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DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n11e283796 ORIGINAL ARTICLE

Microbiological attributes in Oxisol cultivated with sugarcane in savanna region of Central Brazil[1]

Atributos microbiológicos em Latossolo Vermelho cultivado com cana-de-açúcar na região de cerrado do Brasil Central

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HIGHLIGHTS:
- *Microbial biomass carbon predominates in the surface layer of the soil (0-0.1 m).*
- *Microbial quotient increases with the number of sugarcane cycles.*
- *Soil microbial community is associated with soil particles smaller than 0.02 mm, such as silt.*

ABSTRACT: The contribution of plant residues throughout the sugarcane cycles favors the increase of organic matter and the activity of microorganisms in the soil, especially in the surface layers. Soil texture also has an important effect on ecological processes and soil quality. In this context, the objective of this study was to evaluate soil biological attributes in different sugarcane cultivation cycles under mechanized harvesting in an Oxisol in the Savanna region of Central Brazil. The study was conducted in commercial areas under sugarcane cultivation during the 2018/2019 season, which were considered homogeneous in terms of soil and climatic conditions, with the source of variation among the areas being the cultivation cycles (C1: one cultivation cycle; C3: three cultivation cycles; C7: seven cultivation cycles) and a savanna vegetation area selected as a reference. Microbiological variables were determined in two layers, 0-0.1 and 0.1-0.2 m. The variables related to microbial biomass and texture were subjected to principal component analysis. Areas with longer sugarcane cultivation cycles show higher proportion of microbial biomass carbon in the total organic carbon in subsurface layers (microbial quotient). The performance of the soil microbial community, as expressed by total organic carbon and microbial biomass nitrogen indicators, was associated with higher presence of clay and silt, i.e., soil particles smaller than 0.02 mm.

Key words: microbial activity, microbial biomass carbon, microbial biomass nitrogen, soil cover

RESUMO: O aporte de resíduos vegetais ao longo dos ciclos da cana-de-açúcar favorece o incremento de matéria orgânica e atividade de microrganismos no solo, especialmente nas camadas superficiais. A textura do solo também tem um efeito importante nos processos ecológicos e na qualidade do solo. Nesse sentido, o objetivo desta pesquisa foi avaliar atributos biológicos do solo em diferentes ciclos de cultivo de cana-de-açúcar sob colheita mecanizada, em um Latossolo da região de cerrado do Brasil Central. O estudo foi realizado em áreas comerciais de cultivo de cana-de-açúcar na safra 2018/2019, consideradas homogêneas em termos de condições edafoclimáticas, tendo como fonte de variação entre as áreas os ciclos de cultivo (C1: um ciclo de cultivo; C3: três ciclos de cultivo; C7: sete ciclos de cultivo) e uma área de vegetação de cerrado selecionada como referência. Foram determinadas variáveis microbiológicas nas camadas de 0-0,10 e 0,10-0,20 m. As variáveis relacionados à biomassa microbiana e textura foram submetidos à análise de componentes principais. Áreas com ciclos de cultivo de cana-de-açúcar mais longos apresentaram maior proporção de carbono da biomassa microbiana no carbono orgânico total nas camadas subterrâneas (quociente microbiano). O desempenho da comunidade microbiana do solo, expresso pelos indicadores carbono orgânico total e nitrogênio da biomassa microbiana foi associado à maior presença de argila e silte, ou seja, partículas de solo menores que 0,02 mm.

Palavras-chave: atividade microbiana, carbono da biomassa microbiana, nitrogênio da biomassa microbiana, cobertura do solo

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Introduction

Soil microorganisms play an important role in the soil ecosystem and the biogeochemical cycle, especially nitrogen and carbon (Fu et al., 2021). The return of crop residues increases soil organic matter and provides a good environment for the growth and proliferation of microorganisms (Su et al., 2020). The straw generates a significant contribution of carbon (C), enabling nutrient cycling in mechanized sugarcane cultivation systems (Vieira et al., 2021). In addition, a mechanized sugarcane harvest, which keeps the straw in the soil, promotes soil and environmental quality (Moitinho et al., 2021).

Vieira et al. (2021) state that maintaining the straw on the soil favors the increase of soil microbiological attributes such as microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and β-glucosidase enzyme activity. Soil biological quality indicators are more sensitive to environmental changes (Morais et al., 2020), as they detect any changes in soil use and management with greater anticipation (Mendes et al., 2018).

Brazil is the world leader in the production and export of sugarcane derivatives, and the Center-south region is the main producer (Gravina et al., 2021). This expansion of sugarcane cultivation has been observed in sandy, sandy loam or sandy clay loam soils, according to Donagemma et al. (2016). These low-clay soils are considered fragile and more susceptible to degradation processes, showing reduction in biological activity as soil organic matter and clay content decrease (Mendes et al., 2018). Vinhal-Freitas et al. (2017) state that, in addition to soil use and management, soil texture has an important effect on ecological processes and soil quality in the Brazilian Savanna biome.

Therefore, it can be stated that the permanence of sugarcane straw after mechanized harvesting brings benefits to the bioavailability of soil organic matter and microbial activity, especially in soils with low clay content. Research studies like this are innovative, as they are directly involved in the regulation of soil ecosystem services, especially in soils vulnerable to degradation processes. Studies related to the biological quality of sandy soils are still incipient, especially under sugarcane cultivation, in savanna region of Brazil. In this context, the objective of this study was to evaluate soil biological attributes in different sugarcane cultivation cycles under mechanized harvesting in an Oxisol in the Savanna region of Central Brazil.

Material and Methods

The study was conducted in commercial sugarcane cultivation areas during the 2018/2019 season at the Boa Vista sugar mill, at latitude 18° 32’ 55.07” S, longitude 50° 26’ 02.16” W, with an average altitude of 485 m. According to the Köppen-Geiger climate classification, the region is classified as Aw - tropical with dry winter (Alvares et al., 2013) (Figure 1). According to the Brazilian Meteorology Institute - INMET, based on the climatological normal from 1981 to 2010, the average temperature in the study area is 23 °C, and the average annual rainfall is 1,612.90 mm, as reported by Silva et al. (2022).

The study areas, located in the municipality of Paranaiguara, Goiás, were selected based on information provided by the sugarcane mill to select areas as homogeneous as possible regarding edaphoclimatic conditions, with the main source of variation between the areas being the crop cycles (C1: one crop cycle; C3: three crop cycles; C7: seven crop cycles), as shown in Figure 1 and Table 1. An area of natural vegetation (savanna vegetation) was selected as a reference for comparison.

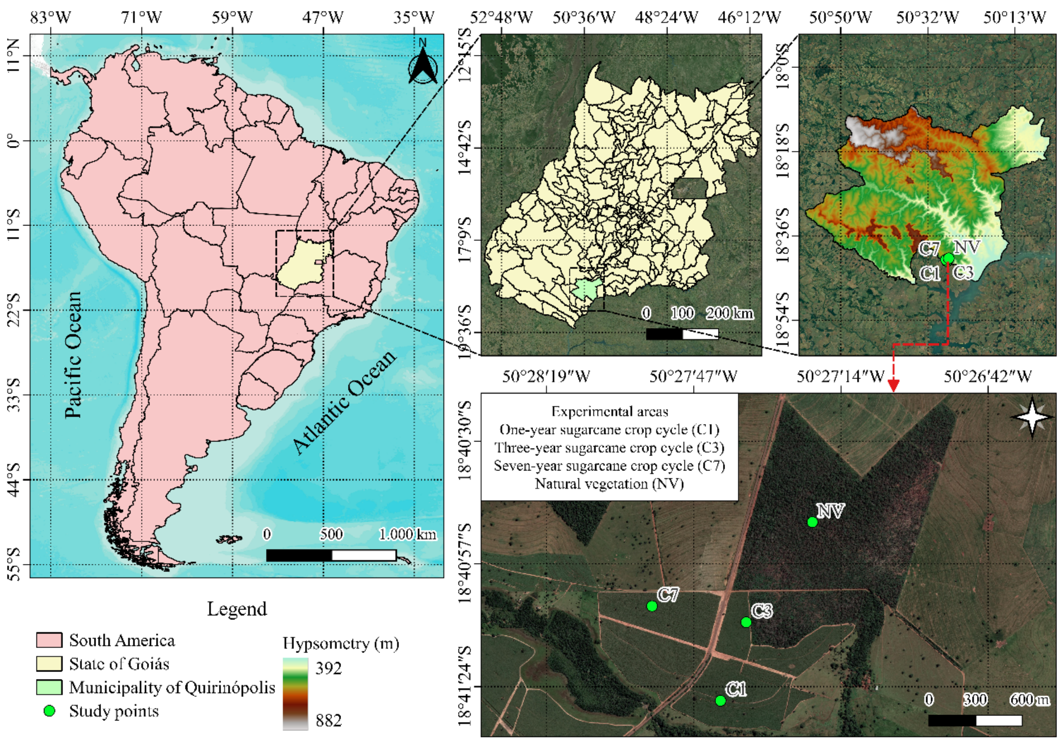


Figure 1. Characterization of the study area location followed by the representation of the area with one-year sugarcane crop cycle (C1), area with three-year sugarcane crop cycle (C3), area with seven-year sugarcane crop cycle (C7) and area of natural vegetation (savanna vegetation)

Table 1. History and location of the study areas

Areas	Description
C1	A recently reformed area with one sugarcane crop cycle. In the sugarcane plantation reform, soybeans were grown in the summer season, and after harvest, sugarcane was planted directly on the leguminous crop residue. This area is located at the Barra do Alegre Far m, with planting on 03/27/2018 of the RB 867515 variety in a conventional soil preparation system in an area of 23.95 ha. Stalk yield of 79.94 Mg ha^{-1} in the 2018/2019 harvest.
C3	An area with three sugarcane crop cycles at Fratari Farm, planted on 09/01/2015 with the RB 867515 variety in a conventional soil preparation system, with an area of 22.75 ha. Stalk yield of 83.29 Mg ha^{-1} in the 2018/2019 harvest.
C7	An area with seven sugarcane crop cycles, located at Campos Farm, planted on 04/03/2013 with the RB 867515 variety in a conve ntional soil preparation system, with an area of 23.95 ha. Stalk yield of 79.94 Mg ha^{-1} in the 2018/2019 harvest.
NV	Area under natural savanna vegetation without anthropic interference, located at Campos Farm.

C1 - Area with one-year sugarcane crop cycle; C3 - Area with three-year sugarcane crop cycle; C7 - Area with seven-year sugarcane crop cycle; NV - Area of natural vegetation (savanna vegetation)

Before the sugarcane cycle, the predominant activity in the region was low-technology livestock farming, with degraded pasture. After renovating the sugarcane fields, the areas were cultivated with soybeans (*Glycine max*) for one season and, after harvest, sugarcane was planted directly on the legume straw. Areas C1 and C3 have already been renovated once, before the first sugarcane cycle; however, the sugarcane field was not renovated in the seventh cycle in C7.

The amount of limestone was calculated according to the recommendation for the crop, in order to meet the recommendation of 50% base saturation, as recommended by Sousa & Lobato (2004). Gypsum was also applied broadcast to the soil after the establishment of the crop for areas C1 (1.1 t ha^{-1}), C3 (1.1 t ha^{-1}) and C7 (1.0 t ha^{-1}).

Fertilization in C1 was carried out in the furrow by applying 50 kg ha^{-1} of monoammonium phosphate (MAP), 230 kg ha^{-1} of urea, 65 kg ha^{-1} of potassium chloride, 3.6 kg ha^{-1} of boric acid and 4.5 kg ha^{-1} of zinc sulfate. In C3, 500 kg ha^{-1} of the granular fertilizer 20-05-19 were applied and, in C7, 660 kg ha^{-1} of the granular fertilizer 08-25-11 kg ha^{-1} were applied, as recommended by Sousa & Lobato (2004), in accordance with the requirements of the crop and yield expectations.

The soil of the study areas was characterized according to United States (2014) and classified as Oxisol, equivalent to Latossolo Vermelho Distrófico típico (LVd), according to the Brazilian Soil Classification System (EMBRAPA, 2018). The chemical and textural characterization in each layer (0-0.1 and 0.1-0.2 m) for the area cultivated with sugarcane in different crop cycles evaluated in this study are shown in Tables 2 and 3.

Soil sampling was performed in February 2019, about five months after the sugarcane harvest. Soil samples were collected in layers of 0-0.1 m and 0.1-0.2 m with five replicates. Each replicate represented a composite sample, originating from eight sub-samples collected at intervals of ten meters from each other along a transect 20 cm away from the sugarcane planting row.

Table 3. Particle-size characterization of soil in the layers of 0-0.1 and 0.1-0.2 m, under sugarcane cultivation cycles and natural vegetation (NV)

Areas	Sand	Silt	Clay	Textural classes
		(%)		
		0-0.01 m		
C7	70.92	10.63	18.45	Medium texture
C3	80.83	5.01	14.16	Sandy texture
C1	69.97	10.40	19.63	Medium texture
NV	71.39	10.31	18.30	Medium texture
		0.01-0.02 m		
C7	67.69	9.53	22.78	Medium texture
C3	81.62	3.86	14.52	Sandy texture
C1	69.39	9.38	21.23	Medium texture
NV	69.89	10.94	19.17	Medium texture

C1 - Area with one-year sugarcane crop cycle; C3 - Area with three-year sugarcane crop cycle; C7 - Area with seven-year sugarcane crop cycle; NV - Area of natural vegetation (savanna vegetation)

Total organic carbon (TOC) was analyzed by wet oxidation of organic matter with potassium dichromate in sulfuric acid, according to the methodology proposed by Teixeira et al. (2017). The particle-size characterization was based on the densimetric method (Teixeira et al., 2017).

Microbial biomass carbon (MBC) and nitrogen (MBN) were determined by the irradiation-extraction method, according to the methodology of Ferreira et al. (1999). The MBC/TOC ratio was used to calculate the microbial quotient (qMic). Basal respiration (BR) of the soil was determined by the CO_2 evolved from 20 g of soil, incubated for seven days in a hermetically sealed flask (Wardle, 1994). The metabolic quotient (qCO_2) was calculated by the ratio between BR and MBC (Anderson & Domsch, 1993).

The data were tested for normality using the Shapiro-Wilk test and for homogeneity of variances using the Levene test.

Table 2. Soil chemical characterization in the 0-0.1 and 0.1-0.2 m layers, under sugarcane crop cycles and natural vegetation (NV)

Areas	pH	P	K	K	Ca	Mg	Al	H + AL	CEC	OM
	(water)	(mg dm^{-3})		(cmol$_c$ dm^{-3})						(g dm^{-3})
					(0-0.1 m)					
C7	5.3	7.83	50.83	0.13	1.57	0.83	0.23	2.57	5.17	18.67
C3	5.5	6.47	27.37	0.07	1.53	0.53	0.13	2.03	4.18	14.33
C1	6.0	5.03	27.37	0.07	3.53	1.23	0.00	1.80	6.65	14.67
NV	5.2	5.07	46.92	0.12	1.10	0.97	0.23	3.40	6.60	26.33
					(0.1-0.2 m)					
C7	4.67	4.63	23.46	0.06	0.20	0.10	0.87	3.57	3.94	14.0
C3	5.7	4.23	27.37	0.07	1.30	0.53	0.00	2.03	3.94	11.33
C1	5.83	3.67	27.37	0.07	2.00	0.53	0.00	2.47	5.08	12.67
NV	4.97	5.30	23.46	0.06	0.73	0.53	0.77	3.23	4.57	26.33

P - Phosphorus; K - Potassium; Ca - Calcium; Mg - Magnesium; Al - Aluminum; H + Al - Potential acidity; CEC - Cation exchange capacity; OM - Organic matter; C1 - Area with one-year sugarcane crop cycle; C3 - Area with three-year sugarcane crop cycle; C7 - Area with seven-year sugarcane crop cycle; NV - Area of natural vegetation (savanna vegetation)

After checking the assumptions, an analysis of variance was carried out, and Tukey test was applied at $p \leq 0.05$. These analyses were performed in SISVAR software (Ferreira, 2019), considering the plots as areas with different sugarcane cultivation ages (1, 3, and 7 cycles) and the subplots as the evaluated soil layers (0-0.1 and 0.1-0.2 m).

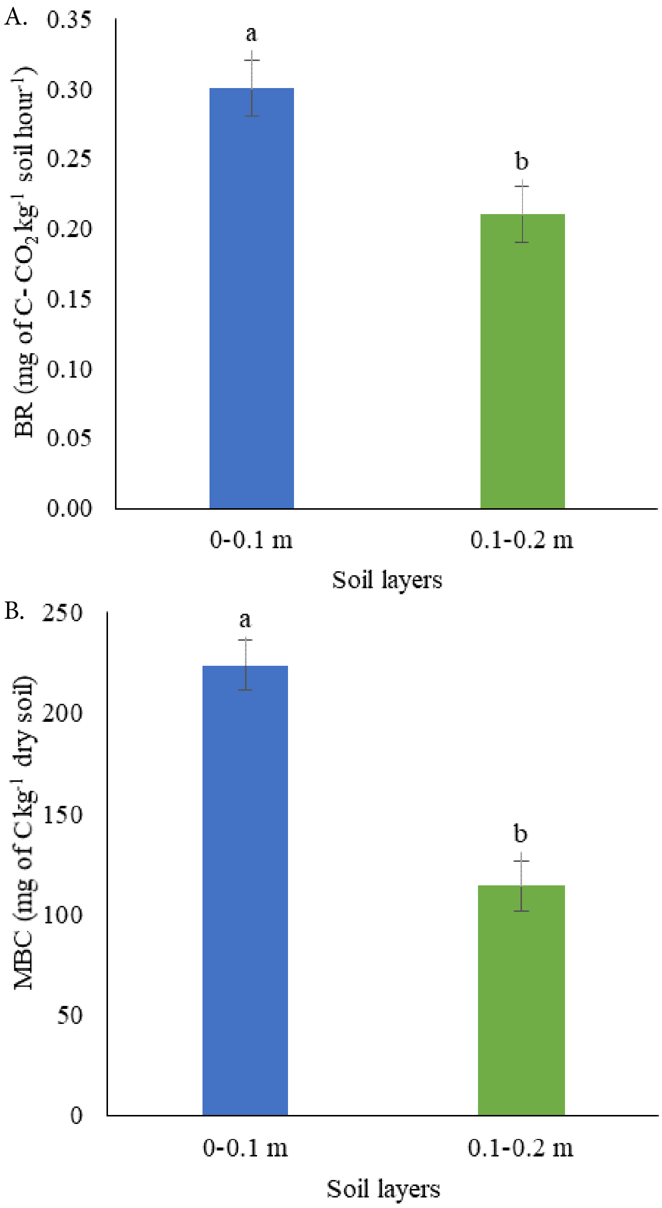
The variables related to microbial biomass and particle size were subjected to principal component analysis (PCA), to obtain linear combinations of variables to describe the most important sources of variation in the data. The Kaiser criterion was used to select the quantity of principal components (Kaiser, 1958). PCA was performed between microbial and sugarcane cultivation areas in the two evaluated layers, using the Past program (Hammer et al., 2001), as well as the Pearson's correlation between them.

Results and Discussion

The analysis of variance (Table 4) showed significant effects of total organic carbon (TOC) and microbial quotient (qMic) for the sources of variation: soil layer (L), harvest cycles after the establishment of sugarcane (C), and the interaction of both. Individual effects were observed for harvest cycles on microbial biomass nitrogen (MBN) and for soil layer on basal respiration (BR) and microbial biomass carbon (MBC).

Figure 2 shows the effect of soil layers on basal respiration (Figure 2A) and microbial biomass carbon (Figure 2B). In the most superficial soil layer (0-0.1 m), MBC is greater than in the subsurface layer (0.1-0.2 m). The higher MBC reflects a greater and active soil organic matter, which increases the rate of decomposition of crop remains and consequently the microbial activity expressed by basal soil respiration. Mkhonza & Muchaonyerwa (2023) evaluated the effect of green sugarcane as compared to burned sugarcane on microbial biomass carbon and concluded that MBC was higher in the surface layer, indicating that the increase in microbial activity is related to the amount of substrate available.

Higher concentrations of total organic carbon (TOC) were observed in the cultivation areas with 1 and 7 harvest cycles after establishment for the 0-0.1 m layer, with values of 22.70 and 25.97 g kg^{-1}, respectively (Table 5). The area with three years of cultivation had average level of 13.76 g kg^{-1} in the same layer. In the 0.1-0.2 m layer, TOC did not differ among the studied areas. Therefore, it can be noted that in the surface layer (0-0.1 m) of the soil, due to a greater input of plant residues associated with soil with a higher clay content (Table 3), there is a tendency for higher TOC concentrations, regardless of the sugarcane crop cycle. Souza et al. (2023) identified higher organic matter (OM) content in the same soil layer, which has higher clay content. This accumulation of OM occurs due to the positive influence of aggregation on forming a connection between OM and the microorganisms (Guhra



Bars with the same letter do not differ from each other, according to the Tukey test ($p \leq 0.05$). Values are expressed as mean ± standard error (n=15).

Figure 2. Basal respiration (BR) (A) and microbial biomass carbon (MBC) (B) of sugarcane-cultivated soil in two soil layers

Table 4. Summary of analysis of variance and F values for basal respiration (BR), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), metabolic quotient (qCO_2), total organic carbon (TOC) and microbial quotient (qMic) of sugarcane-cultivated soil in different layers (L) and harvest cycles after establishment (C)

Source of variation	DF	BR	MBC	MBN	qCO_2	TOC	qMic
Cycles (C)	2	2.83 ^{ns}	2.21 ^{ns}	8.55 *	1.48 ^{ns}	13.57 **	0.55 ^{ns}
Residual 1	8	-	-	-	-	-	-
Layer (L)	1	9.35 **	37.54 **	0.08 ^{ns}	1.31 ^{ns}	26.21 **	7.11 *
C × L	2	0.75 ^{ns}	0.05 ^{ns}	0.87 ^{ns}	0.79 ^{ns}	12.28 **	6.77 **
Residual 2	16	-	-	-	-	-	-
Total	29	-	-	-	-	-	-
CV 1 (%)	-	29.61	26.14	34.75	33.93	14.23	35.77
CV 2 (%)	-	21.27	19.01	43.29	37.72	17.99	21.20

** - Significant at $p \leq 0.01$ by the F test; * - Significant at $p \leq 0.05$ by the F test; ns - Not significant; DF - Degrees of freedom; CV - Coefficient of variation.

et al., 2022). Pang et al. (2021) evaluated the effect of years of sugarcane cultivation on the soil physical-chemical parameters related to soil microbial composition, which is determinant in fungal and bacterial dissemination. These authors reported that continuous cultivation changes the composition of soil microbial communities, including soil bacteria and fungi, and that these microorganisms are closely related to soil functions, which suggests that the impacts of continuous cultivation on the soil microbial community are linked to changes in the physical-chemical properties of the soil.

Regarding the time of sugarcane crop implementation, significant differences were found in MBN between the cultivation areas, with the area with seven crop cycles (Table 5) showing higher values (9.07 mg N kg^{-1} dry soil), but distinguishing only from the area with three years of sugarcane implementation (3.89 mg N kg^{-1} dry soil). This area with seven crop cycles (C7) probably has a higher quality and quantity of organic matter, either due to the accumulation of residues or the volume of roots that have concentrated over the years, or even due to the fertilizer management to which the area was subjected, which may have promoted increases in microbial nitrogen. According to Vieira et al. (2021), nitrogen immobilization by microbial biomass is a temporary phenomenon since, as the microorganisms die, nitrogen is mineralized and the immobilized nutrients are released, especially when there is an increase in the amount of plant residues on the soil.

The values of the microbial quotient (*q*Mic) were similar for the times of implementation of the sugarcane crop in the 0-0.1 m layer, ranging from 0.88 to 1.30 dag kg^{-1} (Table 5). In the 0.1-0.2 m layer, *q*Mic varied between 0.60 and 1.11 dag kg^{-1}, with a higher value in the area with the longest sugarcane cycle (seven cycles). The values found in this study were close to those presented in the study by Novak et al. (2022), who worked in areas of ecological restoration and an area under sugarcane cultivation in a clayey Oxisol in the state of Mato Grosso do Sul. The *q*Mic values were 0.32 and 1.26 dag kg^{-1} in the first and second sampling periods in the area cultivated with sugarcane, respectively. This increase in *q*Mic between the sampling periods in sugarcane areas was justified by the authors due to the addition of high-quality organic matter or the reduction of a stressful factor, such as soil disturbance.

The lowest *q*Mic was found in the 0.1-0.2 m layer in the areas under sugarcane cultivation for 1 and 3 years, related to a reduction in the capacity for converting organic carbon into microbial biomass due to some stress or to the fact that microbial abilities to assimilate soil C decreased with soil depth (Sun et al., 2020). According to Cunha et al. (2012), the conversion of organic carbon into microbial biomass resulting from stress may be related to a reduction in the availability of nutrients that support microbial biomass, inhibition of microbial activity due to excessive acidity, or to the degree of stabilization of organic carbon.

On the other hand, high values of *q*Mic, such as those observed in the seven-year sugarcane cycle area in the 0.1-0.2 m layer (1.11 dag kg^{-1}), indicate more suitable conditions for microbial growth due to the addition of better-quality OM or the elimination of some limiting factor, as indicated by Vieira et al. (2021). However, in this study, in soil layers with medium and sandy texture, a significant difference and increase in *q*Mic were observed in sugarcane areas with seven cultivation cycles, especially in the 0.1 to 0.2 m layer, which can be justified by the higher concentration of roots due to the depth of sugarcane planting.

Mendes et al. (2018) indicate that sandy soils, when managed properly, with the adoption of high C/N ratio species in the rotation system, for example, guarantee a high input of plant biomass and, when showing organic matter levels in the superficial layer above 1.5%, can have biological activity comparable to that of clayey soils. Donagemma et al. (2016) also emphasize that maintaining straw on the soil surface promotes its protection, as it keeps the soil organic matter at favorable levels for microbial activity. In this context, it is observed that the MBN of the area with a three-year cultivation cycle had similar values to the area with only one year of sugarcane cultivation, regardless of the soil layer evaluated. This indicates that, even with lower clay content, due to the input of TOC mainly from sugarcane straw deposition under the three-year cycle, the microbial activity, represented here by MBN, was similar to that of a newly planted sugarcane area (C1), but with higher clay content.

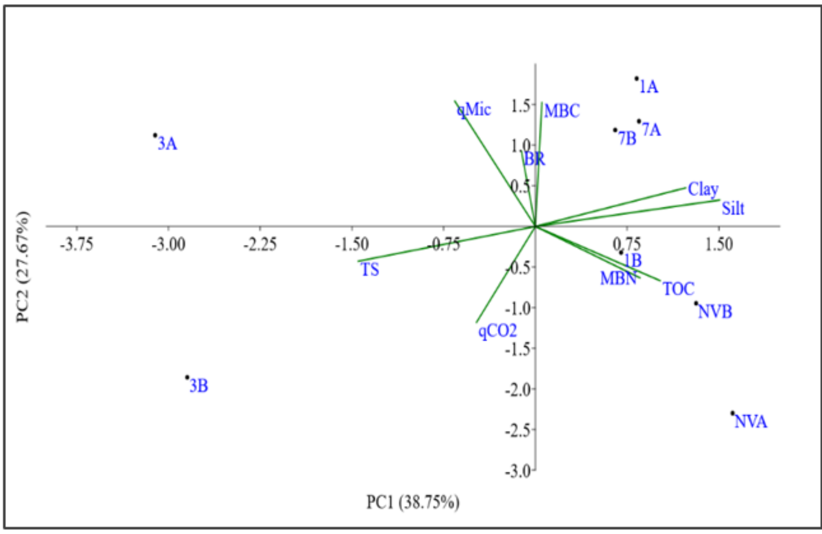
The data ordering by principal component analysis (PCA) (Figure 3) under sugarcane cultivation in different harvesting cycles and soil layers, under the influence of soil microbial biomass and derived indices, explains 66.42% of the total variance of the data, with 38.75% explained by PC1 and 27.67% by PC2. According to the criterion established by Kaiser (1958), the eigenvalues of PC1 and PC2 were above 1, indicating a significant information load to explain the set of observed data.

Figure 3 shows different positions of sugarcane crop areas under different cycles and soil layers (0-0.1 and 0.1-0.2 m), with a separation of the three-year sugarcane crop area. In PC1, the areas of natural vegetation (NVA and NVB) and sugarcane cultivation of 1 (1A and B) and seven years (6A and 6B),

Table 5. Average values of soil total organic carbon (TOC) and microbial quotient (*q*Mic) for the interaction between sugarcane crop implementation times and the 0-0.1 and 0.1-0.2 m soil layers, and microbial biomass nitrogen (MBN) for sugarcane cultivation cycles, and under natural vegetation

Areas	TOC* (g kg^{-1})		*q*Mic* (dag kg^{-1})		MBN** (mg de N kg^{-1})
	0-0.1 m	0.1-0.2 m	0-0.1 m	0.1-0.2 m	
C1	22.70 ± 0.88 aA	16.34 ± 1.22 bA	0.99 ± 0.12 aA	0.62 ±0.13 aB	5.96 ± 0.83 AB
C3	13.76 ± 1.64 aB	15.05 ± 1.37 aA	1.30 ± 0.18 aA	0.60 ±0.14 bB	3.89 ± 0.71 B
C7	25.97 ± 1.43 aA	13.07 ± 1.12 bA	0.88 ± 0.16 aA	1.11 ± 0.11 aA	9.07 ± 1.18 A
NV	33.71 ± 1.40	27.09 ± 1.49	0.41 ± 0.12	0.42 ± 0.09	10.19 ± 1.40

Means followed by the same uppercase letter in the column and lowercase letter in the row do not differ from each other by the Tukey test at a $p \leq 0.05$ (*n=5; **n=10)
C1 - Area with one-year sugarcane crop cycle; C3 - Area with three-year sugarcane crop cycle; C7 - Area with seven-year sugarcane crop cycle; NV - Area of natural vegetation (savanna vegetation)



	PC1	PC2
BR	-0.0395	0.3219
MBC	0.0185	0.5285
MBN	0.2963	-0.2194
qCO_2	-0.1668	-0.4098
TOC	0.3535	-0.2316
qMic	-0.2282	0.5344
TS	-0.5020	-0.1487
Clay	0.4255	0.1646
Silt	0.5218	0.1125

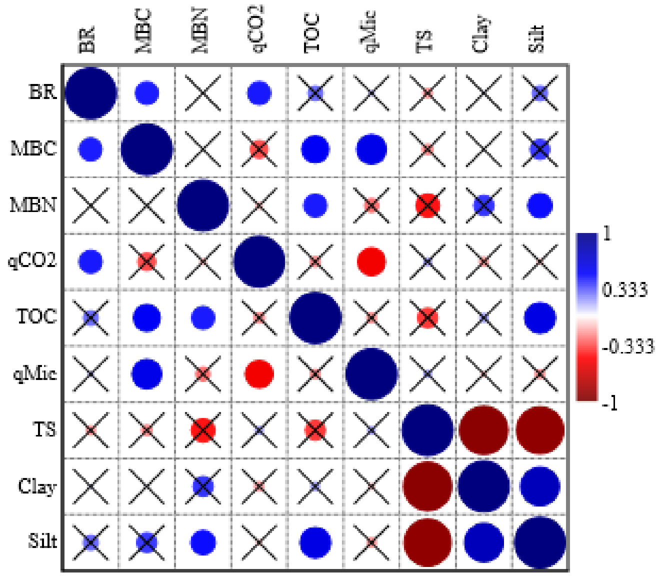
BR - Soil basal respiration; MBC - Microbial biomass carbon; MBN - Microbial biomass nitrogen; qCO_2 - Metabolic quotient; TOC - Total organic carbon; qMic - Microbial quotient; TS - Sand; Clay - Clay; Silt - Silt

Figure 3. Biplot graph of the principal component analysis of the soil microbiological variables under different sugarcane crop cycles (1, 3, 7 years) and natural vegetation (NV) in the 0-0.1 (A) and 0.1-0.2 m (B) layers

regardless of the soil layer, were associated with MBN, TOC, clay, and silt variables, while the 3A and B sugarcane crop area grouped with sand (TS). These results indicate improvements in soil microbial community development associated with the greater presence of clay or a lesser amount of sand in the soil. According to Mendes et al. (2018), the ability of a particular soil class to stabilize and protect microbial biomass is related to its texture and capacity to conserve soil organic matter, so the lower the clay and OM contents, the lower the microbial activity in the soil.

In PC2, there is a grouping of younger crop areas in the superficial layer (1A and 3A), which are positively associated with MBC and *q*Mic variables. In these same areas, the subsurface layers (1B and 3B) were inversely associated with qCO_2, which may be related to a greater concentration of roots at this depth, depending on the sugarcane planting depth. Also, in the Savanna biome, in areas under sugarcane cultivation for 2, 6, and 8 years, Galdos et al. (2009) observed higher levels of MBC in the superficial soil layers (0-0.1 m) and a tendency of increase with crop implementation time. These values are justified by the greater deposition of organic matter, higher root concentration in these layers, and the production of exudates, thus favoring soil microbial community activity (Galdos et al., 2009).

Figure 4 shows the Pearson correlation between the microbiological variables (MBC, MBN, TOC, BR, qCO_2, qMic) and granulometric variables (TS, Clay, and Silt). It is observed that TOC and variables such as MBC, MBN, and Silt show a close positive and significant relationship. Vieira et al. (2021) confirm that an increase in the quantity of plant residues on the soil surface contributes to a good supply of energy, nutrients, and an increase in soil organic matter, promoting an increase in microbial activity, which justifies the relationship between TOC and soil microbial biomass. This justifies, in the present study, the strong positive correlation between basal soil respiration and indicators related to microbial carbon (MBC and qCO_2), as, according to Vinhal-Freitas et al. (2017), BR is an indicator used to evaluate the transformation and mineralization of OM and is positively associated with MBC.



BR - Soil basal respiration; MBC - Microbial biomass carbon; MBN - Microbial biomass nitrogen; qCO_2 - Metabolic quotient; TOC - Total organic carbon; qMic - Microbial quotient; TS - Sand; Clay - Clay; Silt - Silt. Boxes filled with an "X" were not significant at probability ≤ 0.05 by t test.

Figure 4. Pearson correlation between microbiological and granulometric variables of sugarcane-cultivated soil in different layers and times of establishment

An inverse correlation between qCO_2 and *q*Mic was observed in Figure 4, indicating that soils cultivated with sugarcane, regardless of the time of crop establishment, had higher qCO_2 values and lower qMic values. This phenomenon is related to some disturbance or microbial stress due, for example, to loss of TOC, as observed in Table 1, which reached a loss of up to 59% of TOC in the area with a three-year sugarcane cycle for the 0-0.1 m layer. Increasing values of qCO_2 reflect lower carbon use efficiency and, consequently, higher mineralization and loss rates. Novak et al. (2022) suggest that the microbial community in agricultural cultivation is less efficient in using carbon than in soils from areas considered to be in microbial balance, such as native forest environments, as the microbial community requires more energy to maintain itself, and tends to consume more substrate to survive.

A strong positive correlation between silt content and microbiological variables TOC and MBN is observed in Figure 4. Although the sand fraction represents a higher percentage in the studied areas, the silt fraction (0.002-0.02 mm) is relevant because it is related to the soil quality bioindicators studied, as shown in the correlation matrix. This corroborates the study conducted by Wiesmeier et al. (2014), who state that most of the organic carbon in most cultivated soils is contained in the finer mineral fraction (silt + clay). Soil particles smaller than 0.02 mm in diameter (clay + silt) show a strong positive correlation with soil organic matter when the soil is cultivated with sugarcane, which is due to a large amount of fresh organic material (straw) deposited on the soil.

Conclusions

1. Soil microbiological attributes, as they respond to changes caused by the time of sugarcane establishment, can be considered soil quality indicators of an Oxisol.

2. Areas with longer sugarcane cultivation time (seven cycles) have higher portion of microbial biomass carbon in the total organic carbon (microbial quotient) in the subsurface layer, 0.1-0.2 m.

3. Performance of the soil microbial community, as expressed by the total organic carbon and microbial biomass nitrogen indicators, is associated with greater percentage of clay and silt, i.e., soil particles smaller than 0.02 mm.

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