Carbon and nitrogen stocks of soils under different land uses in Pernambuco state, Brazil

Mônica da Silva Santana^{a,*}, Everardo Valadares de Sá Barretto Sampaio^a, Vanderlise Giongo^b, Rômulo Simões Cezar Menezes^a, Kennedy Nascimento de Jesus^a, Eliza Rosário Gomes Marinho de Albuquerque^c, Diego Marcelino do Nascimento^a, Frans Germain Corneel Pareyn^d, Tony Jarbas Ferreira Cunha^b, Raquel Menezes Bezerra Sampaio^e, Dário Costa Primo^a

^a Departamento de Energia Nuclear, Universidade Federal de Pernambuco, CEP: 50740-540 Recife, PE, Brazil

^b Embrapa Semiarido, CEP: 56302-970 Petrolina, PE, Brazil

^c Departamento de Biologia, Universidade Federal Rural de Pernambuco, CEP: 52171-900 Recife, PE, Brazil

^d Associação Plantas do Nordeste, CEP: 50731-280 Recife, PE, Brazil

^e Escola de Ciências e Tecnologia, Universidade Federal do Rio Grande do Norte, CEP: 59078-970 Natal, RN, Brazil

ARTICLE INFO

Article history:

Received 18 September 2018

Received in revised form 1 February 2019

Accepted 2 February 2019

Available online xxxx

Keywords:

Semiarid

Acrisols

Leptosols

Ferralsols

Planosols

Soil C and N stocks

Soil depth

Land use change

ABSTRACT

Acrisols, Ferralsols, Leptosols and Planosols were sampled in layers down to 1 m under dense caatinga, open caatinga, pasture and agriculture. Agricultural Leptosols and Planosols had the lowest C and N concentrations among the land uses, although in some cases differences were not statistically significant. On average, conversion of dense caatinga to agriculture reduced C stocks from 63 to 47 Mg ha⁻¹. Acrisols had the highest concentrations of C and N, and Planosols had the lowest concentrations and stocks. Conversion to pasture did not reduce stocks, but open caatinga also had lower C stocks (50 Mg ha⁻¹) than dense caatinga. Nitrogen stocks did not differ among land uses, implying that losses are greater for C than for N. Despite the fact that the western portion of Pernambuco state covers 3% of the Brazilian semi-arid area, it stocks about 0.20 Pg of C (and 0.019 Pg of N), which represents 2% of the total estimated soil C stock in the semiarid region (8.9 Pg). Therefore, the stock per hectare in the west portion of Pernambuco is about one-third smaller than the stock per hectare in the whole Brazilian semiarid region, probably a consequence of the lower average C concentration in the 20 cm superficial layer, a higher proportion of agricultural fields and shallower depths of some soil classes in western Pernambuco than in the whole semiarid region.

© 2019 Elsevier B.V. All rights reserved.

1. Introduction

Land use changes, driven by deforestation or agricultural activities, may have a significant impact on the total amount of greenhouse gas (GHG) emissions (Minasny et al., 2017). In Brazil, this contribution has been particularly high, having reached 58% of all CO₂eq emitted in 2005 (MCT, 2014). Soil types and land use changes may affect the stock of soil organic carbon (Maia et al., 2010; Minasny et al., 2017; Paz et al., 2016; Pringle et al., 2014; Schulz et al., 2016). This is particularly important because it is the largest and most stable active part of the planet that can be directly affected by anthropogenic activities (Stockmann et al., 2013). Land use change also affect organic N stocks,

which are closely linked to C stocks and have a direct influence on native vegetation and crop productivity (Freitas and Sampaio, 2008; Lal, 2008a). Due to this importance, several attempts have been made to quantify regional, national and global C and N stocks (Assefa et al., 2017; Batjes, 1996; Bernoux et al., 2002; Grinand et al., 2017; Sampaio and Costa, 2011; Stockmann et al., 2015).

Information is required regarding the effects of land use changes on carbon and nitrogen stocks on different soil types to mitigate GHG emissions. This may range from the possibility of raising soil C and N stocks in several countries (Minasny et al., 2017), recovery of degraded pasture and cropland (Cerri et al., 2004; Rittl et al., 2017), installation of complex agricultural systems (Lal, 2016) and different crop management practices, especially residue management (Giongo et al., 2016; Luca et al., 2018).

Among the factors that influence C and N stocks in soils are climate, vegetation cover, management, texture and soil type. Land use change can reduce or increase stocks depending on the management applied

* Corresponding author.

E-mail addresses: monica_ssantana@hotmail.com, monicassantana12@gmail.com (M.S. Santana), esampaio@ufpe.br (E.V.S.B. Sampaio), vanderlise.giongo@embrapa.br (V. Giongo), rmenezes@ufpe.br (R.S.C. Menezes), tony.cunha@embrapa.br (T.J.F. Cunha).

(Aquino et al., 2017; Post and Kwon, 2000), but the variation of impacts on different soil types remains a knowledge gap (Chaplot et al., 2010; Paz et al., 2016). Each soil type has particular characteristics and different capacities of C and N storage; soils with higher clay and silt content tend to contain more C and N than sandy soils, and shallower soils hold smaller stocks than deeper ones (Lal et al., 2015; Torn et al., 1997).

Knowledge of the interactions between soil types and land uses is particularly scarce for semi-arid regions (Mayes et al., 2014). Among these regions, the one-million-square-kilometer northeast Brazilian region is an ideal area to investigate the interaction between soil types and land uses on C and N stocks, since it has a great diversity of soil types (Giongo et al., 2011a; Araújo Filho, 2013), and half of the area is still covered with native vegetation, while the other half is primarily pasture and agricultural fields (IBGE, 2013). In this region, soil diversity is expressed in a multifaceted mosaic of fragments of small dimensions, with soils of extremely different characteristics occurring near each other (Sampaio, 2010). Land use systems are characterized by large spatial and temporal changes, with native vegetation cover over a vast aggregated area being replaced each year by a multiplicity of small farming or pasture plots that are exploited for a few years and then abandoned for longer periods of time (Sampaio and Costa, 2011). Thus, most of the native vegetation cover is a dry forest at different regeneration stages, and agricultural fields are annual crops under an itinerant minimum input system (Ribeiro et al., 2016; Sousa et al., 2012; Tiessen et al., 1998).

A few localized studies on carbon and nitrogen stocks of isolated soil types under different land uses have been carried out in this region (Fracetto et al., 2012a; Fraga and Salcedo, 2004; Galindo et al., 2008; Sacramento et al., 2013). Also, preliminary evaluations of regional stocks have been attempted (Giongo et al., 2011a, b; Sampaio and Costa, 2011) that put together information from many different sources to fill knowledge gaps with the best possible estimates; this is to provide some general regional data for the National Inventory of GHG Emissions and Removals (Brasil, 2015). However, none of the localized studies jointly evaluated predominant soil classes and the most common land uses in the region, and most of them were restricted to the topsoil layers. The regional evaluators pointed out the absence of these data not only for the whole region but also for its sub-regions. They also stressed the absence of data for subsoil layers, the difficulty of evaluating regional stocks considering the scarcity of information on the effects of different uses on the C and N dynamics of the different soil types and the need for temporal monitoring of land use changes.

Quantifying these stocks in the semiarid Brazilian region and understanding the impacts of soil types and land use changes can contribute to a better scaling of global and national stocks, as well as to the identification of strategies to maintain and/or increase stocks in the soil systems of this and other semiarid regions of the world (Lal, 2004; Minasny et al., 2017). In our study, we determined soil C and N stocks of the main soil classes associated with the most important land uses in the western part of Pernambuco state, which is representative of the core of the Brazilian semiarid region. We aimed to: 1) quantify soil stocks under pasture or agricultural fields and compare them to well preserved or disturbed native vegetation, 2) verify how these stocks are different in various soil types and 3) collect data for soil profiles down to 1 m, the depth that is becoming a standard practice in world estimates (Minasny et al., 2017), and which has recently been accorded by Brazilian scientists as the protocol depth for regional estimates (Urquiaga et al., 2016).

2. Material and methods

2.1. Selection of sampling sites

The four most representative soil types in the 32,631-km² western portion of Pernambuco state (Fig. 1) were combined, in a factorial

way, with the four main vegetation covers and land uses to quantify their C and N stocks, superimposing maps using geographic information system tools. Together the four soil types (WRB, 2014) occupy 85% of the western area: Acrisols, 30%; Leptosols, 26%; Ferralsols, 22%; and Planosols, 7%. The proportions were calculated by the coverage area, considering the polygons where the soil is dominant and the areas that have greater participation in the soil association, based on the Agroecological Zoning of the State of Pernambuco - ZAPE (Araújo Filho et al., 2000). The four vegetation cover and land uses were: 1) dense caatinga (DC), a wooded and forested savannah steppe; 2) open caatinga (OC), a woody and grassy savannah; 3) pasture (PA), predominantly herbaceous vegetation, including both planted and native pastures; and 4) agriculture (AG), rainfed annual crops, mostly corn and beans plots cultivated with minimum inputs (Fig. 2). The identification of DC and OC was based on criteria determined by the Brazilian vegetation technical manual (IBGE, 2012).

For each of the 16 combinations of soil types and land uses, three different sites were selected, which were considered replications for each situation. The covers and land uses were updated by satellite images, and the sampling sites were defined by visual interpretation based on images for the rainy season, confirmed with images for the dry season and superimposed on the soil map. The images for the rainy season were obtained from the LIS3 sensor of the IRS P6 satellite or ResourceSat-1 of India (orbit scene 337 and point 082) passage on March 4, 2012, and the image for the dry season from the CCD1XS sensor of the CBERS-2B satellite (orbit scene 147 and point 110) passage on January 3, 2009. Ground-truthing was used to verify if the chosen site corresponded to the remote sensing data and, if it did not, a new site was chosen until there was correspondence. The four land covers of each replicate of soil type were chosen to be as close as possible, whereas the replicates of soil types were distributed throughout the region, usually in different municipalities.

2.2. Estimates of soil carbon and nitrogen

At each site, a pit 0.7 m long, 0.7 m wide, and 1 m deep was opened, and soil collected from the 0–10, >10–20, >20–30, >30–40, >40–60, >60–80 and >80–100 cm deep layers, except when the soil was shallower than 1 m. The soil of each layer was sieved to separate out gravel, and the samples were packed and taken to the laboratory to be weighed and analyzed for carbon and nitrogen concentrations. Three samples in each layer were collected with a 3-cm diameter and 6-cm long auger to determine soil density by the volumetric method (Donagema et al., 2011). Some layers in the B horizons of some Planosols did not have their densities determined by the volumetric method due to their hard- to extremely hard consistency. For these layers, densities were assumed to be the averages of the other replicates for the same soil type and land use.

The soil samples were air-dried and sieved (2 mm), and an aliquot was sent for physical characterization (Table 1). Another aliquot was macerated in a ball mill until it passed through a 100 mesh (0.150 mm) sieve. Carbon and nitrogen concentrations were determined by dry combustion, using a CHN elemental analyser (TruSpec CHN LECO® 2006). Stocks were calculated based on C and N concentrations and the volume and density of each soil layer, correcting for the proportion of gravel volume. Stocks were calculated by Eq. (1):

$$C \text{ or } N \text{ stock } (\text{Mg ha}^{-1}) = C_{\text{conc}} \text{ or } N_{\text{conc}} \times BD \times TI \times CF_{\text{stone}} \quad (1)$$

where C_{conc} or N_{conc} = concentration (%), BD = bulk density in the layer (g cm^{-3}), TI = sampled soil layer thickness (cm) and CF_{stone} = stone correction factor ($1 - (\% \text{stone}/100)$).

Fig. 1. Study area in the western portion of Pernambuco state, Brazil.

Fig. 2. Land uses studied. A dense Caatinga; B open Caatinga; C pasture; and D agriculture.

Table 1
Values of soil density, gravel and granulometric fractions of soils under different uses in the semi-arid region of Pernambuco. Dense Caatinga (CD); Open caatinga (OC); Pasture (PA); Agriculture (AG); Acrisol (AC); Ferralsol (FE); Leptosol (LE); Planosol (PL)

	AC	FE	LE	PL	AC	FE	LE	PL	AC	FE	LE	PL	AC	FE	LE	PL	AC	FE	LE	PL	AC	FE	LE	PL	AC	FE	LE	PL
Bulk density (g cm ³) ^a																												
	0–10 cm				10–20 cm				20–30 cm				30–40 cm				40–60 cm				60–80 cm				80–100 cm			
DC	1.45	1.38	1.22	1.47	1.54	1.32	1.19	1.43	1.44	1.36	1.29	1.49	1.46	1.37	1.37	1.50	1.43	1.31	1.39	1.50	1.48	1.34	–	–	1.46	1.34	–	–
OC	1.50	1.30	1.34	1.52	1.50	1.41	1.40	1.46	1.47	1.40	1.38	1.55	1.42	1.40	1.40	1.70	1.36	1.36	1.43	1.76	1.43	1.30	–	–	1.44	1.31	–	–
PA	1.56	1.44	1.44	1.58	1.49	1.44	1.44	1.56	1.45	1.47	1.37	1.63	1.38	1.44	1.45	1.59	1.36	1.37	1.36	1.60	1.36	1.29	–	–	1.42	1.31	–	–
AG	1.44	1.40	1.39	1.41	1.53	1.48	1.41	1.43	1.54	1.49	1.38	1.42	1.45	1.45	1.45	1.41	1.39	1.50	1.50	1.41	1.40	1.41	–	–	1.38	1.40	–	–
Gravel (g kg ^{–1}) ^a																												
DC	0	0	222.0	76.3	0	0	152.4	234.9	0	0	184.3	0	0	0	95.4	0	4.8	27.0	0	0	68.6	26.2	–	–	53.3	58.9	–	–
OC	0	0	118.0	100.8	0	0	64.7	0	0	0	228.8	0	0	0	194.7	56.0	236.8	0	79.8	0	62.8	44.9	–	–	–	–	–	–
PA	0	0	200.2	0	0	0	161.4	0	0	0	255.4	0	0	0	173.3	54.9	20.8	0	29.8	15.9	13.1	–	–	–	–	–	–	–
AG	0	0	22.5	0	0	0	25.8	0	0	0	40.5	0	0	0	120.1	0	0	0	123.2	0	8.1	30.9	–	–	–	–	–	–
Sand (g kg ^{–1}) ^{a,b}																												
DC	765	772	447	707	716	749	388	661	624	800	370	516	602	794	340	574	568	733	345	530	571	581	–	–	565	580	–	–
OC	725	788	479	753	665	758	493	723	598	725	501	724	557	714	491	633	554	621	537	604	558	576	–	–	568	568	–	–
PA	779	801	518	694	702	771	499	686	620	741	415	779	613	723	483	544	599	652	469	559	579	585	–	–	566	555	–	–
AG	798	721	617	796	812	662	643	760	757	666	554	798	710	654	491	829	669	623	543	696	635	597	–	–	623	618	–	–
Silt (g kg ^{–1}) ^{a,b}																												
DC	117	84	333	241	124	81	301	260	158	50	261	202	163	60	239	179	185	66	271	154	180	103	–	–	190	126	–	–
OC	168	76	325	198	154	77	279	232	137	79	258	157	163	69	286	134	164	99	232	219	180	113	–	–	168	127	–	–
PA	110	66	301	252	132	73	280	213	154	69	321	156	141	67	259	392	159	69	231	175	175	89	–	–	192	112	–	–
AG	141	91	291	189	116	90	248	210	117	95	273	155	118	94	247	116	141	102	330	184	150	109	–	–	155	106	–	–
Clay (g kg ^{–1}) ^{a,b}																												
DC	119	144	221	51	160	171	311	79	218	150	369	282	236	147	422	248	247	201	384	317	250	316	–	–	245	294	–	–
OC	107	137	196	49	181	165	228	46	265	196	241	120	280	218	224	233	283	280	231	177	262	311	–	–	265	305	–	–
PA	112	133	181	53	167	156	221	101	225	191	264	64	246	210	258	64	242	280	300	267	245	327	–	–	242	333	–	–
AG	61	188	92	15	71	248	110	30	127	239	173	47	172	252	262	55	191	276	127	119	216	294	–	–	222	276	–	–

^a Average values obtained from three replicates.

^b Proportions calculated excluding the mass of gravel.

2.3. Statistical analysis

Data on C and N concentrations of different soil types and land uses for the same layer depth were submitted to an analysis of variance after arcsine transformation, because concentrations are proportional values. Averages were compared by the Tukey test at the 0.05 significance level. Data on C and N stocks were analyzed by linear regression with dummy variables, following the equation:

$$y_i = \alpha + \beta_{CA}dCA_i + \beta_{Ag}dAg_i + \beta_PdP_i + \gamma_A dA_i + \gamma_L dF_i + \gamma_{NL} dL_i + u_i \quad (2)$$

where dCA , dAg and dP are dummy variables for land uses open caatinga, agriculture and pasture, respectively, and dA , dF and dL are indicator variables for Acrisol, Ferralsol and Leptosol soil classes, respectively. Since the model uses only dummy variables, the intercept α represents the mean C or N stock for the reference categories. The choice of reference categories was arbitrary and did not affect the results, as long as they were interpreted accordingly. The specified reference categories were dense caatinga and Planosol, since it was expected that dense caatinga was the land use with highest mean stock, and Planosol was the soil type with the lowest mean stock. The inclination coefficients for land use (β 's) measure mean stock differences between each land use category and dense caatinga.

3. Results

As expected, in general, C and N concentrations were progressively lower in deeper soil layers for all land uses (Figs. 3 and 4). Planosols had the lowest C and N concentrations. In almost all layers of all soil types except Acrisols, soils under agriculture had the lowest C and N concentrations, although in several cases the differences from the other land uses were not statistically significant. On the other hand, dense caatinga had the highest concentrations in most layers of all soil types except Acrisols; some of them were significantly higher than all other land uses, including pasture and open caatinga. The most noticeable case of significantly higher C and N concentrations in a land use other than dense caatinga was that of pastures in the superficial layer (0–10 cm deep) of Leptosols. In Acrisols, there were no significant differences among all land uses. Consistent with the similar patterns of concentrations for all soil types, layers and land uses, C and N were highly correlated, with an average ratio of 10:1 (Figs. 3 and 4).

Acrisols had the largest C and N stocks, followed by Ferralsols and Leptosols, while Planosols had the lowest stocks (Figs. 5 and 6). There

were no significant differences among land uses between Acrisols and Ferralsols. Pastures had the largest C and N stocks in Leptosols. Land under agriculture had the smallest stocks in both Leptosols and Planosols.

Total C stocks down to 1 m or the maximum sampling depth were significantly lower under agriculture and open caatinga than under dense caatinga when the four soil types were analyzed together (Table 2). The differences between dense caatinga and agricultural sites were larger for the shallower soils (55% less for Leptosols and 47% for Planosols) than for the deeper ones (18% for Acrisols and 10% for Ferralsols) while the difference from open caatinga was larger for Acrisols (33% less) than for the other three soil types (4–22% less). Total N stocks did not differ among land use types, and the absence of differences was partly due to the lower C:N ratio with agriculture (7.8:1) than with both dense (10.9:1) and open (10.1:1) caatingas. Among the four soil types, Planosols had the lowest C and N stocks, independent of land use, and the lowest C:N ratio (7.2:1 versus 9.5–11.5:1 for the other soils).

4. Discussion

4.1. C and N concentrations

Planosols were the soil type with lowest C and N concentrations. They have high sand content in the superficial layers, resulting in low C and N stocks even under dense caatinga. At other sites of the Brazilian semiarid region, the soils have been reported to have C concentrations as low as those found in our study, varying from 5 to 8 g kg⁻¹C in the superficial layers and from 1.5–5.5 g kg⁻¹C in the sub-superficial layers (Cunha et al., 2010). These low concentrations can be explained by the high susceptibility of Planosols to erosion, since they have low permeability and abrupt textural changes. They are also shallow, have low fertility and limited drainage, which hinders aggregation and the stabilization of organic matter (Oliveira et al., 2009; Prasad et al., 2016; WRB, 2014).

Acrisols and Ferralsols had the highest C and N concentrations with no significant differences among land use types. They are less environmentally fragile than the other soil classes because they are deep, well drained and with loamy to clayey textures, which facilitate aggregation and greater C and N accumulation when well managed. Acrisols are often found on slopes and areas more susceptible to erosion, while Ferralsols are usually located in flatter regions (WRB, 2014). Leptosols had the largest differences in stocks for the different land uses among

Fig. 3. Carbon concentrations in the predominant soil classes under the main land use types in the western semi-arid portion of Pernambuco state, Brazil. Average values of three replicates, followed by standard errors in bars. Averages in the soil depth and class are significantly different (*, $p < .05$) or not (NS).

Fig. 4. Nitrogen concentrations in the predominant soil classes under the main land use types in the western semi-arid portion of Pernambuco state, Brazil. Average values of three replicates, followed by standard errors in bars. Averages in the soil depth and class are significantly different (*, $p < .05$) or not (NS).

soil classes. They are young soils with good fertility, but they have low agricultural aptitude due to the presence of stones and shallow profiles that diminish the volume of soil to be exploited; thus, they are mostly used for pastures (Cunha et al., 2010).

The presence of higher C and N concentrations with dense caatinga than with agriculture confirms the general global pattern that the conversion of forest vegetation to agriculture and sometimes also pasture fields results in decreased soil C and N concentrations (Dalal et al., 2013; Gelaw et al., 2014; Jenkins, 1988; Stevenson et al., 2010). This pattern for C had already been reported for other areas in the semiarid North-eastern Brazilian region, but almost all determinations considered only the upper soil layer, usually 20 or 30 cm deep (Fracetto et al., 2012a; Fraga and Salcedo, 2004; Tiessen et al., 1992).

In their review of C stocks in the region, Sampaio and Costa (2011) estimated that areas under native caatinga would have an average concentration of 12 g kg^{-1} , and those under agriculture would have a concentration of 8 g kg^{-1} , in the upper 20 cm layer, without distinguishing soil types. In the west of Pernambuco, Acrisols, both with caatinga and agriculture, and Leptosols with caatinga, had concentrations similar to these estimates, but concentrations were lower for all other soil and land use combinations (Fig. 3). Combining all land uses for the entire semiarid area, Sampaio and Costa (2011) estimated a C concentration of 9.5 g kg^{-1} , for the upper layer, based on hundreds of values found in the literature. In the west of Pernambuco, the weighted average

was 8.1 g kg^{-1} , considering the proportional area of each soil type and admitting that this average value stands for the remaining 15% area covered by soil types not sampled.

The lower average value and differences in soil types in the west of Pernambuco indicates that the estimates need to be refined while accounting for soil types and environmental conditions. The lower average C concentration value is probably a reflection of the lower and more erratic rainfall and higher temperatures in the west of Pernambuco than in most other areas of the semiarid north-eastern region of Brazil (Araújo Filho et al., 2000), resulting in lower organic matter deposition and higher relative soil respiration.

The concentrations in this western part of Pernambuco are in the same range found in Planosols (Galindo et al., 2008), Acrisols (Amorim, 2009) and Ferralsols (Antunes et al., 2010) of the north-eastern Brazilian region and in other semiarid regions of the world: Argentina (Urioste et al., 2006), Mongolia (Wu et al., 2013) and Burkina Faso (Traoré et al., 2015). However, higher concentrations have also been reported in the region (Fracetto et al., 2012a).

Subsoils generally have lower C concentrations compared to topsoils (Gelaw et al., 2014; Lal, 2008a, b); this a consequence of the larger aboveground versus underground plant biomass and its deposition on the soil surface, where it is slowly transferred to deeper layers. The pattern holds for caatinga, despite the higher proportion of root biomass than in other forest types (Costa et al., 2014), and it was also validated

Fig. 5. Carbon stocks in the predominant soil classes under the main land use types in the western semi-arid portion of Pernambuco state, Brazil. Average values of three replicates, followed by standard errors in bars. Averages in the soil depth and class are significantly different (*, $p < .05$) or not (NS).

Fig. 6. Nitrogen stocks in the predominant soil classes under the main land use types in the western semi-arid portion of Pernambuco state, Brazil. Average values of three replicates, followed by standard errors in bars. Averages in the soil depth and class are significantly different (*, $p < .05$) or not (NS).

in the west of Pernambuco (Fig. 2). Sampaio and Costa (2011) found C concentration averages of 5.3 g kg^{-1} , decreasing to 3.8 g kg^{-1} , for the 20–100 cm soil layer of caatinga and agricultural fields, respectively; however, they acknowledged the scarcity of data used to compose these averages. These averages are similar to those for dense caatinga (5.5 g kg^{-1}) and agricultural areas (3.4 g kg^{-1}) in the western part of Pernambuco state. However, the lower values in the agricultural fields were only significantly different from those with caatinga and Leptosols and Planosols (Fig. 3). In fact, in many tropical semiarid areas, like those in Ethiopia (Demessie et al., 2013), no significant differences have been found in subsoil layer C concentrations for different land uses. In our study, the relatively large variation in C and N concentrations from site to site and the small number of replicates may explain the absence of significant differences in some cases. This pattern indicates the need for more studies to increase the amount of data on this topic and to generate averages that are more robust.

Data on soil N concentrations in the semiarid Brazilian region are extremely scarce since N determinations are not included in soil surveys and routine soil analysis. There are no reviews or estimates for the region as a whole or any of its subdivisions (Menezes et al., 2012), and the few available data refer only to superficial layers (Barreto et al., 2006; Freitas et al., 2012a, b; Schulz et al., 2016) and C:N ratios (Fracetto et al., 2012; Sousa et al., 2012).

The higher C and N concentrations for pastures than with dense caatinga (16.2 g kg^{-1} and 1.4 g kg^{-1}) in the superficial layer of the Leptosols probably resulted from the high biomass of fine roots, determined in the same areas and composed mainly of the grasses *Cenchrus ciliaris* L., *Urochloa mosambicensis* (Hanck) Dandy and *Aristida pallens* Cav. (Albuquerque, 2015). Grass root systems tend to be more superficial than those of trees and shrubs (Jobbágy and Jackson, 2000),

frequently resulting in higher carbon concentrations in the soil superficial layers after forest conversions. This pattern was observed in the 0–10 cm layers in Arenosols in Ethiopia (Gelaw et al., 2014), sometimes even equalizing concentrations down to 60 cm, as in pastures converted from Cerrado vegetation in the central-western Brazilian region (Wantzen et al., 2012).

The lower C and N concentrations with open versus dense caatinga, observed in some layers of some soil types, as well as the lower C stocks, are consistent with the assumption that open caatinga produce and incorporate less biomass to the soil. However, comparisons between soil concentrations for dense and open caatinga are scarce and hampered by the lack of a clear definition, in most cases, of the causes of lower tree and shrub densities. They may be the product of anthropization, such as selective cutting of plants to be used as firewood that open the canopy and allow greater growth of the herbaceous stratum used as native pasture or the result of an incomplete regeneration of native vegetation after one or more cycles of agriculture. However, the lower plant cover densities may also be a consequence of natural conditions, such as shallow soil or very low water availability. Although the sampling sites were chosen where the vegetation did not show visible signs of fire and plant cutting, and the land use history was investigated with local residents, it is not possible to be sure that the openness of the vegetation was natural. In caatinga areas with degraded vegetation, soil C and N concentrations are lower than those in areas with preserved vegetation (Galindo et al., 2008), a pattern also found in other semi-arid regions, such as Burkina Faso (Traoré et al., 2015). However, in Australia, differences in land use accounted for only 9.2% of the soil carbon variation, while soil properties and environmental variability accounted for 42.8% (Rabbi et al., 2014).

Table 2

Carbon and nitrogen stocks (Mg ha^{-1}) in the top 1 m soil layer under different land uses (Dense Caatinga, DC; Open Caatinga, OC; Pasture, PA; Agriculture, AG) and soil types (Acrisol, AC; Ferralsol, FE; Leptosol, LE; Planosol, PL).

Land use	Carbon (Mg ha^{-1})					Nitrogen (Mg ha^{-1})				
	AC	FE	LE ^a	PL ^a	Mean	AC	FE	LE ^a	PL ^a	Mean
	0–100 cm		0–50 cm	0–60 cm		0–100 cm		0–50 cm	0–60 cm	
DC	98.3(10.4)	72.1(11.6)	54.5(11.8)	27.7(5.5)	63.2	8.6(0.7)	5.8(0.3)	5.0(1.0)	3.1(0.8)	5.63
OC	66.1(3.9)	63.5(11.1)	42.4(4.6)	26.7(0.9)	49.7*	7.1(0.5)	4.8(0.9)	4.0(0.5)	3.6(0.1)	4.88 ^{NS}
PA	74.2(13.3)	68.2(10.0)	58.4(1.4)	20.5(3.3)	55.3 ^{NS}	8.4(1.2)	6.3(0.5)	5.4(0.2)	2.8(0.5)	5.73 ^{NS}
AG	88.8(9.1)	59.4(8.5)	24.7(1.9)	14.6(0.9)	46.9*	10.3(1.1)	6.0(0.2)	3.2(0.2)	2.9(0.2)	5.60 ^{NS}
Mean	81.9**	65.8**	45.0**	22.4		8.6**	5.7**	4.4**	3.1	

Average values of three replicates, followed by standard errors in parentheses. Averages are significantly different (* $p < .05$ and ** $p < .01$) or not (NS) in the row when compared to Planosols and in the column when compared to Dense Caatinga, according to an analysis by linear regression with dummy variables.

^a Full depth of these shallow soils.

4.2. C and N stocks

The patterns of C and N stocks were similar to those of C and N concentrations because their variations were much larger than those of soil densities; thus, they had larger influences on stock calculations, particularly for different land uses. The larger N stock in Planosols with dense caatinga could be explained by the action of deep roots, which create pores and facilitate the movement of this nutrient (Poirier et al., 2018). The only difference in concentration and stock patterns arises in the comparisons of soil classes due to the limited depth of two of the soil classes.

On the other hand, the lower stocks in Planosols versus the other soil classes were partly due to their shallowness; they lacked the layers from 60 to 100 cm deep. The larger difference in C stocks between dense caatinga and agricultural sites in the shallower as opposed to the deeper soils may be due to the lower biomass of crop productions and residue incorporations on these shallower soils, which are less frequently put to agricultural use. The larger differences between the stocks with dense rather than open caatinga in the Acrisols versus the other soil types is more difficult to explain with the available information, but it could be related to a shorter fallow cycle in this soil which is preferred for agricultural use.

In general, shallow soils accumulate less water than deep ones, and this is a cause of lower plant productivity in an area with low and erratic rainfall, and consequently lower C input to the soil (Prasad et al., 2016). However, lower inputs are also influenced by the herbivory by the ubiquitous herds of cattle, goats and sheep, which eat the crop residues and even dry leaves of caatinga species that fall with the onset of the dry season (Araújo Filho, 2013; Santos et al., 2010). Water limitation and this consumption attenuate differences in C stocks under native vegetation due to different soil textures and chemical characteristics. However, these characteristics are important determinants of land use; agriculture is established preferentially on deeper and more fertile soils, since it is practiced with a low input system with almost no fertilizer applications. Despite being located in better soils, C inputs under crops tended to be lower than under caatinga because of their short cycle, starting from bare soils, exporting products and livestock residue consumption. Pastures can produce almost as much biomass annually as caatinga, but C inputs are also lower due to higher consumption by herbivores and the absence of woody residues.

Considering that the stocks differed with soil class and land use, estimates for the entire area of the western part of Pernambuco state must take into account their different proportions in the area. In this area, Acrisols corresponded to approximately 30% of the area, Ferralsols to 22%, Leptosols to 26% and Planosols to 7%. Dense caatinga covered about 30%, open caatinga 29%, pastures 17% and agriculture 24% (Araújo Filho et al., 2000). Considering the significantly lower C stocks under agriculture than under dense caatinga and calculating the weighted average based on soil class, the stock with agriculture was $45.9 \text{ Mg C ha}^{-1}$, almost 25% lower than that under dense caatinga ($60.0 \text{ Mg C ha}^{-1}$). This reduction increased to 50% if we considered only the two classes of shallower soils.

Contrary to C stocks, the absence of significant differences in N stocks due to land use is difficult to explain. Fertilizers, both inorganic and organic, may have been applied to a higher degree than reported in regional surveys. Symbiotic N fixation from the atmosphere could contribute tens of kg ha^{-1} to the agricultural systems, usually through cowpea intercropped with maize, both of which are capable of fixation (Ferreira Neto et al., 2017; Freitas et al., 2012b). Fixation by native legume species growing in the pasture areas could also add symbiotic N (Freitas et al., 2011). The lower N stock in Planosols than in the other soil classes is probably related to their lower capacity to stabilize N in the organic form, since they had the lowest C stocks and C:N ratios (7.2:1), not only lower than those of the other soils in the region but also lower than most of the other soils in the world, which usually range from 10 to 15:1.

The western part of Pernambuco extends for $32,631 \text{ km}^2$. Considering the proportions of land uses and soils classes, the total C and N stocks in the area studied were estimated to be $197.5 \times 10^6 \text{ Mg C ha}^{-1}$ and $19.3 \times 10^6 \text{ Mg N ha}^{-1}$, which are equivalent to $0.20 \text{ Pg C ha}^{-1}$ and $0.019 \text{ Pg N ha}^{-1}$. The study area corresponds to approximately 3.3% of the Brazilian semi-arid area (about 10^6 km^2) and has 2.2% of the total C of the semi-arid region (8.9 Pg) as estimated by Sampaio and Costa (2011). Therefore, it has a C stock per unit area one third lower than that estimated for the entire semi-arid region. This could be attributed to three main reasons: 1) the 15% lower average C concentration in the 20-cm superficial layer of western Pernambuco soils than in the whole semi-arid region (8.1 and 9.5 g kg^{-1} , respectively) and 2) the higher proportion of area occupied by agricultural fields (24 and 15%, respectively), that have significantly lower C concentrations. These fields are concentrated in the Acrisols and Ferralsols, deep soils with little rockiness and good structure, which are preferred for agriculture and which cover a majority of the western part of Pernambuco (Acrisols, 30%; Ferralsols 22%) than in the whole caatinga area (15 and 21%; Sampaio et al., 2009); and 3) the fact that Sampaio and Costa (2011) estimated stocks to a depth of 1.0 m for the whole area, but some soil classes may be shallower, as are the sampled Leptosols and Planosols in the western part of Pernambuco and also other classes common in the whole semi-arid region (Luvisols and Regosols), which together comprise about 45% of the whole region. Therefore, they may have overestimated the regional stocks, which indicate that the refinement of estimates based on sub regions with relatively more uniform soil and climate conditions are necessary to yield stock values closer to reality.

5. Conclusion

Acrisol and Ferralsol C and N concentrations were similar for all land uses, while Planosols had the lowest C and N concentrations and stocks. Soils types with agricultural land uses had the lowest C and N concentrations among different land uses, although in some cases differences were not statistically significant. Dense caatinga on Leptosols and Planosols had significantly higher C and N concentrations in some layers than other uses, but pastures on Leptosols had higher concentrations in the superficial layer (0–10 cm).

Conversion of dense caatinga to agriculture reduced soil C stocks from 63 to 47 Mg ha^{-1} . Conversion to pasture did not reduce soil C stocks, but open caatinga also had lower C stocks (50 Mg ha^{-1}) than dense caatinga. N stocks did not differ among land uses, implying that losses are greater for C than for N, reflected in the lower C:N ratio under agriculture (7.8:1) than under dense caatinga (10.9:1). The western portion of Pernambuco state, which corresponds to 3.3% of the Brazilian semi-arid area, stocks about 0.20 Pg of C (and 0.019 Pg of N), which represented 2.2% of the total estimated soil C stock in the semi-arid region (8.9 Pg), implying that the stock per hectare in the west portion of Pernambuco is about one-third smaller than the stock per hectare in the whole Brazilian semiarid region. The difference is probably a consequence of lower average C concentration in the 20-cm superficial layer, a higher proportion of agricultural fields and the shallower profiles of Leptosols and Planosols.

Declarations of interest

None.

Acknowledgment

The authors of this paper thank CNPq and Facepe for the scholarships to students and research scientists and also for financial support through the following research grants: CNPq 403129/2013-3, CNPq 465764/2014-2, CNPq 446137/2015-4 and Facepe APQ-0532-5.01/14. The authors also thank the Brazilian Agricultural Research Company

(Embrapa Semiárido) for providing structures and materials for the research activities of this study.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at <https://doi.org/10.1016/j.geodrs.2019.e00205>. These data include the Google map of the most important areas described in this article.

References

- Albuquerque, E.R.G.M., 2015. Biomassa de raízes em áreas com diferentes usos da terra e tipos de solos. Thesis (Doctor in Botany) Universidade Federal Rural de Pernambuco. Recife, Departamento de Biologia.
- Amorim, L.B., 2009. Caracterização da serrapilheira em caatinga preservada e mudanças no carbono do solo após desmatamento sem queima. Dissertation (Master in Soil Science) – Universidade Federal Rural de Pernambuco.
- Antunes, P.D., Sampaio, E.V.S.B., Ferreira Júnior, A.L.G., Galindo, I.C.L., Salcedo, I.H., 2010. Distribuição de ^{137}Cs em três solos representativos do estado de Pernambuco. Rev. Bras. Cienc. Soil. 34, 935–943. <https://doi.org/10.1590/S0100-06832010000300035>.
- Aquino, D.N., Andrade, E.M., Almeida Castanho, A.D.A., Pereira Júnior, L.R., Palácio, H.A.Q., 2017. Belowground carbon and nitrogen on a thinned and un-thinned seasonally dry tropical forest. Am. J. Plant Sci. 8, 2083–2100. <https://doi.org/10.4236/ajps.2017.89140>.
- Araújo Filho, J.A., 2013. Caracterização física do Semiárido Nordeste. Manejo pastoril sustentável da Caatinga. Projeto Dom Helder Câmara, Recife-PE.
- Araújo Filho, J.C., Burgos, N., Lopes, O.F., Silva, F.H.B.B., Medeiros, L.A.R., Melo Filho, H.F.R., Parahyba, R.B.V., Cavalcanti, A.C., Oliveira Neto, M.B., Silva, F.B.R., Leite, A.P., Santos, J.C.P., Sousa Neto, N.C., Silva, A.B., Luz, L.R.Q.P., Lima, P.C., Reis, R.M.G., Barros, A.H.C., 2000. Levantamento de reconhecimento de baixa e média intensidade dos solos do Estado de Pernambuco. Bol. Pes. Embrapa Solos 11, 1–378.
- Assefa, D., Rewald, B., Sandén, H., Rosinger, C., Abiyu, A., Yitaferu, B., Godbold, D., 2017. Deforestation and land use strongly effect soil organic carbon and nitrogen stock in North-west Ethiopia. Catena 153, 89–99. <https://doi.org/10.1016/j.catena.2017.02.003>.
- Barreto, A.C., Lima, F.H.S., Freire, M.B.G.S., Araújo, Q.R., Freire, F.J., 2006. Características químicas e físicas de um solo sob floresta, sistema agroflorestal e pastagem no sul da Bahia. Rev. Caatinga. 19 (4), 415–425.
- Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 65, 4–21. <https://doi.org/10.1111/j.1365-2389.1996.tb01386.x>.
- Bernoux, M., Carvalho, M.C.S., Volkoff, B., Cerri, C.C., 2002. Brazilian soil carbon stocks. Soil Sci. Soc. Am. J. 66, 888–896. <https://doi.org/10.2136/sssaj2002.0888>.
- Brasil, 2015. Estimativas Anuais de Emissões de Gases de Efeito Estufa no Brasil. Ministério da ciência, tecnologia, inovações e comunicações – MCTIC, 3ed Available in: sirene.mcti.gov.br/publicacoes (Access in: March 30, 2018).
- Cerri, C.E.P., Bernoux, M., Chaplot, V., Volkoff, B., Victoria, R.L., Melillo, J.M., Paustian, K., Cerri, C.C., 2004. Assessment of soil property spatial variation in an Amazon pasture: basis for selecting an agronomic experimental area. Geoderma 123, 51–68. <https://doi.org/10.1016/j.geoderma.2004.01.027>.
- Chaplot, V., Bouahom, B., Valentin, C., 2010. Soil organic carbon stocks in Laos : spatial variations and controlling factors. Glob. Chang. Biol. 16, 1380–1393. <https://doi.org/10.1111/j.1365-2486.2009.02013.x>.
- Costa, T.L., Sampaio, E.V.S.B., Accioly, L.J.O., Althoff, T.D., Pareyn, F.G.C., Albuquerque, E.R.G.M., Menezes, R.S.C., 2014. Root and shoot biomasses in the tropical dry forest of semi-arid Northeast Brazil. Plant Soil 378, 113–123. <https://doi.org/10.1007/s11104-013-2009-1>.
- Cunha, T.J.F., Giongo, V., Silva, D.J., Mendes, A.M.S., Melo, R.F., Oliveira Neto, M.B., Silva, M.S.L., Alvarez, I., 2010. Principais solos do Semiárido tropical brasileiro: caracterização, potencialidades, limitações, fertilidade e manejo. In: Sa, I.B., Silva, P.C.G. (Eds.), Semiárido Brasileiro: Pesquisa, Desenvolvimento e Inovação, pp. 50–87.
- Dalal, R.C., Thornton, C.M., Cowie, B.A., 2013. Turnover of organic carbon and nitrogen in soil assessed from $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ changes under pasture and cropping practices and estimates of greenhouse gas emissions. Sci. Total Environ. 465, 26–35. <https://doi.org/10.1016/j.scitotenv.2013.04.101>.
- Demessie, A., Singh, B.R., Lal, R., 2013. Soil carbon and nitrogen stocks under chronosequence of farm and traditional agroforestry land uses in Gambo District. South. Ethiop. Nutr. Cycl. Agroecosyst. 95, 365–375. <https://doi.org/10.1007/s10705-013-9570-0>.
- Donagema, G.K., De Campos, D.V.B., Calderano, S.B., Teixeira, W.G., Viana, J.H.M., 2011. Manual de métodos de análise de solo. 2 ed. Embrapa Solos, Rio de Janeiro, p. 230.
- Ferreira Neto, R.A., Giongo, V., Camargo, P., Freitas, A.D.S., Menezes, R.S.C., Sampaio, E.V.S.B., 2017. Nitrogen fixation in Poaceae and Leguminosae species used as green manure in Northeast Brazil. Austral. J. Crop Sci. 11, 1474–1480. <https://doi.org/10.21475/ajcs.17.11.11.pne726>.
- Fracetto, F.J.C., Fracetto, G.G.M., Cerri, C.C., Feigl, B.J., Siqueira Neto, M., 2012. Estoques de carbono e nitrogênio no solo cultivado com mamona na caatinga. Rev. Bras. Cienc. Soil 36, 1545–1552. <https://doi.org/10.1590/S0100-06832012000500019>.
- Fraga, V.S., Salcedo, I.H., 2004. Declines of organic nutrient pools in tropical semi-arid soils under subsistence farming. Soil. Sci. Soc. Amer. J. 68, 215–224. <https://doi.org/10.2136/sssaj2004.2150>.
- Freitas, A.D.S., Sampaio, E.V.S.B., 2008. Fixação biológica do N_2 em leguminosas arbóreas da Paraíba e de Pernambuco. In: Menezes, R.S.C., Sampaio, E.V.S.B., Salcedo, I.H. (Eds.), Fertilidade do Solo e Produção de Biomassa no Semi-Árido. Ed. Universidade UFPE, Recife.
- Freitas, A.D.S., Silva, T.O., Menezes, R.S.C., Sampaio, E.V.S.B., Araújo, E.R., Fraga, V.S., 2011. Nodulação e fixação de nitrogênio por forrageiras da caatinga cultivadas em solos do semi-árido paraibano. Rev. Bras. Zootec. 40, 1856–1861. <https://doi.org/10.1590/S1516-35982011000900003>.
- Freitas, A.D.S., Sampaio, E.V.S.B., Silva, A.F., 2012a. How much nitrogen is fixed by biological symbiosis in tropical dry forests? 2. Herbs. Nutr. Cycl. Agroecosyst. 94, 181–192. <https://doi.org/10.1007/s10705-012-9545-6>.
- Freitas, A.D.S., Silva, A.F., Sampaio, E.V.S.B., 2012b. Yield and biological nitrogen fixation of cowpea varieties in the semi-arid region of Brazil. Biomass Bioenergy 45, 109–114. <https://doi.org/10.1016/j.biombioe.2012.05.017>.
- Galindo, I.C.L., Ribeiro, M.R., Santos, M.F.A.V., Lima, J.F.W.F., Ferreira, R.F.A.L., 2008. Relações solo-vegetação em áreas sob processo de desertificação no município de Jataúba-PE. Rev. Bras. Cienc. Solo 32, 1283–1296 (S0100-06832008000300036).
- Gelaw, A.M., Singh, B.R., Lal, R., 2014. Soil organic carbon and total nitrogen stocks under different land uses in a semi-arid watershed in Tigray, Northern Ethiopia. Agric. Ecosyst. Environ. 188, 256–263. <https://doi.org/10.1016/j.agee.2014.02.035>.
- Giongo, V., Cunha, T.J.F., Mendes, A.M.S., Gava, C.A.T., 2011a. Carbono no sistema solo-planta no Semiárido brasileiro. Rev. Bras. Geog. Fis. 4 (6), 1233–1253.
- Giongo, V., Galvão, S.R.S., Mendes, A.M.S., Gava, C.A.T., Cunha, T.J.F., 2011b. Soil organic carbon in the Brazilian Semi-arid Tropics. Dynam. Soil, Dynam 1, 12–20 Plant 5, Special issue.
- Giongo, V., Salviano, A.M., Santana, M.S., Costa, N.D., Yuri, J.E., 2016. Soil management systems for sustainable melon cropping in the Submedian of the São Francisco Valley. Rev. Caatinga. 29, 537–547.
- Grinand, C., Le Maire, G., Vieilledent, G., Razakamanarivo, H., Razafimbelo, T., Bernoux, M., 2017. Estimating temporal changes in soil carbon stocks at ecoregional scale in Madagascar using remote-sensing. Int. J. Appl. Earth Obs. Geoinf. 54, 1–14. <https://doi.org/10.1016/j.jag.2016.09.002>.
- IBGE, 2012. Indicadores de desenvolvimento sustentável. Estudos e Pesquisas. vol. 9. Informação Geográfica, Rio de Janeiro.
- IBGE, 2013. Levantamento sistemático da produção agrícola: pesquisa mensal de previsão e acompanhamento das safras agrícolas no ano civil (Rio de Janeiro, v. 26 n. 1).
- Jenkins, D.S., 1988. The turnover of organic matter in soil. In: Wild, A. (Ed.), Russell's Soil Conditions and Plant Growth. Longman Scientific and Technical, Harlow, pp. 564–607.
- Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10 (2), 423–436. [https://doi.org/10.1890/1051-0761\(2000\)010\[0323:FHAP\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0323:FHAP]2.0.CO;2).
- Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627. <https://doi.org/10.1126/science.1097396>.
- Lal, R., 2008a. Carbon sequestration. Philos. Trans. R. Soc. B 363, 815–830. <https://doi.org/10.1098/rstb.2007.2185>.
- Lal, R., 2008b. Sequestration of atmospheric CO_2 in global carbon pools. Energy Environ. Sci. 2008 (1), 86–100. <https://doi.org/10.1039/B809492F>.
- Lal, R., 2016. Beyond COP 21: potential and challenges of the “4 per Thousand” initiative. J. Soil Water Conserv. 71, 20A–25A. <https://doi.org/10.2489/jswc.71.1.20A>.
- Lal, R., Negassa, W., Lorenz, K., 2015. Carbon sequestration in soil. Curr. Opin. Environ. Sustain. 15, 79–86. <https://doi.org/10.1016/j.cosust.2015.09.002>.
- Luca, E.F., Chaplot, V., Mutema, M., Feller, C., Ferreira, M.L., Cerri, C.C., Couto, H.T.Z., 2018. Effect of conversion from sugarcane preharvest burning to residues green-trashing on SOC stocks and soil fertility status: results from different soil conditions in Brazil. Geoderma 310, 238–248. <https://doi.org/10.1016/j.geoderma.2017.09.020>.
- Maia, S.M.F., Ogle, S.M., Cerri, Carlos C., Cerri, C.E.P., 2010. Changes in soil organic carbon storage under different agricultural management systems in the Southwest Amazon Region of Brazil. Soil Tillage Res. 106, 177–184. <https://doi.org/10.1016/j.still.2009.12.005>.
- Mayes, M., Marin-Spiotta, E., Szymanski, L., Erdo, M.A., Ozdo, M., Clayton, M., 2014. Soil type mediates effects of land use on soil carbon and nitrogen in the Konya Basin, Turkey. Geoderma 234, 517–527. <https://doi.org/10.1016/j.geoderma.2014.06.002>.
- MCT - Ministério da Ciência, Tecnologia e Inovação, 2014. Estimativas anuais de emissões de gases de efeito estufa no Brasil. 2nd ed. (Brasília).
- Menezes, R.S.C., Sampaio, E.V.S.B., Giongo, V., Pérez-Marin, A.M., 2012. Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. Braz. J. Biol. 72 (3), 643–653. <https://doi.org/10.1590/S1519-69842012000400004>.
- Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.C., Vågen, T.G., Van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. <https://doi.org/10.1016/j.geoderma.2017.01.002>.
- Oliveira, L.B., Fontes, M.P.F., Ribeiro, M.R., Ker, J.C., 2009. Morfologia e classificação de Luvisolos e Planossolos desenvolvidos de rochas metamórficas do semiárido do Nordeste brasileiro. Rev. Bras. Cienc. Solo 33, 1333–1345. <https://doi.org/10.1590/S0100-06832009000500026>.
- Paz, C.P., Goosem, M., Bird, M., Preece, N., Goosem, S., Fensham, R., Laurance, S., 2016. Soil types influence predictions of soil carbon stock recovery in tropical secondary forests. For. Ecol. Manag. 376, 74–83. <https://doi.org/10.1016/j.foreco.2016.06.007>.
- Poirier, V., Roumet, C., Munson, A.D., 2018. The root of the matter: linking root traits and soil organic matter stabilization processes. Soil Biol. Biochem. 120, 246–259. <https://doi.org/10.1016/j.soilbio.2018.02.016>.
- Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land use change: processes and potential. Glob. Chang. Biol. 6, 317–327. <https://doi.org/10.1046/j.1365-2486.2000.00308.x>.
- Prasad, J.V.N.S., Srinivasa Rao, Ch., Srinivas, K., Naga Jyothi, Ch., Venkateswarlu, B., Ramachandrapa, B.K., Dhanapal, G.N., Ravichandran, K., Mishra, P.K., 2016. Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil

- organic carbon and its fractions in Planosols of semiarid tropics of southern India. *Soil Tillage Res.* 156, 131–139. <https://doi.org/10.1016/j.still.2015.10.013>.
- Pringle, M.J., Allen, D.E., Phelps, D.G., Bray, S.G., Orton, T.G., Dalal, R.C., 2014. The effect of pasture utilization rate on stocks of soil organic carbon and total nitrogen in a semi-arid tropical grassland. *Agric. Ecosyst. Environ.* 195, 83–90. <https://doi.org/10.1016/j.agee.2014.05.013>.
- Rabbi, S.M.F., Tighe, M., Cowie, A., Wilson, B.R., Schwenke, G., Mcleodd, M., Badgery, W., Baldock, J., 2014. The relationships between land uses, soil management practices, and soil carbon fractions in South Eastern Australia. *Agric. Ecosyst. Environ.* 197, 41–52. <https://doi.org/10.1016/j.agee.2014.06.020>.
- Ribeiro, K., Sousa-Neto, E.R., Carvalho Junior, J.A., Lima, J.R.S., Menezes, R.S.C., Duarte-Neto, P.J., Guerra, G.S., Ometto, J.P.H.B., 2016. Land cover changes and greenhouse gas emissions in two different soil covers in the Brazilian Caatinga. *Sci. Total Environ.* 571, 1048–1057. <https://doi.org/10.1016/j.scitotenv.2016.07.095>.
- Rittl, T.F., Oliveira, D., Cerri, C.E.P., 2017. Soil carbon stock changes under different land uses in the Amazon. *Geoderma. Reg.* 10, 138–143. <https://doi.org/10.1016/j.geodrs.2017.07.004>.
- Sacramento, J.A.A.S., Araújo, A.C.M., Escobar, M.E.O., Xavier, F.A.S., Cavalcante, A.C.R., Oliveira, T.S., 2013. Soil carbon and nitrogen stocks in traditional agricultural and agroforestry systems in the semiarid region of Brazil. *Rev. Bras. Ci. Solo.* 37, 784–795. <https://doi.org/10.1590/S0100-06832013000300025>.
- Sampaio, E.V.S.B., 2010. Caracterização do bioma Caatinga. In: Gariglio, M.A., Sampaio, E.V.S.B., Cestaro, L.A., Kageyama, P.Y. (Eds.), *Uso sustentável e conservação dos recursos florestais da caatinga*. Brasília, Serviço Florestal Brasileiro.
- Sampaio, E.V.S.B., Costa, T.L., 2011. Estoques e fluxos de carbono no semi-árido nordestino: Estimativas preliminares. *Rev. Brasil. Geogr. Fis.* 6, 1275–1291.
- Sampaio, E.V.S.B., Araújo, M.S.B., Salcedo, I.H., Menezes, R.S.C., 2009. *Agricultura sustentável no semiárido Nordeste*. 1st ed. UFPE, Recife.
- Santos, M.V.F., Lira, M.A., Dubeux Jr., J.C.B., Guim, A., Mello, A.C.L., Cunha, M.V., 2010. Potential of Caatinga forage plants in ruminant feeding. *Rev. Bras. Zootec.* 39, 204–215. <https://doi.org/10.1590/S1516-35982010001300023>.
- Schulz, K., Voigt, K., Beusch, C., Almeida-Cortez, J.S., Kowarik, I., Walz, A., Cierjacks, A., 2016. Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil. *For. Ecol. Manag.* 367, 62–70. <https://doi.org/10.1016/j.foreco.2016.02.011>.
- Sousa, F.P., Ferreira, T.O., Mendonça, E.S., Romero, R.E., Oliveira, J.G.B., 2012. Carbon and nitrogen in degraded Brazilian semi-arid soils undergoing desertification. *Agric. Ecosyst. Environ.* 148, 11–21. <https://doi.org/10.1016/j.agee.2011.11.009>.
- Stevenson, B.A., Parfitt, R.L., Schipper, L.A., Baisden, W.T., Mudge, P., 2010. Relationship between soil $\delta^{15}\text{N}$, C/N and N losses across land uses in New Zealand. *Agric. Ecosyst. Environ.* 139, 736–741. <https://doi.org/10.1016/j.agee.2010.10.020>.
- Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchi, N., Jenkins, M., Minasny, B., Mcbratney, A.B., Courcelles, V.R., Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agric. Ecosyst. Environ.* 164, 80–99. <https://doi.org/10.1016/j.agee.2012.10.001>.
- Stockmann, U., Padian, J., McBratney, A., Minasny, B., de Brogniez, D., Montanarella, L., Hong, S.Y., Rawlins, B.G., Field, D.J., 2015. Global soil organic carbon assessment. *Glob. Food. Sec.* 6, 9–16. <https://doi.org/10.1016/j.gfs.2015.07.001>.
- Tiessen, H., Salcedo, I.H., Sampaio, E.V.S.B., 1992. Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. *Agric. Ecosyst. Environ.* 38, 139–151. [https://doi.org/10.1016/0167-8809\(92\)90139-3](https://doi.org/10.1016/0167-8809(92)90139-3).
- Tiessen, H., Feller, C., Sampaio, E.V.S.B., Garin, P., 1998. Carbon sequestration and turnover in semiarid savannas and dry forest. *Clim. Chang.* 40, 105–117. <https://doi.org/10.1023/A:1005342932178>.
- Torn, M.S., Trumbore, S.E., Chadwick, O.A., Vitousek, P.M., Hendricks, D.M., 1997. Mineral control of soil organic carbon storage and turnover content were measured by horizon down to the depth at which. *Lett. Nat.* 389, 170–173.
- Traoré, S., Ouattara, K., Ilstedt, U., Schmidt, M., Thiombiano, A., Malmer, A., Nyberg, G., 2015. Effect of land degradation on carbon and nitrogen pools in two soil types of a semi-arid landscape in West Africa. *Geoderma* 241–242, 330–338. <https://doi.org/10.1016/j.geoderma.2014.11.027>.
- Urioste, A.M., Hevia, G.G., Hepper, E.N., Anton, L.E., Bono, A.A., Buschiazzi, D.E., 2006. Cultivation effects on the distribution of organic carbon, total nitrogen and phosphorus in soils of the semiarid region of Argentinian Pampas. *Geoderma* 136, 621–630. <https://doi.org/10.1016/j.geoderma.2006.02.004>.
- Urquiaga, S., Alves, B.J.R., Jantalia, C.P., Madari, B.E., Machado, P.L.O.A., Boddey, R.M., 2016. Protocolo para avaliar o potencial de sistemas agrícolas no sequestro de C e acúmulo de N no solo. *Documents Embrapa Agrobiologia* 303, 1–23.
- Wantzen, K.M., Couto, E.G., Mund, E.E., Amorim, R.S.S., Siqueira, A., Tielbörger, K., Seifan, M., 2012. Soil carbon stocks in stream-valley-ecosystems in the Brazilian Cerrado agroscape. *Agric. Ecosyst. Environ.* 151, 70–79. <https://doi.org/10.1016/j.agee.2012.01.030>.
- WRB - World Reference Base for Soil Resources, 2014. *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. FAO - Food and agriculture organization of the United Nations, Rome.
- Wu, X., Liu, G., Butterbach-Bahl, K., Fu, B., Zheng, X., Brüggemann, N., 2013. Effects of land cover and soil properties on denitrification potential in soils of two semi-arid grasslands in Inner Mongolia. *China. J. Arid. Environ.* 92, 98–101. <https://doi.org/10.1016/j.jaridenv.2013.02.003>.