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Soil Organic Matter and Aggregate Stability in Soybean, Maize and Urochloa Production Systems in a Very Clayey Soil of the Brazilian Savanna

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Abstract: Forage grasses cultivation in production system with soybean and maize is an alternative to improve tropical weathered soils quality in Brazil. The aim of the study was to evaluate the effects in the production systems involving cultivation of *Urochloa brizantha* cv. Piatã, in monoculture or in succession with soybean and maize crops, on organic matter and structuring of soil in Brazilian savanna. The experiment was implemented in the 2010/2011 season. The treatments consisted of nine production systems and a native forest (savanna) as a reference area. In March 2017, soil sampling was carried out for C and N analysis, physical and chemical fractionation of SOM and aggregate stability. Production systems influenced total organic carbon (TOC) and aggregate stability, mainly in the surface layers, leading to changes in SOM quality. TOC was 31% lower in monoculture soybean production system, when compared to native savanna area, in the 0.00–0.20 m layer. The agricultural production systems influence organic matter quality and soil aggregates stability. For the Brazilian savanna conditions, grain cultivation systems under no-tillage that integrate *Urochloa brizantha* cv. Piatã contribute to the soil quality improvement. Soybean monoculture generally provides worse soil quality indices compared to other agricultural production systems.

Keywords: typic haplorthox; soil organic carbon; no-tillage system; *Glycine max*; *Zea mays*; *Urochloa brizantha*

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1. Introduction

Conservation agriculture has been based on the search for soil quality improvement aiming at the sustainability of the production system, maintaining and/or increasing grain and forage yield [1,2]. A no-tillage system (NT) is the main agricultural management technique related to soil conservation, and its introduction into agriculture was one of the greatest advances in the Brazilian production process [3]. With the NT, it was possible to expand the cultivation to the tropical region in Brazil, and it was possible to increase the efficiency of the second crop production (fall–winter crop). In the Brazilian savanna, the main challenge for the establishment of NT is the difficulty in maintaining plant residues on the soil surface due to high temperatures and the dry period, which makes it difficult to implement an off-season or winter crop, compromising crop rotation and increasing soil organic matter in these regions [4].

Covering species, especially grasses, play an important role in the search for technical and economic viability of NT in different regions of Brazil, especially in tropical regions, due to the difficulty of production in the off-season and the rapid decomposition of the accumulated biomass [5,6], leaving the soil unprotected [7]. Intercropping of perennial forages with maize is an alternative for establishing ground cover crops, with the objective of producing maize and soybean grains in NT, keeping the soil permanently covered [8–10].

In addition to the high production and persistence of straw, perennial forages have been considered to improve the soil environment. The high contribution of aerial and root residues results in an increase in the soil organic matter content (SOM), which contributes to the formation of stable aggregates, due to the cementing and binding action that SOM exerts on the soil mineral particles [7,11–13]. Salton et al. [14] observed that systems with the use of forages for straw production, compared to those exclusively with crops, showed higher levels of C in the soil, which must be associated with the high input of plant material commonly provided by pastures.

SOM has an important role in the physical, chemical, and biological soil properties and, as a result, the study of its labile and recalcitrant fractions has been used as a soil quality indicator [15,16]. SOM analysis does not always detect the effects promoted by changes in management systems. One of the ways to improve the understanding of this issue is through the study of total organic carbon compartments, which are more sensitive to soil management and is characterized one of the better indicators of this dynamics [17].

Thus, the aim of this research was to evaluate the aggregates stability and soil organic carbon compartments in different production systems conducted in a long-term experiment under the no-tillage (NT) in the Brazilian savanna, involving the cultivation of *Urochloa brizantha* cv. Piatã in monoculture or in succession with soybean and maize crops.

2. Materials and Methods

2.1. Site Description, History and Experimental Area Characterizationubsection

The experiment was carried out in an experimental area belonging to Embrapa Maize and Sorghum in the Sete Lagoas, Minas Gerais, Brazil (19°28′ S; 44°15′ W and 732 m). Soil of the experimental area is a Typic Haplorthox [18], very clayey texture (Table 1), subdeciduous cerrado phase and smooth wavy relief [19]. Before the implementation of this experiment, the area had been already conducted in NT since 1995 with interspersed sowing of maize and soybeans. Table 1 shows the granulometric and chemical characteristics of the experimental area in a collection carried out in the area adjacent to the experiment (native savanna) in March 2017.

Table 1. Chemical and granulometric soil analysis of the experimental area in March 2017.

Soil Depth	PH	P_{resin} [1]	H + Al	Ca	Mg	K	SB	CTC	V	Sand [2]	Silt [3]	Clay [4]
m	$CaCl_2$	mg dm^{-3}			mmol$_c$ dm^{-3}				%		g kg^{-1}	
0.00–0.20	4.0	5.0	114	40	8	1.2	48	162	30	117	113	770
0.20–0.40	3.6	2.0	123	15	5	0.9	21	144	14	110	116	774

[1] P determination using ion exchange resin; [2] particles > 0.05 mm and <2 mm; [3] particles > 0.002 mm and <0.05 mm; [4] particles < 0.002 mm.

2.2. Treatments and Experimental Design

Experimental design was carried out in completely randomized blocks, with three replications. Treatments consisted of nine cropping systems, plus a control with native forest (Table 2 and Figure 1). Each plot was 12 m wide and 14 m long (168 m^2) with lanes between plots and between blocks of 2.5 m. Production systems were implemented in the 2010/11 crop year and conducted for seven years. Before the implementation of this experiment, the area had been already managed in NT since 1995, with intercrop sowing of maize and soybeans in the summer and fallow in the off-season.

Table 2. Treatments description.

Treatments	Production System	Code
T1	Single Maize in annual succession (monoculture)	M
T2	Maize intercropped with *U. brizantha* cv. Piatã in annual succession	MP
T3	Soybean in annual succession (monoculture)	S

Table 2. *Cont.*

Treatments	Production System	Code
T4	*U. brizantha* cv. Piatã pasture implanted in single cultivation	P
T5	Maize + Piatã intercropped and Soybean in annual rotation	MP/S
T6	Sequence of Maize + Piatã intercropping and Piatã pasture in annual rotation	MP/P
T7	Sequence of Maize + Piatã intercropping and Piatã pasture for two years	MP/P/P
T8	Sequence of Maize + Piatã intercropping, Piatã pasture and Soybean in annual rotation	MP/P/S
T9	Sequence of Soybean, Maize + Piatã intercropping and Piatã pasture for two years in rotation	S/MP/P/P
T10	Native savanna (reference for soil parameters)	NS

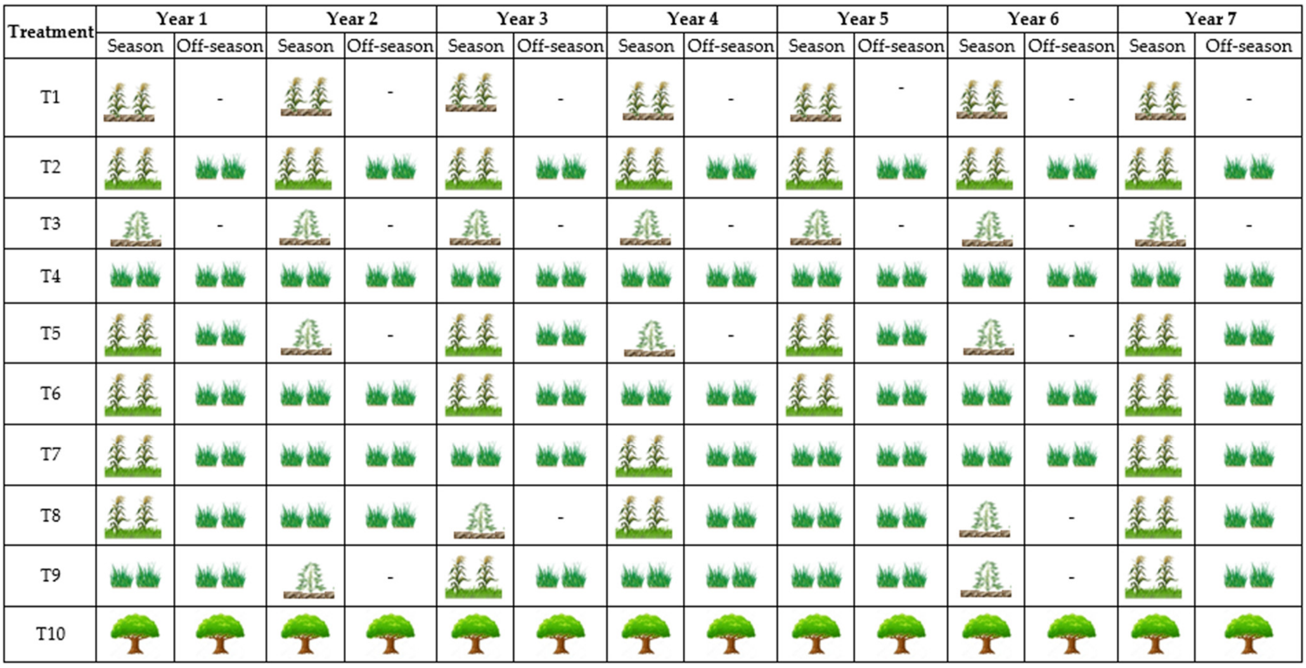

Figure 1. Crop sequence representation referring to the 9 treatments in the 7 agricultural years between the 2010/11 and 2016/2017 seasons. Year 1: 2010/11 season; Year 2: 2011/12 season; Year 3: 2012/13 season; Year 4: 2013/14 season; Year 5: 2014/15 season; Year 6: 2015/16 season; Year 7: 2016/17 season.

2.3. Conducting the Experimental Area

Sowing and management of the treatments, with the exception of system 4, Piatã pasture (*Urochloa brizantha* cv BRS Piatã), were carried out mechanically from the first year of implantation, with soybean and maize being sown with 0.5 m spacing between rows. For maize and soybean crops, an average of 3.5 and 15 seeds m^{-1} were used over the years, respectively, with 360 kg ha^{-1} of 08-28-16 NPK for maize and 315 kg ha^{-1} of formulated 06-30-16 NPK for soybeans.

In the V2 stage of maize development, topdressing fertilization was carried out in maize with 112.5 kg ha^{-1} of N via urea. In the maize plots intercropped with grass, 4.0 kg ha^{-1} of viable pure seeds of *U. brizantha* cv. Piatã were treated with fipronil and mixed with fertilizer at the time of maize sowing. Management was always carried out according to the need and current recommendations.

In the plots with Piatã grass, throughout the years, the management was carried out simulating hay production; that is, when the plants, for the most part, reached 0.5 m in height, the cut was carried out at 0.2 m in height, and the material was then removed from the area.

2.4. Soil Sampling

Samples were sampled in March 2017. For analysis of total organic carbon (TOC) and total nitrogen (TN) and the physical and chemical fractionation of carbon, the deformed soil samples were collected using a soil probe at three random points in each plot at depths of 0.00–0.10, 0.10–0.20 and 0.20–0.40 m. In the laboratory, the samples were air-dried, crushed and passed through a 2 mm sieve to obtain air-dried soil.

For the aggregate stability analysis, trenches measuring 0.30 m $\times$ 0.30 m $\times$ 0.30 m were opened in each experimental plot. In each trench, at a depth of 0.00–0.10 m, two monoliths were removed (one on each side of the trench) with approximate dimensions of 0.10 m in height by 0.20 m in length and 0.10 m in width, which were then placed in plastic containers to avoid crumbling.

2.5. Soil Analysis

2.5.1. Total Organic Carbon (TOC), Total Nitrogen (TN) and Soil Carbon Fractionation

The TOC and NT analyses were performed in an automatic elemental analyzer (LECO-TruSpec1 CHN, Leco Corp., St. Joseph, MI, USA) using 0.2 g of soil.

Soil organic matter physical fractionation was performed according to the method proposed by [20]. A 20 g soil sample (air-dried and sieved through a 2 mm mesh) was homogenized in an 80 mL sodium hexametaphosphate solution (5 g L^{-1}). The samples were horizontally shaken for 15 h and sieved through 0.053 mm mesh sieves using deionized water. The retained material was transferred to aluminum dishes and dried at 45 C in a forced-air oven to a constant mass, after which it was ground with a porcelain mortar and pestle and homogenized. The particulate organic carbon (POC) was measured via dry combustion with an elemental analyzer, which is defined as the N and C content in the 0.053–2 mm soil fraction. The mineral-associated organic carbon (MOC) was calculated by the difference between TOC and POC. From the results of the physical fractionation, the carbon management index (CMI) was calculated [21]. This index is a relative measure of alterations caused by soil management, comparing it with a situation considered original or ideal. In this research, the native savanna (NS) was taken as the original situation (CMI = 100).

To obtain the CMI, the carbon pool index (CPI) and the TOC lability index (LI) are needed (Equations (1)–(3)):

$$\mathrm{CMI} = \mathrm{CPI} \times \mathrm{LI} \times 100 \tag{1}$$

where CPI is the carbon pool index and LI is the lability index.

The CPI and the LI were calculated as follows:

$$\mathrm{CPI} = \mathrm{TOC}_{\mathrm{treatment}} / \mathrm{TOC}_{\mathrm{reference}} \tag{2}$$

$$\mathrm{LI} = \mathrm{L}_{\mathrm{treatment}} / \mathrm{L}_{\mathrm{reference}} \tag{3}$$

where L refers to the C lability, calculated according Equation (4):

$$\mathrm{L} = \mathrm{POC} / \mathrm{MOC} \tag{4}$$

The chemical fractionation of soil organic matter was determined according to the method suggested by the International Humic Substances Society and described by [22]. Fulvic acids (FA), humic acids (HA) and humin (HUM) were obtained based on the solubility in acids and alkalis. After the separation of each fraction, the levels of C were determined by obtaining C_{Hum}, C_{HA} and C_{FA}.

2.5.2. Aggregates Stability in Water

The soil monoliths were initially sieved using 8 and 4 mm sieves. Above of the 8 mm sieve, the monoliths were manually fragmented by the planes of weakness, using moderate force to avoid grinding all the soil. The material retained in the 4 mm sieve was used for the aggregate stability test [23]. Water stability of the aggregates was estimated by wet sieving of 4–8 mm aggregates by a set of 2.00, 1.00, 0.50, 0.25 and 0.105 mm sieves [23] using a vertical oscillation device [24]. Based on the distribution of aggregates in each sieve, the percentage of aggregates retained on the 2 mm sieve (%Aggregation > 2mm), mean weight-diameter (MWD), geometric mean diameter (GMD) and aggregate stability index were calculated. (ASI) according to [23].

2.6. Data Analysis

Data were submitted to analysis of variance (ANOVA) using the F test and the means compared using the *t* test (LSD-Student) at 5% error probability.

3. Results

3.1. Total Organic Carbon (TOC), Total Nitrogen (NT) and Soil Carbon Physical Fractionation

In NS, the highest TN levels and TOC (Table 3) occurred in the layers from 0.00 to 0.10 m and 0.10 to 0.20 m ($p < 0.05$); however, for TN, there were no differences ($p > 0.05$) between NS and M and MP/P/P in the 0.00–0.10 m layer and between NS and MP in the 0.10–0.20 m layer (Table 3). For TOC, in the 0.10–0.20 m layer, there was no difference ($p > 0.05$) between NS with the treatments MP and MP/S (Table 3), and thus they present higher levels of TOC but without differing from P and MP/P.

Among the systems studied, MP/P, MP/S, S/MP/P/P and M presented higher TOC content in relation to the S system in the 0.00–0.10 m layer. For the 0.10–0.20 m layer, the MP and MP/S systems did not differ from the NS and thus showed higher TOC contents but without differing from P and MP/P. In the 0.20–0.40 m layer, there were no differences between treatments for both TOC and TN (Table 3).

In the TOC physical fractionation, the main differences occurred in the POC (Table 3). In the 0.00–0.10 m layer, the highest content occurred in the NS (17.4 g kg^{-1}), and the lowest levels occurred in the S and MP/P/S treatments (7.2 and 8.4 g kg^{-1}, respectively). In the 0.10–0.20 m layer, the highest POC content occurred in the MP treatment and in the 0.20–0.40 m layer in the P, MP/S, M/P/P and MP/P/S treatments. As for MOC (Table 3), there was no significant difference ($p > 0.05$) between treatments in the surface layer and at 0.20–0.40 m (Table 3). However, in the 0.10–0.20 m layer, the highest content was found in the NS, without differing ($p > 0.05$) from the MP and MP/S treatments. On the other hand, the S/MP/P/P system promoted the lowest MOC content, differing from the MP and MP/S systems, in addition to NS ($p < 0.05$).

Table 3. Content of total nitrogen (TN), total organic carbon (TOC), particulate organic carbon (POC) and mineral-associated organic carbon (MOC) in layers 0.0–0.10, 0.10–0.20 and 0.20–0.40 m.

Production System	TN	TOC	POC	MOC
	g kg^{-1}			
	0.00–0.10 m			
M [1]	2.12 ab	33.07 bcd	9.58 cd	23.48 a
MP	1.98 b	31.90 cde	9.98 cd	21.91 a
S	1.78 b	27.60 e	7.18 e	20.41 a
P	1.75 b	31.40 cde	10.42 bcd	20.97 a
MP/S	1.97 b	35.47 bc	10.71 bcd	24.75 a
MP/P	2.02 b	36.50 b	12.19 b	24.30 a
MP/P/P	2.16 ab	31.93 cde	11.28 bc	20.65 a
MP/P/S	1.95 b	29.07 de	8.09 de	20.16 a
S/MP/P/P	1.89 b	34.70 bc	10.22 bcd	24.48 a
NS	2.53 a	42.90 a	17.09 a	25.81 a
P Fcalc	0.0506	<0.0001	<0.0001	0.1011
	0.10–0.20 m			
M	1.56 c	26.07 d	4.70 g	21.36 bc
MP	2.00 a	34.63 ab	9.95 a	24.68 abc
S	1.59 c	26.77 d	5.16 fg	21.60 bcd

Table 3. *Cont.*

Production System	TN	TOC	POC	MOC
	g kg^{-1}			
	0.10–0.20 m			
P	1.54 c	29.83 bcd	8.74 b	21.09 cd
MP/S	1.64 c	31.90 abc	5.90 ef	26.00 ab
MP/P	1.64 c	30.50 bcd	7.02 cde	23.47 bcd
MP/P/P	1.55 c	27.77 cd	6.14 def	21.62 bcd
MP/P/S	1.76 bc	29.03 cd	7.19 cd	21.84 bcd
S/MP/P/P	1.45 c	25.47 d	5.45 fg	20.01 d
NS	2.23 a	35.93 a	7.72 bc	28.21 a
P Fcalc	0.0041	0.0046	<0.0001	0.0255
	0.20–0.40 m			
M	1.45 a	24.90 a	4.38 bc	20.52 a
MP	1.58 a	27.13 a	5.08 b	22.04 a
S	1.40 a	22.73 a	4.02 bc	18.70 a
P	1.32 a	25.13 a	6.55 a	18.57 a
MP/S	1.47 a	27.53 a	6.86 a	20.67 a
MP/P	1.38 a	25.90 a	5.09 b	20.80 a
MP/P/P	1.50 a	25.73 a	6.43 a	19.30 a
MP/P/S	1.50 a	27.20 a	6.98 a	20.22 a
S/MP/P/P	1.34 a	24.67 a	5.00 b	19.67 a
NS	1.52 a	23.30 a	3.44 c	19.86 a
P Fcalc	0.2725	0.1317	<0.0001	0.4648

[1] Means followed by different letters differ from each other by the *t* test (LSD, $p \leq 0.05$). M: Single Maize in annual succession (monoculture); MP: Maize intercropped with *U. brizantha* cv. Piatã in annual succession; S: Soybean in annual succession (monoculture); P: *U. brizantha* cv. Piatã pasture implanted in single cultivation; MP/S: Maize + Piatã intercropped and Soybean in annual rotation; MP/P: Sequence of Maize + Piatã intercropping and Piatã pasture in annual rotation; MP/P/P: Sequence of Maize + Piatã intercropping and Piatã pasture for two years; MP/P/S: Sequence of Maize + Piatã intercropping, Piatã pasture and Soybean in annual rotation; S/MP/P/P: Sequence of Soybean, Maize + Piatã intercropping and Piatã pasture for two years in rotation; NS: Native savanna.

3.2. Soil C/N Ratio, Carbon Pool Index (CPI), Lability (L), Lability Index (LI) and Carbon Management Index (CMI)

In the 0.0–0.10 and 0.20–0.40 m layers, there was no difference ($p > 0.05$) between treatments for the soil C/N ratio, with the average of these layers being 16.73 and 17.69, respectively. In the 0.10–0.20 m layer, areas with P, MP/S and MP/P showed a higher C/N ratio than NS, which did not differ ($p > 0.05$) from the other treatments (Table 4).

In general, an increased CPI was observed at the 0.20–0.40 m depth for the cropping systems. At a 0.0–0.10 m depth, all treatments were below 1.00, the standard value of the reference area (NS); however, the MP/P, MP/S and S/MP/P/P systems obtained indices closer to the EC, differing ($p < 0.05$) from S and MP/P/S with lower CPI. For the 0.10–0.20 m layer, it was found that MP and MP/S did not differ ($p > 0.05$) from the NS, and in the 0.20–0.40 m layer, there was no difference ($p > 0.05$) between the evaluated treatments (Table 4).

As for the C lability (L), in the 0.0–0.10 m layer, the L index was higher in NS, without differing from the MP/P/P system (Table 4). Treatments P, MP/P and MP/P/P resulted in higher L compared to the S system, which showed lower lability due to its lower POC content (Table 3). In the 0.10–0.20 m layer, in treatments with MP and P, the greatest soil carbon lability was observed in relation to the other cropping systems, which did not differ from the NS. At 0.20–0.40 m, it was observed that L in treatments with M, MP and S did not differ from NS; however, higher L was observed in P, MP/S, MP/P/P and MP/P/S (Table 4).

The LI increased in depth, due to the reduction in L values in NS and in the treatments in general. In the 0.0–0.10 m layer, the LI in the MP/P/P system did not differ from the NS, being, therefore, closer to 1.00. It was also verified that the LI in the P and MP/P treatments were superior to area with S, where the lowest LI was observed, as well as verified for L.

In the 0.10–0.20 m layer, the MP and P treatments presented the highest LI. In this layer, the lowest LI was obtained in the M system, which did not differ ($p > 0.05$) from S, MP/S, S/MP/P/P and NS. At 0.20–0.40 m, the LI results followed the same behavior observed for L described previously (Table 4).

Table 4. Soil C/N Ratio, Carbon Pool Index (CPI), Lability (L), Lability Index (LI) and Carbon Management Index (CMI) in layers 0.0–0.10, 0.10–0.20 and 0.20–0.40 m.

Production System	C/N	CPI	L	LI	CMI
			0.00–0.10 m		
M [1]	15.70 a	0.77b cd	0.41 bc	0.64 bcd	49 cd
MP	16.22 a	0.74 cd	0.45 bc	0.70 bcd	52 cd
S	15.54 a	0.64 e	0.35 c	0.54 d	34 e
P	17.93 a	0.73 cde	0.51 b	0.80 bc	57 bcd
MP/S	17.99 a	0.83 bc	0.43 bc	0.68 bcd	56 bcd
MP/P	18.08 a	0.85 b	0.50 b	0.78 bc	66 b
MP/P/P	15.13 a	0.74 cde	0.54 ab	0.83 ab	62 bc
MP/P/S	15.13 a	0.67 de	0.44 bc	0.67 bcd	46 de
S/MP/P/P	18.61 a	0.81 bc	0.42 bc	0.63 cd	51 cd
NS	16.95 a	1.00 a	0.67 a	1.00 a	100 a
P Fcalc	0.0846	<0.0001	0.0097	0.0076	<0.0001
			0.10–0.20 m		
M	16.74 bc	0.72 d	0.22 d	0.80 e	58 f
MP	17.58 abc	0.97 ab	0.40 a	1.48 a	142 a
S	16.83 bc	0.75 cd	0.24 cd	0.88 cde	65 f
P	19.29 a	0.83 bcd	0.42 a	1.53 a	125 b
MP/S	19.46 a	0.89 abc	0.22 cd	0.82 de	73 ef
MP/P	18.55 ab	0.85 bcd	0.30 b	1.09 bc	92 cd
MP/P/P	17.97 abc	0.77 cd	0.28 bc	1.04 bcd	81 de
MP/P/S	16.62 bc	0.81 cd	0.33 b	1.23 b	98 c
S/MP/P/P	17.55 abc	0.71 d	0.27 bcd	1.00 cde	71 ef
NS	16.17 c	1.00 a	0.27 bcd	1.00 cde	100
P Fcalc	0.0009	0.0046	<0.0001	<0.0001	<0.0001
			0.20–0.40 m		
M	17.20 a	1.07 a	0.21 bc	1.25 bc	135 bc
MP	17.25 a	1.16 a	0.23 bc	1.34 bc	155 b
S	16.34 a	0.98 a	0.22 bc	1.26 bc	121 bc
P	19.00 a	1.08 a	0.35 a	2.06 a	222 a
MP/S	18.69 a	1.17 a	0.33 a	1.94 a	230 a
MP/P	18.76 a	1.11 a	0.24 b	1.42 b	157 b
MP/P/P	17.37 a	1.11 a	0.33 a	1.94 a	212 a
MP/P/S	18.19 a	1.17 a	0.34 a	2.01 a	235 a
S/MP/P/P	18.63 a	1.06 a	0.25 b	1.46 b	155 b
NS	15.40 a	1.00 a	0.17 c	1.00 c	100 c
P Fcalc	0.1117	0.1453	<0.0001	<0.0001	<0.0001

[1] Means followed by different letters differ from each other by the *t* test (LSD, $p \leq 0.05$). M: Single Maize in annual succession (monoculture); MP: Maize intercropped with *U. brizantha* cv. Piatã in annual succession; S: Soybean in annual succession (monoculture); P: *U. brizantha* cv. Piatã pasture implanted in single cultivation; MP/S: Maize + Piatã intercropped and Soybean in annual rotation; MP/P: Sequence of Maize + Piatã intercropping and Piatã pasture in annual rotation; MP/P/P: Sequence of Maize + Piatã intercropping and Piatã pasture for two years; MP/P/S: Sequence of Maize + Piatã intercropping, Piatã pasture and Soybean in annual rotation; S/MP/P/P: Sequence of Soybean, Maize + Piatã intercropping and Piatã pasture for two years in rotation; NS: Native savanna.

The CMI values were higher with the increasing soil depth for the nine cropping systems evaluated, adopting 100% for the reference area (NS) (Table 4). In the 0–0.10 m layer, the CMI with cropping systems were lower than in the reference area. In this layer, treatment S resulted in the lowest CMI (34%) without differing from MP/P/S (46%), and the closest management to NS was MP/P (66%). The CMIs at 0.10–0.20 m with the MP and P treatments were higher than NS, 142% and 125%, respectively. The CMI with MP/P and MP/P/S did not differ from NS. In this layer, the lowest CMI occurred in areas with M (58%) and S (65%) systems, without differing from MP/S and S/MP/P/P. In the 0.20–0.40 m layer, all production systems showed a CMI greater than 100 (NS), with the highest CMI observed in areas cultivated with MP/P/S (235%), MP/S (230%), P (222%) and MP/P/P (212%) (Table 4).

3.3. Soil Organic Matter Chemical Fractionation

The NS area showed the highest C_{Hum} in the surface layer of the soil (18.12 g kg^{-1}) (Table 5). Still in this layer, the MP/P system resulted in a higher C_{Hum} content compared to M, with the other treatments being statistically similar to both. In the 0.10–0.20 m layer, NS also showed higher C_{Hum} (14.67 g kg^{-1}) but did not differ from MP and P. At 0.20–0.40 m, the MP/P/S treatment provided the highest C_{Hum} (13.01 g kg^{-1}), however, without differing from NS and MP, MP/S and S/MP/P/P, and in the S system, there was the lowest C_{Hum} (8.14 g kg^{-1}), without differing from M and MP/P/P (Table 5).

Table 5. Organic carbon content in the chemical fractions of soil organic matter: Humin (C_{Hum}), humic acid (C_{HA}), fulvic acid (C_{FA}) and CHA/ CFA ratio in layers 0.0–0.10, 0.10–0.20 and 0.20–0.40 m.

Production System	C_{Hum}	C_{HA}	C_{FA}	C_{HA}/C_{FA}
	g kg^{-1}			
	0.0–0.10 m			
M [1]	10.60 c	5.87 abcd	7.85 a	0.74 cd
MP	12.97 bc	4.63 de	6.70 abc	0.70 d
S	12.52 bc	4.61 de	3.75 f	1.24 a
P	12.47 bc	3.86 e	6.08 bcde	0.64 d
MP/S	11.82 bc	5.00 bcde	8.04 a	0.62 d
MP/P	13.89 b	6.22 ab	4.75 ef	1.31 a
MP/P/P	13.23 bc	6.03 abc	6.20 bcde	1.00 b
MP/P/S	13.21 bc	4.75 cde	5.15 def	0.94 bc
S/MP/P/P	12.87 bc	5.04 bcde	5.37 cde	0.94 bc
NS	18.12 a	7.15 a	7.04 ab	1.01 b
P Fcalc	0.0035	0.0028	<0.0001	<0.0001
	0.10–0.20 m			
M	10.60 c	5.45 de	4.17 cde	1.35 ab
MP	13.33 ab	6.92 bc	4.44 cde	1.57 a
S	10.47 c	5.78 cd	3.44 e	1.86 a
P	13.33 ab	5.01 de	5.46 bc	0.92 bc
MP/S	11.06 bc	8.37 a	5.03 bcde	1.73 a
MP/P	11.22 bc	7.20 ab	3.80 de	1.90 a
MP/P/P	10.27 c	5.17 de	3.67 de	1.42 ab
MP/P/S	11.17 bc	4.30 e	7.36 a	0.60 c
S/MP/P/P	11.52 bc	5.54 de	5.15 bcd	0.88 bc
NS	14.67 a	5.65 d	6.48 ab	0.88 bc
P Fcalc	0.0163	<0.0001	0.0014	0.0006
	0.20–0.40 m			
M	8.21 de	4.82 a	4.55 bc	1.07 abc
MP	12.59 ab	4.30 a	5.27 ab	0.82 c
S	8.14 e	4.30 a	3.65 c	1.21 ab
P	10.56 bc	4.06 a	5.68 ab	0.72 c
MP/S	11.83 ab	4.67 a	5.41 ab	0.86 bc
MP/P	10.43 bcd	4.56 a	5.87 a	0.78 c
MP/P/P	9.50 cde	3.36 a	4.52 bc	0.84 c
MP/P/S	13.01 a	4.45 a	4.47 bc	1.00 abc

Table 5. *Cont.*

Production System	C_{Hum}	C_{HA}	C_{FA}	C_{HA}/C_{FA}
	g kg^{-1}			
	0.20–0.40 m			
S/MP/P/P	10.97 abc	4.07 a	5.41 ab	0.75 c
NS	11.88 ab	4.59	3.38 c	1.37 a
P Fcalc	0.0019	0.1495	0.0041	0.0218

[1] Means followed by different letters differ from each other by the *t* test (LSD, $p \leq 0.05$). M: Single Maize in annual succession (monoculture); MP: Maize intercropped with *U. brizantha* cv. Piatã in annual succession; S: Soybean in annual succession (monoculture); P: *U. brizantha* cv. Piatã pasture implanted in single cultivation; MP/S: Maize + Piatã intercropped and Soybean in annual rotation; MP/P: Sequence of Maize + Piatã intercropping and Piatã pasture in annual rotation; MP/P/P: Sequence of Maize + Piatã intercropping and Piatã pasture for two years; MP/P/S: Sequence of Maize + Piatã intercropping, Piatã pasture and Soybean in annual rotation; S/MP/P/P: Sequence of Soybean, Maize + Piatã intercropping and Piatã pasture for two years in rotation; NS: Native savanna.

For C contents in humic acid fraction (C_{HA}), there was only a difference between treatments in the 0.0–0.10 m and 0.10–0.20 m layers. In the 0.0–0.10 m layer, higher levels were observed in NS (7.15 g kg^{-1}) but without differing from MP/P, MP/P/P and M ($p > 0.05$). In the 0.10–0.20 m layer, the highest C_{HA} content occurred in MP/S (8.37 g kg^{-1}) but without differing ($p > 0.05$) from MP/P (Table 5).

The C_{FA} contents in the soil surface layer were higher in M and MP/S (7.85 and 8.04 g kg^{-1}, respectively), without differing ($p > 0.05$) from MP and NS. In the 0.10–0.20 m layer, the highest C_{FA} occurred in the MP/P/S treatment (7.36 g kg^{-1}), being a similar value to that obtained in NS (6.48 g kg^{-1}). The lowest levels in this fraction occurred in the S treatment (3.44 g kg^{-1}), without differing from M, MP, MP/S, MP/P and MP/P/P. At 0.20–0.40 m, a lower C_{FA} value occurred in NS (3.38 g kg^{-1}) and in the S system (3.65 g kg^{-1}), without differing ($p > 0.05$) from the M, MP/P/P and MP/P/S cultivation systems, while MP/P resulted in the highest C_{FA} content (5.87 g kg^{-1}) without differing from MP, P, MP/S and S/MP/P/P (Table 5).

The S and MP/P treatments resulted the highest C_{HA}/C_{FA} ratios in the 0.0–0.10 m layer (1.31 and 1.24, respectively) (Table 5). At 0.10–0.20 m, the highest ratios were obtained in the MP, S, MP/S and MP/P systems without differing from M and MP/P/P, and at 0.20–0.40 m, the NS had the highest C_{HA}/C_{FA} ratio but was not different from M, S and MP/P/S.

3.4. Aggregate Stability

The NS soil presented greater aggregates stability, with higher values of %Aggregation > 2 mm (98.1%), GMD (4.76 mm) and MWD (4.91 mm); however, it did not differ ($p < 0.05$) from the P, MP/P and MP/P/P systems (Table 6). On the other hand, lower soil structuring was observed in the S treatment, with values of %Aggregation > 2mm, GMD and MWD of 41, 53 and 35%, respectively. These values were lower than those found in NS, however, without differing ($p < 0.05$) from those obtained in MP/S and S/MP/P/P.

Table 6. Percentage of water-stable aggregates larger than 2.0 mm (%Aggregation > 2 mm), geometric mean diameter (GMD), mean weight-diameter (MWD) and the aggregate stability index (ASI).

Production System	%Aggregation > 2 mm	GMD	MWD	ASI
	%	Mm		%
M [1]	78.6 bcd	3.13 bcde	4.08 bcd	96.13 a
MP	82.1 bcd	3.40 bcd	4.24 bcd	97.22 a
S	57.4 e	2.21 e	3.21 e	94.61 a
P	90.9 ab	4.08 ab	4.60 ab	98.06 a
MP/S	68.0 de	2.54 de	3.66 de	95.27 a
MP/P	85.1 ab	3.62 bc	4.37 ab	97.04 a

Table 6. *Cont.*

Production System	%Aggregation > 2 mm	GMD	MWD	ASI
	%	Mm		%
MP/P/P	84.4 abc	3.53 bcd	4.34 abc	96.70 a
MP/P/S	77.6 bcd	3.14 bcde	4.06 bcd	96.36 a
S/MP/P/P	69.4 cde	2.69 cde	3.70 cde	94.49 a
NS	98.1 a	4.76 a	4.91 a	99.38 a
P Fcalc	0.0015	0.0021	0.0017	0.1300

[1] Means followed by different letters differ from each other by the *t* test (LSD, $p \leq 0.05$). M: Single Maize in annual succession (monoculture); MP: Maize intercropped with *U. brizantha* cv. Piatã in annual succession; S: Soybean in annual succession (monoculture); P: *U. brizantha* cv. Piatã pasture implanted in single cultivation; MP/S: Maize + Piatã intercropped and Soybean in annual rotation; MP/P: Sequence of Maize + Piatã intercropping and Piatã pasture in annual rotation; MP/P/P: Sequence of Maize + Piatã intercropping and Piatã pasture for two years; MP/P/S: Sequence of Maize + Piatã intercropping, Piatã pasture and Soybean in annual rotation; S/MP/P/P: Sequence of Soybean, Maize + Piatã intercropping and Piatã pasture for two years in rotation; NS: Native savanna.

The ASI values did not differ between the cropping systems ($p < 0.05$), with an overall average of 96.52%.

4. Discussion

TOC, TN, Physical Fractionation and Carbon Management Index of Soil

The MP treatment provided higher levels of TN and TOC in the 0.10–0.20 m layer, similar to those obtained in NS (Table 3). This system is implemented annually in the summer, and after the maize harvest, the forage remains in the area; thus, the soil remains covered throughout the year, favoring the development of forage roots and organic material accumulation in subsurface, evidenced by the high POC values (Table 3), which are highly related to recent plant materials deposition [20]. In systems with one or two years of *U. brizantha* cv. Piatã, the forage remains in the area without receiving maintenance fertilization; thus, the nutrients supply via replacement is lower, compromising dry matter productivity. In the MP system, forage is desiccated annually for maize sowing, and these residues are important for increasing the N and C levels in the soil [25,26].

Considering the superficial layers average (0.0–0.20 m), where differences for TOC were significant, it is observed that in area with the P treatment there was a reduction of 22% in the TOC content in relation to the NS. However, in the MP, MP/S and MP/P systems, this average proportion is around 15%, suggesting that these treatments were more efficient in the maintenance and/or accumulation of TOC in the soil. This result may be due to the plant residues' input and management with annual fertilization (MP and MP/S), or every two years in the case of MP/P. For the other treatments, the mean TOC was between 24 and 26%. The CPI establishes a relationship between the TOC of the cultivated areas and the TOC of the reference area (NS). The treatments MP/P, MP/S and S/MP/P/P in the 0–0.10 m layer and MP and MP/S in the 0.10 to 0.20 m layer showed CPIs closer to 1. In the 0.20–0.40 m layer, all treatments showed a CPI equal to or greater than 1. It can be inferred in these systems with higher CPI that there was an increase in, or at least maintenance of, C in the soil over the years with no-tillage [27]. Thus, the contribution of residues from crop and forage straw over the years provided increasing increases in TOC, mainly in depth.

In treatments referring to monocultures (M and S), there is a lower proportion of labile C being added compared to other systems with the presence of forage, in which the highest POC levels were observed in the 0.20–0.40 m layer. This result may be related to the greater presence of residues from roots that are still in the initial decomposition stage [28]. Forage roots have a well-developed root system and are able to reach greater depths in the soil, increasing POC levels [29,30]. Systems with the use of forages for straw production, compared to those exclusively with crops, showed higher C levels, which must be associated with the high plant material input commonly provided by pastures [14].

For MOC contents, there was no significant difference ($p > 0.05$) between treatments in the surface layer and at 0.20–0.40 m (Table 3). Changes in this carbon fraction occur more slowly and gradually, and it represents the stable carbon in the soil [31–33]. However, in the 0.10–0.20 m layer, high MOC levels in the MP and MP/S systems were similar to those observed in the NS, which can be explained by the constant C supply by cultivated species and also because they were treatments that received fertilization annually, or with N input via soybean in the case of the MP/S system. Increases in C levels in more stable SOM fractions depend on the balanced relationship between C and N inputs, in addition to the availability of other nutrients [16]. Biomass-associated N availability has also been reported as another strategy to increase stabilized SOM content, as it increases microbial activity [34]. It is understood that most stable SOM compounds have been transformed through N-accelerated biological activities [35].

The lower lability (L) in the S system, in the 0.0–0.10 m layer, occurs due to the lower labile C (POC) content obtained in this treatment. Soybean crop provides less plant residues, and these residues have a low C/N ratio; therefore, it decomposes faster than Piatã residues. As the soil collection took place in March, that is, approximately one year after the previous year's soybean harvest, it is likely that a large part of labile C was lost. Salton et al. [36] studying SOM and soil aggregation in crop-pasture rotation, observed L lower than the values found in the present research, both for the area with native vegetation, ranging from 0.08 to 0.28, as in the area with NT farming, from about 0.08 to 0.26, in the 0.0–0.20 m layer. The divergence in the results is related to the lower TOC levels verified by Salton et al. [36] and shorter conduct time in the experimental area.

However, as observed by Salton et al. [36], there was greater L in the soil surface layer, which can be attributed to the greater amount of plant residues and POC concentration. The LI increased in depth, due to the reduction in L values in the reference area and, in general, in the treatments. This observation is also verified in studies by [36,37]. Although there is a difference in C levels between the treatments, through the LI, it is possible to observe whether the L of these is close to or below the natural condition without anthropic intervention, so that LI values close to or above 1.00 indicate that the production system employee is providing labile C addition similar to or greater than the original condition, respectively.

Therefore, the greatest contributions to the addition of labile C by production systems occurred at the deepest layer (0.20 to 0.40 m), where all cultivation systems that use Piatã grass presented LI > 1, with emphasis on the P, MP/P/S, MP/S and MP/P/P systems with ILs of 2.06, 2.01, 1.94 and 1.94, respectively, most likely due to the addition of labile C by grass roots. These values were lower than those obtained by [37] with rotation systems involving *Urochloa ruziziensis*, soybean and sorghum, in which the authors obtained LI between 1.1 and 4.9 in the 0.0–0.10 m layer and above 5.0 in the 0.10–0.20 m layer.

In general, the low CMI values in the 0.0 to 0.10 m layer indicate the need to improve cropping systems in order to match the original condition of the soil in a native forest condition. This is a difficult condition to be obtained in the region where the research was conducted due to the rapid degradation of labile organic matter in a tropical climate because of the higher decomposition rates favored by high temperatures characteristic of these regions [38]. However, at greater depths in the profile, it is already possible to obtain CMI > 100 due to the constant contribution of root biomass, lower micro-organisms activity in deeper layers and the greater aggregates preservation due to lower anthropic action. Production systems with higher CMI values show the ability to promote the sustainability in tropical regions by maintaining C in the agricultural system [39,40].

Thus, higher CMI values mean a positive effect of soil use and management practices on organic matter content [41,42], while the lowest values indicate that the C compounds are being degraded [21], reflecting the lower quantity and quality of residues added by the production systems, that is, lower labile C content [43]. The CMI represents a measure of sustainability of different production systems or land uses and can be used to compare the changes that occur in labile C and TOC contents as a result of agricultural practices [44]. Thus, low CMI values with monocultures S and M obtained in layers 0 to 0.10 and 0.10 to

0.20 m, respectively, indicate the lower capacity of these crops to promote sustainability to production systems.

Stable C presence in the soil is also an indication of the quality and sustainability of production systems, which generally suffer the greatest interference in the more superficial layers. In the layer from 0 to 0.10 m, there were the greatest differences in C_{Hum} between the production systems and the NS. Humin fraction makes up the most stable carbon and is very resistant to decomposition [45], generally representing most of humidified C in tropical soils [46], as verified in this research, since the C_{Hum} represented on average about 53% of humic substances in cultivated areas and 57% in the NS. The C reduction in this fraction of SOM indicates that soil management practices led to the loss of part of stable C over the cultivation years because of the native forest's conversion into arable land.

The lower C_{FA} levels in soybean monoculture, mainly in the layer from 0 to 0.10 m, is related to the lower POC levels with this production system, due to the lower biomass contributions. The POC detects the portion of SOM that has been newly deposited and is less humified, justifying the lower C_{FA} levels in this treatment, since, among the humic substances evaluated, fuvic acid has a lower polymerization and humification degree [47].

In this study, it was found that the C_{HA}/C_{FA} ratio varied between soil layers and cropping systems (Table 5). Humic acid fractions were not always higher than those of fuvic acid, although, for the most part, the C_{HA}/C_{FA} values are close to or above 1.00, which indicate areas where there is a predominance of more stable and better-quality organic material [38,48]. However, it is noted that treatment S showed a C_{HA}/C_{FA} ratio greater than 1.00 in the entire profile, but this did not lead to higher C_{HA} and C_{Hum} levels compared to the other treatments, indicating that the highest C_{HA}/C_{FA} ratio in S is actually due to a lower C labile proportion (Table 3), from which the humified SOM is formed, leading to lower C_{FA} levels in this treatment.

As for soil structure, the area without anthropic interference (NS) maintains its structure unchanged, and therefore, it has better soil aggregation indices. Production systems that involved the exclusive Piatã (P) growed and without soybean crop succession (M, MP, MP/P, MP/P/P) obtained, in general, better aggregation indices. Effective surface coverage by forages reduces or even prevents raindrop impact [49], promotes hydraulic roughness and reduces surface runoff [50,51], favoring the preservation of soil moisture and contributing to a more favorable environment for aggregation [52,53].

In the research, treatments that presented higher CMI (Table 4) also had better aggregation, except for the MP/S treatment. A possible explanation is the period with uncovered soil from the previous crop (2015/16), after the soybean harvest. It is observed that the cultivation time in the S treatment has a negative effect on the aggregation, and to a lesser extent, this effect occurs in other systems in which the area is left without cultivation in the fall–winter season (when there is soybean cultivation in the summer). This shows that the fact that soil remains part of year without vegetation implies soil destabilization over time because, in addition to soil protection, the vegetation acts in forming aggregates through the roots' mechanical action and/or through the excretion of substances with cementing action [54], which can serve as a substrate for microorganisms, stimulating their activity and leading to the production of new cementing agents [55].

Larger aggregates can be formed around residues recently added to the soil, which make up the particulate organic matter [56]. These residues allow the macroaggregates' formation, as they are a source of labile C for microbial activity and for the production of binding agents [57]. Therefore, particulate carbon probably favored aggregates formation and MWD in NS, P, MP/P and MP/P/P, given that NS and MP/P/P, followed by P and MP/ P, showed higher carbon lability (L) in relation to the other systems (Table 4). In addition, in NS, MP/P and MP/P/P, there was a higher POC content in the soil surface layer (Table 3).

In addition to effect of labile C (POC), the aggregation in treatments NS, MP/P and MP/P/P may be related to the higher C_{HA} values in these treatments (Table 5) and to C_{Hum} values in the MP/P system in the surface layer. Humified organic matter has the ability to associate with soil mineral particles, forming clay–metal–humic bonds, which contributes to soil aggregation [58].

The greater aggregation in NS and P areas can also be attributed, in part, to chemical processes, since these areas were not chemically corrected; thus, an acidic condition with high aluminum contents is expected, which may favor aggregation, as polyvalent cations have aggregating action in the soil [59].

5. Conclusions

Soybean monoculture generally provides worse soil quality indices compared to other agricultural production systems.

The agricultural production systems influence organic matter quality and soil aggregates stability. Maize intercropped with *U. brizantha* cv. Piatã in annual succession and Maize + Piatã intercropped and Soybean in annual rotation are better options to improve the organic matter quality in Brazilian savanna conditions and very clayey soil. Agricultural production systems involving maize cultivation provide better soil structuring than those with soybean.

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