Ciência Rural, Santa Maria, v.52:10, e20200845, 2022
http://doi.org/10.1590/0103-8478cr20200845
ISSNe 1678-4596
SOIL SCIENCE

Organic matter compartments in an Ultisol under integrated agricultural and livestock production systems in the Cerrado

Leovânio Rodrigues Barbosa[1*] **Henrique Antunes de Souza**[2]
Marcos Lopes Teixeira Neto[2] **Luiz Fernando Carvalho Leite**[2]

[1]Departamento de Solos e Engenharia Rural, Universidade Federal da Paraíba (UFPB), Campus Areia, 58397-000, Areia, PB, Brasil. E-mail: leovaniobarbosa@hotmail.com. *Corresponding author.
[2]Empresa Brasileira de Pesquisa Agropecuária, Embrapa Meio-Norte, Teresina, PI, Brasil.

ABSTRACT: *Integrated agricultural production systems have the potential to increase organic matter content, which is reflected in the soil carbon (C) and nitrogen (N) concentrations. Here, we evaluated the C and N stocks and its compartments in a typical distro cohesive yellow Ultisol under the no-till (NT) and crop-livestock integration (CLI) systems, in eastern Maranhão. Five areas with different management strategies were evaluated, more specifically, one area was managed under the NT system in succession for 14 years (soybean/millet), three areas had different CLI system adoption histories (i.e., CLI was adopted 2, 4, or 8 years prior to sample collection); and finally, one area consisted of native Cerrado (savannah) vegetation. Soil samples were collected at depths of 0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.50 m,to analyze the content and total stocks of carbon (C) and its compartments (physical and chemical), N content, soil microbial biomass, and basal respiration. Results revealed higher content and stock of C and N in areas with CLI. The principal humic substance reported was humin, and higher concentrations of C associated with minerals were present in areas under more recent CLI adoption (2 and 4 years). We demonstrated that the adoption of CLI, even if recent, leads to immediate increases in the concentrations of C and its fractions as a result of using forage crops. NT for 14 years and CLI for 8 years exhibited higher levels of C management and higher soil biological activity due to the greater stability of these systems.*
Key words: *carbon fractionation, conservation management, crop-livestock integration.*

Compartimentos da matéria orgânica em Argissolo sob sistemas integrados de produção agropecuária no Cerrado

RESUMO: *Os sistemas integrados de produção agropecuária possuem potencial de incrementar a matéria orgânica, com reflexos nas concentrações de carbono e de nitrogênio no solo. O objetivo do trabalho foi avaliar estoques de carbono e nitrogênio e seus compartimentos em um Argissolo Amarelo Distrocoeso típico sob plantio direto e integração lavoura-pecuária no Leste maranhense. Os manejos avaliados foram: sistema de plantio direto em sucessão há 14 anos (soja/milheto), três áreas com diferentes históricos de sucessão com a adoção do sistema integração lavoura-pecuária (ILP), sendo dois, quatro e oito anos, além de uma área de Cerrado nativo. Foram coletadas amostras de solo nas profundidades de 0,00-0,10; 0,10-0,20; 0,20-0,30; 0,30-0,50 metros para análise de teores e estoques totais de carbono (C) e de seus compartimentos (físico e químico), nitrogênio (N) e da biomassa microbiana do solo e respiração basal. Os resultados revelam maior teor e estoque de C e N nas áreas com ILP. A substância húmica predominante foi a humina e maiores concentrações do carbono associado a minerais estiveram presentes na área sob ILP mais recente (dois e quatro anos). A adoção da ILP, mesmo que recente, proporciona incrementos imediatos nas concentrações de C e suas frações em função do emprego de forrageiras. O plantio direto há 14anos e ILP há oito anos são sistemas com maior índice de manejo do C, como, também, apresentam maior atividade biológica do solo, devido à maiores estabilidade destes sistemas.*
Palavras-chave: *fracionamento do carbono, manejo conservacionista, integração lavoura-pecuária.*

INTRODUCTION

Agricultural practices which are more sustainable, economically feasible, and conservation-orientated, such as integrated agricultural production systems (IAPS), have received special attention from researchers and have been adopted by farmers in Brazil, especially in rotation systems or in the implementation of crops (BONETTI et al., 2015).

The crop-livestock integration (CLI) system is aprocedure within IAPS which consists of cultivating grain-producing crops with forage crops in the same area, in rotation, succession, or consortia, in order to diversify agricultural production, ultimately

Received 09.10.20 Approved 10.26.21 Returned by the author 05.02.22
CR-2020-0845.R3
Editors: Leandro Souza da Silva Tales Tiecher

benefiting both agricultural production and livestock; in addition, the resultant increase in dry matter production per unit area can be used as soil cover for cultivation in the no-till (NT) system, or even as an alternative in the recovery of degraded pastures (CHIODEROLI et al., 2012; MAZZUCHELLI et al., 2020).

Due to its capacity to provide economic and environmental benefits, the NT system is widely considered as a conservation-orientated system. This perception, together with the ensuing increase in crop yields, has made the NT system popular in Brazil, the management practice is being studied in various parts of the country and in the 2017/18 crop year, it was implemented in 32.8 million hectares of land (FERREIRA et al., 2020).

IAPS can be modified to use the most suitable intercropping for the edaphoclimatic conditions inherent to different regions of Brazil. A main advantage of adopting these systems, which are widely accepted as contributing to the generation of more sustainable and efficient practices, is the improvement of soil quality (SKORUPA & MANZATTO, 2019). Compared to other conservation management models that do not make use of pastures, the CLI system fosters a greater increase in carbon (C) content in the soil due to its maintenance principles, i.e., permanent soil cover, minimum disturbance, intercropping and crop rotation, and the introduction of animals into the system (GUESMI et al., 2019). In fact, in the Brazilian Cerrado (savannah) reported in the state of Goiás, increases of up to 40% in soil C content have been found under CLI systems compared to areas under the NT system (GAZOLLA et al., 2015).In addition, studies in the Cerrado by SILVA et al. (2016), SOARES et al. (2019), and SOUSA et al. (2020) also report improvement in the content and compartments of soil C through the adoption of CLI.

However, several factors have compromised the successful development of these management systems, including inherent risks related to the complexity of IAPS management, regional intricacies, limited information, and the unavailability of suitable technologies (TAKAHASHI et al., 2019).

Sandy soils, reported in agricultural frontier regions, the major constraints related to management information and organic matter gains when adopting IAPS, mainly by improving soil attributes (DONAGEMMA et al., 2016).

Despite the sandy properties of some soils in agricultural frontier regions, the presence of the cohesive horizon can diminish the potential of agricultural systems designed for soils in the Cerrado that have developed in sediments of the Formação Barreiras. This is as a result of cohesion and the ensuing high soil density and resistance to penetration, which forces dramatic restrictions to the deepening of root systems, leading to are duction in the water and nutrient storage capacity of plants, development (VIEIRA et al., 2012; RIBEIRO et al., 2016), and ultimately, soil C stocks (GATTO et al., 2010).

In eastern Maranhão (MA), the position of the landscape determines the distinction of cohesive soils, for example, those that develop in concave pedoformex hibit the greatest expression of the cohesive character. Soil surveys carried out in the region indicated that the B textural horizon is below 60 cm depth (DANTAS et al., 2014; RESENDE et al., 2014). Thus, the adoption of systems that favor root production, such as NT and IAPS should be considered.

In this study, we hypothesized that the adoption of IAPS, such as the CLI, increases the soil C and nitrogen (N) stock compared to the NT systems. Thus, this study evaluated and compared the composition and accumulation of total C and N stocks and their compartments under the NT and CLI systems in a typical dystrocohesive yellow Ultisol in eastern Maranhão.

MATERIALS AND METHODS

Description of the area and management systems

The study was conducted on the Barbosa farm located in the municipality of Brejo, MA, Brazil (03°42′0.93″S and 42°56′25.57″W) (Figure 1).The Barbosa farm has an average altitude of 95 m, a flat to gently undulating relief, and a hot and humid tropical climate. The average annual temperature of the study area is 27 °C and rainfall, which typically occurs between the months of November and April, has an annual average of 1,835 mm (Figure 1). The area falls under the Cerrado type biome, and the soil is classified as typical dystrocohesive yellow Ultisol (DANTAS et al., 2014).

Three areas were selected which were managed using NT systems that followed soybean/millet succession and had different histories of CLI adoption; one area was managed exclusively under NT systems; and one area consisted of native Cerrado vegetation (Figure 2). The areas are described as follows:

(i) The NT system for 14 years (NT14); this area was first initiated (originally native Cerrado biome) in 2003 with plowing and harrowing. Thereafter, 2 t ha^{-1} of limestone was incorporated, and the first year of cultivation (soybean) was in 2004. The subsequent years followed the NT system (first crop, soybean;

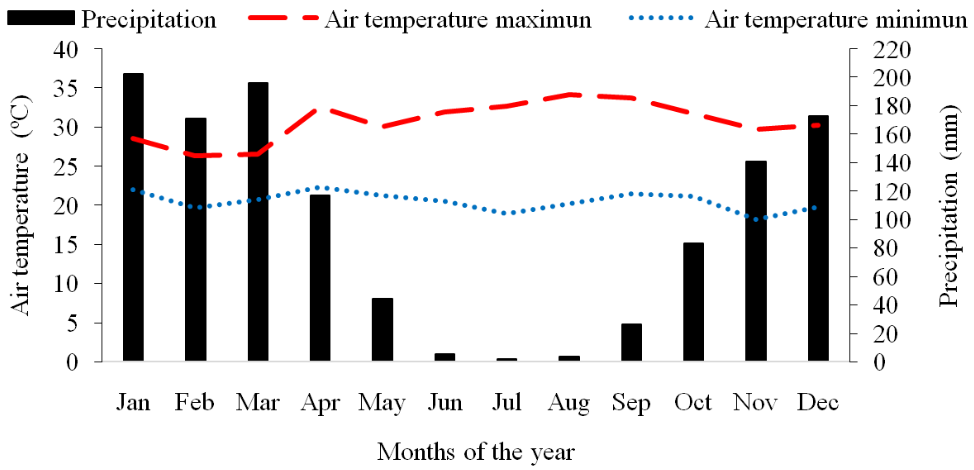

Figure 1 - Historical timeseries of climate data of the studied region for the period 1990–2017 (INMET, 2019).

second crop, millet) until 2018, and fertilization was under taken based on the recommendation for soybean culture (SOUSA & LOBATO, 2004).

(ii) The CLI system was adopted 8 years ago (CLI8); this area, which has the same management history as NT14 until 2009; in 2010, the soil was turned over (via plowing and harrowing) and 3.7 t ha^{-1} of calcareous limestone was applied. Thereafter, the area was managed in a CLI system (maize + *Urochloa ruziziensis* with an input of 0,7 animal units [male/female cattle - AU = 450 kg] per hectare in the off-season) until 2018, when the area returned to the NT system (soybean and millet) and fertilization was undertaken based on the recommendation for soybean and corn crops (SOUSA & LOBATO, 2004).

(iii) CLI adopted 4 years ago (CLI4); this area, which has the same management history as NT14 until 2009, had its soil turned over (via plowing and harrowing) and 3.7 t ha^{-1}of limestone incorporated in 2010. In 2014, the area was managed using the CLI system (maze + *Urochloa ruziziensis* with an input of 0.8 animal units [male cattle - AU = 450 kg] per hectare in the off-season) until 2018, when the area returned to the NT system (soybean and millet) and fertilization was undertaken based on the recommendation for soybean and maze culture (SOUSA & LOBATO, 2004).

(iv) CLI adopted two years ago but with two animal introductions (CLI2); this area, has the same management history as NT14 until 2011. Thereafter, in 2012, the area had its soil turned over (via plowing and harrowing), 3.8 t ha^{-1} of calcitic limestone incorporated, and CLI adopted (maize + *Urochloa ruziziensis* with an input of 1.5 animal units [male cattle - AU = 450 kg] per hectare in the off-season). From 2013 to 2015, the area was managed under the NT system (soybean and millet), and in 2016, after being subsoiled to 0.30 m, the area returned to being managed under the CLI system (corn + *Urochloa ruziziensis* with an input of 0.8 animal units [male cattle - AU = 450 kg] per hectare in the off-season). In the following years, the area returned to the NT system (soybeans and millet) and fertilization was undertaken based on the recommendation for soybean and maize culture (SOUSA&LOBATO, 2004). (v) Native Cerrado (FOREST); this area of native Cerrado biome vegetation was included as a reference point.

Soil Sampling and Analysis

In each area, four trenches with a width, length, and depth of approximately 0.60 × 0.60 × 0.60 m, respectively, were dug in randomly distributed positions, 50 m apart. Four not deformed soil samples were taken from each trench with the aid of aluminum volumetric rings (98.17 cm^{3}volume, 0.05m diameter, 0.05 m height). An additional nine deformed samples were collected using a Dutch auger; one was taken from the central point of the respective trench, and eight were taken from points around the trenches spaced 3 m apart. Soil samples were collected in June 2018 (the dry season), at 0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.50 m soil depth.

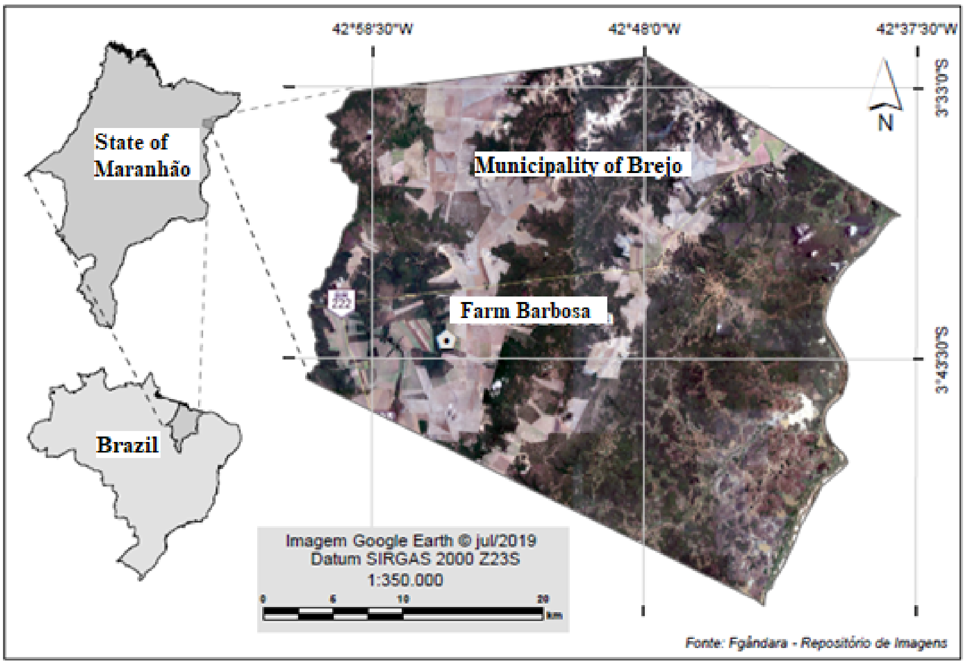

Figure 2 - Location of Barbosa Farm, Brejo, MA, Brazil.

Part of the not deformed samples were used in determining the soil density (SD) via the volumetric ring method, and another part of the samples were used for chemical characterization and particle size analyses using the pipette method (TEIXEIRA et al., 2017) (Table 1).

The remaining samples of deformed structure were used for determining the total organic carbon (TOC) (YOEMANS & BREMNER, 1988), the total nitrogen (TN) using sulfuric digestion via Kjeldahl distillation (BREMNER & MULVANEY, 1982), the granulometric fractioning of the soil organic matter (CAMBARDELLA & ELLIOT, 1992), the particulate organic carbon (POC) and mineral associated organic carbon (MAOC), the chemical fractioning of organic matter (SWIFT, 1996), with adaptation (BENITES et al, 2003), and the organic carbon of fulvic acids (FA), humic acids (HA) and humin (HUMIN) fractions.

Soil biomass carbon (SBM) was only analyzed in the superficial layer (0–0.20 m) using the irradiation extraction method (ISLAM & WEIL, 1998), and after the samples were collected, refrigerated, and taken to the laboratory, the basal respiration (C-CO_2) was obtained by incubating the samples for 7 days (ALEF et al., 1995). The microbial quotient (qMIC) obtained using the CBM (soil microbial biomass carbon)/TOC ratio (ANDERSON & DOMSCH, 1989) and the metabolic quotient (qCO_2) from the C-CO_2/CBM ratio (ANDERSON & DOMSCH, 1990) were also calculated.

After obtaining the laboratory data, the C stock (CS) and N stock (NS) were determined using the layer method (BAYER et al., 2000) and equivalent soil mass (ELLERT & BETTANY, 1995), this was carried out using the calculations by layer and thereafter using the sum of stocks of all the layers, resulting in an accumulated stock (0–0.50 m). The carbon management index (CMI) and its components were determined (BLAIR; LEFROY & LISLE, 1995) while considering the POC as representative of the labile fraction of the TOC, the MAOC as the non-labile fraction, and the carbon lability (CL) as the ratio between POC/MAOC (DIEKOW et al., 2005; VIEIRA et al., 2007).

Data analysis

The limitations for extrapolation produced by pseudo replication were considered, and an analysis of variance (F test) was performed. Considering the different management strategies as treatments in

Table 1 - Average values of chemical attributes, granulometric and soil density at four depths, of an Ultisol under different conservation management systems in Brejo, MA, Brazil.

Area	pH	P	Ca^{2+}	Mg^{2+}	K^{+}	H+Al	CEC	BS	Sand	Silt	Clay	Ds
	H_2O	mg/dm^3	--------------------cmol$_c$ dm^3--------------------					%	-------------g kg^{-1}-------------			kg dm^{-3}
----------0.00 – 0.10 m----------												
CLI2	6.08	41.7	3.65	1.13	0.26	3.17	8.21	61.3	782.0	100.0	118.0	1.59
CLI4	5.51	37.9	4.78	1.12	0.31	3.20	9.41	65.1	721.9	100.2	177.9	1.55
CLI8	5.67	33.9	3.64	0.94	0.11	3.44	8.16	58.2	757.8	58.9	183.3	1.60
NT14	5.70	49.9	3.26	1.18	0.13	2.04	6.60	69.1	713.4	141.3	145.3	1.68
FOREST	5.46	1.52	0.47	0.41	0.14	4.61	5.63	18.2	747.7	77.7	174.6	1.50
----------0.10 – 0.20 m----------												
CLI2	6.08	40.1	3.93	1.11	0.17	2.90	8.12	64.2	783.9	24.7	191.4	1.62
CLI4	5.35	40.8	3.74	0.68	0.20	3.64	8.26	55.4	707.0	154.4	138.6	1.71
CLI8	5.75	22.2	2.81	0.75	0.11	2.71	6.38	58.2	727.5	69.6	202.9	1.75
NT14	5.80	42.1	2.81	1.04	0.07	2.67	6.59	59.4	724.5	90.4	185.1	1.73
FOREST	5.39	1.32	0.23	0.41	0.10	4.47	5.21	14.8	704.5	112.1	183.4	1.59
----------0.20 – 0.30 m----------												
CLI2	5.48	18.6	1.44	0.86	0.11	4.16	6.08	31.5	725.8	55.8	218.4	1.55
CLI4	5.39	11.9	1.54	0.55	0.09	4.98	7.16	30.4	707.7	63.60	228.7	1.62
CLI8	5.48	11.7	1.71	0.52	0.17	4.40	6.79	34.4	715.9	61.7	222.4	1.69
NT14	5.97	15.4	2.02	0.76	0.10	3.88	6.76	42.5	698.0	89.2	212.8	1.73
FOREST	5.22	0.82	0.00	0.19	0.04	4.15	4.42	6.5	679.8	85.9	234.3	1.59
----------0.30 – 0.50 m----------												
CLI2	5.02	9.32	0.20	0.37	0.13	4.47	5.66	20.2	685.3	102.7	212.7	1.63
CLI4	5.34	5.57	1.32	0.49	0.06	5.23	7.10	26.3	639.8	104.3	255.8	1.68
CLI8	5.53	3.10	1.10	0.37	0.07	4.92	6.45	23.8	648.5	101.1	250.4	1.69
NT14	5.81	8.92	1.61	0.63	0.16	3.88	6.28	38.1	673.1	113.7	213.2	1.66
FOREST	5.21	0.85	0.00	0.18	0.07	4.69	5.05	6.8	660.5	96.2	243.3	1.62

P = phosphorus and K = potassium (Mehlich^{-1}extractor), Ca^{2+}= calcium, Mg^{2+}= magnesium (1M KCl extractor), H+Al = hydrogen plus aluminum (Calcium Acetate extractor), CEC = cation exchange capacity at pH 7.0, BS = base saturation, Ds = soil density.

an entirely randomized design and, depending on normality, a test of means (Tukey, 5% probability) was performed using the statistical program SISVAR 5.6 (FERREIRA, 2014). Correlation and principal component analysis (PCA) were performed using the statistical program R (R CORE TEAM, 2017) to assess the response variables as a function of depth. Variables were standardized for the multivariate tests (MANLY, 2008). Correlation between the variables were interpreted according to the following coefficient categories: insignificant (0.0–0.3), low (0.31–0.50), moderate (0.51–0.70), high (0.71–0.90), and very high (0.91–1.0) (MUKAKA, 2012).

RESULTS

The highest TOC values in the 0–0.20 m layer were observed in the CLI systems (CLI2, CLI4 and CLI8), while the lowest values were in NT14 and FOREST (Table 2). In the subsurface layers, the highest concentrations of TOC were observed in CLI2, an area with recent CLI adoption; these values differed from the values observed in NT14 and FOREST (Table 2). In general, the TOC content observed in CLI2 was 15% higher than in NT14 (Table 2).

The highest concentrations of TN were observed in area CLI4, while they did not differ from those of CLI8 in the 0–0.10, 0.20–0.30,and 0.30–0.50 m layers, nor from those of NT14 in the 0.20–0.30 m layer (Table 2). The C/N ratio; however, showed an inverse signal to that of TN and a similar signal to that observed in TOC, with area CLI2 having the highest ratio regardless of soil layer (Table 2).

The highest CS values were observed in the areas CLI2 and CLI4, and these values differed from those observed in areas NT14 and FOREST

Table 2 - Total organic carbon, total nitrogen, carbon and nitrogen ratio, and carbon and nitrogen stocks at four depths, as well as accumulated stocks, of an Ultisol under different conservation management systems in Brejo, MA, Brazil.

Area	TOC	TN	C/N	CS	NS
	--------------------g kg^{-1}--------------------			--------------------Mg ha^{-1}--------------------	
-----0.00 – 0.10 m-----					
CLI2	16.9 a[1]	0.7 b	23.9 a	25.4 a[1]	1.17 b
CLI4	17.2 a	1.1 a	15.6 b	25.8 a	1.72 a
CLI8	16.0 a	1.0 a	15.9 b	23.9 ab	1.51 a
NT14	14.2 b	0.8 b	17.7 b	21.3 bc	1.08 b
FOREST	13.4 b	0.8 b	16.7 b	19.8 c	1.21 ab
-----0.10 – 0.20 m-----					
CLI2	17.3 a	0.7 b	23.0 a	26.6 a	1.8 a
CLI4	16.7 ab	1.1 a	14.5 c	27.5 a	1.1 bc
CLI8	15.2 b	0.8 b	17.3 b	24.2 ab	1.3 ab
NT14	14.3 bc	0.8 b	18.0 b	22.6 b	1.0 c
FOREST	13.5 c	0.7 b	18.0 b	21.5 b	1.2 b
-----0.20 – 0.30 m-----					
CLI2	14.5 a	0.5 b	28.9 a	22.0 a	0.7 b
CLI4	13.9 ab	0.7 a	19.9 b	22.1 a	1.3 a
CLI8	13.5 ab	0.7 a	19.2 b	21.4 b	1.2 a
NT14	11.8 b	0.6 ab	19.7 b	19.0 b	0.7 b
FOREST	10.8 b	0.5 b	21.0 ab	17.6 b	0.9 b
-----0.30 – 0.50 m-----					
CLI2	13.9 a	0.4 b	33.9 a	38.1 ab	1.3 b
CLI4	11.9 ab	0.5 a	23.0 b	44.4 a	2.2 a
CLI8	11.9 ab	0.5 a	21.3 bc	38.1 ab	1.8 ab
NT14	10.9 b	0.4 b	27.4 b	34.9 b	1.0 b
FOREST	10.7 b	0.4 b	26.3 b	34.2 b	1.7 ab
-----Cumulative stock (0 - 0.50 m)-----					
	CLI2	CLI4	CLI8	NT14	FOREST
	-----CS Mg ha^{-1}-----				
0-0.50 m	112.3 ab[2]	121.0 a	107.8 b	98.0 c	93.3 c
	-----NS Mg ha^{-1}-----				
0-0.50 m	4.9 c	6.3 a	5.8 3b	3.8 d	5.0c

CLI2 = no-till soy/no-till twice with history of crop-livestock integration, CLI4 = no-till soy/no-till with history of crop-livestock integration system once for 4 years prior to soil collection, CLI8 = no-till soy/no-till with history of crop-livestock integration system once for 8 years prior to soil collection, NT14 = no-till soy/no-till for 14 years and no history of animal inputs, FOREST = area under native Cerrado vegetation. TOC = total organic carbon, TN = total nitrogen, C/N = carbon nitrogen ratio, CS = carbon stock, NS = nitrogen stock. [1] Means followed by the same letter in the column do not have differences between them based on the Tukey's test (5%) and [2] Means followed by the same letter in the row do not have differences between them based on the Tukey's test (5%).

until the 0–0.30 m layer (Table 2). Below this layer, the highest CS was observed in CLI4, being 9.5 and 10.2 Mg ha^{-1} higher than those observed in NT14 and Forest, respectively (Table 2).

The highest NS values were observed in area CLI4 for the 0–0.10, 0.20–0.30, and 0.30–0.50 m layers. These values; however, did not differ from CLI8 in the 0–0.10, 0.20–0.30, and 0.30–0.50 m layer, nor from FOREST in the 0–0.10 and 0.30–0.50 m layers (Table 2). Finally, in the 0.10–0.20 m layer, the highest NS was observed in CLI2 and CLI8 (Table 2).

Areas CLI4 and CLI2 displayed a higher CS accumulation than areas CLI8, NT14, and FOREST, the latter being 22.9% lower compared to CLI4 (Table 2). NS accumulation for the 0–0.50 m layer was highest in area CLI4 (Table 2).

With regard to C compartments, in general the concentration of FA were higher than that of HA, and the highest HA/FA ratio observed among all layers was in area CLI4 (Table 3). However, these

Table 3 - Chemical and physical fractionation, lability, and carbon management indices of an Ultisol under different conservation management systems at four depths in Brejo, MA, Brazil.

Area	FA	HA	HA/FA	Hum	POC	MAOC	CL	CMI
----------g kg^{-1}----------								
----------0.00 – 0.10 m----------								
CLI2	4.8 a[1]	0.6 b	1.3 b	11.5 a	0.2 a[1]	16.7 a	0.1 b	100.4 c
CLI4	5.6 a	2.2 a	3.6 a	10.0 ab	0.2 a	17.6 a	0.1 b	177.8 ab
CLI8	5.2 a	1.2 ab	2.3 ab	9.5 ab	0.2 a	15.6 b	0.1 b	144.7 b
NT14	4.7 a	0.7 b	1.4 b	8.7 b	0.3 a	13.8 c	0.2 a	200.0 a
FOREST	5.3 a	1.4 ab	2.6 ab	6.4 c	0.1 a	13.0 c	0.1 b	100.0 c
----------0.10 – 0.20 m----------								
CLI2	4.8 b	0.8 bc	1.8 b	10.9 a	0.2 a	17.6 a	0.1 b	144.2 bc
CLI4	6.2 a	1.9 a	3.1 a	9.4 ab	0.2 a	17.5 a	0.1 b	110.7 c
CLI8	5.2 ab	1.0 bc	2.1 ab	8.3 bc	0.2 a	14.7 b	0.2 a	171.4 ab
NT14	4.2 b	0.6 c	1.4 b	9.3 ab	0.3 a	13.9 c	0.2 a	198.1 a
FOREST	5.3 ab	1.1 b	2.2 ab	7.0 c	0.2 a	13.3 c	0.1 b	100.0 c
----------0.20 – 0.30 m----------								
CLI2	4.0 a	0.5 b	1.2 b	9.4 a	0.2 a	13.7 ab	0.1 c	72.5 bc
CLI4	5.2 a	1.3 a	2.6 a	8.2 a	0.1 a	14.7 a	0.1 c	56.9 c
CLI8	5.4 a	0.6 b	1.1 b	7.2b	0.3 a	12.8 ab	0.2b	112.4 a
NT14	4.2 a	0.4 b	1.2 b	7.1 b	0.3 a	11.6 b	0.3 a	96.7 ab
FOREST	4.3 a	0.8 ab	1.8 ab	5.7 c	0.2 a	10.6 c	0.3 a	100.0 ab
----------0.30 – 0.50 m----------								
CLI2	4.3 a	0.4 a	1.1 b	7.0 ab	0.2 a	11.7 ab	0.1 b	89.7 b
CLI4	2.7 b	0.5 a	2.7 a	9.3 a	0.2 a	13.6 a	0.1 b	70.0 b
CLI8	2.2 b	0.5 a	1.2 b	6.9 ab	0.3 a	11.6 ab	0.2 a	111.4 ab
NT14	4.4 a	0.6 a	1.3 b	5.9 b	0.2 a	10.7 b	0.2 a	145.5 a
FOREST	4.0 a	0.7 a	1.9 ab	5.9 b	0.3 a	11.6 ab	0.1 b	100.0 b

CLI2 = no-till soy/no-till twice with history of crop-livestock integration, CLI4 = no-till soy/no-till with history of crop-livestock integration system once for 4 years prior to soil collection, CLI8 = no-till soy/no-till with history of crop-livestock integration system once for 8 years prior to soil collection, NT14 = no-till soy/no-till for 14 years and no history of livestock input, FOREST = area under native Cerrado vegetation, POC= particulate organic carbon, MAOC = mineral associated organic carbon, CL = carbon lability, CMI= carbon management index. [1] Means followed by the same letter in the column do not have differences between them based on the Tukey's test (5%).

high HA/FA ratios did not differ from all layers in a FOREST area, nor from the superficial layers (0–0.10 and 0.10–0.20 m) in area CLI8 (Table 3).

Among the humic fractions, humin was reported in the highest concentrations. The humin concentrations observed in the 0–0.10, 0.10–0.20,and 0.20–0.30 m layers in area CLI2 did not differ from the same layers in area CLI4, nor from the superficial layer (0–0.10 m) in area CLI8, nor from the 0.10–0.20 m layer in area NT14 (Table 3). In the 0.30–0.50 m layer, the highest concentrations of humin were reported in area CLI4, and these concentrations did not differ from areas CLI2 and CLI8 (Table 3).

With regard to the physical fractionation of C, no differences in POC by area or depth were observed, however, changes in the MAOC were observed (Table 3). The areas with more recent adoption of CLI (i.e., CLI2 and CLI4) showed higher values of MAOC in the 0–0.10 and 0.10–0.20 m layers compared to areas NT14 and FOREST (Table 3). In the subsurface layers (0.20–0.30 and 0.30–0.50 m), area CLI4 had higher MAOC values than area NT14, and higher values in the 0.20–0.30 m layer compared to area FOREST (Table 3).

The highest CL values in the superficial layer (0–0.10 m) were observed in area NT14; in the 0.10–0.20 and 0.30–0.50 m layers, the highest values were observed in areas NT14 and CLI8; and in the 0.20–0.30 m layer, the highest values were observed in areas NT14 and FOREST (Table 3).

Considering the POC, MAOC, and CL data used when determining the CMI, it was found that for the 0–0.20 m layer, all areas under agricultural management had CMI values higher than the reference value (100) of the FOREST area, with the highest CMI values being observed in area NT14. However, in the subsurface layers (0.20–0.30 and 0.30–0.50 m), higher CMI values were observed in areas CLI8 and NT14, with values being 11% and 46% higher than the CMI of the reference area, respectively (Table 3).

The CBM and qMIC values reflected differences according to the management type adopted in each area. The highest values were observed in areas NT14 and CLI8 and the lowest were observed in the FOREST area (Table 4). The highest concentration for basal respiration (C-CO_2) was observed in area NT14, while the highest metabolic quotient (qCO_2) value was observed in area CLI2.

The assessment of the possible association between the variables for the 0–0.01 m layer revealed several strong correlations: TOC and CS (0.97), TOC and MAOC (0.99), TN and NS (0.99), C/N and NS (-0.91), and CS and MAOC (0.98) (Figure 3A). Strong correlations in the 0.10–0.20 m layer were found for TOC and CS (0.99), TOC and MAOC (0.99), TN and FA (0.93), CS and MAOC (0.99), and FA and POC (-0.95) (Figure 3B).

In the 0.20–0.30 m layer, strong correlations were reported for TOC and CS (0.99), TOC and MAOC (0.98), TN and NS (0.99), TN and FA (0.97), CS and MAOC (0.98), NS and HA/FA (0.97), and HA and HA/FA (0.96) (Figure 3C); in the 0.30–0.50 m layer, strong correlations were found for TOC and CS (0.97), TOC and MAOC (0.99), TN and NS (0.99), C/N and NS (-0.91), and CS and MAOC (0.98) (Figure 3D).

Joint analyses of the results (the soil biology data were excluded, as they were sampled in the superficial layer i.e., the 0–0.20 m layer), revealed relationships between the soil variables. More specifically, two principal components (CP1 and CP2) explained 84.40%, 88.50%, 82.79%, and 82.53% of the total data variance for the 0–0.10, 0.10–0.20, 0.20–0.30,and 0.30–0.50 m layers, respectively. Variables with weight coefficients > 0.3 were considered relevant in the PCA (Table 5).

All layers in area CLI4 were associated with positive CP1values, with the TN and NS variables displaying particularly high scores. However, area NT14 was associated with negative values for CP1, with the most notable variables being the C/N ratio for all layers and POC for the 0–0.10, 0.10–0.20, and 0.20–0.30 m layers (Figures 4A, B, C and D).

Nonetheless, apart from the 0.20–0.30 m layer, area FOREST displayed some similar results; the FOREST area was associated with positive CP2 values, while conversely, area CLI2 was associated with negative CP2 values, largely as a result of a negative humin concentration (Figures 4A, B, C and D).

In the surface layer, no attribute was associated with positive values for CP2, which was defined by the FOREST area. Thus, at the depth of 0–0.10 m, the highest values of N, C, its fractioning (chemical and physical), and stocks were all related to the agricultural management strategies (Figure 4A).

Table 4 - Microbial carbon biomass, metabolic quotient, basal respiration, and metabolic quotient in the surface layer (0–0.20 m) of an Ultisol under different conservation management systems in Brejo, MA, Brazil.

Area	CBM	qMIC	Respiration	qCO_2
	mg kg $^{-1}$ of soil	CBM:TOC	mg C-CO_2 g^{-1} day^{-1}	mg C-CO_2 g^{-1} mg CBM day^{-1}
CLI2	81.6 ab	2.3 ab	14.8 bc	0.6 a
CLI4	75.6 ab	2.0ab	19.1ab	0.1c
CLI8	112.5 a[1]	3.5 a	17.6 ab	0.1 c
NT14	107.9 a	3.6 a	24.3 a	0.2 b
FOREST	50.6 b	1.8 b	16.2 b	0.2 b

CLI2 = no-till soy/no-till twice with history of crop-livestock integration, CLI4 = no-till soy/no-till with history of crop-livestock integration system once for 4 years prior to soil collection, CLI8 = no-till soy/no-till with history of crop-livestock integration system once for 8 years prior to soil collection, NT14 = no-till soy/no-till for 14 years and no history of animal inputs, FOREST = area under native Cerrado vegetation, CBM = soil microbial biomass carbon, SBM = soil microbial biomass nitrogen, qMIC = microbial quotient, Respiration = basal respiration, qCO_2 = metabolic quotient. [1] Means followed by the same letter in the column do not have differences between them based on the Tukey's test (5%).

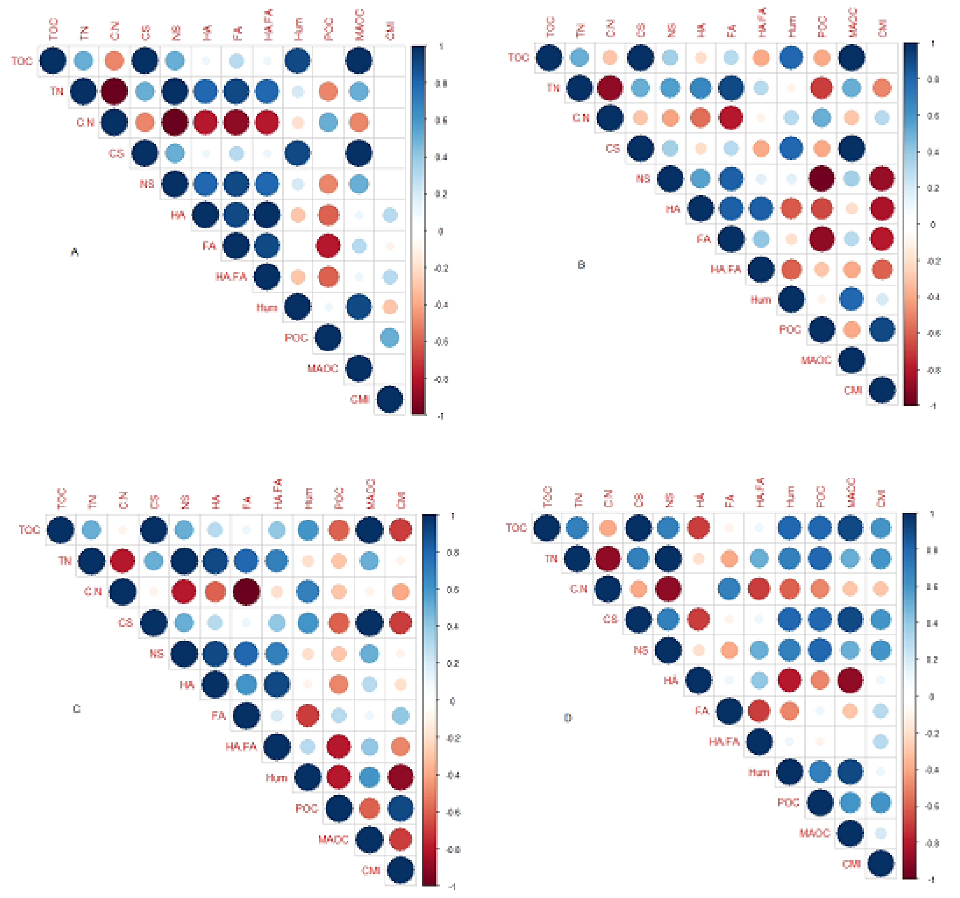

Figure 3 - Correlation of variables studied in areas under different conservation management systems, for the (A) 0–0.1 m, (B) 0.10–0.20 m, (C) 0.20–0.30 m, and (D) 0.30–0.50 m layers of an Ultisol in Brejo, MA, Brazil.

DISCUSSION

The higher contents and stocks of C and N, and C/N ratio observed in areas under the CLI system compared to areas under exclusive soil management in NT (Table 2), is likely attributed to the intercropping of corn with *Urochloa*, which can lead to a greater amount of cultural residues in the soil (MATEUS et al., 2020). This affect is particularly prevalent in *Urochloa* pasture, a crop which causes a considerable addition of organic matter to the soil, ultimately increasing C and N contents (SIGNOR et al., 2018). The productivity of forage dry mass when *Urochloa* is intercropped with corn, depending on the cut, in fall/winter can enter the system at approximately 1.6–1.7 t/ha in the first cut and 3.9–4.2 t/ha in the second cut (MATEUS et al., 2020).

Furthermore, the higher values of accumulated C in the CLI system, independent of the time of adoption, can be justified by the increment of C in depth. The land use change provided gains or stability for soil C at up to 0.5 m depth, a finding which can be justified by the co-dependence verified in the correlation results.

The correlations presented here allow several other inferences to be made. Firstly, there was a high correlation between TOC and MAOC in all layers, which also provided high correlations with the stock of C, this suggested that the stabilization of soil organic matter (SOM) in the long term occurs by increasing the levels of MAOC (LIMA et al., 2016). This result indicates that in the edaphoclimatic conditions of eastern MA, the accumulation of TOC depends on the increase in MAOC content. Therefore,

Table 5 - Coefficient weights (eigenvectors), eigenvalues and variance explained by each principal component (CP1 and CP2) of C, N, C/N ratio, chemical and physical fractionation, stocks and CMI concentration of an Ultisol under different conservation management systems in Brejo, MA, Brazil.

Attributes	--------0-0.1 m--------		---------0.1-0.2 m------		--------0.2-0.3 m-------		---------0.3-0.5 m------	
	CP1	CP2	CP1	CP2	CP1	CP2	CP1	CP2
TOC	0.25	-0.40	0.27	-0.35	0.28	-0.16	0.34	-0.22
TN	0.39	-0.01	0.36	-0.02	0.34	0.26	0.36	0.17
C/N	-0.32	-0.27	-0.29	-0.24	-0.22	-0.40	-0.28	-0.32
CS	0.24	-0.41	0.27	-0.35	0.30	-0.16	0.34	-0.26
NS	0.39	-0.01	0.35	-0.06	0.34	0.27	0.36	0.16
HA	0.35	0.19	0.26	0.34	0.35	-0.03	-0.07	0.56
FA	0.35	0.24	0.37	0.10	0.30	0.32	-0.32	-0.06
HA/FA	0.35	0.19	0.10	0.41	0.30	-0.10	0.20	0.40
Hum	0.08	-0.50	0.02	-0.49	-0.40	-0.53	0.28	-0.37
POC	-0.18	-0.26	-0.38	-0.06	-0.28	0.28	0.17	0.07
MAOC	0.27	-0.37	0.29	-0.33	0.32	-0.20	0.35	-0.21
CMI	0.00	-0.10	-0.28	-0.23	-0.25	0.37	0.24	0.25
Eigenvalues	6.44	3.68	6.73	3.88	6.35	3.57	6.96	2.93
Total variance (%)	53.71	30.68	56.16	32.34	52.98	29.80	58.08	24.45
Cumulative variance (%)	53.71	84.40	56.16	88.50	52.98	82.79	58.08	82.53

TOC = total organic carbon, TN = total nitrogen, C/N = carbon nitrogen ratio, CS = carbon stock, NS = nitrogen stock, HA = humic acid fraction, FA = fulvic acid fraction, HA/FA = humic acid fulvic acid fraction ratio, Hum = humin, POC = particulate organic carbon, MAOC = mineral associated organic carbon, CMI = carbon management index.

it is possible to infer that the stabilization of SOM is fundamental for an increase in TOC content.

The HA/FA ratio observed in the 0–0.20 m layer among all the studied areas was higher than the average value of 1.2 for the Cerrado biome (SANTOS et al., 2013). This finding is important, because an increase in the HA/FA ratio allows the chemical quality of the soil to improve, as a higher HA/FA ratio contributes to a greater cation exchange capacity, it allows the formation of complexes with various metal ions and acts as a buffer for chemical reactions (ROSA et al., 2017). In addition, the higher humin content found, especially in areas under the CLI, corroborate with what has been observed in tropical soils (ZHU et al., 2014). Furthermore, the higher humin and MAOC values observed in areas CLI2 and CLI4 (Table 3) likely result from the more recent intercropping of maize with pasture in area CLI8, these are plants that release large amounts of organic material via rhizo deposition (CARMO et al., 2012).

The similar CBM and qMIC values reported among the native vegetation and areas with different management strategies, indicates the efficiency of both the CLI system and the strategy applied in area NT14, in the immobilization of the available C in microbial cells in the soil (DADALTO et al., 2015). However, in area CLI2, the higher qCO_2value is likely due to the quality of the organic matter, which has a high C/N ratio (Table 2) and lower C lability (Table 4). This may have generated microbial stress during its degradation, which along with the fact that the recent soil mobilization promotes exposure of organic matter to oxidation and mineralization, may have ultimately allowed a greater influx of energy (C) through the CBM (LACERDA et al., 2013).

TOC correlated best with the other variables and considering that the PCA showed a distinction between the systems studied, it suggests that the CLI system is differentiated in relation to NT14 and FOREST (Figure 1).

The recent introduction of pastures and animals in the off-season of soybean cultivation in areas CLI2 and CLI4 were likely the main factors that distinguished these areas from area NT14. Pastures have high dry biomass production capacity and root mass density (SARTO et al., 2020). Thus, the use of *Urochloa* in the CLI system promotes better soil

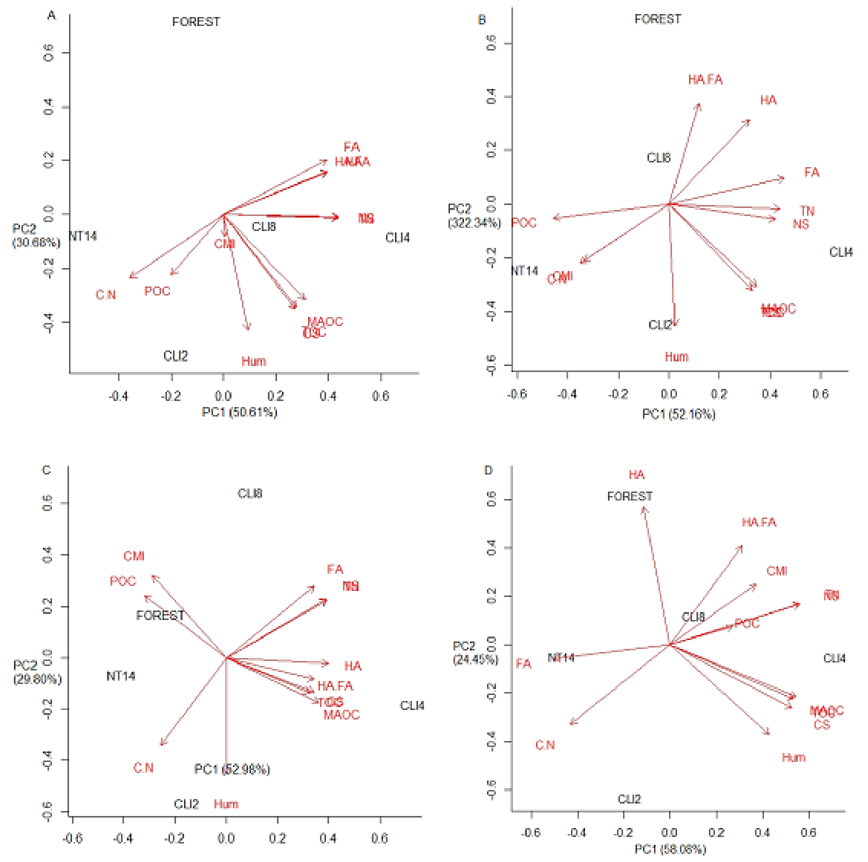

Figure 4 - Biplot of the studied variables under different conservation management systems for the (A) 0–0.1 m, (B) 0.10–0.20 m, (C) 0.20–0.30 m, and (D) 0.30–0.50 m layers of an Ultisol in Brejo, MA, Brazil.

chemical quality, which contributes to the C stock and fractionation, and the soil CMI (SOARES et al., 2019); in addition, the added material contributed by animal excrement also improved soil quality by raising C and N contents (GUESMI et al., 2019).

In addition to the above, it is worth noting that the distance observed between the NT14 and CLI areas is due to the type and quality of the C present in each environment, while the CLI and the NT14 area was more associated with particulate organic C (Figure 3), that is, more easily degraded, it was also the area that showed higher C lability (Table 3).

Consideration of the effect of the management strategy adopted and the C reported in the soil over time reveals an interesting finding, 14 years after the removal of native vegetation for agricultural exploration, area NT14 showed a 4.7 t/ha increase in C, which translates to an average gain of 0.33 t/ha/year; area CLI8, however, showed a 14.5 t/ha increase in C, which represents a gain of 1.03 t/ha/year. In other words, the exclusive use of soybean with millet under the NT strategy does not increase the C in the system in the same quantity as in the CLI system, which uses crop rotation, intercropping of corn with forage, and the input of animals, is adopted. Although, the 112.3 t/ha increase in C content observed in area CLI2 was higher than the increases observed in areas NT14 and CLI8, it was still 8.7 t/ha lower than the increase in C content observed in area CLI4 (121.0 t/ha), this is despite the sub soiling that occurred, with aggregate breakage exposing the physically protected C to microbial oxidation (MELO et al., 2016), which corroborates with the higher rate of qCO_2 (Table 4). These results reveal that the increase in soil C is easily influenced by management strategies, even in conservation systems.

Maize intercropped with *Urochloa* contribute residues to the surrounding system that have a high C/N ratio and high lignin quantity compared to the residues derived from soybean/millet crops, which allows the straw greater perenniality (GARCIA et al., 2014; SOUSA et al., 2019). In this sense, when observing the trends of the results presented here, which were processed through uni and multivariate statistical analyses showed that the area without recent history of soil tillage which had the CLI system introduced 4 years ago, was most efficient in increasing soil C (121 t/ha) and N (3.4 t/ha) (Table 2), since it is linked to the largest number of studied C and N response variables (Figure 4).

CONCLUSION

CLI adopted in typical distro cohesive yellow ultisol in the Cerrado of eastern Maranhão incorporates higher soil C and N contents and stocks compared to the NT system.

Areas under the CLI system with adoption times of 2, 4, and 8 years ago, increase the C stock in soil up to 0.5 m in depth by 14.5%, 23.4%, and 10.0%, respectively, in relation to the NT system with soybean and millet.

The NT system with soybean and millet has lower N stocks in soil up to 0.5 m in depth, in relation to the native Cerrado and areas managed by the CLI system. Humin is the predominant soil fraction in the studied areas, with higher concentrations being associated with areas managed by the CLI system. Higher concentrations of C fraction associated with minerals are related to the recent adoption of the CLI system. The NT and CLI conservationist agricultural management systems presented CMI percentages above 100% for soil up to 0.20 m in depth. In conservation management, tillage history alters C biomass and microbiological activity.

ACKNOWLEDGEMENTS

The authors wish to thank the Empresa Brasileira de Pesquisa Agropecuária (Embrapa) for supporting this research (Project No. 22.13.11.004.00.03) and Barbosa Fam for all support in field and information. “And was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brasil – Finance code 001.”

DECLARATION OF CONFLICT OF INTEREST

We have no conflict of interest to declare.

AUTHORS' CONTRIBUTIONS

All authors critically reviewed the manuscript and approved the final version.

REFERENCES

ALEF, K. et al. Phosphatase activity. In: ALEF, K; NANNIPIERI, P. (eds.) **Methods in applied soil microbiology and biochemistry**. Academic Press, 1995, p.335-344.

ANDERSON, J. P. E.; DOMSCH K. H. Ratios of microbial biomass carbon to total organic carbon in arable soils. **Soil Biology and Biochemistry**, v.21, n.4, p.471-479, 1989. Available from: <https://www.sciencedirect.com/science/article/abs/pii/003807178990117X>. Accessed: Aug. 18, 2020. doi: 10.1016/0038-0717(89)90117-X.

ANDERSON, T. H.; DOMSCH, K. H. Application of eco-physiological quotients (qCO2 and qD) on microbial biomasses from soils of different cropping histories. **Soil Biology and Biochemistry**, v.22, n.2, p.251-255, 1990. Available from: <https://www.sciencedirect.com/science/article/abs/pii/003807179090094G>. Accessed: Aug. 18, 2020. doi:1016/0038-0717(90)90094-G.

BAYER, C. et al. Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in Southern Brazil. **Soil and Tillage Research**, v.54, p.101-109, 2000. Available from: <https://www.sciencedirect.com/science/article/pii/S0167198700000908>. Accessed: Jun. 18, 2021. doi: 10.1016/S0167- 1987(00)00090-8.

BENITES, V.M. et al. **Extração e fracionamento quantitativo de substâncias humicas do solo**: um procedimento simplificado de baixo custo. Rio de Janeiro: Ministry of Agriculture, Livestock and Supply, 2003. 7p.

BLAIR, G. J.; LEFROY, B.; LISLE, L. 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**, v.46, n.7, p.1459-1466, 1995. Available from: <https://www.publish.csiro.au/cp/AR9951459>. Accessed: Mar. 28, 2021. doi: 10.1071/AR9951459.

BONETTI, J. de A. et al. Influence of integrated crop production system on soil and productivity of soybean and brachiaria. **Pesquisa Agropecuária Tropical**, v.45, n.1, p.104-112, 2015. Available from: <https://www.scielo.br/pdf/pat/v45n1/1983-4063-pat-45-01-0104.pdf>. Accessed: Mar, 30, 2021.

BREMNER, J. M.; MULVANEY, C. S. Nitrogen total. In: Page, A.L. (ed.) **Methods of soil analysis**. Part 2. Madison: American Society of Agronomy, 1982. p.595-624.

CAMBARDELLA, C. A.; ELLIOT, E.T. Particulate soil organic-matter changes across a grassland cultivation sequence. **Soil Science Society of American Journal**, v.56, n.3, p.777-783, 1992. Available from: <https://acsess.onlinelibrary.wiley.com/doi/epdf/10.2136/sssaj1992.03615995005600030017x>. Accessed: Aug. 18, 2020. doi: 10.2136/sssaj1992.03615995005600030017x.

CARMO, F. F.et al. GRANULOMETRIC FACTIONS OF ORGANIC MATTER IN LATOSSOLO UNDER DIREAR PLANTING WITH GRAMMES. **Bioscience Journal**, v.28, n.3, p.420-431, 2012. Available from: <http://www.seer.ufu.br/index.php/biosciencejournal/article/view/12351>. Accessed: Aug. 18, 2020.

CHIODEROLI, C. A. et al. Atributos físicos do solo e produtividade de soja em sistema de consórcio milho e braquiária. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.16, n.1, p.37-43, 2012. Available from: <https://www.scielo.br/scielo.php?pid=S1415-43662012000100005&script=sci_abstract&tlng=pt>. Accessed: Mar. 31, 2021.doi:10.1590/S1415-43662012000100005.

DADALTO, J. P. et al. Soil preparation system and its influence on microbial activity. **Agricultural Engineering**, v.35, n.3, p.506-513. 2015. Available from: <https://www.scielo.br/pdf/eagri/v35n3/1809-4430-eagri-35-3-0506.pdf>. Accessed: Aug. 18,2020. doi: 10.1590/1809-4430-Eng.Agric.v35n3p506-513/2015.

DANTAS, J. S. et al. Gênese de solos coesos do leste maranhense: relação solo-paisagem. **Revista Brasileira de Ciência Solo**, v.38, n.4, p.1039-1050. 2014. Available from: <https://www.scielo.br/scielo.php?pid=S0100068320140004000001&script=sci_abstract&tlng=pt>. Accessed: Aug. 18, 2020. doi: 10.1590/S0100-06832014000400001.

DIEKOW, J. et al. Carbon and nitrogen stocks in physical fractions of a subtropical Acrisol as influenced by long-term no-till cropping systems and N fertilisation. **Plant and Soil, Dordrecht**, v.268, p.319-328, 2005. Available from: <https://link.springer.com/article/10.1007/s11104-004-0330-4>. Accessed: Mar. 29, 202. doi: 10.1007/s11104-004-0330-4.

DONAGEMMA, G. K. et al. Characterization, agricultural potential and management perspectives of light soils in Brazil. **Pesquisa Agropecuária Brasileira**, v.51, n.9, p.1003-1020, 2016. Available from: <https://www.scielo.br/pdf/pab/v51n9/pt_0100-204X-pab-51-09-1003.pdf>. Accessed: Aug. 18, 2020. doi: 10.1590/s0100-204x2016000900001.

ELLERT, B. H.; BETTANY, J. R. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. **Canadian Journal of Soil Science**, v.75, p.529-538, 1995. Available from: <https://cdnsciencepub.com/doi/abs/10.4141/cjss95-075>. Accessed: Jun. 14, 2021.doi:10.4141/ cjss95-075.

FERREIRA, C dos R. et al. Dynamics of soil aggregation and organic carbon fractions over 23 years of no-till management. **Soil and Tillage Research**, v.198, p.104533-104542, 2020. Available from: <https://www.sciencedirect.com/science/article/pii/S016719871931284X>. Accessed: Mar. 30, 2021. doi: 10.1016/j.still.2019.104533.

FERREIRA, D. F. Sisvar: a Guide for its Bootstrap procedures in multiple comparisons. **Ciência e Agrotecnologia**, v.38, n.2, p.109-12,2014. Available from: <https://www.scielo.br/scielo.php?script=sci_arttext&pid=S1413-70542014000200001>. Accessed: Aug. 18,2020. doi:10.1590/S1413-70542014000200001.

GARCIA, C. M de P. et al. Decomposition of forage straw as a function of nitrogen fertilization after intercropping with corn and soybean productivity in succession. **Bragantia**, v.73, n.2, p.143-152, 2014. Available from: <https://www.scielo.br/pdf/brag/v73n2/aop_bragantia_0050.pdf>. Accessed: Mar. 31, 2021. doi: 10.1590/brag.2014.016.

GATTO, A. et al. CARBON STORAGE IN SOIL AND BIOMASS IN EUCALYPT PLANTATIONS. **Revista Brasileira de Ciência do Solo**, v.34, p.1069-1079, 2010. Available from: https://www.scielo.br/j/rarv/a/bw6zdw4sxbs9VzhgpqDd3qB/abstract/?lang=pt>. Accessed: Jun. 18, 2021.doi:0.1590/S0100-67622011000500015.

GAZOLLA, P. R. et al. Fractions of soil organic matter under pasture, no-tillage system and crop-livestock integration. **Semina: Agricultural Sciences**, v.36, n.2, p.693-704, 2015.Available from: <http://www.uel.br/revistas/uel/index.php/semagrarias/article/viewFile/16159/16108>. Accessed: Aug. 18, 2020. doi: 10.5433/1679-0359.2015v36n2p693.

GUESMI, H. et al. Crop-livestock integration under conservation agriculture system. **Journal of New Sciences**, v.65, n.1, p.4061-4065, 2019. Available from: <file:///C:/Users/ASUS/Downloads/JNS_AB_65_1%20(1).pdf>. Accessed: Aug. 18, 2020.

INMET - National Institute of Meteorology: **Meteorological database for teaching and research**. 2019. Available from: <http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep>. Accessed: Dec. 14, 2019.

ISLAM, K. R.; WEIL R. R. A rapid microwave digestion method for colorimetric measurement of soil organic carbon. **Communications in Soil Science and Plant Analysis**. v.29, n.15, p.2269 - 2284, 1998. Available from: <https://www.tandfonline.com/doi/abs/10.1080/00103629809370110>. Accessed Aug. 18, 2020. doi: 10.1080/00103629809370110.

LACERDA, K. A. P. et al. Organic carbon, biomass and microbial activity in an Oxisol under different management systems. **Amazonian Journal of Agricultural and Environmental Sciences**, v.56, n.3, p. 249-254, 2013. Available from: <https://www.cabdirect.org/cabdirect/abstract/20133341002>. Accessed: Aug. 18, 2020. doi: 10.4322 / rca.2013.036.

LIMA, C. E. P. et al. Organic carbon compartments in Latosol cultivated with vegetables under different managements. **Pesquisa Agropecuária Brasileira**, v.51, n.4, p.378-387, 2016. Available from: <https://www.scielo.br/scielo.php?pid=S0100-204X2016000400378&script=sci_arttext>. Accessed. Mar, 30, 2021. doi: 10.1590/S0100-204X2016000400011.

MANLY, B. F. J. **Multivariate statistical methods**: an introduction. Porto Alegre: Bookman, 2008. 229 p.

MATEUS, G. P. et al. Corn intercropped with tropical perennial grasses as affected by sidedress nitrogen application rates. **Nutrient Cycling in Agroecosystems**. Available from: <https://link.springer.com/article/10.1007/s10705-019-10040-1>. Accessed: Jun. 10, 2021. doi: 10.1007/s10705-019-10040-1.

MAZZUCHELLI, R. de C. L. et al. Changes in Soil Properties and Crop Yield as a Function of Early Desiccation of Pastures. **Journal of Soil Science and Plant Nutrition**, v.20, p.840-848, 2020. Available from: <https://link.springer.com/article/10.1007/s42729-019-00169-x>. Accessed: Jun. 20, 2021. doi: 10.1007/s42729-019-00169-x.

MELO, G. B. et al. Stocks and fractions of soil organic matter under no-till and conventional cabbage systems. **Pesquisa Agropecuária Brasileira**, v.51, n.9, p.1511-1519, 2016. Available from: <https://www.scielo.br/j/pab/a/mwNhfd5dGqxQv3bkZG7jccx/?lang=pt&format=pdf>. Accessed: Jun. 18, 2021.

MUKAKA, M. M. Statistics corner: A guide to appropriate use of correlation coefficient in medical research. **Malawi Medical Journal**, v.24, n.3 p.69-71, 2012. Available from: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3576830/>. Accessed: May, 12, 2020.

R CORE TEAM (2017). **R: A language and environment for statistical computing**. R Foundation for Statistical Computing, Vienna, Austria. URLhttps://www.R-project.org/. Available from: <http://finzi.psych.upenn.edu/R/library/dplR/doc/intro-dplR.pdf>. Aug. 18, 2020.

RESENDE, J. M. et al. Spatial variability of attributes of cohesive soils in eastern maranhense. **Revista Brasileira de Ciência do Solo**, v.38, p.1077-1090, 2014. Available from: <https://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-06832014000400004>. Accessed: Mar. 29, 2020. doi: 10.1590/S0100-06832014000400004.

RIBEIRO, L. da S. et al. Spatial variability of physical attributes of cohesive soil under conventional and no-till management systems. **Pesquisa Agropecuária Brasileira**, v.51, n.9, p.1699-1702, 2016. Available from: <file:///C:/Users/ASUS/Downloads/22446-114236-1-PB.pdf>. Accessed: Aug. 18, 2020. doi: 1590/s0100-204x2016000900071.

ROSA, D.M, et al. Humic substances of soil cultivated with cover crops in rotation with corn and soybean. **Agronomic Science Journal**, v.48, n.2, p.221-230, 2017. Available from: <https://www.scielo.br/scielo.php?pid=S1806-66902017000200221&script=sci_arttext&tlng=pt>. Accessed: Aug. 18, 2020. doi: 10.5935/1806-6690.20170026.

SANTOS, L.L. et al. Partition of humic substances in brazilian soils. **RevistaBrasileira de Ciência do Solo**, v.37, n.4, p.95-968, 2013. Available from: <https://www.scielo.br/scielo.php?pid=S0100-06832013000400013&script=sci_arttext>. Accessed: Aug. 18, 2020. doi: 10.1590/S0100-06832013000400013.

SARTO, M. V. M. et al. Soil microbial community and activity in a tropical integrated crop-livestock system. **Applied Soil Ecology**, v.145, n.103350, p.2-11, 2020. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0929139318309909>. Accessed: Aug. 18, 2020. doi: 10.1016/j.apsoil.2019.08.012.

SIGNOR, D. et al. Quantity and quality of soil organic matter as a sustainability index under different land uses in Eastern Amazon. **Sientia Agricola**, v.75, n.3, p.225-232, 2018. Available from: <https://www.scielo.br/scielo.php?pid=S0103-90162018000300225&script=sci_arttext>. Accessed, Aug. 18, 2020. doi: 10.1590/1678-992x-2016-0089.

SILVA, G.N. et al. Management systems and soil use on fractions and stocks of organic carbon and total nitrogen in cerrado latosol. **Bioscience Journal**, v.32, n.6, p.1482-1492, 2016. Available from: <http://www.seer.ufu.br/index.php/biosciencejournal/article/view/32923>. Accessed: Aug. 18, 2020. doi: 10.14393/BJ-v32n6a2016-32923.

SKORUPA, L. A.; MANZATTO, C. V.(Ed.).**Crop-livestock-forest integration systems in Brazil**: regional strategies for technology transfer, adoption and impact assessment.Brasília: DF, Embrapa, 2019. 471 p. il. color.

SOARES, D. dos S. et al. How diversity of crop residues in long-term no-tillage systems affect chemical and microbiological soil properties. **Soil & Tillage Research**, v.194, n.104316, p.1-12, 2019. Available from: <https://www.sciencedirect.com/science/article/pii/S0167198719300248>. Accessed: Aug. 18, 2020. doi: 10.1016/j.still.2019.104316.

SOUSA, D.M. G.; LOBATO, E. eds. **Cerrado: Correção do solo e adubação**. Planaltina: Embrapa Cerrados, 2004. 416p.

SOUSA, D. C. et al. Dry Mass Accumulation, Nutrients and Decomposition of Cover Plants. **Journal of Agricultural Science**, v.11, p.152-160, 2019. Available from: <http://www.ccsenet.org/journal/index.php/jas/article/view/0/39088>. Accessed: Mar. 29, 2021. doi:10.5539 /jas.v11n5p152.

SOUSA, H. M. et al. Dynamics of soil microbiological attributes inintegrated crop-livestock systems in the cerrado-amazônia ecotone. **Revista Caatinga**, v.33, n.1, p.09-20, 2020. Available from: <https://www.scielo.br/scielo.php?pid=S1983-21252020000100009&script=sci_arttext>. Accessed: Aug. 18, 2020. doi:10.1590/1983-21252020v33n102rc.

SWIFT, R.S. Organic matter characterization. In: SPARKS, D. L. **Methods of soil analysis**. 5. ed. Madison: SSSA, 1996. Cap. 35, p.1011-1069.

TAKAHASHI, K. et al. Technology adoption, impact, and extension in developing countries' agriculture: a review of the recent literature. **Agricultural Economics**, v.51, n.1, p.1-50, 2019. Available from: <https://onlinelibrary.wiley.com/doi/abs/10.1111/agec.12539>. Accessed: Aug. 18, 2020. doi: 10.1111/agec.12539.

TEIXEIRA, et al. **Manual de métodos de análise de solos**. 4.ed. Rio de Janeiro: EMBRAPA, 2017. 574p.

VIEIRA, F. C. B. et al. Carbon management index basedon physical fractionation of soil organic matter in aAcrisolunder long-term no-till cropping systems. **Soil and Tillage Research**, v.96, p.195-204, 2007. Available from: <https://www.sciencedirect.com/science/article/pii/S0167198707001110>. Accessed: Mar. 30, 2021. doi:10.1016/j.still.2007.06.007.

VIEIRA, J. M. et al. Contribution of amorphous material in the genesis of cohesive horizons in Argissolos from the Coastal Tablelands of Ceará. **Revista Ciência Agronômica**, v.43, n.4, p.623-632, 2012. Available from: <http://ccarevista.ufc.br/seer/index.php/ccarevista/article/view/1734>. Accessed: Aug. 19, 2020.

YOEMANS, J. C.; BREMNER, J. M. A rapid and precise method for routine determination of organic carbon in soil. **Communications in Soil Science and Plant Analysis**, v.19, n.13, p.1467-1476, 1988. Available from: <https://www.tandfonline.com/doi/abs/10.1080/00103628809368027>. Accessed: Aug. 19, 2020. doi: 10.1080/00103628809368027.

ZHU, L. et al. Effects of different tillage and straw return on soil organic carbon in a rice-wheat rotation system. **PLoS One**, v.9, n.2, p.1-7, 2014. Available from: <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0088900>. Accessed: Aug. 19, 2020. doi: 10.1371/journal.pone.0088900.