Acta Scientiarum

http://www.periodicos.uem.br/ojs/
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v45i1.60794

Carbon, nitrogen, and physical fractions of organic matter in recovered pastures of the Maranhense Amazon

Carlos Augusto Rocha de Moraes Rego[1*], Paulo Sérgio Rabello de Oliveira[2], Jean Sérgio Rosset[3], Luciano Cavalcante Muniz[4], Eloisa Mattei[2], Victor Roberto Ribeiro Reis[4], Bruna Penha Costa[2] and Wallace Ribeiro Nunes Neto[5]

[1]Centro de Ciências de Chapadinha, Universidade Federal do Maranhão, BR-222, km 04, Boa Vista, 65500-000, Chapadinha, Maranhão, Brazil. [2]Universidade Estadual do Oeste do Paraná, Campus Marechal Cândido Rondon, Marechal Cândido Rondon, Paraná, Brazil. [3]Universidade Estadual de Mato Grosso do Sul, Unidade Universitária de Mundo Novo, Mundo Novo, Mato Grosso do Sul, Brazil. [4]Universidade Estadual do Maranhão, Campus São Luís, São Luís, Maranhão, Brazil. [5]Centro de Ciências Exatas, Universidade Federal do Maranhão, São Luís, Maranhão, Brazil. *Author for correspondence. E-mail: carlos.moraes@ufma.br

ABSTRACT. In Maranhão State, Brazil, soils are naturally acidic, nutrient-deficient, and prone to cohesion and erosion. Removing the natural cover to establish pastures causes physical, chemical, and biological changes in the soil. Therefore, this study aimed to evaluate the contents and stocks of carbon (C), nitrogen (N), and particle-size fractions of soil organic matter (SOM) in pastures with different years of recovery, and compare them with a secondary forest in the Legal Amazon. Four treatments were evaluated: secondary forest, perennial pasture, and perennial pastures recovered for five years and eight years, both of the latter through corn + brachiaria intercropping. The contents and stocks of total organic carbon, total nitrogen, C, and N from the soil organic matter particle-size fractions, as well as the carbon management indexes (CMI) of the 0.00–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m layers were evaluated. The perennial pasture environment presented the highest total soil C and N contents; however, when observing the granulometric fractions and CMI, these increases were qualitative in relation to the secondary forest. Pasture recovery over eight years contributed to an improvement of soil quality similar to secondary forest, indicating that an increase in SOM quality, quantity, and recovery time related to increased pasture capacity to accumulate C and N in the soil.

Keywords: *Brachiaria brizantha*; soil management; particle-size fractions.

Received on September 6, 2021.
Accepted on March 10, 2022.

Introduction

The Amazon region of Maranhão state, Brazil, has the highest deforestation levels of all states containing this biome (Santos et al., 2018a; INPE, 2019), in which 75% of the natural vegetation has been deforested, and the remaining parts are concentrated in small portions of the forest that are protected by law (Santos et al., 2018a; INPE, 2019; Celentano et al., 2020). After deforestation, pastures are commonly established in large areas or temporary crops, causing physical, chemical, and biological changes in the soil (Santos et al., 2018a).

In Maranhão State, soils are naturally acidic, nutrient-deficient, and prone to cohesion and erosion processes, which are negative characteristics that are amplified by the adoption of low-tech management practices, such as slash-and-burn agriculture, as well as a lack of correction and soil fertilization, causing variability in soil quality (Santos et al., 2018a; Celentano et al., 2020). Adopting conservation management practices and recovering degraded areas can improve the conditions by increasing soil organic matter (SOM) content (Bungenstab, Almeida, Laura, Balbino, & Ferreira, 2019).

SOM influences the dynamics of soil attributes by acting as an energy source and nutrient reservoir, and by forming and maintaining the soil structure. Therefore, its reduction directly affects the quality and yield of soil (Beltrán, Sainz-Rozas, Galantini, Romaniuk, & Barbieri, 2018; Santos et al., 2018a). The SOM balance acts as a carbon (C) and nitrogen (N) sink and source and is an important reservoir with its dynamics influenced by soil tillage type, management system, and environmental conditions (Assunção, Pereira, Rosset, Berbara, & Garcia, 2019).

Studies of SOM fractions have shown promising results in demonstrating the management impacts, even within a short adoption time or in areas where no differences were observed in the total contents of C and N.

Physical particle-size fractionation can quantify the labile and recalcitrant forms within the textural fractions of soil (Rosset et al., 2019; Ozório et al., 2020). The particulate fraction (>53 μm, associated with the sand fraction) is a labile form of SOM as it presents organic compounds not fully processed by microorganisms that are still in the decomposition phase, and its increase may indicate improvements in nutrient release and C fixation, thereby providing the recovery and/or increase of recalcitrant fractions (<53 μm, associated with the silt and clay fraction) (Conceição, Bayer, Dieckow, & Santos, 2014; Beltrán et al., 2018; Lavalle, Soong, & Cotrufo, 2020). The recalcitrant fraction is strongly linked to SOM, as it forms more stable organomineral complexes, contributes to structural improvements in the soil, and physically protects C from microbial attack (Conceição et al., 2014; Beltrán et al., 2018; Lavalle et al., 2020; Ozório et al., 2020).

Therefore, SOM is an edaphic component that is sensitive to human action. As a result of its variation, a diversity of disturbances can be observed in soil attributes, which impair the functioning of agroecosystems and their ecosystem services (Bungenstab et al., 2019). Therefore, understanding changes in C and N levels can help to elucidate and devise management systems that are more adaptable to regional conditions.

The recovery of pastures with the integration of livestock farming is hypothesized to increases the contents and stocks of C and N and particle-size fractions of the SOM. Therefore, this study aimed to evaluate the impacts on the contents and stocks of C, N, and particle-size fractions of SOM in pastures with different numbers of recovery years and compare them to secondary forests in the Legal Amazon.

Material and methods

Study location

The study was conducted at the Technological Reference Unit (TRU) of Embrapa Cocais and State University of Maranhão (UEMA), Pindaré-Mirim, Maranhão State, Brazil (Figure 1). According to the Köppen classification, the climate of the region is AW-type with dry winters, an average annual temperature between 26 and 27°C, and an average annual rainfall between 1,900 and 2,100 mm (Maranhão, 2013; Alvares, Stape, Sentelhas, Moraes Gonçalves, & Sparovek, 2014).

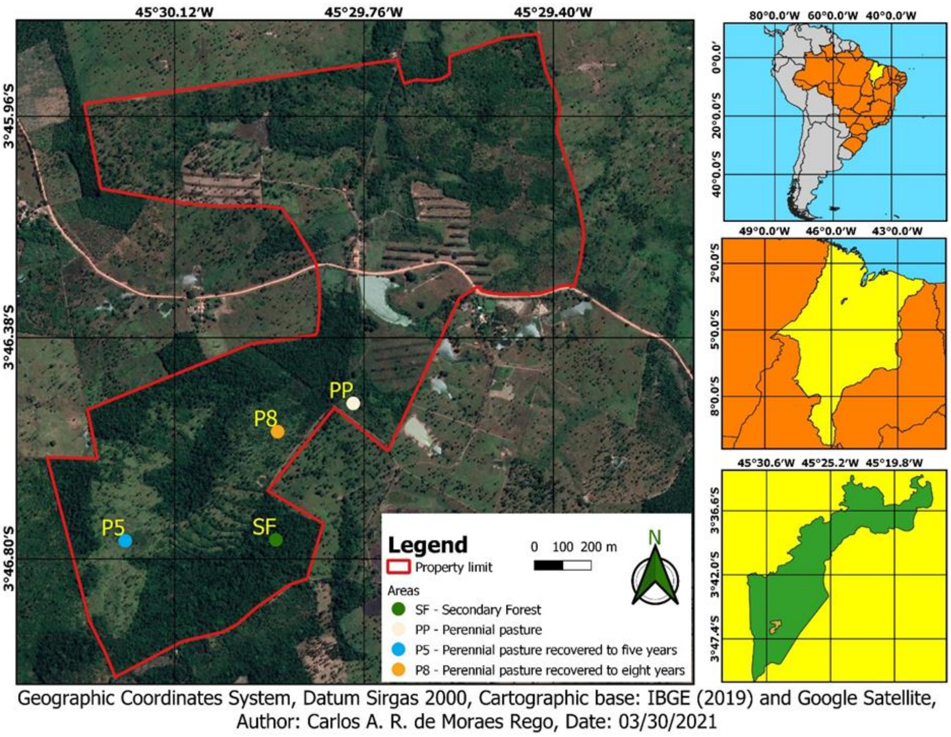

Figure 1. Geographic location of the study areas in the Pindaré-Mirim, Maranhão State, Brazil.

The soil of the TRU was classified as Plinthosols (IUSS Working Group WRB, 2015) and Plintossolo Argilúvico according to the Brazilian Soil Classification System (Santos et al., 2018b), with a medium texture classified as sandy loam for all areas (Table 1), originating from sediments of the Itapecuru Formation and composed of fine sandstones (Maranhão, 2013). The relief varies from soft-wavy to wavy and is covered by an ombrophilous forest associated with secondary forest vegetation, predominantly babassu palm (*Attalea speciosa* Mart.) (Mata dos Cocais), which is dominant in the mid-northern region of the state of Maranhão (Maranhão, 2013).

Table 1. Chemical and particle-size characterization of the soil under different management systems and layers in the Pindaré-Mirim region, Maranhão State, Brazil.

Management System	Layer (m)	pH	P	K	Ca	Mg	Al	H+Al	Sand	Silt	Clay
		$CaCl_2$	mg dm^{-1}	-----------cmol$_c$ dm^{-1}-----------					-------g kg^{-1}-------		
SF	0.0–0.2	4.49	1.78	0.15	1.61	1.73	0.26	2.67	747	135	118
	0.2–0.4	4.18	1.74	0.14	0.97	2.21	0.91	3.65	707	124	169
PP	0.0–0.2	4.58	1.56	0.28	2.36	2.28	0.16	2.51	579	343	78
	0.2–0.4	4.25	1.37	0.29	2.42	3.45	1.37	4.97	616	260	124
P5	0.0–0.2	4.33	1.36	0.14	0.58	1.24	0.28	2.84	746	104	151
	0.2–0.4	4.15	0.92	0.10	0.38	1.33	0.62	3.09	705	170	126
P8	0.0–0.2	4.56	1.10	0.20	1.67	3.16	0.23	3.60	742	121	137
	0.2–0.4	4.38	0.95	0.23	1.25	4.22	1.04	5.96	723	97	180

SF, secondary forest; PP, perennial pasture; P5, perennial pasture restored to five years, and P8, perennial pasture restored to eight years. pH, hydrogenic potential; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Al, aluminum; H + Al, hydrogen + aluminum; P and K, Mehlich^{-1} extractor; Al, Ca; and Mg, KCl (1 mol L^{-1}) extractor; H+Al – pH SMP (7.5).

Assessed systems and use history

The soil management systems evaluated were secondary forest (SF), perennial pasture (PP), perennial pastures recovered to five years (P5) through corn + brachiaria intercropping, and those recovered to eight years (P8) through corn + brachiaria intercropping. Table 2 presents the history and characteristics of the systems.

Table 2. History and characteristics of the management models studied in the technology reference unit in the Pindaré-Mirim region, Maranhão State, Brazil.

Management System	Area History
Secondary Forest (SF)	Transitional Amazon Forest to the babassu forest, with a strong expression of secondary vegetation, classified as Open Ombrophilous Forest, with babassu palms predominating (*Attalea speciosa* Mart.) (Mata dos Cocais) (Maranhão, 2013; Reis et al., 2018). Also consisting of açaí palm (*Euterpe Oleracea* Mart.), bacaba (*Oenocarpus* spp.), andiroba (*Carapa* spp.), jatobá (*Hymenaea* spp.), and embaúba (*Cecropia* spp.) (Rios, 2001). This area was used to reference natural soil conditions due to its preservation history, as it has an average age of over 50 years.
Perennial pasture (PP)	Pasture area with Jaraguá grass (*Hyparrhenia rufa* (Ness) Stapf) that was planted in approximately 1970 and remained until 1999. The pasture was renewed (without soil correction and fertilization) with *Brachiaria brizantha* cv. Marandu by mowing, burning plant remains, and broadcast seeding. The pasture was used for continuous grazing of beef cattle in an extensive regime with a stocking rate of approximately 0.7 AU/ha/year, with mechanized mowing being conducted periodically to contain the natural regeneration.
Perennial pasture recovered to five years (P5)	Initial management similar to that of PP, with recovery in 2014 with an integrated crop-livestock system (ICLS), by removing vegetation with a loader machine, harrowing the total area, and correcting the soil (as needed). Subsequently, mechanized sowing of corn hybrid (DKB 175) + *Brachiaria brizantha* cv. Marandu, the forage seeds, were mixed with fertilizer at the sowing time, with 200 kg ha^{-1} of the formula 08-20-20 + Zn in the foundation and 100 kg ha^{-1} of urea in the topdressing. The formed pasture was used for rotational beef cattle grazing with a stocking rate of 1.0 AU/ha/year.
Perennial pasture recovered to eight years (P8)	Initital management similar to that of PP, with recovery in 2012 with an ICL system, by removing the vegetation with a wheel loader machine, harrowing the entire area, and correcting the soil (as needed), followed by mechanized seeding. A corn hybrid (DKB 175) + *Brachiaria brizantha* cv. Marandu, the forage seeds, were mixed with fertilizer at the sowing time, with 200 kg ha^{-1} of the formula 08-20-20 + Zn with sowing and 100 kg ha^{-1} of urea in the topdressing. The formed pasture was used for rotational grazing of beef cattle with a stocking rate of 1.0 AU/ha/year.

Collection of soil samples and evaluations

In the management systems, five trenches with dimensions of 1 × 1 × 1 m were created and randomly arranged. Undeformed samples were collected on opposite walls of each trench using an Uhland-type auger with volumetric stainless-steel rings of known volume, comprising layers of 0.0–0.10; 0.10–0.20; 0.20–0.30, and 0.30–0.40 m to determine soil density (Ds) (Teixeira, Donagemma, Fontana, & Teixeira, 2017). Deformed samples were collected for C and N determination at three equidistant points 10 m from the trench walls with the aid of a Dutch auger, totaling 12 simple samples to compose one representative sample in the layers previously mentioned.

Total organic carbon (TOC) was determined by wet oxidation, using 0.167 mol L^{-1} potassium dichromate solution and concentrated sulfuric acid, with heating in a digester block, according to Mendonça and Matos (2017) and adapted by Yeomans and Bremner (1988). Total nitrogen (TN) was determined by Kjeldahl distillation after sulfuric digestion, according to Mendonça and Matos (2017), and adapted by Bremner and Mulvaney (1982) and Tedesco, Wolkweiss, and Bohnen (1985).

TOC and TN stocks were calculated using the following equation: St = (C or N × Ds × *e*)/10, where St represents the stock of C or N in a given layer expressed in Mg ha-1, C or N represents the content in the soil layer (g kg-1), Ds represents soil density (g cm-3), and *e* represents soil layer thickness (cm). To properly compare the stocks between management systems, it would be necessary to compare equal soil masses and adjust the values of the layers used in the calculations. However, as no differences were found in Ds (Table 3), the stocks were calculated without correction by the equivalent mass. The sum of the individual values from each layer was calculated to obtain the accumulated stock of TOC and TN within the 0.00–0.40 m soil layer.

Table 3. Soil density (g cm^{-3}) of a Plintossolo Argilúvico soil under different management systems.

Management System	Layer			
	0.00–0.10	0.10–0.20	0.20–0.30	0.30–0.40
SF	1.33 ± 0.06^{ns}	1.41 ± 0.03^{ns}	1.43 ± 0.02^{ns}	1.48 ± 0.01^{ns}
PP	1.42±0.03	1.43±0.02	1.43±0.04	1.45±0.03
P5	1.35±0.03	1.48±0.02	1.43±0.01	1.43±0.01
P8	1.37±0.03	1.43±0.02	1.43±0.02	1.44±0.03

SF, secondary forest; PP, perennial pasture; P5, perennial pasture restored to five years; P8, perennial pasture restored to eight years. ±: Standard error; ns: not significant by the *t*-test ($p < 0.05$) between treatments in the column.

For the physical particle-size fractionation of SOM, the procedures described by Mendonça and Matos (2017), adapted from Cambardella and Elliott (1992), were followed to obtain the particulate fraction associated with sand, and the organic C and N contents (POC and PN) were quantified according to the same procedures as for TOC and TN. The organic C and N contents associated with silt and clay minerals (OCAM and NAM, respectively) were obtained by comparing the total soil contents with those obtained in the particulate fractions (OCAM = TOC-POC; NAM = TN-PN). In addition, the relationship between the particulate fraction and total contents (POC/TOC; PN/TN) were determined.

The C stocks of the physical particle-size fractions of organic matter were calculated to determine the carbon management index (CMI) (Blair, Lefroy, & Lisle, 1995), according to Conceição et al. (2014), to measure the changes caused by different management systems compared to the secondary forest (non-anthropized reference).

The carbon stock index (CSI) was calculated from the ratio of the StTOC of the managed area to that of the SF area, which was used as a reference to determine the CMI. The lability (L) of the SOM was determined by the relationship between the POC and OCAM stocks of each management system, and the lability index (LI) was obtained from the relationship between L of the managed area and that of the SF area (reference). The CMI of each management was then calculated using the equation: CMI = CSI × LI × 100.

Statistical analysis

Data from the different systems were subjected to normality and homogeneity tests using the Shapiro-Wilk and Bartlett tests. When these assumptions were met, the means were compared using the *t*-test at 5% probability. Statistical analyses were performed using the R 4.1 software (R Core Team, 2021).

Results and discussion

The highest contents of TOC were observed in the SF and P8 areas in the superficial layer (0.00–0.10 m), while P8 and PP showed the highest TOC values in the 0.10–0.20 m layer, which were 30.63 and 24.83%, respectively, higher than those found in SF (Table 4). In the last two layers, the PP and P8 areas had the highest TOC contents compared to the SF, showing values that were 29.07 and 19.73% (0.20–0.30 m) and 35.88 and 26.91% (0.30–0.40 m) higher, respectively.

The TOC results of the SF are due to the constant deposition of organic residues to the superficial layer of soil (Assunção et al., 2019; Ozório et al., 2020). In the P8 area, the recovery provided for TOC accumulation that was similar in content to the SF, which was 36% higher than the amount of C in the PP area. The PP and P8 areas showed higher TOC contents than SF in the deeper soil layers (Table 4). This may be due to the growth of forage plant roots and deposition speed (Oliveira et al., 2018; Sarto et al., 2020; Bieluczyk et al., 2020).

Table 4. Contents of total organic carbon (TOC) and carbon (C) of particle-size fractions of soil organic matter in different management systems in the Amazon region of Maranhão State, Brazil.

Management System	TOC		POC		OCAM		POC/TOC	
	------------------------------ ($g\ kg^{-1}$) ------------------------------						%	
				0.00–0.10 m				
SF	9.65±0.17	a	4.11±0.22	a	5.54±0.23	a	42.64±2.1	a
PP	7.27±0.19	b	2.41±0.39	b	4.85±0.38	a	33.17±5.2	a
P5	7.66±0.14	b	3.14±0.19	b	4.52±0.28	a	41.11±2.9	a
P8	9.86±0.26	a	4.29±0.37	a	5.57±0.56	a	43.86±4.6	a
				0.10–0.20 m				
SF	4.31±0.06	c	1.41±0.18	a	2.90±0.20	c	32.71±4.3	a
PP	5.38±0.06	a	0.72±0.03	b	4.66±0.07	a	13.42±0.6	b
P5	4.68±0.12	b	1.41±0.12	a	3.27±0.19	c	30.08±2.9	a
P8	5.63±0.11	a	1.72±0.29	a	3.91±0.25	b	30.52±4.9	a
				0.20–0.30 m				
SF	3.75±0.06	c	1.20±0.11	a	2.54±0.16	c	32.32±3.4	a
PP	4.84±0.07	a	0.66±0.18	b	4.18±0.22	a	13.68±3.8	b
P5	4.05±0.08	c	1.10±0.19	a	2.95±0.25	b	28.35±4.9	a
P8	4.49±0.10	b	1.31±0.05	a	3.19±0.11	b	29.16±1.4	a
				0.30–0.40 m				
SF	3.79±0.08	b	0.97±0.15	a	2.82±0.17	c	29.74±5.0	a
PP	5.15±0.06	a	0.41±0.12	a	4.73±0.17	a	8.14±2.5	b
P5	4.06±0.05	b	0.88±0.16	a	3.17±0.19	b	21.89±4.1	a
P8	4.81±0.08	a	0.91±0.19	a	3.90±0.27	b	19.24±4.1	ab

POC, particulate organic carbon; OCAM, organic carbon associated with silt and clay minerals. SF, secondary forest; PP, perennial pasture; P5, perennial pasture restored to five years; P8, perennial pasture restored to eight years. ±: Standard error. Means followed by the same letter in the column do not differ by the *t*-test ($p < 0.05$).

Several studies have observed similar results concerning TOC content in pastures compared to forest areas (Santos et al., 2018a; Rosset et al., 2019; Martins et al., 2020; Bastos, Sanquetta, Maniesi, Sanquetta, & Corte, 2021). These have indicated that perennial pastures, due to the root system with high deposition and soil exploration speed, when well managed, can increase soil C content and stocks to levels that match those of the native vegetation (Reis et al., 2018; Santos et al., 2018a; Rosset et al., 2019; Sarto et al., 2020).

The highest levels of POC were observed in the SF (0.00–0.10 m) and P8 (0.00–0.10 to 0.20–0.30 m) areas, while in the deepest layer, no differences were found between the systems. There were no differences between the management methods at 0.00–0.10 m in the POC/TOC ratios. In contrast, the PP area presented the smallest contributions of C in the labile fraction with respect to the TOC in the other layers (Table 4), that is, less labile organic residue was deposited in the soil. The labile fraction is easily decomposable; therefore, POC indicates the deposition of organic residues in the soil (Rosset et al., 2019). Low POC levels and their proportion within the TOC in the PP area indicated less residue deposition, possibly caused by plant vigor loss (Pereira et al., 2020) after 20 years of implantation. Pasture recovery in the P5 and P8 areas contributed to the increments of the POC contents and their proportion within the TOC, with no differences in the SF in the different layers, due to the establishment of new plants and the adopted management method.

At 0.00–0.10 m, there was no difference between management systems for OCAM (Table 4). In the other layers, PP presented the highest C accumulation in this fraction compared to SF, with increments of 61, 65, and 68%, as the depth increased (Table 4). This accumulation within the recalcitrant fraction may be related to silt content, as observed by particle-size analysis (Table 1), and may aid in the protection of C from attack by microorganisms, and stabilization of C in the long term against mineralization, thereby highlighting the relevance of silt and clay , especially in tropical soils (Conceição et al., 2014; Oliveira et al., 2016; Beltrán et al., 2018; Lavalle et al., 2020).

No differences were observed between the PP and P8 areas for TN and NAM in the evaluated layers, and the lowest levels were found in the P5 area (Table 5). This result for P5 may be associated with the initial preparation process for pasture recovery, which, as a tropical region with sandy textured soil, caused rapid degradation of soil nitrogen compounds (Campos, Soares, Nascimento, & Silva, 2016; Pegoraro, Moreira, Dias, & Silveira, 2018), which would then be recovered with the deposition of animal waste (Oliveira et al., 2018). Observing the results of area P8, which endured the same recovery procedure (Table 2), it is likely that a longer time would be necessary to verify C and N accumulation in area P5, which may be similar to that observed in SF.

Table 5. Total nitrogen (TN) and nitrogen (N) contents of particle-size fractions of soil organic matter in different management systems in the Amazon region of Maranhão State, Brazil.

Management System	TN	PN	NAM	PN/TN
	($g\ kg^{-1}$)			%
		0.00–0.10 m		
SF	1.01±0.04ab	0.26±0.01a	0.75±0.03bc	25.73±0.7ab
PP	1.11±0.07a	0.22±0.02a	0.89±0.06ab	19.87±1.8bc
P5	0.86±0.11b	0.22±0.02a	0.64±0.11c	26.82±3.1a
P8	1.15±0.03a	0.21±0.02a	0.94±0.01a	17.95±1.6c
		0.10–0.20 m		
SF	0.70±0.04ab	0.09±0.01a	0.61±0.04ab	13.01±1.6ab
PP	0.77±0.07a	0.09±0.01a	0.68±0.06a	11.72±1.0b
P5	0.57±0.08b	0.09±0.01a	0.48±0.07b	15.50±1.1a
P8	0.83±0.03a	0.09±0.01a	0.74±0.03a	10.48±0.3b
		0.20–0.30 m		
SF	0.70±0.04ab	0.06±0.00b	0.63±0.05ab	9.40±1.4b
PP	0.75±0.09a	0.07±0.00ab	0.68±0.09a	9.25±1.0b
P5	0.52±0.07b	0.08±0.00a	0.44±0.07b	15.27±1.6a
P8	0.85±0.05a	0.05±0.00c	0.80±0.05a	5.91±0.3b
		0.30–0.40 m		
SF	0.76±0.06a	0.05±0.00a	0.71±0.06a	6.55±0.9b
PP	0.79±0.06a	0.06±0.00a	0.73±0.06a	7.32±1.0b
P5	0.50±0.06b	0.06±0.00a	0.44±0.06b	12.02±1.4a
P8	0.87±0.03a	0.06±0.01a	0.82±0.00a	6.38±1.0b

PN, particulate nitrogen; NAM, nitrogen associated with silt and clay minerals. SF, secondary forest; PP, perennial pasture; P5, perennial pasture restored to five years; P8, perennial pasture restored to eight years. ±: Standard error. Means followed by the same letter in the column do not differ by the t-test ($p < 0.05$).

For PN, differences were found between management systems in the 0.20–0.30 m layer, with P5 showing the highest levels (Table 5). With respect to the PN/TN ratio, P5 had the largest N deposition contribution in the labile fraction in all layers concerning TN. This indicates a significant deposition of labile nitrogen-rich organic residues in the soil (Table 5). This increase in the P5 area, as compared to the other management systems, could reaffirm that with the deposition of animal waste (manure + urine), recovery may occur within the total content and the recalcitrant fraction because these deposits can represent 50% of the TN in the soil in livestock systems (Oliveira et al., 2018).

The N of the labile fraction presented a participation of 5 to 26% of the NT composition in all areas, comprising most of the recalcitrant fraction, indicating organomineral complex protection and a higher resistance to consumption by microorganisms (Cantarella, 2007; Conceição et al., 2014), even with a low content in the smaller fractions such as silt and clay (Table 1). Silva et al. (2011) evaluated labile and recalcitrant SOM fractions under different management conditions and verified that the highest N concentrations occurred in the most recalcitrant SOM fractions. This can be attributed to the greater production of plant residues with higher C/N and lignin/N ratios, which have slower residue decomposition and favor an increase in recalcitrant fractions in the soil (Silva & Mendonça, 2007; Bieluczyk et al., 2020).

In the stocks of total organic carbon (StTOC) and total nitrogen (StTN), pasture recovery over eight years provided an increase of 4.97 and 0.78 Mg ha^{-1}, respectively, compared to that of the native vegetation, indicating C and N accumulation rates of 0.621 and 0.098 Mg $ha^{-1}\ yr^{-1}$, respectively (Table 6). The results from the P8 area for C and N stocks corroborate those observed individually in the layers within the TOC and NT contents (Tables 4 and 5). These high values can be related to rapid growth and soil cover, animal residue deposition, and consequent microbial biomass stimulation and high rhizodeposition with uniform distribution, which favor the increase in the contents and stocks of C and N in the soil (Oliveira et al., 2016; Sampaio et al., 2020; Bieluczyk et al., 2020). Pegoraro et al. (2018) observed gains in the values of StTOC and StTN when the native vegetation was replaced by pasture with three years of implantation, thus corroborating the behavior observed in the present study in the deeper layers due to the action of roots on C and N accumulation.

Figure 2 presents the changes caused by the management system to the carbon management index. CSI values greater than 1 indicate a TOC content increase compared to the reference area, which demonstrates the potential for a rise in the soil carbon content by the system, with the highest values of CSI being observed in the P8 and PP areas (Figure 2A).

Table 6. Stocks of organic carbon and total nitrogen and accumulation rates and losses in the 0.00–0.40 m deep section in the soil under different management methods in the Amazon region of Maranhão State, Brazil.

Management System	StTOC (Mg ha^{-1})	Variation		
		StTOC (Mg ha^{-1})	Time (year)	Accumulation or loss rate (Mg ha^{-1} yr^{-1})
SF	29.92 ±0.67 c	-	-	-
PP	32.46 ±0.27 b	3.30	49	0.052
P5	28.90 ±0.25 c	-1.03	5	-0.206
P8	34.89 ±0.48 a	4.97	8	0.621
Management System	**StTN (Mg ha^{-1})**	**Variation**		
		StTN (Mg ha^{-1})	Time (year)	Accumulation or loss rate (Mg ha^{-1} yr^{-1})
SF	4.45 ±0.21 a	-	-	-
PP	4.90 ±0.38 a	0.44	49	0.009
P5	3.46 ±0.42 b	-0.99	5	-0.198
P8	5.24 ±0.17 a	0.78	8	0.098

StTOC: total organic carbon stock; StTN: total nitrogen stock. SF, secondary forest; PP, perennial pasture; P5, perennial pasture restored to five years; P8, perennial pasture restored to eight years. ±: Standard error. Means followed by the same letter in the column do not differ by the *t*-test ($p < 0.05$).

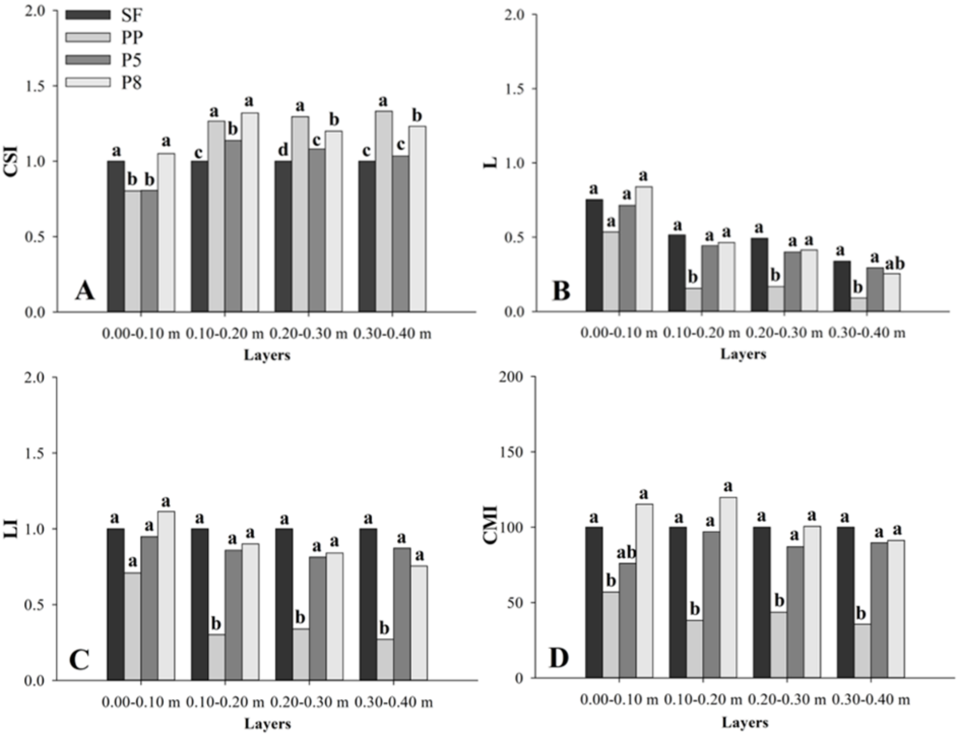

Figure 2. Carbon stock index (CSI), lability (L), lability index (LI), and soil carbon management index (CMI) of the different management systems in the Amazon region of Maranhão state, Brazil. SF: secondary forest, PP: perennial pasture, P5: perennial pasture restored to five years; P8: perennial pasture restored to eight years. The same letter indicates no difference by the *t*-test ($p < 0.05$) within each layer.

In relation to the CSI, the differences in SF compared to P5 and PP on the surface were related to C deposition and accumulation (Figure 2A). This behavior was also observed with the TOC contents and StTOC values, confirming the difference between management systems in the surface layer, since this index was obtained from the relationship between the StTOC of each management system and the reference. In deeper layers, SF had the lowest values compared to the other areas, possibly because of plant traits (Table 2), such as density and plant numbers, and root C deposition velocity, in which forage plants have a greater capacity for root exploration in the soil (Oliveira et al., 2018; Sarto et al., 2020; Bieluczyk et al., 2020). Rosset et al. (2019) also observed potential C accumulation in the root system of pasture after long cultivation periods, equating the values to those found in an area of deep native vegetation.

There were no differences between the systems in the 0.00–0.10 m layer for L, while in the other layers, the lowest values were observed in the PP (Figure 2B). The smallest L found in the PP area demonstrates a difference in the quality of C inserted into the soil, as this variable is obtained from the relationship between the labile and recalcitrant fractions, indicating an imbalance in these SOM fractions (Blair et al., 1995). L is an indicator of soil quality and a marker to verify the effects of production systems on soil (Conceição et al., 2014; Rosset et al., 2019; Ozório et al., 2020). Therefore, the entry of new organic residues preserves recalcitrant forms of carbon, and is required for the decomposition process to proceed efficiently, since higher C entry into the soil relates to a greater ability to reach equilibrium due to improved microbial activity.

The lowest LI values were observed in PP, except for the superficial layer, which did not differ between the management systems (Figure 2C). These results reinforce the reduction in the bioavailability of C in the PP area. Therefore, an environment with less protection of the labile C in the soil was similar to the reference area (Blair et al., 1995; Ozório et al., 2020). The adoption of practices such as pasture recovery should be combined with conservation systems to renew forage plants and improve residue deposition to the soil. Conservation systems have a great influence on SOM stocks and can maintain or increase these stocks in relation to native vegetation (Rosset et al., 2019; Ozório et al., 2020; Sarto et al., 2020; Bieluczyk et al., 2020).

The lowest and highest CMI values were observed in PP and P8, respectively. The latter did not differ from SF and P5, demonstrating that the pasture recovery practice with brachiaria integration provided quantitative and qualitative C improvements (Figure 2D). In the P5 and P8 areas, the addition of organic residues with high lignin content, which slowed the microbial attack, combined with constant deposition, non-disturbed soil, and the entry of animal waste (Bungenstab et al., 2019; Silva et al., 2020), contributed to the highest values observed for CMI, equating these systems to that of SF. These CMI results indicate improvements in water retention capacity, soil fertility, aggregate stability, and biological activity, with a consequent greater resistance in erosive processes (Rosset et al., 2019; Silva et al., 2020).

Conclusion

The perennial pasture reduced the levels and stocks of TOC and particle-size fractions in the surface layer, while showing an opposite trend in deeper layers compared to the secondary forest. Regarding nitrogen, the perennial pasture restored to five years exhibited the lowest values among the areas. The CMI efficiently demonstrated that even though the perennial pasture had high levels of TOC and recalcitrant fractions in deeper layers, there would be an imbalance in the quality and availability of labile organic residues. The perennial pasture restored to eight years promoted enhanced carbon and nitrogen accumulation and improving soil organic matter quality.

Acknowledgements

This study was financed in part by the Coordination for Improvement of Higher Education Personnel - Brazil (CAPES), Finance Code 001. We wish to thank the Coordination for Improvement of Higher Education Personnel - Brazil (CAPES) for the scholarship and resources to conduct the research, and the National Council for Scientific and Technological Development (CNPq) for granting the productivity scholarship.

References

Alvares, C. A., Stape, J. J., Sentelhas, P. C., Moraes Gonçalves, J. L., & Sparovek, G. (2014). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711-728. DOI: https://doi.org/10.1127/0941-2948/2013/0507

Assunção, S. A., Pereira, M. G., Rosset, J. S., Berbara, R. L. L., & Garcia, A. C. (2019). Carbon input and the structural quality of soil organic matter as a function of agricultural management in a tropical climate region of Brazil. *Science of The Total Environment*, *658*(3), 901-911. DOI: https://doi.org/10.1016/j.scitotenv.2018.12.271

Bastos, A. S., Sanquetta, C. R., Maniesi, V., Sanquetta, M. N. I., & Corte, A. P. D. (2021). Amazon plinthosols: carbon stocks and physical properties under different land uses. *Ciência Florestal*, *31*(2), 749-765. DOI: https://doi.org/10.5902/1980509838211

Beltrán, M. J., Sainz-Rozas, H., Galantini, J. A., Romaniuk, R. I., & Barbieri, P. (2018). Cover crops in the Southeastern region of Buenos Aires, Argentina: effects on organic matter physical fractions and nutrient availability. *Environmental Earth Sciences*, *77*(6), 1-11. DOI: https://doi.org/10.1007/s12665-018-7606-0

Bieluczyk, W., Piccolo, M. C., Pereira, M. G., Moraes, M. T., Soltangheisi, A., Bernardi, A. C. C., ... Cherubin, M. R. (2020). Integrated farming systems influence soil organic matter dynamics in southeastern Brazil. *Geoderma*, *371*(6), 1-8. DOI: https://doi.org/10.1016/j.geoderma.2020.114368

Blair, G. J., Lefroy, R. D. B., & Lisle, L. (1995). Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research*, *46*(7), 1459-1466. DOI: https://doi.org/10.1071/AR9951459

Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen total. In A. L. Page (Ed.), *Methods of soil analysis* (p. 595-624). Part 2. Madison, US: American Society of Agronomy.

Bungenstab, D. J., Almeida, R. G., Laura, V. A., Balbino, L. C., & Ferreira, A. D. (2019). *ILPF: inovação com integração de lavoura, pecuária e floresta*. Brasília, DF: Embrapa.

Cambardella, C. A., & Elliott, E. T. (1992). Particulate soil organic matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal*, *56*(3), 777-783. DOI: https://doi.org/10.2136/sssaj1992.03615995005600030017x

Campos, M. C. C., Soares, M. D. R., Nascimento, M. F., & Silva, D. M. P. (2016). Carbon storage in soil and aggregates of Inceptisols under different land use management systems in southern Amazonas. *Revista Ambiente & Água*, *11*(2), 339-349. DOI: https://doi.org/10.4136/ambi-agua.1819

Cantarella, H. (2007). Nitrogênio. In R. F. Novais, V. H. Alvarez Venegas, N. F. Barros, R. L. F. Fontes, R. B. Cantarutti, & J. C. L. Neves (Eds.), *Fertilidade do solo* (p. 375-470). Viçosa, MG: SBCS.

Celentano, D., Rousseau, G. X., Paixão, L. S., Lourenço, F., Cardozo, E. G., Rodrigues, T. O., ... Reis, F. O. (2020). Carbon sequestration and nutrient cycling in agroforestry systems on degraded soils of Eastern Amazon, Brazil. *Agroforestry Systems*, *94*(5), 1781-1792. DOI: https://doi.org/10.1007/s10457-020-00496-4

Conceição, P. C., Bayer, C., Dieckow, J., & Santos, D. C. (2014). Physical fractionation of organic matter and carbon management index of an Alfisol subjected to conservation management systems. *Ciência Rural*, *44*(5), 794-800. DOI: https://doi.org/10.1590/S0103-84782014005000004

Instituto Nacional de Pesquisas Espaciais [INPE]. (2019). *Monitoramento da cobertura florestal da Amazônia por satélites - sistemas Prodes, Deter, Degrad e Queimadas*. São José do Campos, SP: INPE. Retrieved on Mar. 20, 2021 from http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes

IUSS Working Group WRB. (2015). *World Reference Base for Soil Resources 2014, update 2015*. International soil classification systems for naming soils and creating legends for soil maps (Update 2015). Rome, IT: FAO. (World Soil Resources Reports, 106).

Lavalle, J. M., Soong, J. L., & Cotrufo, M. F. (2020). Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology*, *26*(10), 261-273. DOI: https://doi.org/10.1111/gcb.14859

Maranhão. (2013). *Atlas do Maranhão*. Secretaria de Estado do Planejamento e Orçamento, Núcleo Geoambiental UEMA. São Luís, MA: SEPLAN.

Martins, L. F. B. N., Troian, D., Rosset, J. S., Souza, C. B. S., Farias, P. G. S., Ozório, J. M. B., ... Castilho, S. C. P. (2020). Soil carbon stock in different uses in the southern cone of Mato Grosso do Sul. *Revista de Agricultura Neotropical*, *7*(4), 86-94. DOI: https://doi.org/10.32404/rean.v7i4.5351

Mendonça, E. S., & Matos, E. S. (2017). *Matéria orgânica do solo: métodos de análises* (2. ed.). Viçosa, MG: Gefert.

Oliveira, S. P., Cândido, M. J. D., Weber, O. B., Xavier, F. A. S., Escobar, M. E. O., & Oliveira, T. S. (2016). Conversion of forest into irrigated pasture I. Changes in the chemical and biological properties of the soil. *Catena*, *137*(2), 508-516. DOI: https://doi.org/10.1016/j.catena.2015.10.017

Oliveira, T. P., Ensinas, S. C., Barbosa, G. F., Nanzer, M. C., Barreta, P. G. V., Silva, M. F. G., ... Prado, E. A. F. (2018). Carbono lábil e frações oxidáveis de carbono em solos cultivados sob diferentes formas de uso e manejo. *Revista Brasileira de Agropecuária Sustentável*, *8*(3), 49-56. DOI: https://doi.org/10.21206/rbas.v8i4.3068

Ozório, J. M. B., Rosset, J. S., Schiavo, J. A., Souza, C. B. S., Farias, P. G. S., Oliveira, N. S., ... Panachuki, E. (2020). Physical fractions of organic matter and mineralizable soil carbon in forest fragments of the Atlantic Forest. *Revista Ambiente & Água*, *15*(6), 2601. DOI: https://doi.org/10.4136/ambi-agua.2601

Pegoraro, R. F, Moreira, C. G, Dias, D. G., & Silveira, T. C. (2018). Carbon and nitrogen stocks in the soil and humic substances of agricultural crops in the semi-arid region. *Revista Ciência Agronômica*, *49*(4), 574-583. DOI: https://doi.org/10.5935/1806-6690.20180065

Pereira, M. A., Costa, F. P., Montagner, D. B., Euclides, V. P. B., Araújo, A. R., Barbosa, R. A., & Souza, J. A. B. A. (2020). *Pastagens: condicionantes econômicos e seus efeitos nas decisões de formação e manejo*. Campo Grande, MS: Embrapa Gado de Corte. (Comunicado técnico, 150).

R Core Team. (2021). *R: A language and environment for statistical computing*. Vienna, AT: R Foundation for Statistical Computing.

Reis, V. R. R., Deon, D. S., Muniz, L. C., Garcia, U. S., Cantanhêde, I. S. L., Rego, C. A. R. M., ... Marques, E. O. (2018). Soil chemical attributes under crop-livestock-forest integration system and in different land uses in mata dos cocais region. *Journal of Agricultural Science*, *10*(4), 370-380. DOI: https://doi.org/10.5539/jas.v10n4p370

Rios, L. (2001). *Estudos de geografia do Maranhão*. São Luís, MG: Gráphis Editora.

Rosset, J. S., Lana, M. C., Pereira, M. G., Schiavo, J. A., Rampim, L., & Sarto, M. V. M. (2019). Organic matter and soil aggregation in agricultural systems with different adoption times. *Semina: Ciências Agrárias*, *40*(6), 3443-3460. DOI: https://doi.org/10.5433/1679-0359.2019v40n6supl3p3443

Sampaio, A. C. F., Silva, E. S., Vale Júnior, J. F., Silva, E. E., Santos, B. R., & Oliveira, R. F. (2020). Granulometry and carbon and nitrogen contents at different depths of a soil under integrated production systems. *Agropecuária Científica no Semiárido*, *16*(2), 58-63. DOI: https://doi.org/10.30969/acsa.v16i2.1083

Santos, C. C., Ferraz Junior, A. S. L., Sá, S. O., Muñoz Gutiérrez, J. A., Braun, H., Sarrazin, M., ... Desjardins, T. (2018a). Soil carbon stock and Plinthosol fertility in smallholder land-use systems in the eastern Amazon, Brazil, *Carbon Management*, *9*(6), 655-664. DOI: https://doi.org/10.1080/17583004.2018.1530026

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., ... Cunha, T. J. F. 2018b. *Sistema brasileiro de classificação de solos* (5. ed.). Brasília, DF: Embrapa.

Sarto, M. V. M., Borges, W. L. B., Bassegio, D., Pires, C. A. B., Rice, C. W., & Rosolem, C. A. (2020). Soil microbial community, enzyme activity, C and N stocks and soil aggregation as affected by land use and soil depth in a tropical climate region of Brazil. *Archives of Microbiology*, *202*(6), 2809-2824. DOI: https://doi.org/10.1007/s00203-020-01996-8

Silva, E., Lourente, E. P. R., Marchetti, M. E., Mercante, F. M., Ferreira, A. K. T., & Fujii, G. C. (2011). Labile and recalcitrant fractions of soil organic matter under integrated crop-livestock system. *Pesquisa Agropecuária Brasileira*, *46*(10), 1321-1331. DOI: https://doi.org/10.1590/S0100-204X2011001000028

Silva, I. R., & Mendonça, E. S. (2007). Matéria orgânica do solo. In R. F. Novais, V. H. Alvarez Venegas, N. F. Barros, R. L. F. Fontes, R. B. Cantarutti, & J. C. L. Neves (Eds.), *Fertilidade do solo* (p. 275-374). Viçosa, MG: SBCS.

Silva, J. R. M., Ensinas, S. C., Barbosa, G. F., Rezende, J. V. O., Barreta, P. G. V., & Zuffo, A. M. (2020). Total organic carbon and the humic fractions of the soil organic matter in silvopastoral system. *Revista Brasileira de Ciências Agrárias*, *15*(2), 1-6. DOI: https://doi.org/10.5039/agraria.v15i2a6874

Tedesco, J. M., Wolkweiss, S. J., & Bohnen, H. (1985). *Análise de solo, planta e outros materiais*. Porto Alegre, RS: UFRGS. (Boletim Técnico, 5).

Teixeira, P. C., Donagemma, G. K., Fontana, A., Teixeira, W. G. (2017). *Manual de métodos de análises de solo* (3. ed.). Brasília, DF: Embrapa.

Yeomans, J. C., & Bremner, J. M. (1988). A rapid and precise method for routine determination of carbon in soil. *Communications in Soil Science and Plant Analysis*, *19*(13), 1467-1476. DOI: 10.1080/00103628809368027