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Agroforestry system improves soil carbon and nitrogen stocks in depth after land-use changes in the Brazilian semi-arid region

Rafael Gonçalves Tonucci[(1)], **Renato Falconeres Vogado**[(2)*], **Rodrigo Dias Silva**[(3)], **Roberto Cláudio Fernandes Franco Pompeu**[(1)], **Melissa Oda-Souza**[(4)] and **Henrique Antunes de Souza**[(5)]

[(1)] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Caprinos e Ovinos, Sobral, Ceará, Brasil.
[(2)] Universidade Federal da Paraíba, Campus II, Departamento de Solos e Engenharia Rural, Programa de Pós-Graduação em Ciência do Solo, Areia, Paraíba, Brasil.
[(3)] Universidade Estadual do Vale do Acaraú, Centro de Ciências Agrárias e Ambiental, Programa de Pós-Graduação em Zootecnia, Sobral, Ceará, Brasil.
[(4)] Universidade Estadual do Piauí, Centro de Ciências Agrárias, Teresina, Piauí, Brasil.
[(5)] Empresa Brasileira de Pesquisa Agropecuária, Embrapa Meio-Norte, Teresina, Piauí, Brasil.

*** Corresponding author:**
E-mail: renatoagro86@hotmail.com

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ABSTRACT: Agroforestry systems have the potential to increase soil organic matter, with effects on soil carbon and nitrogen contents, but information on the application of these systems in semi-arid regions is still scarce. This study aimed to analyze soil carbon and nitrogen stocks in the conversion of native forest from the Caatinga Biome into integrated agriculture systems in the Brazilian semi-arid region. We evaluated the following management systems in the Haplic Inceptisol (*Cambissolo Háplico eutrófico*): (1) Intercropping area, cultivated with corn and Massai grass; (2) Caatinga (natural vegetation); (3) AFS10: agroforestry system with native woody forest rows occupying 33 % and agriculture occupying 66 % of the total area; and (4) AFS20: agroforestry system presenting inverse proportions of AFS10. The agroforestry systems were intercropped with sorghum or millet, pigeon pea and Massai grass. We collected disturbed and undisturbed soil samples at the layers of 0.00-0.10; 0.10-0.20; 0.20-0.40, 0.40-0.60 and 0.60-1.00 m for analysis of carbon (SOC), nitrogen (N), soil bulk density, and calculation of SOC and N stocks and C/N ratio, two years after the conversion of natural vegetation to the agricultural area (intercropping) and agroforestry system (AFS10 and AFS20). We applied principal component and cluster analysis to explore the data, and confidence interval to compare the means of accumulated SOC and N stocks up to 1 m soil depth. No differences exist for the properties analysed in superficial layers (0.00-0.10 and 0.10-0.20 m), regardless of land-use systems. AFS20 increase the SOC content and, consequently, SOC stock, in subsurface layers; on the other hand, intercropping increases N content and N stock. AFS20 presented higher accumulated SOC stocks up to 1.00 m (114.97 Mg ha^{-1}). Agroforestry systems management is an alternative for increasing carbon sequestration under the conversion from Caatinga to agricultural areas.

Keywords: soil quality, soil organic matter, climate change mitigations, integrated systems.

INTRODUCTION

Soil is the largest reservoir of carbon in the terrestrial biosphere and has the potential to mitigate the projected climate changes (Scharlemann et al., 2014). However, land-use changes from natural areas for agricultural purposes can significantly impact greenhouse gas emissions and reduce soil organic carbon (SOC) stocks (Santana et al., 2019). This situation can be more drastic in arid and semi-arid regions, where local climate conditions and the conversion to agriculture areas can increase SOC mineralization. Arid and semi-arid regions cover more than 30 % of the Earth's surface, and it is essential to develop more sustainable agricultural management systems for these areas to ensure food security and maintain or increase SOC. In the Brazilian semi-arid region, the SOC can be reduced by 12 to 27 % due to inadequate management of pastures and edaphoclimatic conditions (Medeiros et al., 2020). Agroforestry system is a more sustainable land-use management and can be an option to improve SOC in pasture and agriculture areas, but information about its potential to increase SOC stocks in semi-arid environments is still underdeveloped (Sacramento et al., 2013).

The Brazilian semi-arid region is characterized by the Caatinga vegetation, a natural vegetation composed of small trees, shrublands, and herbaceous plants. Caatinga soils have low SOC contents, and their agricultural productivity is intrinsically linked to efficient soil conservation measures (Schulz et al., 2016). Nevertheless, the agricultural activities in the Caatinga biome are characterized by cutting and burning natural vegetation, and overgrazing commonly occurs, decreasing nutrient cycling and soil fertility. For instance, degraded pastures in tropical regions led to SOC losses from 3 to 9 % (Ogle et al., 2004; Maia et al., 2009). These conditions reduce the contribution of organic material to the soil and its capacity to provide nutrients to the pasture, increasing degradation and compaction processes (Araujo Filho, 2013; Schulz et al., 2016). These management practices have been accelerating the degradation and desertification processes of the Caatinga biome (Sá and Angelotti, 2009). On the other hand, conservation management practices can increase organic matter inputs, and SOC and nitrogen contents (Wells et al., 2019), cooperating to mitigate climate change (Gao et al., 2017).

Agroforestry systems increase the biomass inputs to soil due to the spatial and temporal design of their diverse components (wooden, herbaceous, agricultural, and forage strata) in the same area. In addition, the high diversity of species and interactions between these components (Miccolis et al., 2019) maximize the land-use, simultaneously producing food, fodder and wood, and increasing the yield per area (Korwar et al., 2014). Then, agroforestry systems have the potential to increase the quantity and quality of organic matter, which is directly proportional to the availability of nutrients, maintenance of the microbiota and the physical soil properties (Oliveira et al., 2019).

Agroforestry systems create a microclimate that changes soil moisture and temperature, affecting agroecosystems carbon and nitrogen cycles. The mineralization of organic matter is directly linked to soil microorganisms that are very sensitive to moisture change. Modelling studies simulating intense drought and rain conditions have demonstrated higher sensitivity of microorganisms in dry periods than in rainy ones (Liang et al., 2021). The increase of SOC and N contents, and moisture, associated with a decrease in soil temperature, promotes a favorable environment for soil microorganisms development, which increases the mineralization rates of organic matter (Oliveira et al., 2014). These processes are important strategies for maintaining sustainable production systems in semi-arid regions.

In this study, we hypothesize that the adoption of Agroforestry systems minimizes the impact of SOC loss after the land-use change from Caatinga to traditional agriculture systems, such as suppression with slashing and burning of the forest component. This study aimed to i) analyze the SOC and N dynamics in different integrated agriculture management systems (Intercropping, Agroforestry systems) and Caatinga; and ii) compare the similarity of these systems in improving soil quality.

MATERIALS AND METHODS

Study area and management systems

The study was carried out in an agroforestry system in the municipality of Sobral, Ceará state (3° 44' 53.642" S, 40° 21' 46.231" W), Brazil. The region's climate is hot and semi-arid (BSh) (Alvares et al., 2013), with a mean annual temperature between 26-28 °C and precipitation of 821.6 mm. The soil in the study area is classified as Haplic Inceptisol (*Cambissolo Háplico eutrófico*) with a medium texture. In this study, we analyzed the following management systems:

Native vegetation (Caatinga): Area of native vegetation of the Caatinga biome, with the presence of hyperxerophilic shrub and arboreal species, characterized by smaller plants adapted to water scarcity. There is no history of cultivation or logging in the area since the 1980s, and it is occasionally used for moderate animal grazing. The most frequent forest species are: pau-branco (*Auxemma oncocalyx*), marmeleiro (*Croton sonderianus*), jurema-preta (*Mimosa tenuiflora*), sabiá (*Mimosa caesalpiniifolia*), juazeiro (*Ziziphus joazeiro*), umburana (*Amburana cearenses*) and catingueira (*Caesalpinia pyramidalis*).

Intercropping: This area was converted from Caatinga to an agriculture area between 2016 and 2017, with the exclusive aim of cultivating forage (corn or sorghum) intercropped with Massai grass, which was mechanically harvested. The materials resulting from the regrowth were not grazed, being left as a soil cover, and incorporated with a plow and harrow in the following year. After the Caatinga removal, the soil was prepared with plowing and harrowing and cultivated in its first year (2017) with forage sorghum (0.9 m spacing between rows and 15 seeds per linear meter), with 2 kg ha^{-1} of Massai grass seeds sown at haul between the planting lines. Fertilizations comprise 200 kg ha^{-1} of NPK (8-28-16) (at planting) and 50 kg ha^{-1} of N (urea) and sheep manure (7 Mg ha^{-1}) were applied in the total area. In the following year (2018), the area was cultivated with corn (0.90 × 0.20 m), intercropped with Massai grass (*Megathyrsus maximus* cv. Massai) (2 kg ha^{-1} of seeds), broadcast sown in the between rows and fertilized with 300 kg ha^{-1} of NPK (8-28-16) at planting and 50 kg ha^{-1} of N (urea) and 20 kg ha^{-1} of K_2O (KCl) were applied during the vegetative growth period of corn.

Agroforest 10 (AFS10): This area was converted from Caatinga to an agroforestry system between 2016 and 2017. The agroforestry system consists of strips of native woody forest vegetation (row) 10 m wide and an arable strip (interrow) 20 m wide and from 220 to 240 m in length, with total suppression of vegetation. After removing the wood of commercial interest, the remaining material (19 Mg ha^{-1} of biomass) was crushed and incorporated by plowing and harrowing the soil. The agricultural area of the AFS10 was prepared with plowing and harrowing, with the cultivation of sorghum/millet + pigeon pea + Massai, receiving planting fertilization with 150 kg ha^{-1} of NPK (8-28-16), and 100 kg ha^{-1} of N (urea) and 20 kg ha^{-1} of K_2O (KCl) that were applied during the vegetative growth period of intercropped forage followed by mechanical harvesting.

Agroforest 20 (AFS20): This area was converted from Caatinga to an agroforestry system between 2016 and 2017. The agroforestry system consists of strips of native woody forest vegetation (row) 20 m wide and an arable strip (interrow) 10 m wide and from 220 to 240 m in length, with total suppression of vegetation. After removing the wood of commercial interest, the remaining material (19 Mg ha^{-1} of biomass) was crushed and incorporated by plowing and harrowing the soil. The agricultural area of the AFS20 was prepared with plowing and harrowing, with the cultivation of sorghum/ millet + pigeon pea + Massai, receiving planting fertilization with 150 kg ha^{-1} of NPK (8-28-16), and 100 kg ha^{-1} of N (urea) and 20 kg ha^{-1} of K_2O (KCl) we applied during the vegetative growth period of intercropped forage followed by mechanical harvesting. No fire or liming was used in any of the management systems.

Soil sampling

For soil analysis, we collected disturbed and undisturbed soil samples (four repetitions) in each management system (Intercropping, Caatinga, AFS10 and AFS20) at the layers of 0.00-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60, and 0.60-1.00 m, in the rainy season of 2018. We collected soil samples in suppressed and conserved areas in the AFS systems. First, we opened soil profiles with dimensions of 0.80 × 2.00 m and 1.3 m in depth. Soil sampling to determine carbon and nitrogen contents was carried out around each soil profile, in all cardinal directions. Four equidistant points were marked to collect deformed samples, which were combined into a composite sample for each depth. We also collected four undisturbed soil samples in the inner walls of the soil profile for soil density analysis using a stainless steel volumetric ring of 100 cm^3.

Analysis of carbon and nitrogen contents and stocks

Disturbed soil samples were air-dried, sieved (2 mm) and macerated in porcelain grade until passing through a 70 mesh (0.210 mm) sieve. Carbon (SOC) and nitrogen (N) contents were determined by dry combustion. We analyzed soil bulk density (BD) using the volumetric ring method described by Teixeira et al. (2017). Soil bulk density in each sample was calculated by the relationship between the dry soil mass present in each ring and the ring volume expressed in g cm^{-3}. The carbon and nitrogen stocks were calculated based on the concentrations of C and N and the volume and soil bulk density of each soil layer (Equation 1), correcting for the thickness of the reference area, according to Veldkamp (1994).

$$SOCs = \frac{SOC \times BD \times e}{10} \qquad \text{Eq. 1}$$

in which: SOCs is soil organic carbon stock at a given depth (Mg ha^{-1}); SOC is the total organic carbon content at the sampled depth (g kg^{-1}); BD is the soil bulk density for sampled depth (kg dm^{-3}); and e is the thickness of the considered layer (cm).

We applied the same methodology described above to calculate the nitrogen stocks (Equation 2).

$$Ns = \frac{N \times BD \times e}{10} \qquad \text{Eq. 2}$$

in which: Ns is the organic nitrogen stock at a certain depth (Mg ha^{-1}); N is the total organic nitrogen content at the sampled depth (g kg^{-1}); BD is the soil bulk density for sampled depth (kg dm^{-3}); and e is the layer thickness.

Data analysis and systematization

Comparisons between the sample properties were made using the mean confidence interval ($p<0.05$), according to Payton et al. (2000). When the upper and lower limits of the confidence interval do not overlap; it is considered that there is a significant difference. We also applied principal component analysis (PCA) (Jolliffe, 2002) and clustering, using the Euclidean distance by the Ward method (Ward, 1963), to identify the relations between the variables in this study and the different management systems. The Ward method allows to identify different groups with minimal internal variance, minimizing the square of the Euclidean distance to the group means. We analyzed the main components of the PCA based on the graphical representation (Biplot), considering the parameter Cos2, an indicator of the quality of representation and, simultaneously, the contributions (%) of the variables (Abdi and Williams, 2010).

All the analyses were performed in the R software for statistical computing (R Development Core Team, 2020) using the packages *FactoMineR* (Lê et al., 2008), *factoextra* (Kassambara and Mundt, 2017) and *dendextend* (Galili, 2015).

RESULTS

Soil properties

Considering the upper and lower limits of the confidence interval for the surface layer (0.00-0.10 and 0.10-0.20 m), there were no difference for SOC, N, ratio and stock, however for the layer 0.20-0.40 m for SOCs, the management ASF20 show interval without overlap of Intercropping and Caatinga, in the same layer, ASF20 and Intercropping were superior in relation the Caatinga for Ns and for C/N ratio ASF10 was superior in relation of Caatinga and Intercropping (Table 1).

For layer 0.40-0.60 m, the management AFS20 show confidence interval without overlap for SOC and N contents in relation to Caatinga and Intercropping. The AFS20 and AFS10, in the same layer, show confidence interval without overlap for BD in relation to Caatinga. In the same layer for SOCs the systems management of AFS20 and AFS10 show confidence interval without overlap in relation to Caatinga and Intercropping, and for Ns the management AFS20 was superior in relation the other systems management (Caatinga, Intercropping and AFS10).

In the subsurface layer (0.60-1.00 m), the management AFS20 show superiority in relation to the Caatinga, Intercropping and AFS10 for SOC content and stock; Intercropping shows higher values for N content and stock, while the higher values for C/N ratio were verified for AFS10 and AFS20.

The AFS20 presented higher SOC stocks (114.97 Mg ha^{-1}) for SOC accumulated stock (0.00-1.00 m). Although AFS10 (96.69 Mg ha^{-1}) had a smaller accumulated SOC stock than the AFS20, it was superior to the values from Intercropping (75.43 Mg ha^{-1}) and Caatinga (76.37 Mg ha^{-1}) (Figure 1a). For the accumulated N stock (0.00-1.00 m), Intercropping (7.91 Mg ha^{-1}) presented the highest values, followed by AFS20 (6.26 Mg ha^{-1}) (Figure 1b).

Multivariate analysis

In the superficial layer (0.00-0.10 m), CP1 explained 69.28 % of the variability associated with the variables, and CP2 23.12 % (Figure 2a). The properties N and Ns were highly positively correlated with CP1, and the C/N ratio was highly and negatively correlated with CP1, while the properties SOC and SOCs were positively correlated with CP2. In the 0.10-0.20 m layer, the properties SOC, SOCs and C/N ratio correlated highly and positively, but N and Ns showed a high and negative correlation with CP1 (Figure 2b), and the BD correlated highly and positively with CP2.

In the 0.20-0.40 m layer, SOC, BD, SOCs and C/ N correlated highly and positively with CP1 (Figure 2c); however, the N and Ns variables showed a high and positive correlation with CP2. In the 0.40-0.60 m layer, SOC, N, SOCs and Ns had high and positive correlation with CP1 (Figure 2d); however, the C/N ratio correlated with high and positive values with CP2. In the 0.60-1.00 m layer, the parameters BD and C/N ratio correlated highly and positively with CP1, but the variables SOC, N, SOCs and Ns showed a high and positive correlation with CP2 (Figure 2e). The CP2 in the studied layers resulted in higher values

Table 1. Mean and confidential interval (p<0.05) of carbon (SOC) and nitrogen (N) contents, soil bulk density (BD), stock (SOCs and Ns), and C/N ratio under the managements Intercropping, Caatinga and agroforestry systems (AFS10 and AFS20), and groups of clusters analysis for the evaluated soil layers

Management system	SOC	N	BD	SOCs	Ns	C/N
	g kg^{-1}		Mg m^{-3}	Mg ha^{-1}		
			0-00-0.10 m			
Intercropping	16.5±4.2	1.25±0.38	1.56±0.07	23.3±4.9	1.77±0.50	13±3.5
Caatinga	16.0±3.5	0.79±0.10	1.41±0.14	22.8±5.5	1.13±0.21	20±2.9
AFS10	16.3±2.0	0.87±0.11	1.56±0.09	23.1±2.6	1.23±0.24	19±2.3
AFS20	15.4±1.0	0.91±0.04	1.49±0.16	21.8±1.0	1.28±0.10	17±0.5
G1 (Intercropping)	16.5	1.25	1.56	23.3	1.77	13
G2 (Caatinga+AFS10+AFS20)	15.9	0.85	1.49	22.6	1.22	19
			0.10-0.20 m			
Intercropping	8.1±1.5	0.78±0.11	1.60±0.05	11.9±2.9	1.12±0.20	10±0.5
Caatinga	9.3±3.1	0.61±0.19	1.46±0.11	13.5±3.4	0.89±0.21	15±1.8
AFS10	11.4±2.4	0.52±0.19	1.52±0.05	16.7±3.3	0.77±0.27	22±4.3
AFS20	11.5±2.2	0.65±0.13	1.52±0.03	16.9±3.9	0.96±0.21	18±1.3
G1 (Intercropping + Caatinga)	8.7	0.69	1.53	12.7	1.01	13
G2 (AFS10+AFS20)	11.4	0.59	1.53	16.8	0.87	20
			0.20-0.40 m			
Intercropping	5.47±1.3	0.57±0.11	1.53±0.10	16.7±3.3	1.77±0.28	9±0.2
Caatinga	5.87±1.2	0.42±0.12	1.53±0.05	18.0±3.6	1.31±0.36	13±2.4
AFS10	7.99±2.0	0.37±0.05	1.58±0.04	24.5±5.7	1.16±0.16	21±2.8
AFS20	9.33±0.9	0.52±0.06	1.59±0.03	28.6±2.0	1.59±0.22	18±2.9
G1 (Intercropping + Caatinga)	5.67	0.5	1.54	17.4	1.54	12
G2 (AFS10+AFS20)	8.65	0.45	1.59	26.6	1.38	20
			0.40-0.60 m			
Intercropping	3.38±0.6	0.19±0.03	1.61±0.08	10.6±1.8	0.62±0.07	17±2.5
Caatinga	3.91±0.1	0.21±0.02	1.57±0.05	12.3±0.8	0.68±0.06	18±1.0
AFS10	5.35±1.3	0.23±0.03	1.66±0.02	16.8±4.0	0.73±0.09	23±4.0
AFS20	7.42±0.8	0.42±0.07	1.66±0.02	23.4±3.2	1.32±0.25	18±1.4
G1 (Intercropping + Caatinga)	3.64	0.20	1.59	11.4	0.65	18
G2 (AFS10+AFS20)	6.38	0.33	1.66	20.1	1.03	20
			0.60-1.00 m			
Intercropping	1.95±0.2	0.39±0.15	1.60±0.10	12.7±1.4	2.58±0.90	5±1.7
Caatinga	1.50±0.4	0.13±0.03	1.62±0.02	9.7±2.6	0.83±0.15	12±1.9
AFS10	2.37±0.4	0.09±0.01	1.66±0.05	15.5±2.9	0.64±0.11	24±0.9
AFS20	3.72±0.6	0.16±0.02	1.69±0.09	24.2±4.2	1.08±0.15	22±3.3
G1 (Intercropping + Caatinga)	1.72	0.26	1.62	11.2	1.70	8
G2 (AFS10+AFS20)	3.05	0.13	1.68	19.8	0.86	23

AFS10: Agroforestry with strips of native forest 10 m wide; AFS20: Agroforestry with strips of native forest 20 m wide.

of the parameter of representation quality (Cos2) and contribution (%). High Cos2 values are associated with a color scale. The warmer the color (red), the greater the importance of these variables. In the first three layers, the properties with the greatest contribution were SOC, N, SOCs, Ns and C/N ratio. In the 0.40-0.60 m layer, the same properties are mentioned, except for the C/N ratio, and in the 0.60-1.00 m layer, the BD join SOC, N, SOCs and Ns.

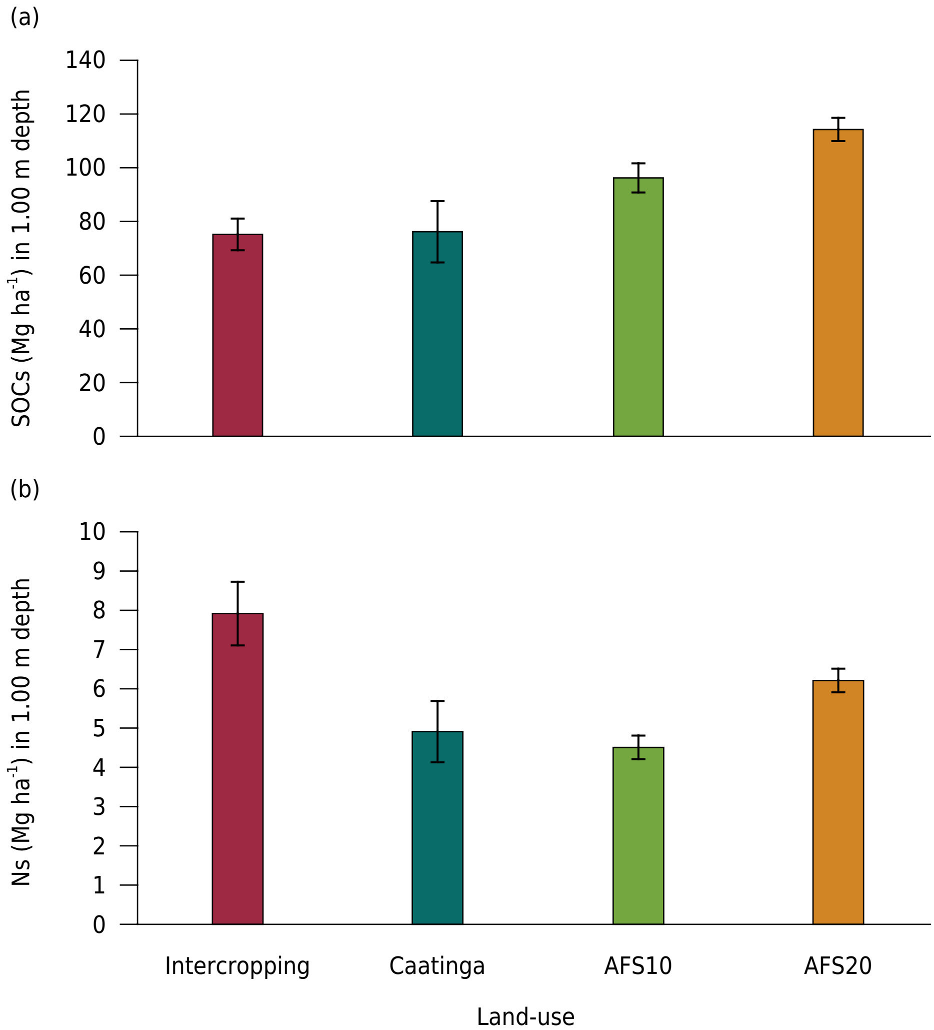

Figure 1. Accumulated soil organic carbon (a) and nitrogen (b) stocks up to 1.00 m of deepth under the influence of intercropping, Caatinga and agroforestry systems (AFS10 and AFS20). Vertical lines on the bars indicate the confidence interval of means ($p<0.05$). AFS10: Agroforestry with strips of native forest 10 m wide; AFS20: Agroforestry with strips of native forest 20 m wide.

The cluster analysis shows the dissimilarity between the different managements. In the surface layer (0.00-0.10 m), the management systems were grouped into two groups (Figure 3a): one formed only by the Intercropped agricultural area and the other group composed by the other managements (Caatinga, AFS10 and AFS20). In the other layers, 0.10-0.20 (Figure 3b), 0.20-0.40 (Figure 3c), 0.40-0.60 (Figure3d) and 0.60-1.00 m (Figure 3e), two groups were created: one composed by Intercropped and Caatinga, and the other by AFS10 and AFS20.

DISCUSSION

Influence of integrated management systems on soil SOC and N after the conversion of the natural vegetation Caatinga to agricultural areas was studied in this paper. The management system does not show differences between the land-use systems for surface layer 0.00-0.10 m. The production of straw can justify this in the area (intercropping with forage grass), which increases dry mass, especially on the surface. The intercropping of corn or sorghum with forage grass promotes changes in the soil's chemical properties, resulting from the high accumulation of plant residues on its surface, which decomposition provides nutrient input to the soil, stimulating biological activity that results in changes in their fertility (Costa et al., 2015).

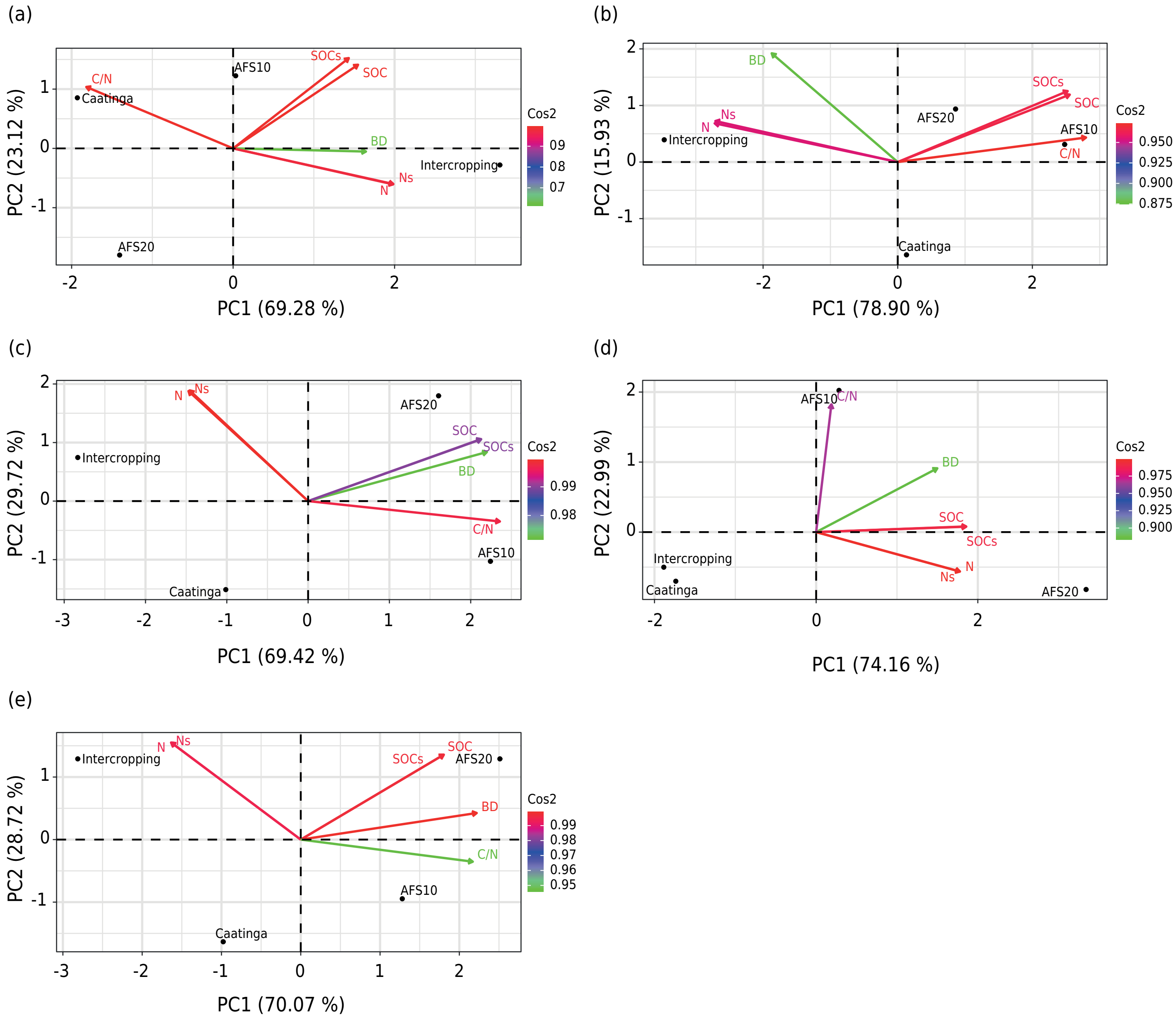

Figure 2. Biplots of principal component analysis between the carbon (SOC), nitrogen (N) content and SOC and N stocks (SOCs and Ns), C/N ratio and soil bulk density (BD) under the managements Intercropping, Caatinga and agroforestry systems (AFS10, AFS20) for the first two main components (CP1 and CP2), for the soil layers 0.00-0.10 (a), 0.10-0.20 (b), 0.20-0.40 (c), 0.40-0.60 (d) and 0.60-1.00 m (e). AFS10: Agroforestry with strips of native forest 10 m wide; AFS20: Agroforestry with strips of native forest 20 m wide.

Our results show that the AFS10 and AFS20 were associated with the highest values of SOC (content and stock), mainly in the subsurface, and it may be due to the heterogeneity of components present in the agroforestry system, such as the presence of trees in the rows, and grasses and legumes cultivated in the rows, which corroborates the formation of the two groups (AFSs x Intercropping + Caatinga) for the subsurface layers. Furthermore, the higher accumulated SOC stock in AFS20 and AFS10 can be explained by the increase in SOC in depth from the tree's roots present in the area that was recently opened as well as the roots of cultivated crops. The change in land-use resulted in gains for SOC up to 1.00 m, which can be justified by the co-dependency verified in the results of principal components (Figure 1).

Adoption of agroforestry systems, regardless of their cultivated area, promoted higher accumulation of soil carbon in agricultural production systems in the semi-arid region, as the forest component exerts a strong influence on the microclimate, contributing to lower

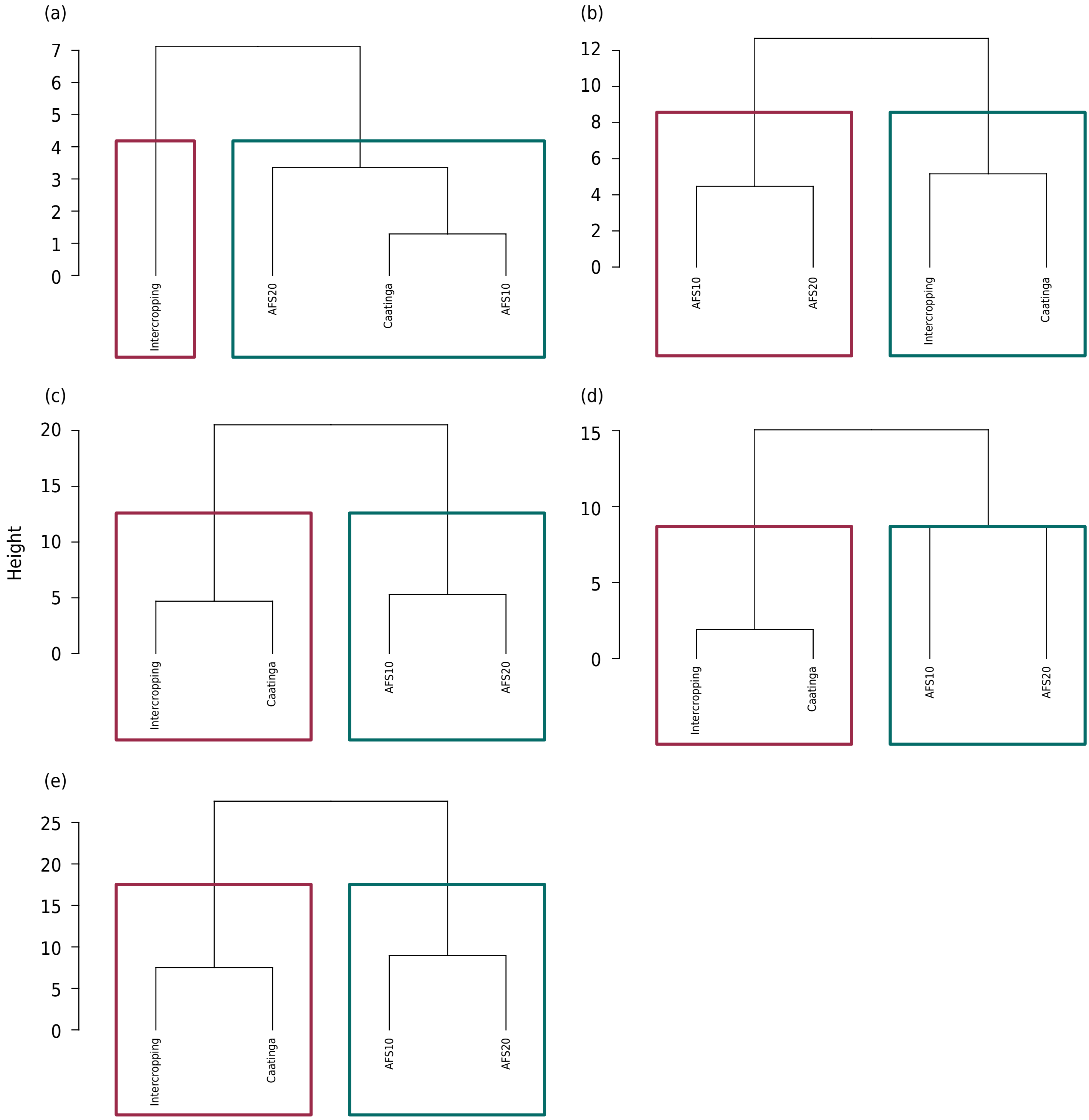

Figure 3. Dendrogram of dissimilarity between carbon and nitrogen contents and stocks, C/N ratio, and soil bulk density under agriculture managements Intercropped, Caatinga and agroforestry systems (AFS10 and AFS20) at 0.00-0.10 m (a), 0.10-0.20 m (b), 0.20-0.40 m (c), 0.40-0.60 m (d) and 0.60-1.00 m (e) soil layers. AFS10: Agroforestry with strips of native forest 10 m wide; AFS20: Agroforestry with strips of native forest 20 m wide.

temperatures, increasing residual moisture, and influencing positively organic matter and nutrient dynamics. Sequestration of carbon and nitrogen varies according to the deposition rates of plant and animal residues and losses resulting from litter consumption by animals, erosion and oxidation by soil microorganisms (Sacramento et al., 2013). The roots of the forest component impact the accumulation of carbon in depth since AFS20 provides a larger row area than the intercropping system. Root exudates are an essential source of SOC and nutrients in soils and are highly variable within management systems, and such contributions in agroforestry systems are often derived from the tree component (Isaac and Borden, 2019).

Accumulated SOC stock in AFS10 and AFS20 showed an increase of 50 and 26 %, respectively, and Intercropping agricultural area provided a decrease in the accumulated SOC stock of 2 % compared to the Caatinga area. Then, agroforestry systems are plausible alternatives for a rapid increase in C, and the intercropping system to maintain this SOC stock. It is also necessary to indicate that the 50 % difference in SOC stock between AFS20 and Caatinga is also affected by the input of Caatinga biomass that was suppressed, as the experimental area is in its first agricultural years. Oliveira et al. (2019) found that SOC stocks in AFSs were approximately 20 % smaller than in secondary forests after 12 years of conversion. After the conversion of native vegetation to pasture (native and planted), SOC stocks were reduced in the order of 12 to 27 % in a semi-arid region (Medeiros et al., 2020), which depending on the period of use and soil layer, generally represent more severe losses than in other regions of Brazil. Furthermore, the greatest losses occur during the first five years after the conversion of native vegetation (Medeiros et al., 2020). In general, the conversion of Caatinga into agricultural areas and pastures reduces soil SOC and N stocks. However, when crops with high biomass production are implemented, they can promote an increase in SOC and N (Barros et al., 2015).

The lower N stocks in the Caatinga and AFS10 and AFS20 compared with Intercropping are explained by the high litter C/N ratio of the Caatinga plants, which is 34.2 according to Primo et al. (2018, 2021). Biomass with a C/N ratio >30 can immobilize N or cause a slow release of this element in the soil (Moreira and Siqueira, 2006). The higher C/N ratio associated with the natural presence of tannins, polyphenols and lignin, hinders the mineralization of organic matter from soil microorganisms reducing the N input to soil (Aita and Giacomini, 2003; Lima et al., 2015).

The complex composition of agroforestry systems, combining leguminous, grass and tree species, promotes qualitative and quantitative increases in soil organic matter and carbon stocks, essential for maintaining soil quality. This is important for the Brazilian semiarid region, which has low carbon contents resulting from the natural input (Iwata et al., 2012). In addition, the use of residues with different organic and structural properties in the agroforestry systems creates a balance of labile and recalcitrant organic matter compartments, ensuring an increase in the complexity and maintenance of SOC (Iwata et al., 2021).

CONCLUSIONS

Conversion of Caatinga forest into Agroforestry Systems is a viable alternative to increase soil carbon stocks in the soil profile. Intercropping area with corn and Massai improves nitrogen stock in the entire soil profile (0.00-1.00 m) in relation to Caatinga and Agroforest Systems. Agroforestry system with strips of native woody forest vegetation with a row 20 m wide and an arable strip (interrow) 10 m wide improves soil organic carbon and stock in subsurface layers. Integrated agriculture systems in the Caatinga biome are sustainable alternatives for land-use in the semi-arid region.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.01.030.

AUTHOR CONTRIBUTIONS

Conceptualization: Henrique Antunes de Souza (equal), Rafael Gonçalves Tonucci (equal) and Rodrigo Dias Silva (equal).

Data curation: Henrique Antunes de Souza (equal), Melissa Oda-Souza (equal), Rafael Gonçalves Tonucci (equal), Roberto Cláudio Fernandes Franco Pompeu (equal) and Rodrigo Dias Silva (equal).

Formal analysis: Melissa Oda-Souza (lead).

Funding acquisition: Henrique Antunes de Souza (equal) and Rafael Gonçalves Tonucci (equal).

Investigation: Renato Falconeres Vogado (equal), Roberto Cláudio Fernandes Franco Pompeu (equal) and Rodrigo Dias Silva (equal).

Methodology: Henrique Antunes de Souza (equal), Melissa Oda-Souza (equal), Rafael Gonçalves Tonucci (equal) and Roberto Cláudio Fernandes Franco Pompeu (equal).

Project administration: Henrique Antunes de Souza (equal) and Rafael Gonçalves Tonucci (equal).

Supervision: Henrique Antunes de Souza (equal) and Rafael Gonçalves Tonucci (equal).

Validation: Henrique Antunes de Souza (lead).

Writing – original draft: Henrique Antunes de Souza (equal), Rafael Gonçalves Tonucci (equal), Renato Falconeres Vogado (equal) and Rodrigo Dias Silva (equal).

Writing – review & editing: Henrique Antunes de Souza (equal), Rafael Gonçalves Tonucci (equal), Renato Falconeres Vogado (equal) and Rodrigo Dias Silva (equal).

REFERENCES

Abdi H, Williams LJ. Principal component analysis. WIREs Comput Stat. 2010;2:433-59. https://doi.org/10.1002/wics.101

Aita C, Giacomini SJ. Decomposição e liberação de nitrogênio de resíduos culturais de plantas de cobertura de solo solteiras e consorciadas. Rev Bras Cienc Solo. 2003;27:601-12. https://doi.org/10.1590/S0100-06832003000400004

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. Köppen's climate classification map for Brazil. Meteorol Zeitschrift. 2013;22:711-28. https://doi.org/10.1127/0941-2948/2013/0507

Araujo Filho JA. Manejo pastoril sustentável da caatinga. Recife: Cidade Gráfica e Editora Ltda.; 2013.

Barros JDS, Chaves LHG, Pereira WE. Carbon and nitrogen stocks under different management systems in the Paraiban Sertão. African J Agric Res. 2015;10:130-6. https://doi.org/10.5897/AJAR2014.8706

Costa NR, Andreotti M, Mascarenhas Lopes KS, Yokobatake KL, Ferreira JP, Pariz CM, Batista Bonini CS, Longhini EVZ. Atributos do solo e acúmulo de carbono na integração lavoura-pecuária em sistema plantio direto. Rev Bras Cienc Solo. 2015;39:852-63. https://doi.org/10.1590/01000683RBCS20140269

Galili T. Dendextend: an R package for visualizing, adjusting and comparing trees of hierarchical clustering. Bioinformatics. 2015;31:3718-20. https://doi.org/10.1093/bioinformatics/btv428

Gao L, Becker E, Liang G, Houssou AA, Wu H, Wu X, Cai D, Degré A. Effect of different tillage systems on aggregate structure and inner distribution of organic carbon. Geoderma. 2017;288:97-104. https://doi.org/10.1016/j.geoderma.2016.11.005

Isaac ME, Borden KA. Nutrient acquisition strategies in agroforestry systems. Plant Soil. 2019;444:1-19. https://doi.org/10.1007/s11104-019-04232-5

Iwata BF, Brandão MLSM, Braz RDS, Leite LFC, Costa MCG. Total and particulate contents and vertical stratification of organic carbon in agroforestry systems in Caatinga. Rev Caatinga. 2021;34:443-51. https://doi.org/10.1590/1983-21252021V34N220RC

Iwata BF, Leite LFC, Araújo ASF, Nunes LAPL, Gehring C, Campos LP. Sistemas agroflorestais e seus efeitos sobre os atributos químicos em Argissolo Vermelho-Amarelo do Cerrado piauiense. Rev Bras Eng Agric Ambiental. 2012;16:730-8. https://doi.org/10.1590/S1415-43662012000700005

Jolliffe IT. Principal component analysis. 2nd. ed. New York: Springer; 2002.

Kassambara A, Mundt F. Package “factoextra” for R: Extract and Visualize the Results of Multivariate Data Analyses. R Packag. 2017.

Korwar GR, Prasad JVNS, Rao GR, Venkatesh G, Pratibha G, Venkateswarlu B. Agroforestry as a strategy for livelihood security in the rainfed areas: experience and expectations. In: Dagar J, Singh A, Arunachalam A, editors. Agroforestry systems in India: Livelihood security & ecosystem services. New Delhi: Springer; 2014. p. 117-54. https://doi.org/10.1007/978-81-322-1662-9_5

Lê S, Josse J, Husson F. FactoMineR: An R Package for Multivariate Analysis. J Stat Softw. 2008;25:1-18. https://doi.org/10.18637/JSS.V025.I01

Liang J, Wang G, Singh S, Jagadamma S, Gu L, Schadt CW, Wood JD, Hanson PJ, Mayes MA. Intensified soil moisture extremes decrease soil organic carbon decomposition: A mechanistic modeling analysis. JGR Biogeosciences. 2021;126:e2021JG006392. https://doi.org/10.1029/2021JG006392

Lima RP, Fernandes MM, Fernandes MRM, Matricardi EAT. Aporte e decomposição da serapilheira na Caatinga no Sul do Piauí. Floresta e Ambient. 2015;22:42-9. https://doi.org/10.1590/2179-8087.062013

Maia SMF, Ogle SM, Cerri CEP, Cerri CC. Effect of grassland management on soil carbon sequestration in Rondônia and Mato Grosso States, Brazil. Geoderma. 2009;149:84-91. https://doi.org/10.1016/j.geoderma.2008.11.023

Medeiros AS, Maia SM, Santos TC, Gomes TC. Losses and gains of soil organic carbon in grasslands in the Brazilian semi-arid region. Sci Agric. 2020;78:e20190076. https://doi.org/10.1590/1678-992X-2019-0076

Miccolis A, Peneireiro FM, Vieira DLM, Marques HR, Hoffmann MRM. Restoration through agroforestry: Options for reconciling livelihoods with conservation in the Cerrado and Caatinga biomes. Exp Agric. 2019;55:208-25. https://doi.org/10.1017/S0014479717000138

Moreira FMS, Siqueira JO. Microbiologia e bioquímica do Solo. 2. ed. Lavras: Editora UFLA; 2006.

Ogle SM, Conant RT, Paustian K. Deriving grassland management factors for a carbon accounting method developed by the intergovernmental panel on climate change. Environ Manage. 2004;33:474-84. https://doi.org/10.1007/s00267-003-9105-6

Oliveira APP, Lima E, Anjos LHC, Zonta E, Pereira MG. Sistemas de colheita da cana-de-açúcar: conhecimento atual sobre modificações em atributos de solos de tabuleiro. Rev Bras Eng Agríc Ambiental. 2014;18:939-47. https://doi.org/10.1590/1807-1929/AGRIAMBI.V18N09P939-947

Oliveira CV, Vicente LC, Gama-Rodrigues EF, Gama-Rodrigues AC, Marques JRB, Barreto-Garcia PAB. Carbon and nitrogen stock of Acrisols and Nitisols in South Bahia, Brazil. Geoderma Reg. 2019;16:e00218. https://doi.org/10.1016/j.geodrs.2019.e00218

Payton ME, Miller AE, Raun WR. Testing statistical hypothesis using standard error bars and confidence intervals. Commun Soil Sci Plant Ana. 2000;31:547-51. https://doi.org/10.1080/00103620009370458

Primo AA, Araújo MDM, Silva KF, Silva LA, Pereira GAC, Fernandes FÉP, Pompeu RCFF, Natale W, Souza HA. Litter production and nutrient deposition from native woody species in the Brazilian semi-arid region. Agrofor Syst. 2021;95:1459-64. https://doi.org/10.1007/s10457-021-00652-4

Primo AA, Melo MD, Pereira GAC, Silva LA, Fernandes FÉP, Souza HA. Potencial fertilizante da serapilheira de espécies lenhosas da Caatinga na recuperação de um solo degradado. Rev Ceres. 2018;65:74-84. https://doi.org/10.1590/0034-737X201865010010

R Development Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2020. Available from: http://www.R-project.org/.

Sá IB, Angelotti F. Degradação ambiental e desertificação no semiárido. In: Angelotti F, SÁ IB, Menezes EA, Pellegrino GQ, editors. Mudanças climáticas e desertificação no Semi-Árido brasileiro. Petrolina: Embrapa Semi-Árido; Campinas: Embrapa Informática Agropecuária; 2009. p. 54-76.

Sacramento JAAS, Araújo ACM, Escobar MEO, Xavier FAS, Cavalcante ACR, Oliveira TS. Soil carbon and nitrogen stocks in traditional agricultural and agroforestry systems in the semiarid region of Brazil. Rev Bras Cienc Solo. 2013;37:784-95. https://doi.org/10.1590/S0100-06832013000300025

Santana MS, Sampaio EVSB, Giongo V, Menezes RSC, Jesus KN, Albuquerque ERGM, Nascimento DM, Pareyn FGC, Cunha TJF, Sampaio RMB, Primo DC. Carbon and nitrogen stocks of soils under different land uses in Pernambuco state, Brazil. Geoderma Reg. 2019;16:e00205. https://doi.org/10.1016/j.geodrs.2019.e00205

Scharlemann JPW, Tanner EVJ, Hiederer R, Kapos V. Global soil carbon: Understanding and managing the largest terrestrial carbon pool. Carbon Manag. 2014;5:81-91. https://doi.org/10.4155/cmt.13.77

Schulz K, Voigt K, Beusch C, Almeida-Cortez JS, Kowarik I, Walz A, Cierjacks A. Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil. For Ecol Manage. 2016;367:62-70. https://doi.org/10.1016/j.foreco.2016.02.011

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev e ampl. Brasília, DF: Embrapa; 2017.

Veldkamp E. Organic carbon turnover in three tropical soils under pasture after deforestation. Soil Sci Soc Am J. 1994;58:175-80. https://doi.org/10.2136/sssaj1994.03615995005800010025x

Ward JH. Hierarchical grouping to optimize an objective function. J Am Stat Assoc. 1963;58:236-44. https://doi.org/10.1080/01621459.1963.10500845

Wells T, Hancock GR, Martinez C, Dever C, Kunkel V, Gibson A. Differences in soil organic carbon and soil erosion for native pasture and minimum till agricultural management systems. Sci Total Environ. 2019;666:618-30. https://doi.org/10.1016/J.SCITOTENV.2019.02.097