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Organic matter and physicochemical attributes of a cambisol under different agricultural uses in a semi-arid region of Brazil

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Abstract

In semiarid environments, it is possible to verify the fragility of soils in terms of decomposition of soil organic matter (SOM) and changes in physicochemical attributes. The objective of this study was to analyze quantitative fractions of soil organic matter (SOM) and soil's physicochemical attributes according to different agricultural uses, aiming to analyze its impact on the soil. The secondary objective was to detect which of these attributes was the most sensitive to distinguish environments. The research was conducted in the city of Governador Dix-Sept Rosado, at the Settlement Project Terra da Esperança, located in the Chapada do Apodi-RN microregion, in a haplic eutrophic cambisol. The studied areas were native forest area (NFA), ambarella orchard area (AOA), collective area with conventional tillage with intercropping (CACTI), colluvial area (COLA), and agro-ecological zone (AEZ). Soil fertility, macronutrient and physical analyses (resistance to penetration, particle size, bulk density, particle density, analyses of total organic carbon and labile and recalcitrant fractions of SOM) were performed. The results showed that in the studied areas, soil fertility had neutral to alkaline reactions without the presence of Al^{3+} and H+Al, and without a high salinity. The highest organic material input in the AOA enhanced the P, Ca^{2+} and K^+ of the soil, reduced Mg^{2+} and an increased resistance to penetration due to animal trampling. The agro-ecological zone had a condition similar to the native forest (NFA) regarding labile and recalcitrant carbon organic matter (SOM) fractions, reaching a carbon management index (CMI) of 111. The main components showed that some chemical parameters (P, K^+ and Ca^{2+}) and labile and recalcitrant fractions of organic matter (SOM) were indicators of environmental separation. However, the most sensitive components were labile C and CMI.

Introduction

The Brazilian semiarid region is characterized by high temperatures, reduced rainfall, little weathered soils and a small biomass production (Maia et al., 2007). It is generally estimated that 40, 30, 15 and 15% of this territory are occupied with Caatinga, native pasture, planted pasture and crops, with biomass stocks of 47, 15, 2 and 1 Mg ha^{-1}, respectively. Overall, carbon concentrations in the soil were estimated at 9.25 and 5 g of C kg $soil^{-1}$ at the 0-20 and 20-100 cm layers, totaling 8.9 Pg of carbon (Sampaio and Costa, 2011).

The Caatinga Biome is considered fragile regarding the decomposition of soil organic matter (SOM) due to high temperatures and low residual inputs. Thus, the agricultural activity of a crop in this environment should be subjected to a rational use taking into account several production factors in order to preserve soil quality. Therefore, physicochemical analyses and periodic soil organic matter (SOM) analyses are fundamental to verify the sustainability of the production system. The study of the soil organic matter is fundamental to achieve the desired maintenance and preservation level of agriculture in agro-ecosystems. Besides, the SOM provides the basic buffering requirements of changes due to soil management. Moreover, it is the primary source of nutrients for plants, influencing infiltration, water retention and susceptibility to erosion. It also has effects on other attributes such as nutrient cycling, complexation of toxic elements and the structuring of the soil (Silva and Mendonça, 2007).

For the Caatinga Biome, several authors described the influence of different land uses and vegetation types on the dynamics of SOM. Maia et al. (2006) used conventional and agroforestry systems in the Ceará semiarid region and observed that the intensive crop agrosylvopastoral system (corn/white leadtree/sheep grazing as a protein source), and the traditional agrosylvopastoral system (corn/sheep grazing) promoted a 40, 38 and 35% reduction in TOC relative to the native Caatinga in the 0-6 cm layer, respectively. Assis et al. (2010), evaluated the impact of irrigated, annual and perennial agroecosystems of SOM in the Chapada do Apodi/RN in a haplic cambisol and concluded that TOC stocks, total nitrogen (TN) and C in humic substances were reduced due to the cultivation of soil independently from its agricultural use. In Irecê, north-central Bahia, Fracetto et al. (2012) found that the conversion of Caatinga to the cultivation of castor beans caused a decrease of about 50% in the stock of C and N in the soil. The SOM half-life was 4.7 for the semiarid region under study. The soil C issuance was 2.47 Mg C $year^{-1}$ due to the change in land use after 20 years, as proposed by the Greenhouse Gases National Inventories (IPCC). With the conventional planting of castor beans and polyculture in two different locations in the semi-arid, Almeida (2010) found that with the use of a polyculture system, there was a 46% and 61.65% increase in TOC and a 45.08% and 61.3% increase in SOM in Cafarnaum and Umburanas, respectively, when compared to the conventional system. This result is likely related to the higher input of plant material in the polyculture system due to an annual dense planting and the pruning on plant residues on the ground.

Thus, it is observed that in most cases, the removal of the original vegetation primarily affects soil's TOC content, and over time, this process can even lead to a declining availability of nutrients, affecting fertility and consequently the productivity of the soil. Martins et al. (2010) aimed to analyze the variability of chemical and microbial soil attributes to be used as indicators of desertification of areas under increasing levels of degradation in the semiarid region of Pernambuco. Through the analysis of main components, they found that microbial biomass carbon (MBC), potential acidity and base saturation (V) are most sensitive for worsening the soil degradation both in the dry and rainy seasons. The attributes such as MBC, microbial metabolic quotient (MMQ), total organic carbon, Ca content, H+Al and V value can be used as indicators of the soil degradation level as well.

In addition to the traditional land use such as plowing and planting of fruit trees and cereals, semi-arid farmers are interested to find a new alternative land use in the agro-ecological system. Its main purpose would be the thinning of the Caatinga and the interrow cultivation aiming to producing fruit trees and forage to meet the needs of families and animals. Importantly, the research actions that focus on understanding the diversity of farming systems require the integration of studies on organic matter fractions and physical-chemical analyses of the soil for direct managements that are more sustainable considering local conditions. Thus, this study aimed to analyze the quantitative fractions of soil organic matter (SOM) and soil's physicochemical attributes after different agricultural uses. It also aimed to analyze its impact on the soil, as well as to detect which of these attributes were the most sensitive in distinguishing environments considering Caatinga as a reference.

Results and Discussion

Chemical properties of soil

Analyzing the chemical properties of the soil, we found that pH is alkaline (low to medium), ranging from 7.1 to 7.9, regardless of the layer (0-5 and 5-10 cm), both different agricultural uses and native forest (NFA) (Table 1). It was not detected by the Al^{3+} and H+Al analyses (Table 1), a fact which contributes to pH increasing. Furthermore, the presence of carbonates from the source material (limestone) is related to the alkalinity of these soils. Probably, the increase in the divalent cation content in the alkaline soil (especially Ca^{2+}) had an effect on the higher pH values found in the soil of the ambarella orchard area (AOA) (7.9), compared to natural forest (NFA) (Table 1). Arthur et al. (2014) found similar results in Chapada do Apodi, Ceará. Verifying a spatial variability of soil chemical attributes associated to the micro-relief, they found a pH ranging from 7.3 to 7.9 (0-20 cm). Also in Chapada, Fialho et al. (2006) found similar values in soils under banana cultivation with the pH around 7.8 and 7.4, and lower values in Caatinga areas (6.7 and 6.5), in the 0-5 and 5-15 cm layers, respectively.

In general, there was an increase in electrical conductivity (EC) in the soils where crops were grown. The EC values were 0.29, 0.26 and 0.22 dS m^{-1} (0-5 cm) and 0.24, 0.23 and 0.19 (5-10) cm in colluvial soils (COLA) with an orchard area (AOA) and in collective areas with conventional tillage with intercropping (CACTI), respectively (Table 1). However, the agro-ecological zone (AEZ) with only the thinning of the Caatinga species (0.16 and 0.11 dS m^{-1}) had EC conditions similar to the reference system (0.17 and 0.13 dS m^{-1}) in the 0-5 and 5-10 cm layers (Table 1). These values are lower than those found by Fialho et al. (2006), with electrical conductivity value averaged 0.32 dS m^{-1} and did not differ among cultivated and natural areas. According to Richards (1954), soils are considered saline when the electrical conductivity (EC) of the saturation extract is greater than or equal to 4 dS m^{-1} and the exchangeable sodium percentage (ESP) is less than 15%. Typically, the pH of this soil is less than 8.5. Thus, the observed values indicate a low concentration of soluble salts, characterizing them as free of salinity's potential risks.

The highest phosphorus contents in the soil occurred in the 0-5 cm layer. In the 5-10 cm layer, no significant differences were detected, with a mean of 5.4 mg kg^{-1} of P (Table 1), probably due to a greater data variation (CV > 70%). In the 0-5 cm layer, there was a 76.2% increase of P in the soil of orchard areas (AOA) (19.6 mg kg^{-1}) in relation to Native Forest areas (NFA) (4.6 mg kg^{-1}), and a 37.1% increase in relation to the colluvium area (COLA) (12.3 mg kg^{-1}). Despite the low P content in the soil of the agro-ecological zone (AEZ) (1.19 mg kg^{-1}), there was no significant difference from the native forest area (NFA). However, after nine years of intercropping cultivation with Caatinga species, P may become a limiting factor of fruit tree productivity due to its low levels found in these soils. Probably, the highest phosphorus content available in orchard areas (AOA) is due to the input of organic material, both by sacking (a great amount of dry leaves and fruit cores beneath the treetops was visually detected on the area) and manure of animals that have free access to the orchard area due to the extensive cattle ranching system.

In Caatinga soils, Menezes et al. (2012) reported that, generally, soils are deficient in nutrients, especially nitrogen and phosphorus. The average concentration of P in the surface layer (0-20 cm) is 19.6 mg kg^{-1}. Fialho et al. (2006) found P levels much higher than in this experiment in a Caatinga area (20.3 mg kg^{-1} of P). In soils cultivated with banana crops using 20 t of organic matter (bovine and goat manure), there was an increase of the P level reaching 143 mg kg^{-1}. The organic matter content is an important controller of organic phosphorus synthesis (Op) in the soil, and its increase also increases the proportion of organic phosphorus in relation to total amounts of P (Harrison, 1987). Guerra et al. (1996) studied different soil types and found that for argisols, Op is positively correlated with total C and total P. In 21 agro-ecological production units (APUs) in the Agreste Paraibano Mesoregion, Jesus (2005) concluded that the continuous input of organic waste has promoted significant pH increases in OM, P, K, Ca, Mg, BS and V in most APUs.

There was no difference among treatments and layers for sodium levels in the soil. The average content of Na^+ was around 0.09 $cmol_c$ dm^{-3}, mainly attributed to the high coefficient of variation (higher than 200%). Thus, it is inferred that different agricultural land uses do not offer potential salinity and sodium saturation risks. These levels reflect the greater leaching capacity of this element (lyotopic series) compared to other cationic elements. For cation exchange capacity (CEC), despite the numerical superiority of orchard area soils (AOA) (22.06 $cmol_c$ dm^{-3}), no significant differences from the other treatments were detected. Mean values were 18.88 and 17.02 $cmol_c$ dm^{-3} in the 0-5 and 5-10 cm layers, respectively (Table 1). Almost all of the soil's CEC is occupied by essential cations (Ca^{2+}, Mg^{2+}

Table 1. Means values of chemical attributes in a haplic cambisol in different agricultural uses and Caatinga in the layers 0-5 and 5-10 cm in the Settlement Project Terra de Esperança in Chapada do Apodi-RN.

Agricultural uses and soil management	pH (water)	EC	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC
		ds m^{-1}	mg dm^{-3}			cmolc dm^{-3}				
					0-5 cm					
NFA	7.4b	0.17b	4.65c	0.69c	0.25a	12.41b	4.42a	0	0	17.79a
AOA	7.9a	0.26a	19.60^{a}	1.76a	0.04a	18.36a	1.88c	0	0	22.06a
CACTI	7.6b	0.22ab	6.39c	1.47b	0.06a	13.57b	3.80ab	0	0	18.90a
COLA	7.1bc	0.29a	12.32b	1.23b	0.04a	13.06b	3.46bc	0	0	17.80a
AEZ	7.4b	0.16b	1.19cd	1.29b	0.05a	14.26b	2.28bc	0	0	17.88a
CV	1.79	26.91	39.28	27.17	231.4	17.1	25.32	-	-	12.46
General Average	7.6	0.22	8.97	1.31	0.09	14.13	3.17	-	-	18.88
					5-10 cm					
NFA	7.3bc	0.13b	2.10^{a}	0.69b	0.33a	11.14b	5.70a	0	0	17.86a
AOA	7.9a	0.23a	7.20^{a}	1.44a	0.04a	16.26a	1.36c	0	0	18.87a
CACTI	7.5bc	0.19a	5.10^{a}	1.20a	0.05a	13.05ab	3.08bc	0	0	17.62a
COLA	7.2c	0.24a	9.56^{a}	1.07ab	0.03a	11.03b	3.40b	0	0	15.54a
AEZ	7.3bc	0.11b	3.03^{a}	0.99ab	0.03a	11.53b	2.62bc	0	0	15.19a
CV	1.96	25.06	70.42	37.17	282.94	11.67	28.68	-	-	10.95
General Average	7.5	0.18	5.4	1.08	0.09	12.6	3.23	-	-	17.02

NFA - native forest area, AOA - ambarella orchard area, CACTI - collective area with conventional tillage with intercropping, COLA - colluvial area, and AEZ - agro-ecological zone.

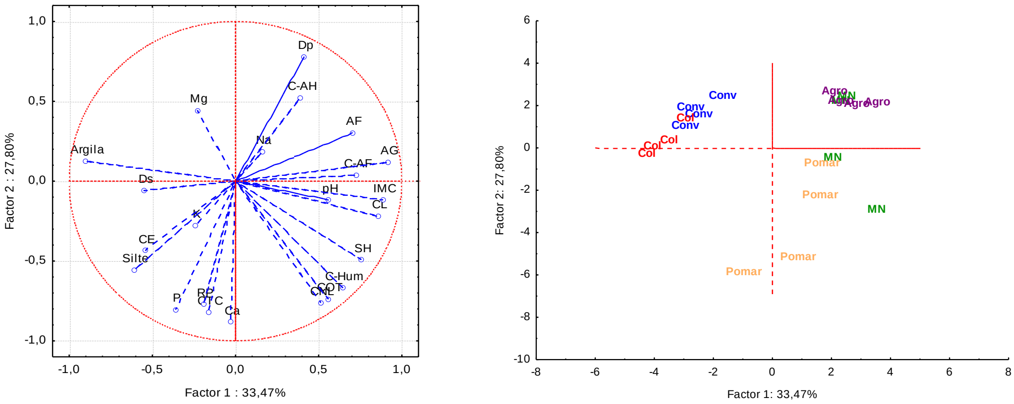

Fig 1. Vector projection diagram for chemical and physical attributes and C fractions of soil organic matter in function of four agricultural use systems and Caatinga in the 0-5 cm layer, and ordination diagram of main components for the collective area with conventional tillage with intercropping (CACTI), colluvium area (COLA), ambarella orchard area (AOA), native forest area (NFA; this is considered as a reference area), and agro-ecological zone (AEZ).

Table 2. Carbon fractions of soil organic matter of a haplic cambisol in different systems of agricultural use and Caatinga in two layers in Chapada do Apodi-RN.

Agricultural uses and soil management	TOC	C-HUM	C-HA	C-FA	HS	LC	NLC	CMI
	dag kg^{-1}					g kg^{-1}		
	0-5 cm							
NFA	4.07a	2.47ab	0.27a	0.34a	3.09a	3.84a	36.94a	100ab
AOA	4.01a	2.60a	0.21a	0.19b	3.00a	3.27ab	36.84a	97ab
CACTI	1.41b	1.16c	0.16a	0.11c	1.43c	1.78b	12.40b	39b
COLA	1.94b	1.42c	0.22a	0.13c	1.77bc	1.66b	17.74b	42b
AEZ	2.39b	1.98ab	0.32a	0.24ab	2.54ab	3.51a	19.44b	111a
CV	21.04	19.67	61.38	33.27	15.86	23.47	22.98	26.43
General Average	27.74	1.92	0.23	0.2	2.36	2.81	24.67	78
	5-10 cm							
NFA	2.18ab	1.76ab	0.25a	0.26a	2.28a	2.45a	19.35ab	100.0a
AOA	2.69a	2.16a	0.15a	0.13b	2.44a	2.36a	24.63a	122.80a
CACTI	1.23b	1.15bc	0.17a	0.09b	1.42b	2.96a	9.33b	112.14a
COLA	1.60b	1.47abc	0.19a	0.12b	1.59b	1.86a	14.20ab	75.64a
AEZ	1.34b	0.96c	0.12a	0.06b	1.15b	2.08a	13.31ab	104.26a
CV								
General Average	1,77	1,5	0,18	0,13	1,82	2,34	15,36	106,97

NFA - native forest area, AOA - ambarella orchard area, CACTI - collective area with conventional tillage with intercropping, COLA - colluvial area, and AEZ - agro-ecological zone.

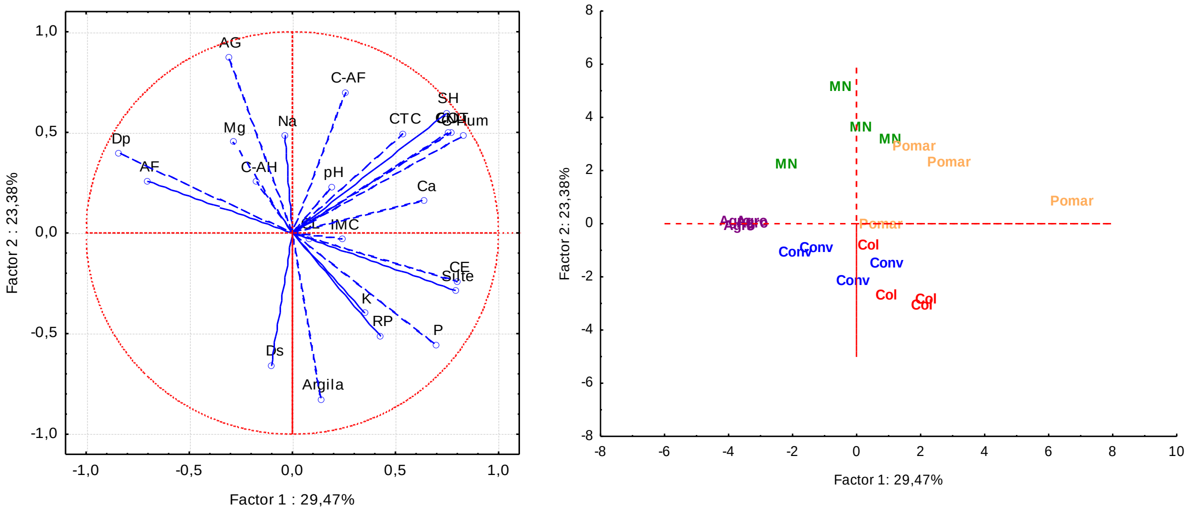

Fig 2. Vector projection diagram for chemical and physical attributes and C fractions of soil organic matter in function of four agricultural use systems of Caatinga in the 0-5 cm layer, and ordination diagram of main components for the collective area with conventional tillage with intercropping (CACTI), colluvium area (COLA), ambarella orchard area (AOA), native forest area (NFA; this is considered as a reference area), and agro-ecological zone (AEZ).

and K^+), mainly from the source material (Jandaíra Formation limestone), providing a good natural fertility to these soils.

Considering the levels of potassium, calcium and magnesium in the soil, it was observed that the soil cultivation increased the levels of K^+ and Ca^{2+} and reduced the Mg^{2+} content regardless of layers, which probably was due to the dissociation of calcium carbonate from the source material and mineralization of organic matter. This is alarming for cultivation in these soils which need complete monitoring, since soils with very low magnesium content may restrict the health benefits and fertility. This concern becomes relevant because there is an interrelation between calcium and magnesium in plant's nutrition related to these chemical properties, such as ionic radius, valence, degree of hydration and mobility, which creates a competition for adsorption sites in the soil and root absorption. Thus, the presence of one may impair the adsorption and absorption processes of the other. This frequently occurs for Ca^{2+} and Mg^{2+} ions (Medeiros et al., 2008).

In soils of orchard area (AOA), there was an increase in the K^+ content (60 and 52%) and an increase in Ca^{2+} of 32 and 31.5% in the 0-5 and 5-10 cm layers, respectively, and a 135 and 319% reduction of Mg^{2+} (0-5 and 5-10 cm layers) in relation to Native Forest areas (NFA). Comparing two very distinct forms of agricultural use, it was observed that both the agro-ecologic zone (AEZ) and the collective area with conventional tillage with intercropping (CACTI), subjected to plowing and harrowing, were statistically similar as to K^+ (1.47 and 1.29 $cmol_c$ dm^{-1}, respectively), Ca^{2+} (14.26 and 13.57 $cmol_c$ dm^{-3}, respectively), and Mg^{2+} (3.8 and 2.28 $cmol_c$ dm^{-3}, respectively) contents at the 0-5 cm layer. A similar tendency was observed for the 5-10 cm layer. Analyzing the effects, within a 5 and 7-year period of conventional farming systems (corn/beans with revolving) and agro-ecological management of the Caatinga (thinning and keeping large trees, introduction of legumes and use as pasture for goats) in crops in Apodi (RN), Lira et al. (2012) observed a loss in soil fertility in conventional agricultural crop areas, which differs from this work's result. The soil of management areas in the Caatinga at five years showed higher values for pH (7.1), cation exchange capacity (20.35 $cmol_c$ dm^{-3}), base sum and base saturation (18.37 $cmol_c$ dm^{-3} and 92%, respectively), and calcium content (16.36 $cmol_c$ dm^{-3}) (average data for the 0-10 cm layer).

Soil organic matter carbon fractions

Except for the orchard area (AOA), all management systems caused a reduction in total carbon levels (TOC) of the soil organic matter (Table 2). The soil in orchard areas (AOA) had TOC levels (4.01 and 2.69 g ka^{-1}) similar to the Native Forest Area (NFA) (4.07 and 2.18 g kg^{-1}) in the two layers studied (0-5 and 5-10 cm, respectively) (Table 2). This is due to the sacking at the AOA associated with the excrement of animals (goats, cattle, horses, donkeys, pigs) in grazing areas. Martins (2009), in studies on conserved hyperxerophilic Caatinga, found TOC stocks of 13.8, 7.8 and 7.7 g kg^{-1} at the end of the dry season and 14.0, 9.5 and 7.2 g kg^{-1} at the end of the rainy season, in the 0-10, 10-20 and 20-30 cm layers, respectively. These values are higher than those found in this study.

Soils with a Caatinga vegetation cover have a vegetal formation that consists of low trees, shrubs, cacti and bromeliads, among other species (Alves et al., 2009). In a study developed in the Caatinga of Rio Grande do Norte, at the Seridó Ecological Station (EsEc-Seridó), Santana & Souto (2011) found that after twelve months, 2,068.55 kg ha^{-1} of sacking were deposited. Leaves were the predominant fraction, being responsible for 79.90% of the deciduous material. The biomass of branches and barks reached 9.27% of the total amount deposited, while the reproductive material was 2.92% and the miscellaneous was 7.91% (fragments of leaves, twigs, branches, flowers, fruits, seeds and other plant materials that are difficult to identify, besides insects or parts thereof and feces). The highest deposition fraction of reproductive matter was in March, during the dry season. All this plant material deposited in the soil caused the organic matter content to be higher than in other land uses (Table 2).

The collective area with conventional tillage in intercropping (CACTI), with revolving and annual crops, caused the greatest losses of TOC (about 188.6 and 77.2%), followed by the soil of colluvium areas (COLA), where it was completely uncovered and in fallow for two years; losses were 109.7 and 36% in the 0-5 and 5-10 cm layers, respectively. However,

Table 3. Physical attributes of a haplic cambisol with various agricultural uses and Caatinga in four layers in Chapada do Apodi-RN.

Agricultural uses and soil management	Clay	Coarse Sand	Fine Sand	Silt	Bd	Pd	RP	Textural Classification
	$g\ kg^{-1}$				$kg\ dm^{-3}$		MPa	
	0-5 cm						0-10 cm	
NFA	315.43c	408.29a	149.75a	126.50b	1.25c	2.38a	1.03b	Sandy Clay Loam
AOA	270.50c	337.51ab	148.50a	243.47a	1.41b	2.29a	1.37a	Sandy Clay Loam
CACTI	431.95b	262.53b	163.57a	141.94b	1.58a	2.14a	1.24a	Clayey
COLA	560.65a	85.96c	58.59b	294.78a	1.32bc	2.29a	0.93b	Clayey
AEZ	253.75c	447.00a	213.50a	84.25b	1.24c	2.46a	0.61c	Sandy Clay Loam
CV	11.05	16.32	12.32	22.34	1.91	2.37	12.37	-
General Average	366.45	308.26	146.78	178.19	1.35	2.37	0.99	-
	5-10 cm						10-20cm	
NFA	330.30c	406.94a	146.61b	116.13c	1.25b	2.45a	1.35bc	Sandy Clay Loam
AOA	305.35c	342.62ab	145.54b	206.46ab	1.45a	2.37a	1.19c	Sandy Clay Loam
CACTI	441.76b	259.34bc	174.72ab	124.17bc	1.49a	2.39a	1.83a	Clayey
COLA	552.71a	146.50c	87.15c	213.61a	1.42a	2.31a	1.88a	Clayey
AEZ	353.25bc	353.50ab	218.50a	74.75c	1.48a	2.55a	0.83d	Clayey
CV	12.66	17.73	16.32	28.09	1.95	0.85	10.49	-
General Average	396.68	301.78	154.5	147.02	1.42	2.41	1.41	-

NFA - native forest area, AOA - ambarella orchard area, CACTI - collective area with conventional tillage with intercropping, COLA - colluvial area, and AEZ - agro-ecological zone.

Table 4. Correlation coefficient of the main components (Factor 1 and 2) for chemical and physical attributes and C fractions of soil organic matter in function of four agricultural use systems and Caatinga in the layers 0-5 and 5-10 cm.

Attributes	Factor 1	Factor 2	Factor 1	Factor 2
	0-5 cm		5-10 cm	
pH	0.56	-0.12	0.19	0.23
EC	-0.54	-0.44	0.80	-0.24
P	-0.36	-0.80	0.70	-0.55
K^+	-0.24	-0.28	0.35	-0.40
Na^+	0.16	0.19	-0.03	0.48
Ca^{2+}	-0.03	-0.88	0.64	0.16
Mg^{2+}	-0.23	0.44	-0.29	0.45
CEC	-0.16	-0.82	0.54	0.49
TOC	0.56	-0.74	0.77	0.50
C-HUM	0.65	-0.67	0.83	0.49
C-HA	0.39	0.52	-0.17	0.26
C-FA	0.73	0.04	0.26	0.70
HS	0.76	-0.49	0.74	0.60
LC	0.86	-0.22	0.08	-0.03
NLC	0.51	-0.76	0.76	0.50
CMI	0.89	-0.12	0.24	-0.03
Clay	-0.90	0.13	0.14	-0.83
CS	0.92	0.12	-0.31	0.87
FA	0.70	0.30	-0.70	0.26
Silt	-0.61	-0.55	0.79	-0.29
Pd	0.41	0.78	-0.84	0.40
Bd	-0.55	-0.06	-0.10	-0.66
RP	-0.19	-0.77	0.43	-0.51
Variance (%)	33.47	27.80	29.47	23.38

Correlation coefficients > |0.70| are significant (Manly, 1994). TOC: Total organic carbon, C-HUM: carbon from humin, C-HA: Carbon - humic acid, C-FA: Carbon - fulvic acid, HS: humic substance, LC: labile carbon, NLC: non-labile carbon, CMI: carbon management index, CS: coarse sand, FS: fine sand, Pd: particle density, Bd: bulk density and RP: resistance to penetration.

when in agro-ecological zones (AEZ) with only the thinning of Caatinga species, TOC losses were reduced up to 70.2% especially in the 0-5 cm layer.

It can be observed that when the natural vegetation was removed for the installation of an agricultural system, there was an imbalance in TOC content, intensifying the mineralization of organic matter. In the semi-arid northeast, the degradation of natural resources was caused by an increased land use and a reduction of native vegetation (Menezes and Sampaio, 2002). There is a marked degradation of the soil, when leaving it uncovered and exposed to the action of active climatic agents for a longer time, when removing the native vegetation, in Caatinga subject to long periods of drought. This consequently reduces the productive potential and degradation (Trevisan et al., 2002). This was also observed in this research. Maia et al. (2006) observed that there was a 40, 38 and 35% reduction in TOC, in the intensive cultivation (corn) using the agrosylvopastoral system (corn/white leadtree/grazing by sheep as a protein source), in the traditional agrosylvopastoral system (corn/grazing by sheep) and in the Ceará semiarid region with conventional and agroforestry systems, respectively, compared to the native Caatinga in the 0-6 cm layer.

Analyzing the HS, there was generally a higher content of C in humin fractions (C-HUM), followed by humic acid (C-HA) and fulvic acid (C-FA). Silva et al. (2011) also observed this for Cerrado soils. The predominance of humin is due to its strong interaction with the mineral matrix, forming organic-mineral complexes with a high stability at the soil surface, in which most of the insoluble organic matter remained attached to this fraction (Majzik; Tombácz, 2007a). Similar to TOC, the orchard area (AOA) had the highest content of C in HS (3.0 and 2.44 g kg^{-1}), being similar to the Native Forest (NFA) (3.09 and 2 28 g kg^{-1}, respectively) in the 0-5 and 5-10 cm layers, respectively (Table 2). Considering humic substances, the fraction that most contributed to this effect was the carbon present in the humin (C-HUM) (2.6 and 2.16 g kg^{-1} in the 0-5, 5-10 cm layers) (Table 2). Probably, this stabilization was favored by a higher organic material input and by higher calcium content in these soils (Table 1). In a classic paper by Oades (1988), he demonstrated that the chemical stabilization of organic matter, especially its humic fractions, could be explained by the availability of Ca in making metallic bonds with groups of acids responsible for the stabilization of SOM, forming the humates of Ca. This shows that not only the organic material input is essential for maintaining soil organic matter, but also that cations are important (Virto et al., 2011; Majzik; Tombácz, 2007a; Brieds et al., 2012; Fontana et al., 2014).

Considering other agricultural use systems, it was observed that the soil in agro-ecological zones (AEZ) was less harmful to the recalcitrant fraction of soil organic matter, being statistically similar to the native forest area (NFA) in all HS (2.54 dag kg^{-1}). Except for the orchard area (AOA), the agro-ecological zone (AEZ) with planting of fruit trees and thinning of Caatinga species had higher levels of C-HUM and C-FA (1.93 and 0 24 dag kg^{-1}) even after nine years. This effect was more restrict to the top layer of soil (0-5 cm). The highest losses in C recalcitrant fractions in relation to Caatinga occurred in soils in collective areas with conventional tillage with intercropping (CACTI), showing 112.9% of C-HUM, and 209%, if compared to C-FA. There was no statistical difference among treatments in soil layers regarding C-HA, with a 0.23 and 0.18 dag kg^{-1} overall average in the 0-5 and 5-10 cm layers, respectively. This showed that the FA fraction is more sensitive than HA to changes in land use. This decrease can be attributed to the soil management system adopted by farmers based on soil revolving with plowing and harrowing, which maximizes the oxidation of C also in recalcitrant fractions due to the breakdown of soil aggregates and to crop systems. This has a reduced input of residues, which decrease the input of C on the soil, thus acting as a source of CO_2. Assis et al. (2010), evaluated the impact of irrigated, annual and perennial agroecosystems of SOM in the Chapada do Apodi/RN in a haplic cambisol and concluded that TOC stocks, total nitrogen (TN) and C in humic substances were reduced by the soil cultivation independently from agricultural use systems.

In the analysis of labile carbon, it was observed that both the soils in agro-ecologic zones (AEZ) (3.51 g kg^{-1}) and in orchard areas (AOA) (3.27 g kg^{-1}) showed no statistically significant differences from the Native Forest Area (NFA) (3.84 g kg^{-1}) (0-5 cm layer) (Table 2). However, for the non-labile C (NLC), the agro-ecological zone (AEZ) had a 47% reduction in its content (19.44 g kg^{-1}) (Table 2). Again, regarding the system in equilibrium (native forest), the collective area with conventional tillage with intercropping (CACTI) showed 53% and 74% LC losses in the NLC. Dieckow et al. (2005) and Souza et al. (2009) observed that LC stocks decreased rapidly, but its recovery was also faster, suggesting the use of LC as a sensitive indicator of the C dynamics in the system.

Blair et al. (1995) proposed that the C management index (CMI) is a measurement related to changes caused by management when compared to the system in equilibrium; in this case the Native Forest (NFA). The CMI values less than 100 indicate practices harmful to organic matter management and consequently to the quality of soil. It was observed that the agro-ecologic zone system (AEZ) (111) and the orchard area (AOA) (97) were statistically similar to Native Forest areas (NFA) (100) (0-5 cm layer). There were no significant differences in the 5-10 cm layer (Table 2). This index takes into account with the lability of C on the soil, aiming to unite quantitative and qualitative characteristics as a way to evaluate the performance of a particular management system. It can be inferred that these systems, despite the losses in TOC stocks, are readapting, seeking a new equilibrium state, without being too harmful in terms of soil organic matter and minimizing the negative impacts of climate change. However, management systems such as the conventional (39) and colluvium areas (COLA) with no vegetation cover (42) are harmful to SOM (Table 2). Thus, it can be seen that the systems based on an excessive soil revolving and/or the absence of any type of vegetation cover promote the chemical degradation and the degradation of soil organic matter fractions by creating a completely unbalanced environment.

Soil physical attributes

The textural classification of the Native Forest (NFA) and orchard areas (OA) were classified as sandy clay loam at both depths studied. The agro-ecologic soil (AEZ) was classified as sandy clay loam in the 0-5 cm layer, and clayey in the 5-10 cm layer. In both depths, the soils in collective areas with conventional tillage with intercropping (CACTI) and in colluvium areas (COLA) were classified as clayey (Table 3). Texturally, soils in colluvium areas (COLA) had a higher clay (560.65 and 552.71 g kg-1) and silt (294.78 and 213.61 g kg-1) content in the 0-5 and 5-10 cm layers, respectively. The highest content of clay and silt comes from its origin. According to Suguio (2003), the flow of debris, characterized as a rapid flow of debris sliding downhill, and the mud flow have a variety of debris consisting mainly of fine particles (silt and clay) with up to 30% of water. Thus, even with higher clay content, the lack of organic input did not contribute to the increase in TOC.

Regarding bulk density (BD), particle density (Pd) and mechanical resistance to penetration (RP) data were obtained from the 0-10 and 10-20 cm layers. Compared to the soil of the Native Forest Area (NFA), there was an increasing tendency in Bd at the surface (0-10 cm) for collective area with conventional tillage with intercropping (CACTI), followed by orchard area (OA) and colluvium area (COLA) (Table 3). This demonstrates that the use of the soil for agricultural purposes, regardless of the management system, promotes changes in its physical properties. However, the highest observed value was in the collective area with conventional tillage with intercropping (CACTI) (1.58 kg dm^{-3}). During the preparation of the soil for planting with plowing and harrowing, the disruption of aggregates and a momentary decrease in Bd occurs. However, in the long term, there was the consolidation of the surface, consequently increasing Bd. One factor that probably contributed to it was the transmission of the pressure on the soil surface by the machinery and implements, the compression exerted by the blades of plow discs or even by the tractor tires running on the plowing line of that system (Costa et al., 2003), as well as clay dispersion causing the clogging of the pores.

There was no significant difference among treatments for particle density analysis (Pd), with average values of 2.37 and 2.41 kg dm^{-3} at 0-10 and 10-20 cm layers, respectively. It is assumed that the soil management may modify its value over time if there is a significant change in soil organic matter (Ferreira, 2010). Despite the change in TOC content, it was not enough to alter this attribute. Regarding soil resistance to penetration, it was observed that it was modified by the soil management systems. Orchard area soils (AOA) and the collective area with conventional tillage with intercropping (CACTI) had the highest RP values (1.37 and 1.24 Mpa) in the 0-10 cm layer. However, it excelled in the 10-20 cm layer, in addition to CACTI (1.88 MPa) and colluvium area (COLA) (1.83 MPa).

In the superficial layer, the highest RP in the orchard area (AOA) was probably due to animal trampling (goats, cattle, horses, mules and pigs) that graze freely all year round in an extensive cattle ranching system. This is very common in soils with pastures, where trampling causes an increased RP (Schiavo and Colodro, 2012, Huber and Souza, 2013, Ortigara et al., 2014). As in Bd, CACTI also provided a better RP probably due to the effect of the accumulation of the loads from soil tillage implementation. Several studies report that a 2 MPa resistance to penetration is restrictive to the growth of roots and shoots of plants. High penetration resistance values range from 2.0 to 4.0 MPa (Azooz et al., 1996). Foloni et al. (2003) concluded that a compressed layer with a bulk density of 1.69 g cm^{-3} presented a 1.4 MPa penetration resistance value and it was impeditive to the penetration of corn roots. In CACTI soils in the 10-20 cm layer, this restriction range is close to be achieved. This serves as a warning to producers.

In Limoeiro do Norte-CE, Chapada do Apodi, in a haplic cambisol in different soil layers associated with the micro-relief (shallow and deep), Miotti et al. (2013) verified soil densities and larger particles in the shallow soil (1.41 and 2.82 g cm^{-3}, respectively). Regarding resistance to penetration (RP), it was more densified in the 0-5, 5-10 and 10-15 cm layers of the topsoil (1.35, 1.84 and 1.77 MPa, respectively) than in the same layers of the deep soil (0.96, 1.44 and 1.48 MPa). From 30 cm deep, soil resistance to penetration further increased in shallow soil, occurring the maximum RP (5.1 MPa) at a 50 cm depth.

Multivariate analysis of soil properties

The qualitative analysis of soil properties was made using the Tukey test. Then, the multivariate analysis was chosen as a tool to distinguish agricultural uses. It generated two main components (Factor 1 and Factor 2) for chemical and physical attributes and C fractions of soil organic matter in two layers (0-5 and 5-10 cm) (Table 4). From the relation between the components, two-dimensional ordination diagrams were designed to visualize the distinction among the five environments. Vector projection diagrams were designed for soil attributes that most influenced this distinction, thus showing a greater sensitivity (Fig 1 and 2). The visualization of the diagrams enabled analyzing, by which agricultural use management system formed these five groups, even with overlapping points tended to distinguish themselves in the ordination diagram (Fig 1 and 2).

The Factor 1, generated for soil attributes in the 0-5 cm layer (Table 4), explained 33.47% of the total variation of the studied attributes. The highest correlation coefficients ($\geq |0.70|$) were identified for variables such as CMI, LC, HS and C-FA. Physical soil clay and sand fractions (coarse and fine) (Table 4), i.e., attributes associated to SOM fractions and particle size, were more sensitive in distinguishing environments. This can be seen in the vector projection diagram, where these attributes are more distant from the axis of the Factor 1 (Fig 1). By analyzing the Factor 2, i.e., attributes, in which the explained variance was lower (27.80%), NLC, TOC, chemical attributes (such as P, Ca $^{2+}$ and CEC) and physical attributes (such as Pd and RP) were identified as attributes sensitive to distinguish the use system and the soil management, with a greater distance from its vector in relation to the Factor 2 axis (Fig 1).

By analyzing the same attributes in the 5-10 cm layer, it was observed that the two major components (Factors 1 and 2) explained 52.85% of the total variation of the attributes (Table 4). The highest correlation coefficients presented for chemical attributes were for P and K^{+}. The SOM, particle size and Pd were those that most influenced changes, with the highest rates for C-HUM, TOC, HS, NLC and LC (Factor 1) and C-FA (Factor 2) for SOM, and FA, silt (Factor 1), clay and CS (Factor 2) (Fig 2).

The change detected in the particle size fraction of the soil (clay, silt and sand) was not assigned to agricultural uses, but probably to the deposition of clay in colluvium areas. Analyzing colluvium areas in Pernambuco, Correa et al. (2008) found in the lower slope that there is a third unit, with a slightly layered structure, which intersperses gravel and coarse sand layers with finer sand layers (with a higher clay content). Analyzing the colluvia of the plateau of Itatiaia, Modenesi and Toledo (1993) also found old colluvia with high levels of clay (48-50%), and similar silt (22-25%) and sand (25-30%) contents.

The use of soil attributes, identifiers of different environments, is a key tool for conducting practices that reduce depletion. Regardless of the soil layer, SOM fractions were the indicators most sensitive to the transformation of management systems, especially LC and CMI. Using the main component analysis to analyze management systems in Nigeria, Wick et al. (1998) observed that the variables related to the nutrient dynamics of soil organic matter contributed to explain more than 80% of the total variance of the data, confirming that variables such as C-MBC and TOC can be used as sensitive indicators to assess soil quality.

Souza et al. (2009) and Silva et al. (2011) observed that the LC stocks decreased fast with the soil management, but its recovery was also faster, confirming the use of LC as a sensitive indicator of the C dynamics in the system. This fraction is thus important because its maintenance is essential to enhance soil quality, formation and stabilization of aggregates and the sustainability of these production systems (Blair and Crocker, 2000).

The colluvium area (COLA), in fallow for two years, and the collective area with conventional tillage with intercropping (CACTI) with plowing and harrowing were environments suffering degradation, distancing themselves from Native Forest areas (NFA). Orchard area soils (AOA), due to a higher deposition of organic input (via sacking), animal waste and the use of desalination waste, created a favorable environment for soil's chemical and organic matter. The use of the soil with agro-ecological systems (AEZ) in the management of the Caatinga was favorable to agricultural sustainability, because even after nine years of cultivation, no significant changes were observed regarding the original vegetation, if compared to other systems. This shows that a new state of balance, especially in the topsoil, is sought after.

Materials and Methods

This work was conducted in the Settlement Project Terra de Esperança. It consisted of 113 families in 6,297 hectares with different agricultural uses. The Settlement is located in the city of Governador Dix-Sept Rosado, on the Chapada do Apodi microregion, in the Rio Grande do Norte state. The coordinates are 05°27'32.4" S and 37°31'15.6" W. The climate, according to the Köppen classification, is BSw'h', hot tropical semi-arid, with an average annual rainfall of 550-940 mm and an annual average temperature of 23°C. It has two well-defined periods: dry (long) and wet (short and irregular). The natural vegetation is hyperxerophilic Caatinga. The soil of the area was classified as a haplic eutrophic cambisol (Souza, 2014).

The study areas with its different agricultural uses were:

(01) Ambarella Orchard Area (AOA), which has deciduous plants in the dry season, with little or no foliage and inflorescences. It has a large concentration of dried leaves and lumps of fruits below the treetops. This characteristic, however, is changed with the onset of the rainy season, when plants begin to sprout and the herb layer is abundant and green. In this area, goats and sheep graze freely throughout the year (extensive cattle ranching).

(02) Colluvial area (COLA), which is saturated with water during the rainy season, thus, making farming impossible. At the end of the rainy season, this saturation decreases, enabling farmers to grow crops such as corn, cowpea, sorghum and sesame in areas whose tillage follows the same patterns of areas with conventional tillage with intercropping (CACTI). In the sample collection period, the site was left fallow for two years due to a long period of drought (years of drought).

(03) Collective Area with Conventional Tillage with Intercropping (CACTI), constituted by soil tillage with one plowing (01) and two diskings (02), which have been done annually since January 2005. In this area, corn (*Zea mays*) and cowpea (*Vigna unguiculata* L.) intercroppings are made. The soil is not fertilized with industrial fertilizers and only organic fertilizers are used. Seeds were sown by casting, and crops were grown only in the rainy season, since the settlers do not have an irrigation system.

(04) Agro-ecological Zone (AEZ), implemented in 2005, has as its main objective the production of food (fruits) and forage to meet the needs of families and animals. The activities carried out for its implementation were the thinning of Caatinga species with criteria established by the experience of families. The waste from thinned plants was shredded to fine parts with the aid of a knife and spread on the soil surface to control erosion. The construction of furrows with coarse and woody crop residues served as runoff containment and favored water infiltration into the soil. The planting of fruit trees and exotic plants adapted to the semi-arid was made.

(05) Native Forest Area (NFA), which was used as a reference, had an area of 30 ha (corresponding to 20% of the settlement lands), with predominance of the following plant species from the hyperxerophilic Caatinga: *Combretum leprosum* L., *Schinustere binthifolius*, quince (*Cydonia oblong* Mill) and *Mimosa hostilis* Benth. Soil sampling with deformed and non-deformed structures in their respective study areas was carried out in the rainy season, in May and June 2013, based on one hectare for each study area.

To conduct laboratory tests, soil samples with a deformed structure were collected, having five composite samples from 15 subsamples of each above-mentioned area in the 0-5 and 5-10 cm layers. They were taken with the aid of a Dutch auger, placed in properly labeled plastic bags and taken to the Soil, Water and Plant Analysis Laboratory (LASAP) of the Federal Rural University of the Semi-Arid (UFERSA). Subsequently, samples were air-dried, harrowed and sieved in a 2 mm sieve to obtain the fine air-dried soil (FADS). They were then subjected to physicochemical analyses. For the analyses of SOM fractions, FADS subsamples were crushed and sieved in a 0.210 mm sieve (mesh 60).

The determination of total organic carbon (TOC) was made using the wet oxidation method with external heating, as proposed by Yeomans and Bremner (1988). For the determination of labile C content (LC), 1.0 g of soil sub-samples (mesh 60) were placed in 50 mL centrifuge tubes with a 25 mL $KMnO_4$ solution (0.033 mol L^{-1}) (Shang and Tiessen, 1997). The tubes were placed in a horizontal shaker at 170 rpm for 1 hour and centrifuged at 960 *g* for 10 min, always protected from light. After centrifugation, 100 μL of the supernatant were added to the test tubes and the volume was completed with 10 mL of deionized water. LC doses were performed with a spectrophotometer with a 565 nm wavelength. The non-labile carbon (NLC) was determined by the difference between TOC and LC.

Based on changes in TOC between a reference system (Native Forest) and an agricultural crop, the carbon pool index (CPIN) was calculated as CPIN = cultivated TOC/reference TOC. Based on changes in the LC ratio (lability = LC/NLC) in the soil, the lability index (LI) was calculated as LI = cultivated L/reference L. These two indexes were used to calculate the carbon management index (CMI), obtained by CMI = CPIN × LI × 100 (Blair et al., 1995). For the determination of recalcitrant C fractions, 1.0 g of soil subsamples (mesh 60) was subjected to fractionation of humic substances according to the method proposed by the International Humic Substances Society (IHSS) (Swift, 2001). From this fractionation, fractions corresponding to fulvic acids, humic acids and humins were obtained by differential solubility in acid and alkaline solutions. From the sum of all these humic fractions, humic substances were obtained and C contents were determined as previously described for TOC.

For soil chemical properties, the following analyses were performed: hydrogenic potential (pH) in water, electrical conductivity (EC) in water, exchangeable calcium content (Ca^{2+}) and exchangeable magnesium content (Mg^{2+}) using potassium chloride extractor, potential acidity (H+Al) using calcium acetate; phosphorous (P), sodium (Na^+) and potassium (K^+) analyses using Mehlich-1 extractant, all in accordance with EMBRAPA (2009). Consequently, the cation exchange capacity was calculated. For physical soil properties, a particle size analysis was conducted by the pipette method with a chemical dispersant (sodium hexametaphosphate) and distilled water in 20 g of fine air-dried soil (FADS), with a slow mechanical agitation in a shaker (Wagner, 50 rpm) for 16 hours (Donagema et al., 2011); sand (2 to 0.05 mm), measured by sieving; clay (< 0.002 mm), measured by sedimentation; and silt (0.05 to 0.002 mm), measured by the difference between total sand and clay fractions. The analysis of particle density (Pd) was performed using the volumetric flask method with fine soil dried in greenhouse (FSDG) at 105°C and ethanol (Donagema et al., 2011).

The bulk density (Bd) was determined by the volumetric ring method, as described by Forsythe (1975), and expressed in $kg.dm^{-3}$. Ten non-deformed soil samples were collected in each study area, but in deeper soil layers: 0-10 and 10-20 cm. The soil resistance to root penetration (RP) was determined under field conditions using an impact penetrometer from VDO® (model SS316), with a 1.386 cm diameter ferrule, a cross sectional area of 1.509 cm^2 and a tapered tip with a 30° angle of penetration. Thirty readings were performed at random on each layer (0-10 and 10-20 cm) to obtain average values. The results were expressed in MPa, as described by Forsythe (1975). At the same time, there was the collection of deformed samples in the respective layers to perform the gravimetric moisture.

Statistical methods used to analyze the distinction between variables were arranged in two groups: one that obtains information from variables in isolation - univariate statistics; when significant differences were detected by the F-test, a Tukey test at 5% probability was used to compare the means. Another multivariate analysis, i.e., principal component analysis, was used as a main tool to distinguish areas surveyed in terms of environmental potentials or restrictions. As a tool to distinguish agricultural use systems, two main components (Factor 1 and Factor 2) were generated for chemical, physical and C fractions of soil organic matter in two layers. From the relation among these components, two-dimensional ordination diagrams were designed to visualize the distinction between the five environments, and vector projection diagrams were designed for most distinguished soil attributes in the surveyed areas.

Conclusions

The reaction of the soil in the areas studied showed neutral to alkaline reactions without the presence of Al^{3+} and H+Al and no high salinity. The highest organic material input in the AOA favored the increase of P, Ca^{2+} and K^+ contents on the soil, and a reduction of Mg^{2+}. There was an increase in soil's resistance to penetration. The agro-ecological zone kept a condition similar to the native forest regarding labile carbon fractions and recalcitrant fractions of organic matter (SOM), reaching a 111 carbon management index (CMI). Through the main components, the multivariate analysis showed that some chemical parameters (P, K^+ and Ca^{2+}) and labile and recalcitrant fractions of organic matter (SOM) were indicators of separation of environments. However, the most sensitive were labile carbon and carbon management index.

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References

Almeida JRC (2010) Atributos de qualidade física, química e biológica do solo sob diferentes sistemas de uso em ambiente semiárido da Bahia. Universidade Federal do Recôncavo da Bahia - UFRB, Cruz das Almas, BA, UFRB. 66p. Dissertation (Master of Agricultural Sciences).

Alves JJA, Araújo MA, Nascimento SS (2009) Degradação da caatinga: uma investigação ecogeográfica. RC. 22(3):126-135.

Arthur AG, Oliveira DP, Costa MC, Romero RE, Silva MVC, Ferreira TO (2014) Variabilidade espacial dos atributos químicos do solo, associada ao microrelevo. Rev Bras Eng Agríc Ambient. 18(2):141–149.

Assis CP, Oliveira TS, Dantas JAN, Mendonça ES (2010) Organic matter and phosphorus fractions in irrigated agroecosystems in a semi-arid region of Northeastern Brazil. Agr Ecosyst Environ. 138:74- 82.

Azooz RH, Arshad MA, Franzlüebbers AJ (1996) Pore size distribution and hydraulic conductivity affected by tillage in northwestern Canada. Soil Sci Soc Am J. 60:1197-1201.

Blair GJ, Lefroy RDB, Lisle L (1995) Soil carbon fractions based on their degree of oxidation, and evelopment of a carbon management index for agricultural systems. Aust J Agr Res. 46:1459-1466.

Blair N, Crocker GJ (2000) Crop rotation effects on soil carbon and physical fertility of two Australian soils. Aust J Soil Res. 38:71–84.

Brieds C, Sá JCM, Caires EF, Navarro JF, Inagaki TM, Boer A, Neto CQ, Ferreira AO, Canalli LB, Santos JB (2012) Soil organic matter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system. Geoderma. 170(1):80–88.

Correa ACB, Silva DG, Melo JS (2008) Utilização dos depósitos de encostas dos brejos pernambucanos como marcadores paleoclimáticos do Quaternário tardio no semi-árido nordestino. RM, ano 07, 14:99-125.

Costa FS, Albuquerque JA, Bayer C, Fontoura SMV, Wobeto C (2003) Propriedades físicas de um Latossolo bruno afetadas pelos sistemas plantio direto e preparo convencional. Rev Bras Ciênc Solo. 27:527-535.

Dieckow J, Mielniczuk J, Knicker H, Bayer C, Dick DP, Kögel-Knabner I (2005) Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a Southern Brazil Acrisol managed under no-tillage for 17 years. Soil Till Res. 81:87-95.

Donagema GK, Campos DVB, Calderano SB, Teixeira WG, Viana JHM (2011) Manual de Métodos de Análise de Solo. 2.ed. Rio de Janeiro: Embrapa – Empresa Brasileira de Pesquisa Agropecuária (1997) Manual de métodos de análises de solo. 230 p. (Ministério da Agricultura e do Abastecimento: Rio de Janeiro).

Ferreira MM (2010) Caracterização Física do Solo In: Rev Bras Ciênc Solo. 298:18-23.

Fialho JS, Gomes VFF, Oliveira TS, Júnior JMTS (2006) Indicadores da qualidade do solo em áreas sob vegetação natural e cultivo de bananeiras na Chapada do Apodi- CE. Rev Ciênc Agron. 37(3):250-257.

Foloni JSS, Calonego JC, Lima SL (2003) Efeito da compactação no desenvolvimento aéreo e radicular de cultivares de milho. Pesq agropec Bras. 38(8):947-953.

Fontana A, Pereira MG, Anjos LHC, Santos AC, Bernini TA (2014) Matéria orgânica de horizontes superficiais em topolitossequências em ambiente de Mar de Morros, Pinheiral, RJ. Rev Ciênc Agron. 45(2):221-229.

Forsythe W (1975) Fisica de suelos: manual de laboratorio 212p. San José, Costa Rica.

Fracetto FJC, Fracetto GGM, Cerri CC, Feigl BJ, Siqueira Neto M (2012) Estoques de carbono e nitrogênio no solo cultivado com mamona na Caatinga. Rev Bras Ciênc Solo. 36(5):1545-1552.

Guerra JGM, Almeida DL, Santos GA, Fernandes MS (1996) Conteúdo de fósforo orgânico em amostras de solos. Pesq Agropec Bras. 31:291-299.

Harrison AF (1987) Soil organic phosphorus. CAB International, Wallingford.

Huber R, Souza BSP (2013) Estudo da fragilidade do relevo-solo através da resistência à penetração de estaca em Argissolos e Neossolos. Rev Bras Geomorfol. 14(3):269-277.

Jesus CAC (2005) Diagnóstico da agricultura agroecológica na mesorregião do agreste paraibano. Universidade Federal da Paraíba – UFPB, Areia, PB:91p. Dissertation (Master in Agronomy).

Lira RB, Dias NS, Alves SMC, Brito RF, Sousa Neto ON (2012) Efeitos dos sistemas de cultivo e manejo da caatinga através da análise dos indicadores químicos de qualidade do solo na produção agrícola em Apodi, RN. Rev. Caatinga. 25(3):18-24, jul-set.

Maia SMF, Xavier FAZ, Oliveira TS, Mendonça ES, Filho JAA (2007) Organic carbon pools in a Luvisol under agroforestry and conventional farming systems in the semi-arid region of Ceara´, Brazil. Agroforest Syst. 71:127–138.

Maia SMF, Xavier FAZ, Oliveira TS, Mendonça ES, Araujo Filho JA (2006) Impactos de sistemas agroflorestais e convencional sobre a qualidade do solo no semi-árido cearense. Rev Árvore. 30:837-848.

Majzik A, Tombácz E (2007) Interaction between humic acid and montmorillonite in the presence of calcium ions I. Interfacial and aqueous phase equilibria: Adsorption and complexation. Org Geochem. 38(8):1319-1329.

Manly BFJ (1994) Multivariate statistical methods.2nd edn. Chapman, Hall, London.

Martins CM (2009) Atributos de solos e sua relação com o processo de desertificação no semi-árido de Pernambuco.Universidade Federal Rural de Pernambuco – UFRPE, Recife, PE, UFRPE, 94 p. Dissertation (Master of Agricultural Sciences).

Martins CM, Galindo ICD, Souza ER, Poroca HÁ (2010) Atributos químicos e microbianos do solo de áreas em processo de desertificação no semiárido de Pernambuco. Rev Bras Ciênc Solo. 34:1883-1890.

Medeiros JC, Albuquerque JA, Mafra AL, Rosa JD, Gatiboni LC (2008) Calcium:magnesium ratio in amendments of soil acidity: nutrition and initial development of corn plants in a Humic Alic Cambisol. Semina: Ciências Agrárias, Londrina. 29(4):799-806.

Menezes RSC, Sampaio EVSB, Giongo V, Pérez-Marin AM (2012) Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. Braz Arch Biol Techn. 12(3):643-653.

Menezes RSC, Sampaio EVSB (2002) Simulação dos fluxos e balanços de fósforo em uma unidade de produção agrícola familiar no semi-árido paraibano. In: SILVEIRA, L.M.; PETERSEN, P. & SABOURIN, E., orgs. Agricultura familiar e agroecologia no semi-árido: Avanços a partir do Agreste da Paraíba. Rio de Janeiro, AS-PTA.

Miotti AA, Costa MCG, Ferreira TO, Romero RE (2013) Profundidade e atributos físicos do solo e seus impactos nas raízes de bananeiras. Rev Bras Frutic. 35(2):536-545.

Oades JM (1998) The retention of soil organic matter in soils. Biogeochemistry. 5:35-70.

Ortigara C, Koppe E, Luz FB, Bertollo AM, Kaiser DR, Silva VR (2014) Uso do solo e propriedades físico-mecânicas de Latossolo Vermelho. Rev Bras Ciênc Solo. 38:619-626.

Richards LA (1954) Diagnosis and improvement of saline and alkali soils. United States Salinity Laboratory Staff, Washington.

Sampaio EVSB, Costa TL (2011) Estoques e Fluxos de Carbono no Semi-Árido Nordestino: Estimativas Preliminares. RBGF, Recife. 6: 1275-1291.

Santana JAS, Souto JS (2011) Produção de serapilheira na Caatinga da região semi-árida do Rio Grande do Norte, Brasil. DESIA (Chile). 29(2):87-94.

Schiavo JA, Colodro G (2012) Agregação e resistência à penetração de um Latossolo Vermelho sob sistema de integração lavoura-pecuária. Bragantia. 71(3):406-412.

Shang C, Tiessen H (1997) Organic matter lability in tropical Oxisol: evidence from shifting cultivation, chemical oxidation, particle size, density, and magnetic fractionations. Soil Sci. 162: 795-807.

Silva IR, Mendonça ES (2007) Matéria orgânica do solo. In: Novais, R.F.; Alvarez V., V.H.; Barros, N.F.; Fontes, R.L.F. (Ed.). Fertilidade do solo. Viçosa: Sociedade Brasileira de Ciência do Solo.

Silva EF, Lourente EPR, Marchetti ME, Mercante FM, Ferreira AKT, Fujii, GC (2011) Frações lábeis e recalcitrantes da matéria orgânica em solos sob integração lavoura-pecuaria. Pesq Agropec Bras. 46(10):1321-1331.

Souza RO (2014) Caracterização Etnopedológica em um Cambissolo Eutrófico em diferentes usos agropecuários na Chapada do Apodi. Universidade Federal do Semmi-Árido - UFERSA, Mossoró, RN, UFERSA. 81 p. Dissertation (Master in Management, Soil and Water).

Souza ED, Costa SEVGA, Anghinoni I, Carvalho PCF, Andrigueti M, Caio E (2009) Estoque de carbono orgânico e de nitrogênio no solo em sistema de integração lavoura-pecuária em plantio direto, submetido a intensidades de pastejo. Rev Bras Ciênc Solo. 33:1829-1836.

Suguio, Kenitiro (2003) Geologia Sedimentar. Editora Edgar Blücher LTDA. São Paulo.

Swift RS (2001) Sequestration of carbon by soil. Soil Sci. v. 166, p. 858-871.

Trevisan R, Mattos MLT, Herter FG (2002) Atividade microbiana em Argissolo Vermelho-Amarelo distrófico coberto com aveia preta (Avena sp.) no outono, em um pomar de pessegueiro. Cienc Rural. 7(2):83-89.

Virto I, Gartzia-Bengoetxea N, Fernández-Ugalde O (2011) Role of organic matter and carbonates in soil aggregation estimated using laser diffractometry. Pedosphere. 21(5):566-572.

Yeomans JC, Bremner JM (1988) A rapid and precise method for routine determination of organic carbon in soil. Commun Soil Sci Plan. 19:1467-1476.