g kg}^{-1}) \times \text{soil mass}\,(\text{kg ha}^{-1})}{1000} \quad (2)$$

$$\text{N stock}\,(\text{kg ha}^{-1}) = \frac{\text{N content}\,(\text{g kg}^{-1}) \times \text{soil mass}\,(\text{kg ha}^{-1})}{1000} \quad (3)$$

The carbon contents in the labile (C_L) and nonlabile (C_{NL}) fractions were determined by oxidizing C with different concentrations

Table 1
Classification of the studied profiles according to the World Reference Base for Soil Resources (WRB, 2006) along with their, location, topographic position and chemical and physical soil features.

Horizons	Depth cm	Color Munsell	pH H_2O	OC $g\,kg^{-1}$	Ca $cmolc\,kg^{-1}$	Mg	Na	K	H + Al	Al	SB	CEC	BS %	ESP	EC $dS\,m^{-1}$	sand $g\,kg^{-1}$	silt	clay	Texture	Topography
Area 1 – Aroeira Farm/Vertic Solonetz (Abruptic, Ruptic)																				
Ap	0–3.5	2.5 YR 4/3	5.1	19.6	5.0	1.6	0.13	0.41	5.77	0.15	7.1	12.9	55	1	0.78	650	260	90	Sandy loam	Plane; 2 percent slope
E	3.5-9	10 YR 6/3	5.2	2.5	1.7	1.4	0.15	0.07	2.80	0.70	3.3	6.1	54	3	0.19	840	110	50	Loamy sand	
Btn1	9-25	10 YR 6/2	6.1	2.1	7.7	3.1	1.36	0.09	1.32	0.15	12.2	13.6	90	10	0.53	690	200	110	Sandy loam	
Btn2	25-43	10 YR 6/4	7.2	1.6	9.6	2.4	2.53	0.11	0.00	0.00	14.6	14.6	100	17	1.46	670	150	180	Sandy loam	
Btn3	43-61	10 YR 6/2	7.9	1.7	10.0	2.3	3.37	0.11	0.00	0.00	15.8	15.8	100	21	2.31	630	190	180	Sandy loam	
Area 2 – Aroeira Farm/Vertic Solonetz (Abruptic, Ruptic)																				
Ap	0–2.5	2.5 y 4/3	5.0	11.3	2.2	1.4	0.08	0.32	4.78	0.70	4.0	8.8	45	1	0.43	800	150	50	Loamy sand	Plane; 3 percent slope
E	2.5–11	10 YR 5/4	4.9	2.9	1.3	1.1	0.08	0.09	2.64	1.05	2.6	5.2	40	1	0.11	850	90	60	Loamy sand	
Btn1	11–24	10 YR 6/3	5.7	2.8	13.4	6.0	3.03	0.17	2.14	0.35	22.6	24.7	91	12	1.82	480	200	320	Sandy clay loam	
Btn2	24–41	10 YR 6/4	7.0	2.0	18.5	5.9	5.90	0.16	0.49	0.00	30.4	30.9	98	19	3.49	480	280	240	Loam	
Area 3 - Formigueiro Farm/Vertic Solonetz (Abruptic, Ruptic)																				
Ap	0–3	10 YR 4/2	4.9	14.3	4.5	1.7	0.11	0.33	6.27	0.60	6.6	12.9	51	1	0.54	740	190	70	Sandy loam	Plane; 3 percent slope
E	3–17	10 YR 5/3	5.5	3.3	4.0	1.8	0.24	0.10	1.15	0.30	6.1	7.3	84	3	0.23	770	160	70	Sandy loam	
Btn1	17–42	10 YR 5/2	6.2	2.6	12.2	3.8	2.55	0.12	1.48	0.05	18.7	20.2	93	13	2.02	620	190	190	Sandy loam	
Btn2	42–90	2.5 YR 5/3	7.6	1.7	26.3	4.1	8.79	0.16	0.00	0.00	39.3	39.3	100	22	6.32	460	250	290	Sandy clay loam	
Area 4 – Cacimba Salgada Farm/Leptic Regosol (Eutric)																				
Ap	0–4.5	10 YR 4/2	4.9	9.5	1.4	1.1	0.06	0.20	3.63	0.75	2.8	6.4	43	1	0.24	830	130	40	Loamy sand	Plane; 4 percent slope
C1	4.5–21	10 YR 5/4	4.9	2.0	1.4	1.1	0.17	0.07	2.47	0.55	2.7	5.2	52	3	0.22	880	90	30	Sandy	
C2	21–32	10 YR 5/6	5.6	1.3	0.9	0.9	0.12	0.05	3.30	0.35	2.0	5.3	37	2	0.12	920	60	20	Sandy	
Area 5 – Cacimba Salgada Farm/Haplic Solonetz (Abruptic, Ruptic)																				
Ap	0–3	2.5 YR 5/3	5.0	19.4	4.9	2.3	0.27	0.49	5.44	0.70	8.0	13.4	59	2	0.69	640	280	80	Sandy loam	Plane; 2 percent slope
E	3–17	2.5 YR 5/4	5.0	4.7	2.2	1.3	0.17	0.18	4.12	0.50	3.8	8.0	48	2	0.22	750	190	60	Sandy loam	
Btn1	17–25	2.5 YR 7/1	6.1	2.6	11.3	3.5	1.75	0.19	2.47	0.15	16.7	19.2	87	9	0.39	550	170	280	Sandy clay loam	
Btn2	25–49	2.5 YR 6/2	8.0	1.3	10.8	4.7	3.70	0.15	1.65	0.00	19.3	21.0	92	18	0.96	600	250	150	Sandy loam	
Area 6 – Vila Mimosa Farm/Solodic Planosol (Ruptic, Eutric)																				
Ap	0–3	2.5 YR 4/3	5.4	9.7	2.3	1.8	0.11	0.44	3.13	0.45	4.6	7.8	60	1	0.38	830	120	80	Loamy sand	Plane; 5 percent slope
E1	3–12	2.5 YR 4/4	5.0	3.5	0.9	0.8	0.09	0.23	2.47	0.85	2.0	4.5	45	2	0.14	870	70	60	Loamy sand	
E2	12–23	2.5 YR 4/3	5.3	2.9	2.0	1.5	0.27	0.35	4.45	1.45	4.1	8.6	48	3	0.13	810	100	90	Loamy sand	
Btn	23–35	2.5 YR 6/4	5.5	1.9	7.0	2.9	1.63	0.15	2.47	0.65	11.7	14.2	82	11	0.57	680	140	180	Sandy loam	

OC: organic carbon; SB: sum of base cations; CEC: cation exchange capacity; BS: base saturation (BS = 100 × sum of bases/cation exchange capacity); ESP: exchangeable sodium percentage; EC: electrical conductivity in the water extracted from a saturated paste.

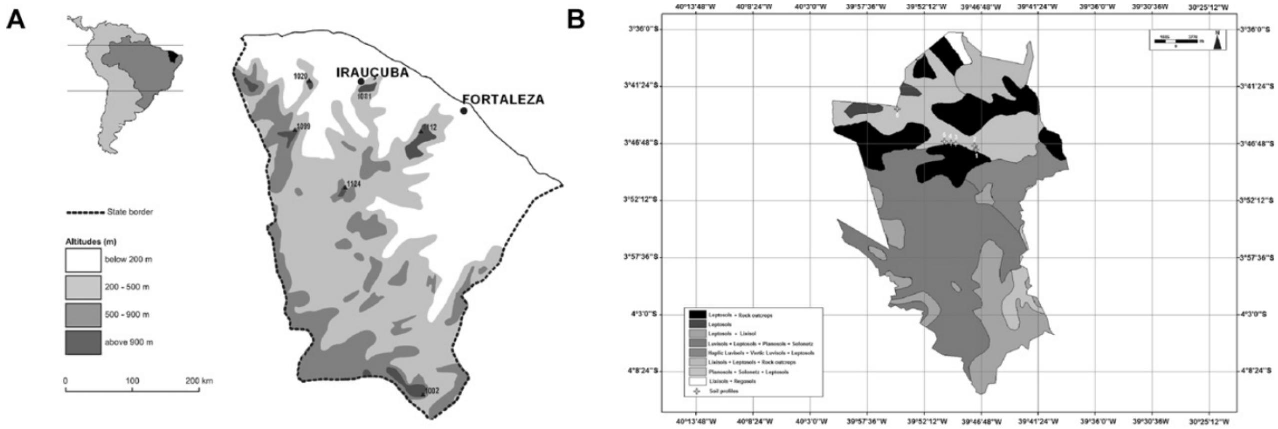

Fig. 1. Brazil, Ceará State, and, in detail, the location of the study site in the rural district of Irauçuba (A) along with the soil survey map of Irauçuba district indicating the present soil associations (B).

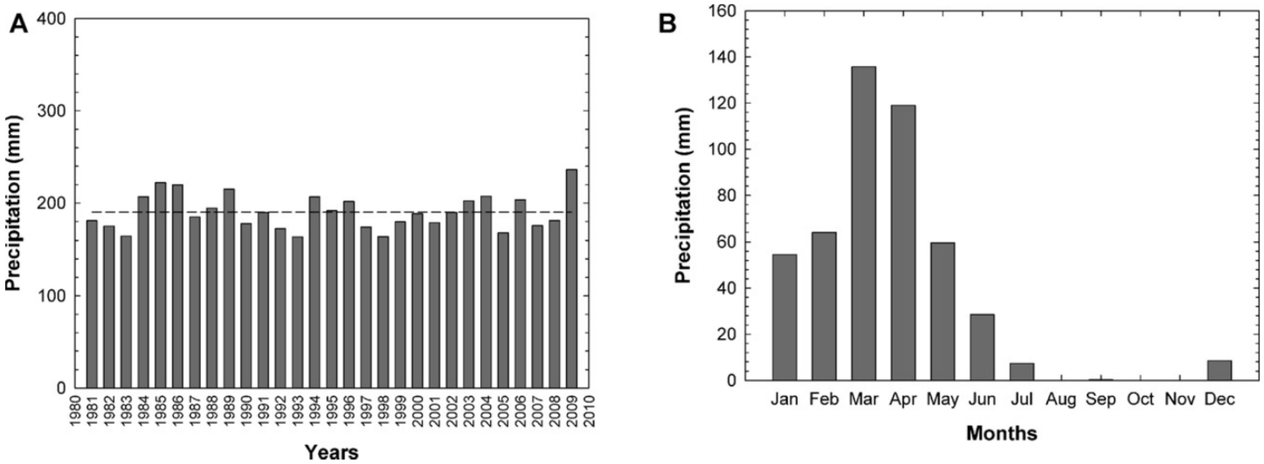

Fig. 2. Data on the average annual (A) and monthly precipitation (B) for the last 30 years in Irauçuba district.

of H_2SO_4 keeping $K_2Cr_2O_7$ concentration and titrating with 0.5 mol L^{-1} ferrous ammonium sulfate using a ferroin solution as an indicator, following the adapted methodology of Chan et al. (2001). In this work, concentrations of 3, 6, and 9 mol L^{-1} of H_2SO_4 were used to better adjust to tropical conditions (Mendonça and Matos, 2005). With the amounts of C oxidized in these different H_2SO_4 concentrations we calculated four distinct fractions: F1 = 3 mol L^{-1}, F2 = 6–3 mol L^{-1}, F3 = 9–6 mol L^{-1}, and F4 = total organic carbon–9 mol L^{-1}; the summation of fractions F1 and F2 was considered as C_L while summation of fractions F3 and F4 was considered C_{NL}.

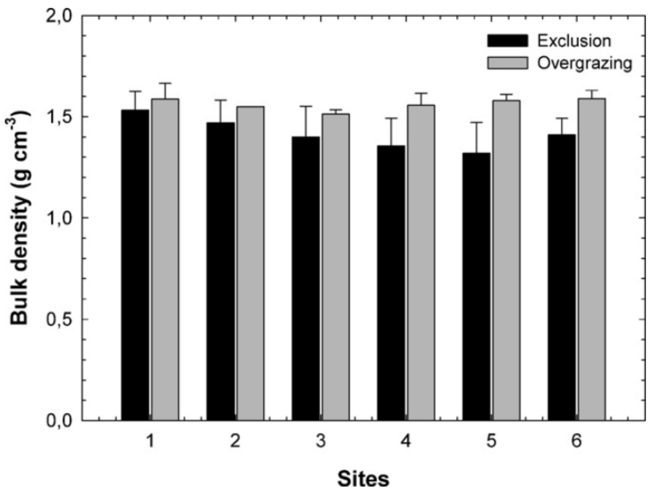

Fig. 3. Mean bulk density, at 0–5 cm depth, for soils under exclusion and overgrazing.

The carbon pool index (CPI) was calculated on the basis of changes in the proportion of TOC in the soil between the control sites ($TOC_{reference\ forests}$) and those subjected to the research treatments ($TOC_{Exc\ or\ Og}$), as shown in Eq. (4).

$$CPI = \frac{TOC_{(Exc\ or\ Og)}}{TOC_{reference\ forest)}} \quad (4)$$

From the changes in the proportion of C_L (i.e., $L = C_L/C_{NL}$) in soil from treatment and control plots we also determined the lability index (LI) using Eq. (5):

$$LI = \frac{L_{(Exc\ or\ Og)}}{L_{reference\ forests}} \quad (5)$$

These indexes were then used to calculate the Carbon Management Index (CMI) according to Eq. (6) (Blair et al., 1995):

$$CMI = CPI \times IL \times 100 \quad (6)$$

The humic substances were chemically fractionated by the differential solubility technique, which separates the fulvic acids (FAF), humic acids (HAF), and humins (HF), according to the humic substances fraction concepts established by the International Humic Substances Society (Swift, 1996). NaOH (0.1 mol L^{-1})

was used as an extractant. The C content of the fractions was quantified by dicromatometry with external heating (Yeomans and Bremner, 1988) and the N content was determined by sulfuric digestion and analyzed by Kjedahl distillation (Bremner, 1996). The summation of the humified organic C (HOC) was calculated as HOC = C-FAF + C-HAF + C-HF (where C-FAF: C in the fulvic acid fraction; C-HAF: C in the humic acid fraction; C-HF: C in the humin fraction), as well as its percentage to TOC. The ratio between the organic C in the humic and fulvic acid fractions was calculated (C-HAF/C-FAF) and also the ratio between the alkaline-soluble fractions and organic C in the humin fraction (C-FAF + C-HAF/C-HF).

The fractions corresponding to the light organic matter (LOM) and the occluded organic matter (OOM) were determined in the fine earth (2 mm) by flotation in sodium iodide (density of 1.85 g cm^3) according to an adapted methodology based on Sohi et al. (2001). The LOM fraction was obtained by centrifugation at 2500 rpm for 15 min and sieving the suspended material through a 0.053-mm sieve using distilled water to remove the excess of NaI. After separation of the LOM fraction, 15 mL of sodium hexametaphosphate was added to the same centrifuge tube and the tube was agitated for 18 h in a horizontal agitator to disperse the soil. After dispersion, the sample was sieved in a 0.053 mm sieve with distilled water to remove the excess of dispersant and to obtain the occluded organic matter (OOM). The sieved LOM and OOM fractions were placed in an oven at 60 °C for 72 h. The C and N contents of the LOM fraction (C_{LF} and N_{LF}) were quantified by dry combustion in a Perkin Elmer CHNS/O 2400 Elemental Analyzer. The C content of the OOM fraction (C_{OF}) was determined according to Yeomans and Bremner (1988) and the N content of the OOM fraction (N_{OF}) was quantified by sulfuric digestion and analyzed by Kjeldhal distillation (Bremner, 1996).

2.4. Statistical analyses

The studied variables were analyzed by descriptive statistics (ie, means of three replicates, standard-deviation, minimum, maximum, sample size) and mean comparison using Student's *t*-test at 5% level of significance. All statistical analyses were performed using the SAS (9.1) statistical software package. Cluster analysis was performed adopting squared Euclidean distances as a measure of dissimilarity and Ward's method as the clustering algorithm. To perform the multivariate analysis the software SPSS (16.0) was used.

3. Results and discussion

3.1. Contents and stocks of TOC and N and carbon lability

Observing the dendrogram of results from cluster analysis (Fig. 4), two clear broad groups can be identified. The first group includes 5 overgrazed sites (2, 3, 4, 5 and 6) and one exclusion area (6), while the second group includes 5 exclusion sites (1, 2, 3, 4 and 5) and one overgrazed site (1). These results evidence a very clear separation of the different treatments (overgrazing and exclusion). The different behavior of exclusion 6 and overgrazed 1 may be related to the absence of significant differences in TOC contents and other measured parameters (Table 2).

The soils under exclusion treatments had the highest TOC contents when compared to the Og plots, except for areas 1 and 6 (Table 2). The TOC increase in soils from exclusion treatments ranged from 4.1 to 37.3%. The TN contents showed a similar behavior to that of TOC, with increasing values from overgrazing to exclusions plots (Table 2), again area 1 did not present a significant difference. In the other exclusion areas, TN contents increased by an average of 15–29%.

Table 2
Total organic carbon (TOC) and nitrogen (TN) contents; C and N stocks; labile (C_L) and nonlabile (C_{NL}) carbon and Carbon Management Index (CMI) under exclusion and overgrazing areas.

Areas	TOC	TN	C/N	C stock	N stock	C_L	C_{NL}	C_L	C_{NL}	CPI	Index L	LI	CMI
		g kg^{-1}		kg ha^{-1}/A horizon-		g kg^{-1}		% TOC					
1 Exc	15.10	1.22	12.38	8.08	0.65	7.50	7.60	49.72	50.28	0.54	0.99	1.11	59.86
1 Og	14.48	1.20	12.07	6.91	0.57	6.70	7.78	49.27	53.73	0.52	0.86	0.97	50.00
p-Value	0.2838	0.2990	0.5387	<.0001	<.0001	<.0001	0.7499	0.0945	0.0945	0.3783	0.0553	0.0727	0.0008
2 Exc	18.09	1.43	12.65	6.65	0.52	8.50	9.59	47.00	53.00	0.64	0.89	1.00	64.32
2 Og	11.34	1.04	10.90	3.52	0.32	5.50	5.84	48.52	51.48	0.40	0.95	1.07	43.09
p-Value	<.0001	<.0001	0.0021	<.0001	<.0001	<.0001	<.0001	0.4516	0.4516	<.0001	0.3487	0.3799	<.0001
3 Exc	18.78	1.52	12.36	7.89	0.64	9.20	9.58	49.03	50.97	0.67	0.96	1.08	72.39
3 Og	14.87	1.17	12.71	4.49	0.35	6.00	8.87	40.37	59.63	0.53	0.68	0.76	40.35
p-Value	<.0001	<.0001	0.4327	<.0001	<.0001	<.0001	0.2325	0.0002	0.0002	<.0001	0.0001	0.0004	<.0001
4 Exc	17.01	1.35	12.60	10.41	0.83	7.80	9.21	45.86	54.14	0.73	0.85	0.94	68.21
4 Og	11.77	0.95	12.39	6.42	0.52	5.20	6.57	44.44	55.56	0.50	0.81	0.89	44.54
p-Value	<.0001	<.0001	0.6753	<.0001	<.0001	<.0001	<.0001	0.4828	0.4828	<.0001	0.5399	0.5717	<.0001
5 Exc	16.85	1.36	12.39	6.67	0.54	7.80	9.05	46.37	53.63	0.60	0.87	0.98	58.54
5 Og	13.86	1.01	13.72	4.38	0.32	4.80	9.06	34.66	65.34	0.49	0.53	0.60	29.46
p-Value	<.0001	<.0001	0.0114	<.0001	<.0001	<.0001	0.9916	<.0001	<.0001	0.0002	<.0001	<.0001	<.0001
6 Exc	13.51	0.99	13.65	5.71	0.42	5.70	7.81	42.65	57.35	0.58	0.75	0.83	47.30
6 Og	12.6	0.84	15.00	4.01	0.27	4.50	8.10	35.77	64.23	0.54	0.56	0.62	33.18
p-Value	0.1179	<.0001	0.0126	<.0001	<.0001	<.0001	0.6155	0.0018	0.0018	0.1251	0.0053	0.0101	<.0001
Forest 1	28.06	1.99	14.10	10.86	0.77	13.20	14.86	47.05	52.95	–	0.89	–	–
Forest 2	23.39	1.64	14.26	10.32	0.72	11.10	12.29	47.45	52.55	–	0.90	–	–

p Values indicate significance of differences between exclusion and overgrazing (p-value < 0.05); TN: total nitrogen; C_L: labile carbon; C_{NL}: nonlabile carbon; CPI: carbon pool index; L: lability; LI: lability index; Exc: exclusion; Og: overgrazing.

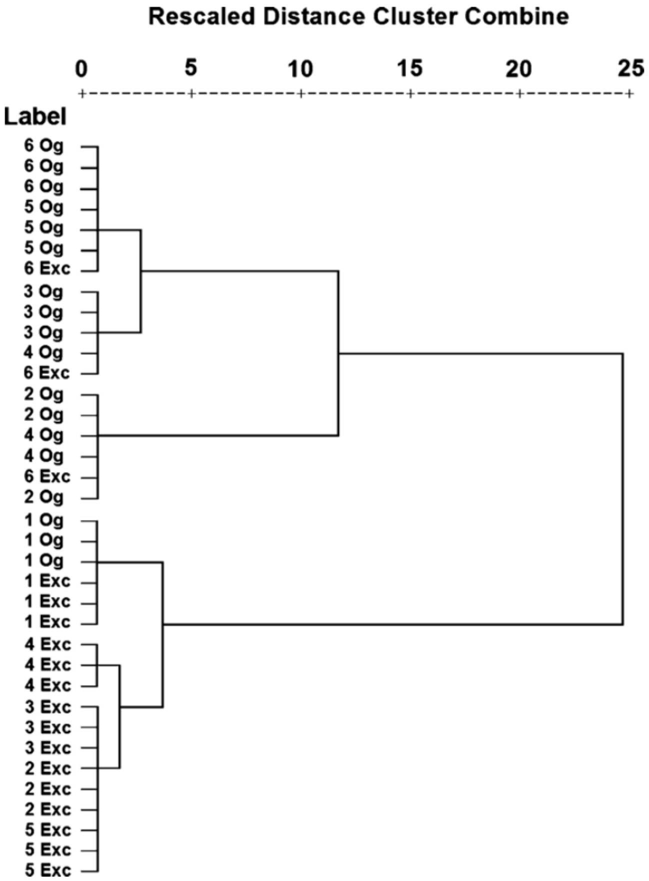

Fig. 4. Dendrogram of results from cluster analysis showing the identification of two broad groups.

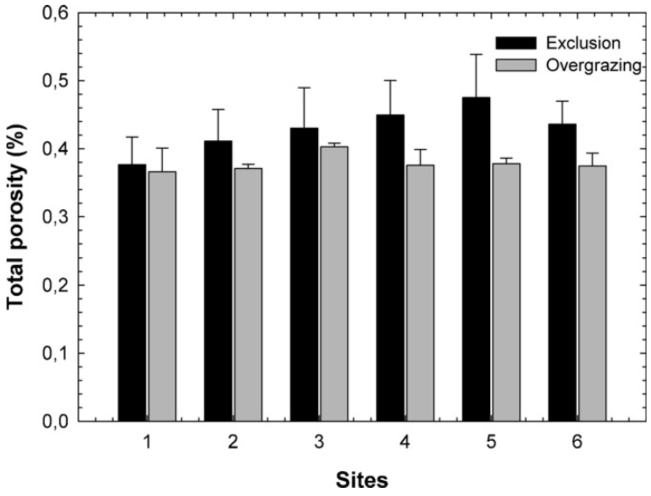

Fig. 5. Mean total porosity, at 0–5 cm depth, for soils under exclusion and overgrazing.

The C/N ratios ranged from 10 to 15 and showed no consistent trends between treatments, with variations that could not be attributed to the differences in soil use. Yong-Zhong et al. (2005), in the semi-arid regions of China, found C/N ratios significantly higher (10.36) in 10-year exclusion sites than in 5-year exclusion (9.57) and continued grazing (8.62). In the same region, Pei et al. (2008) also found higher C/N ratios in exclusion areas, however with lower values (∼6). The highest C/N ratios reported in exclusions sites from other studies are due to a greater organic matter input and also to fire suppression, which reduce N net mineralization and N availability (Johnson and Matchett, 2001).

The TOC and TN stocks in the A horizon of soils from exclusion plots increased by an average of 14–47% and 12–45%, respectively, when compared to the overgrazed areas. Area 6 had the lowest TOC and TN stock values. This result may be due to the high degree of degradation of this particular area before exclusion. In fact, in a previous study, Sales and Oliveira (2005) found a higher proportion of bare soil in area 6 in the year of the beginning of the exclusion treatment (2001), suggesting a higher degree of degradation.

The highest TOC and TN stocks in exclusion areas can be attributed to a higher vegetation cover inside the exclusions. In fact, Sales and Oliveira (2005) found that the percentage area of bare soil significantly decreased from the year 2001 to 2007 in the exclusions areas at Aroeira Farm (areas 1 and 2: from 31% to 10%), Cacimba Salgada Farm (areas 4 and 5: from 21% to 0.8%) and Vila Mimosa Farm (area 6: from 47% to 4%).

This higher vegetation cover, on the other hand, also contributes to increase water infiltration rates, reduce soil erosion and bulk density (Silva and Mendonça, 2007). In fact, lower bulk density values (Fig. 3) were found in the uppermost layers in all exclusion sites, associated to higher total porosity percentages (Fig. 5). These results indicate that the improved surface conditions on these plots are related to a larger fraction of organic substrates returned to the soil by aerial biomass and by the turnover of root system, especially thin roots (Silva and Mielniczuk, 1997), promoting surface horizon thickening and an improved physical quality. This hypothesis is supported by the highly significant correlations between TOC and total porosity (positive correlation: $r = 0.83$; $p < 0.005$, Fig. 6) and TOC and bulk density (negative correlation: $r = -0.861$; $p < 0.001$, Fig. 6) in the surface samples (0–5 cm). Several studies in other semi-arid regions also evidenced similar effects of soil cover on TOC and TN contents in both farming and stock-raising areas (Solomon et al., 2000; Reeder and Schuman, 2002; Yong-Zhong et al., 2005; Descheemaeker et al., 2006; Mekuria et al., 2007; Pei et al., 2008).

These results illustrate, not only the negative effects of trampling by livestock, which may cause soil compaction, reduce soil infiltration rates, soil total porosity, increase bulk density and limit soil aeration (Pei et al., 2008; Wu et al., 2009, 2010; Reszkowska et al., 2011), but also, the important role of exclusions on restoring SOM, aggregation, water-holding capacity (Evrendilek et al., 2004) and also improve soil physical quality.

Contrastingly, other reports in the literature on the effects of grazing on soil organic C and N stocks are contradictory. Descheemaeker et al. (2006) studied grazing and exclusion areas established in different periods of time (5, 14 and 20 years) and found higher biomass, potassium, phosphorus, TOC, and TN in exclusion areas. Additionally, these increases were proportional to

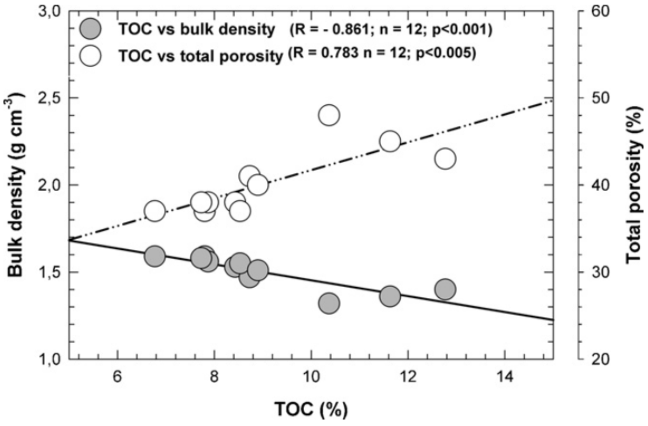

Fig. 6. Relationship between TOC, bulk density and total porosity in surface soil samples (0–5 cm) from both treatments (overgrazing and exclusion).

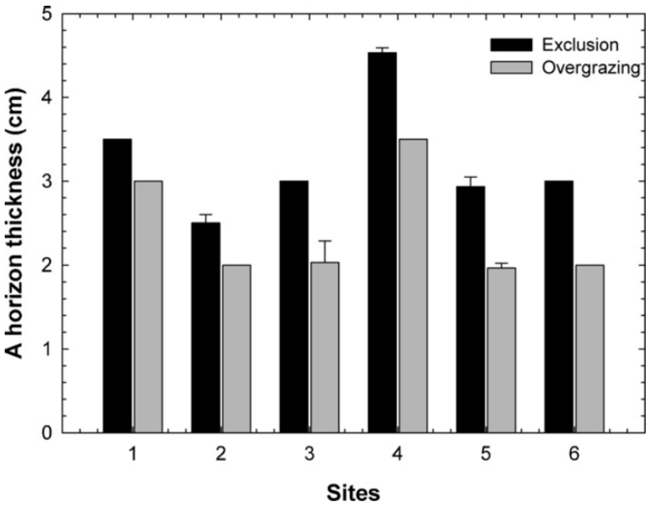

Fig. 7. Mean A horizon thickness for soils under exclusion and overgrazing.

exclusion duration. Shrestha and Stahl (2008) did not find differences in the TOC contents and C/N ratios between four different areas submitted to grazing and exclusion. According to Reeder and Schuman (2002), differences in soil OC contents in response to grazing may vary with climate conditions, soil properties, pasture location, vegetation community composition, and pasture management practices. In our study, the lowest TOC and TN contents were associated with overgrazed plots probably due to the low input of organic matter, consumed as feed for livestock, which results in an unprotected soil surface and a probable increased soil organic matter mineralization rate (Galvão et al., 2005). Other factors, such as excessive trampling by animals and soil losses due to sheet erosion also play an important role.

In fact, the impact of erosion on overgrazed areas, where soil cover was reduced or absent, is evidenced by shallower A horizons at all overgrazed plots (Fig. 7). The A horizons in overgrazed areas (areas 1 and 2) were 0.5–1.0 cm shallower (areas 3, 4, 5, and 6) than those in exclusion areas. These results suggest that the overgrazed soils have lost from 75 to 160 Mg ha^{-1} of the surface layer, between 2000 and 2007, in relation to the exclusion plots. Although these values may vary with soil type, topography and degree of soil degradation, soil losses found in our work agreed with those of Sampaio and Salcedo (1997), who reported annual erosion losses greater than 100 Mg ha^{-1}, for similar Brazilian semiarid soils.

The impact of overgrazing and continued grazing on soil is triggered by lack of soil cover (consumed as pasture) followed by an excessive soil trampling under adverse moisture conditions which results in soil compaction (Figs. 3 and 5) and land degradation. Removal of the vegetation cover also results in a higher susceptibility of soil to water erosion (Fig. 7), which is specially favored by the torrential rains of the wet season. Low water infiltration rate, accompanied by a heavy rain, leads to runoff and erosion which intensifies soil degradation (Li et al., 2006; Sivakumar, 2007). Erosion also reduces the available soil volume for root growth, water storage and nutrient uptake (Accioly and Oliveira, 2004).

The labile carbon contents (C_L) were higher in all exclusion plots ($p < 0.05$) which presented mean values 29% greater than those recorded at the overgrazed areas (Table 2). Maintaining carbon stocks, especially the labile fractions, is essential to sustain the production systems (Blair, 2000). This significant increase in C_L in exclusion plots indicates that conversion of overgrazed areas to exclusions may lead to a soil recovery after some period of time (at least 7 years). The increase of this C pool is usually accompanied by an increase in nutrient cycling in the agroecosystem (Wendling et al., 2008). The labile C pool represents about 25–33% of the SOM in temperate regions. However these percentages are probably lower for tropical soils (Zech et al., 1997). The labile pool represents, approximately 45% of TOC in the semi-arid soils under study, which may be attributed to the low rainfall and high evaporation rates (Fig. 2). These climate conditions, marked by frequent drought events, may contribute to a longer residence time of the labile C fraction (Davidson et al., 1998; Mielnick and Dugas, 2000).

The contents of nonlabile C (C_{NL}) behaved similarly in relation to soil use; however, exclusion areas 2 and 4 presented larger values (9.59 and 9.21 g kg^{-1}, respectively). This result indicates that exclusion may contribute to the formation of more stable organic compounds that work as a soil reservoir for C and nutrients (Blair et al., 1995).

Both the C_{NL} and C_L differed ($p < 0.05$) in areas 3, 5 and 6 and showed opposite trends. While C_L was higher in the exclusion areas, C_{NL} was higher in the overgrazed sites. In general, C_{NL} represented over 50% of the TOC in the studied soils, and the largest amounts were found in the overgrazed areas (58%). This fraction may persist in the soil for thousands of years and is mainly represented by humic substances, especially humins that are resistant to microbial attack or are physically protected by association with clay minerals or by soil aggregates (Zech et al., 1997). The studied soils present 38% of humans (Table 3). In the exclusion areas, both the C input and output are more intense due to the higher decomposition rates, microbial activity and the plant roots exudates, therefore the C_{NL} values tended to be smaller in these areas.

Grazing reduced ($p < 0.05$) the CMI in the overgrazed plots to 16–49% in relation to the exclusion areas (Table 2). According to Blair et al. (1995), CMI ≤ 100 indicates a negative impact of management practices on SOM and soil quality. These results clearly indicate that practices that promote a greater input of organic residues to the soil may have a higher potential for improving soil quality.

In our study, the CMI values varied from 29 (overgrazed area 5) to 72 (exclusion area 3). These results emphasize the high degree of soil degradation in the studied region, even after 7 years of exclusion, which characterizes the desertification process even before the areas were fenced off. Maia et al. (2007) studying different soil management conditions in the Ceará semi-arid region, found similar CMI values at the depth of 0–6 cm in areas with 5 years under traditional agrosilvipastoral system and intensive cultivation. However, they found CMI values > 100 in an area under silvipastoral system. Thus, the exclusion areas results indicate that this activity is a promising alternative for the improvement of the soil quality in the region.

3.2. *Carbon and nitrogen in humic substances*

The exclusion areas presented higher C and N values ($p < 0.05$) in the fulvic, humic acid and humin fractions when compared to the overgrazed areas (Table 3). With the exception of area 3, all overgrazed areas had higher N values in the humic acid fraction (N-HAF) than in the humin fraction (N-HF). These results differed from those of the exclusion areas, where the N content in the humic acid fractions decreased according to its lability (N-FAF, N-HAF, and N-HF, respectively; where N-FAF: N in the fulvic acid fraction). The lower N contents in more labile fractions indicate that overgrazing favors biological activity and the humification process (Stevenson, 1994). Management systems that present lower N content in the HF in relation to the FAF and HAF may indicate the predominance of the degradation route in the formation of humic substances. This is characteristic of environments that do not favor soil biological activity, such as overgrazed areas.

In the humin fraction, C (C-HF) and N (N-HF) contents behaved similarly, with values 36 and 33% higher ($p < 0.05$) in the exclusions than in overgrazed areas. The C-HF and N-HF contents indicate

Table 3
Carbon and nitrogen contents in fulvic acid, humic acid, and humin fractions; and percentages of C fractions under exclusion and overgrazing areas.

Areas	C-FAF	C-HAF	C-HF	N-FAF	N-HAF	N-HF	C-HAF/C-FAF	C-FAF ± C-HAF /C-HF	C-FAF	C-HAF	C-HF	HOC
	($g\,kg^{-1}$)								(% TOC)			
1 Exc	1.80	4.00	7.15	0.19	0.49	0.55	2.22	0.82	11.91	26.47	47.24	85.62
1 Og	1.72	4.04	5.58	0.21	0.51	0.44	2.35	1.07	11.90	27.91	38.55	78.36
p-Value	0.7588	0.5632	0.1010	0.0499	<.0001	<.0001	0.7665	0.5575	0.9947	0.0601	0.1475	0.2561
2 Exc	2.22	3.97	7.89	0.23	0.51	0.62	1.79	0.80	12.29	21.92	43.65	77.86
2 Og	1.44	2.80	4.84	0.18	0.40	0.33	1.97	0.88	12.67	24.69	42.64	80.00
p-Value	0.0032	<.0001	0.0026	<.0001	<.0001	<.0001	0.6698	0.8443	0.8375	0.0008	0.8636	0.7364
3 Exc	1.99	4.66	8.49	0.21	0.54	0.67	2.34	0.79	10.64	24.84	45.25	80.73
3 Og	1.42	2.97	5.66	0.19	0.42	0.49	2.10	0.80	9.56	19.96	38.10	67.62
p-Value	0.0257	<.0001	0.0047	0.0108	<.0001	<.0001	0.5680	0.9794	0.5656	<.0001	0.2307	0.0457
4 Exc	2.19	4.72	7.96	0.23	0.53	0.51	2.16	0.88	12.89	27.76	46.82	87.47
4 Og	1.24	2.71	2.98	0.19	0.35	0.34	2.19	2.16	10.57	23.11	24.49	58.17
p-Value	0.0005	<.0001	<.0001	0.0003	<.0001	<.0001	0.9371	0.0055	0.2212	<.0001	0.0007	<.0001
5 Exc	1.18	2.97	8.19	0.19	0.46	0.67	2.52	0.51	6.99	17.62	48.54	73.15
5 Og	0.57	1.97	4.91	0.14	0.39	0.36	3.51	0.53	4.15	14.21	35.41	53.77
p-Value	0.0195	<.0001	0.0014	<.0001	<.0001	<.0001	0.0243	0.9783	0.1361	<.0001	0.0326	0.0045
6 Exc	0.79	1.80	3.72	0.19	0.33	0.40	2.31	0.71	5.85	13.45	27.93	47.23
6 Og	1.46	1.70	2.98	0.18	0.30	0.30	1.91	1.04	11.35	13.55	23.60	48.50
p-Value	0.0107	0.2372	0.4262	0.0499	<.0001	<.0001	0.3419	0.4402	0.0006	0.8959	0.4637	0.8418
Forest 1	1.86	6.72	19.26	0.23	0.71	0.95	3.61	0.45	6.63	23.94	68.66	99.22
Forest 2	1.35	4.20	14.74	0.24	0.49	0.70	3.12	0.38	5.76	17.96	63.03	86.75

p values indicate significance of differences between exclusion and overgrazing (*p*-value < 0.05). C-FAF: C in the fulvic acid fraction; C-HAF: C in the humic acid fraction; C-HF: C in the humin fraction; N-FAF: N in the fulvic acid fraction; N-HAF: N in the humic acid fraction; N-HF: N in the humin fraction; HOC: humified organic carbon; Exc: exclusion; Og: overgrazing

variations between management systems. All treatments presented lower C percentages in the FAF. The distribution of the C fractions demonstrates the predominance of residual humus (humin) and higher amounts of C-HF in the exclusion areas, with percentages ranging from 27 to 48% (Table 3).

Low C-HF values (C-HF < 45%) indicate a low level of SOM humification (Canellas et al., 2003). Although C-HF corresponds to most of the humified organic carbon (42–55%), its percentage in relation to TOC was low, reflecting characteristics of raw humus, which is typical of environments that restrict microbial activity. These proportions are lower than those reported by other researchers, (Marchiori Júnior and Melo, 2000; Leite et al., 2003a; Fontana et al., 2005) for different soil managements and tropical climate conditions. The semi-arid conditions of the region restrict microbial activity and humification process (Silva and Mendonça, 2007), reducing the contribution of C-HF to the TOC.

The current results corroborate those of Maia et al. (2007), obtained in soils from the Brazilian semiarid region, but under different soil management conditions. However, the results differ from those of Maia et al. (2004) and Morais (2007) from agroforestry systems in the Ceará semi-arid region, where C-FAF and C-HAF were greater than C-HF.

The predominance of HF, regardless of the soil type, may be related to a strong interaction with the mineral fraction, which results in a longer residence time (Stevenson, 1994). Additionally, once FAF and HAF are less stable fractions, they are also more susceptible to transport, polymerization, or mineralization processes, which may reduce their contents in the soil (Leite et al., 2003a). Bayer et al. (2003) stated that less resistant organic fractions favor the fluxes of energy and matter in the agroecosystem leading to its self-organization. The studied soils present low clay content, which are able to form complexes with organic matter and thus stabilize it in the system.

In this study, the percentage of C-FAF in relation to the TOC was not influenced by the soil use type, while the percentages of C-HAF differed ($p < 0.05$) in areas 2, 3, 4, and 5. The index used to evaluate the degree of C humification (C-HAF/C-FAF), varied from 1.79 to 3.51 (Table 3), with no clear trend between different soil uses. However values were higher than those found in other Brazilian soils (Canellas et al., 2000; Fontana et al., 2005) under different edaphic and climatic conditions. Our values, found for shallow and less developed soils from a semi-arid region demonstrate the existence of differences in the SOM dynamics between soil types.

The C-FAF + C-HAF/C-HF ratio and the humified organic C (HOC) percentages varied among exclusion and overgrazed areas, however, no clear trends were observed between these treatments. The C/N ratio of the FAF, HAF, and HF had mean values of 7.6, 7.1, and 12.2, respectively. These data are in agreement with those reported by Morais (2007) for similar soils.

3.3. Light and occluded fraction of the organic matter

Most values of LOM in the exclusion areas were larger than those found in overgrazed sites ($p < 0.05$) (36% on average; Table 4). According to Janzen et al. (1992) under relatively arid conditions, the LOM fraction tends to decompose at lower rates and therefore accumulate. This behavior is mainly related to a reduced microbial activity. Thus, higher values of LOM fraction in exclusion areas are probably due to both a higher accumulation of organic residues and low microbial activity. The maintenance of the LOM fraction is important, because it consists in a fast cycling pool that favors the soil biota and nutrient turnover (Lima et al., 2008).

The C_{LF} contents followed the same behavior of LOM fraction in all areas (Table 4). The C_{LF}/TOC values varied from 20.93 to 49.43% and were generally higher in the exclusion sites (Table 4). These results indicate a higher OM input in the exclusions areas comparatively to the overgrazed and also an impact of different soil management on soil C pools. Previous studies have reported a greater sensitivity of C_{LF} to management effects and also its importance in assessing the degradation of SOM (Leite et al., 2003b). Thus the greater values of C_{LF} obtained in the exclusion areas are related to both the larger input of organic residues, due to the removal of animals and to the recycling of root biomass, especially of thin roots (Six et al., 1998). The C_{LF}/TOC values are in agreement with those reported by Xavier et al. (2006) for the Ceará State, who found values ranging from 26 to 59% in superficial layers.

The C_{OF} values were greater ($p < 0.05$) in exclusion areas 1, 5, and 6 but did not differ in the other areas. C_{OF}/TOC ratio values were lower than those obtained for C_{LF}/TOC (Table 4) and ranged from 1.38% to 10.29%, indicating that a large part of C_{LF} is lost

Table 4
The contents of soil organic C and total N in light and occluded fractions and ratios between different carbon pools.

Areas	LOM	C_{LF}	C_{OF}	N_{LF}	N_{OF}	C_{LF}/TOC	C_{OF}/TOC	C_{LF}/C_{OF}
	$g\,kg^{-1}$		$g\,kg^{-1}$				%	
1 Exc	36.00	5.98	1.53	0.37	0.16	39.65	10.12	3.91
1 Og	22.67	3.92	0.70	0.21	0.12	27.13	4.89	5.67
p-Value	0.0019	0.0005	<.0001	0.0025	<.0001	0.0182	0.0083	0.0550
2 Exc	27.33	4.64	0.67	0.31	0.13	25.67	3.73	6.88
2 Og	18.67	3.38	0.94	0.27	0.15	29.81	8.25	3.61
p-Value	0.0343	0.0217	0.0357	0.3998	0.0001	0.1334	<.0001	0.0072
3 Exc	42.00	7.43	1.10	0.57	0.17	39.62	5.87	6.80
3 Og	30.67	3.67	1.18	0.27	0.13	24.63	7.95	3.17
p-Value	0.0070	<.0001	0.5341	<.0001	<.0001	0.0088	0.0385	0.0101
4 Exc	33.33	5.08	0.24	0.37	0.09	29.85	1.38	29.06
4 Og	18.00	2.45	0.24	0.19	0.16	20.93	2.01	13.93
p-Value	0.0005	<.0001	0.9857	0.0013	<.0001	0.0517	0.2492	0.2316
5 Exc	50.00	8.32	1.73	0.56	0.21	49.43	10.29	4.79
5 Og	24.00	3.77	0.76	0.27	0.13	27.25	5.51	4.94
p-Value	<.0001	<.0001	<.0001	<.0001	<.0001	0.0316	0.0033	0.4130
6 Exc	22.67	3.58	1.05	0.25	0.15	26.85	7.90	3.58
6 Og	20.00	3.14	0.49	0.23	0.10	25.14	3.86	6.81
p-Value	0.4993	0.4074	<.0001	0.6899	<.0001	0.4076	0.0760	0.1182
Forest 1	50.67	10.83	3.28	0.70	0.28	38.59	11.69	3.33
Forest 2	22.67	5.32	0.81	0.36	0.12	22.76	3.46	6.64

p-Values indicate significance of differences between exclusion and overgrazing (p-value < 0.05); C_{LF}: light C fraction; C_{OF}: occluded C fraction; N_{LF}: light N fraction; N_{OF}: occluded N fraction

Table 5
Correlations between total organic carbon and carbon in different fractions (data from all areas and treatments; N = 42).

Variables	TOC	C_L	C_{NL}	C-FAF	C-HAF	C-HF	HOC	C_{LF}
TOC	1							
C_L	0.299^{ns}	1						
C_{NL}	-0.299^{ns}	-1.000^{a}	1					
C-FAF	-0.285^{ns}	0.275^{ns}	-0.275^{ns}	1				
C-HAF	0.133^{ns}	0.692^{a}	-0.692^{a}	0.552^{a}	1			
C-HF	0.797^{a}	0.455^{a}	-0.455^{a}	-0.151^{ns}	0.313^{a}	1		
HOC	0.643^{a}	0.645^{a}	-0.645^{a}	0.249^{ns}	0.678^{a}	0.894^{a}	1	
C_{LF}	0.780^{a}	0.427^{a}	-0.427^{a}	-0.242^{ns}	0.219^{ns}	0.702^{a}	0.599^{a}	1
C_{OF}	0.646^{a}	0.253^{ns}	-0.253^{ns}	-0.306^{a}	0.069^{ns}	0.585^{a}	0.443^{a}	0.801^{a}

TOC: total organic carbon; C_L: labile carbon; C_{NL}: nonlabile carbon; C-FAF: C in the fulvic acid fraction; C-HAF: C in the humic acid fraction; C-HF: C in the humin fraction; HOC: humified organic carbon; C_{LF}: light fraction C; C_{OF}: occluded fraction C.

[a] Differ at $p < 0.05$ and ns: not significant.

before stabilizing. The results also show a minor contribution of C_{OF} to TOC, especially when compared to other studies from tropical regions (Christensen, 2000; Roscoe and Machado, 2002; Roscoe and Buurman, 2003; Souza et al., 2006). On the other hand, the positive correlation between C_{LF} and C_{OF} (Table 5) indicates that exclusion favors the stabilization of organic material, rendering more recalcitrant compounds and thus providing conditions for the improvement of soil quality.

Similarly to C_{LF}, the contents of N_{LF} were higher (49%, on average) in all exclusion areas when compared to overgrazed sites (Table 4). The behavior of C_{LF} and N_{LF} in exclusions sites shows that these fractions are quite responsive to regeneration of the vegetation cover.

With regard to N_{OF}, values differed from exclusion to overgrazing treatments in all areas, following the same trends observed for C_{OF}. These C and N fractions may form complexes with clay minerals and became physically protected by aggregates. Thus variations of C_{OF} and N_{OF} values among different areas and treatments are probably related to changes in soil mineralogy and clay activity, which may vary within small areas in the semi-arid regions.

Correlations between TOC and all analyzed C fractions are presented in Table 5. C-HF, HOC, C_{LF}, and C_{OF} correlated significantly with the TOC, C_L, and C_{NL}. The greatest correlation was found between the TOC and the C-HF. This fraction presents high resistance to microbial degradation due to its interaction with clay fraction. Usually it has the highest content among the humic substances in tropical ecosystems (Silva and Mendonça, 2007). The positive correlation between C_{LF} and TOC is probably associated to the larger OM contents in the exclusion treatments due to the higher OM input. This fraction is related to the C input and mineralization ratio, and is usually related to the amount of organic residue in the system.

The positive correlation coefficients of C_L in contrast to the negative coefficients of C_{NL} with fractions C-HAF, C-HF, HOC, and C_{LF} may be attributed the longer residence time of C_L, in response to the characteristic climatic conditions of the region (ie, low precipitation).

The C-HF presented positive correlations ($p < 0.05$) with HOC, C_{LF}, and C_{OF}. The correlation with HOC is justified by the fact that approximately 50% of the HOC corresponds to C-HF. The positive correlation of C_{LF} and C_{OF} with C-HF indicates that the system with a greater organic matter status favors the humification process and also the stability of the agricultural system.

4. Conclusions

The results show that overgrazing can lead to great changes in soils, mainly by reducing soil organic matter, as shown by the carbon and nitrogen stocks. Exclusion resulted in larger OC contents in the light fraction, labile fraction, and the humic fraction, indicating significant changes in the OM behavior.

Different soil managements caused changes in TOC contents and in soil OM composition. The studied soils had 28–48% of TOC in the humin fraction, reflecting characteristics of raw humus. In contrast, the humin fraction contributed the most to the total humified carbon. The proportions of labile and nonlabile fractions were not affected by different soil managements.

Despite the low CMI values (<100) found for both treatments, indicative of highly degraded soils, grazing exclusion increased CMI in $\sim$20%. Although the period of seven years seems to be insufficient for large TOC and TN accumulations, our results indicate that exclusion may be an important management strategy for the recovery of desertified lands in Brazilian semi-arid regions.

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