



Soil biological attributes in monoculture and integrated systems in the Cerrado region of Piauí State, Brazil

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ABSTRACT. The implementation of integrated agricultural production systems is considered a promising strategy for sustainable agricultural intensification in Brazil. This study aimed to evaluate the effects of different monoculture and integrated production systems on the microbiological attributes and organic carbon of soil from the Cerrado region in Piauí, Brazil. Soil samples were collected from the 0.0-0.10-m layer in the following systems: no-tillage (PD), pasture (PAS), exclusive eucalyptus cultivation (CEE), integrated livestock-forest system (IPF) and a native Cerrado (CN) area, which was used as reference. Total organic carbon (TOC) and nitrogen (NT) contents, microbial biomass carbon (CMIC), microbial respiration (MR), microbial quotient (qMIC), metabolic quotient (qCO₂), as well as the activities of the hydrolysis of fluorescein diacetate (FDA), acid phosphatase, β -glucosidase and urease enzymes were evaluated. High TOC contents were found in the CEE, IPF and PAS systems, and high CMIC and qMIC values were found in the CN and CEE systems. The variables MR, qCO₂ and enzymatic activity varied as a function of the management systems. The IPF and CEE systems caused improvements in the soil attributes, with increases in organic carbon and microbial biomass. The IPF integrated production system promoted improvements in the microbiological indicators of soil quality and was considered an environmentally sustainable agricultural production system. The transition from CN to agricultural areas caused changes in the soil microbiological indicators, which were perceived several years after anthropogenic intervention, indicating that even with the adoption of conservation systems, it was not possible to reestablish the soil microbial biomass.

Keywords: microbial biomass; enzymatic activity; livestock-forest integration.

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Introduction

The Cerrado region of Piauí, Brazil, is located in the territory named MATOPIBA, which refers to the Brazilian states of Maranhão, Tocantins, Piauí and Bahia, currently representing the main Brazilian agricultural frontier. In this region, the opening of new areas is expected to be on the order of 486,000 ha year⁻¹, representing a total of 5.3 million ha by 2022 (Bolfe et al., 2016).

This expansion, which transforms natural environments into agricultural systems, impacts soil quality indicators because conventional cultivation systems are generally adopted during the agricultural exploration of new areas, with soil tillage by heavy machines and the absence of vegetation cover. Thus, in addition to the low nutritional quality of cultivated species, this cultivation system can negatively alter the soil microbiological attributes (Ferreira, Stone, & Martin-Didonet, 2017; Nunes et al., 2018).

In this scenario, the adoption of integrated production systems has been proposed as an important technological solution for sustainable agriculture (Bonetti, Paulino, Souza, Carneiro, & Caetano, 2018). These conservationist systems present the maintenance of plant residues as soil cover in the absence of soil tillage, which is a fundamental factor for improving the quality of the soil.

Studies have shown that integrated production systems promote increases in the carbon contents of microbial biomass as well as in soil enzymatic activity (Balota et al., 2014; Stieven, Oliveira, Santos, Wruck, & Campos, 2014; Nunes et al., 2018).

These microbiological attributes are often used as indicators of soil quality due to their high sensitivity, which rapidly manifest as changes in the management system and pressures in the ecosystem. Microorganisms perform various functions, such as in the decomposition of organic waste and soil nutrient recycling, and assist in soil aggregation and structuring, among other factors (Pulleman et al., 2012). Despite the importance of the integrated production systems, research on the effects of these systems on the soils of the Cerrado region in Piauí State, Brazil, is still incipient.

Therefore, this study aimed to evaluate the effects of different monoculture and integrated production systems on the microbiological attributes and organic carbon of soil from the Cerrado region in Piauí State, Brazil.

Material and methods

The study was conducted from 2016 to 2017 at Fazenda Chapada Grande, which is located in Regeneração, state of Piauí, Brazil (06°21'03" S, 42°28'79" W, altitude 374 m). The climate of the region is classified as Aw according to the Köppen classification and is composed of hot and humid tropical weather, with rainy summers and dry winters. The annual average temperature is 26.4°C, and the annual average rainfall is 1,371 mm. The chemical attributes of the soil, which are classified as Dystrophic Yellow Latosol (Jacomine et al., 1986), are shown in Table 1.

Table 1. Chemical attributes of the 0-0.1-m layer of Dystrophic Yellow Latosol under different management systems in Regeneração-PI, 2017.

| Management systems | pH | P | K ⁺ | Ca ⁺² | Mg ⁺² | Al ⁺³ | Clay | OM |
|--------------------|--------------------|------------------------|---------------------------------------|------------------|------------------|------------------|---------------------------------|------|
| | (H ₂ O) | (mg dm ⁻³) | ----- (cmolc dm ⁻³) ----- | | | | ---- (g kg ⁻¹) ---- | |
| CN | 4.6 | 8.1 | 0.1 | 1.4 | 0.0 | 1.9 | 506 | 38.4 |
| PD | 5.6 | 30.0 | 0.4 | 4.0 | 0.9 | 0.3 | 608 | 41.2 |
| PAS | 6.0 | 17.8 | 0.3 | 4.1 | 0.7 | 0.1 | 635 | 46.3 |
| CEE | 4.7 | 9.4 | 0.1 | 3.7 | 0.1 | 2.2 | 571 | 52.6 |
| IPF | 5.6 | 17.4 | 0.2 | 4.2 | 1.2 | 0.5 | 586 | 53.9 |

OM - organic matter; CN: native Cerrado; PD: no-tillage; PAS: pasture; CEE: exclusive eucalyptus cultivation and IPF: integrated livestock-forest system.

Four different soil management systems were selected for the study: no-tillage (PD), pasture (PAS), exclusive eucalyptus cultivation (CEE), integrated livestock-forest system (IPF) and in a native Cerrado (CN) area, which was used as reference.

In the PD area, deforestation occurred in 2010, and the initial tillage consisted of root plowing and the incorporation of 4 t ha⁻¹ of limestone and fertilization with 250 kg ha⁻¹ of NPK. The area was cultivated with rice in 2011 and with soybean in 2012 under a conventional system, which later adopted no-tillage and crop rotation (soybean and corn) systems. During sampling, the area in this system was cultivated with soybeans. Pasture (PAS) was implemented in 2008 by using plowing and liming applications. The pasture was formed with *Brachiaria brizantha* grass, which was subjected to rotational grazing by Nellore cattle with a stocking rate of 1 UA ha⁻¹ year⁻¹ for 15 days in each paddock. For the exclusive eucalyptus cultivation (CEE) system, planting was carried out in 2007 using MA-2000 clones, with spacing of 2 m between plants in rows and 3 m between rows after soil preparation. In this system, 2 t ha⁻¹ of dolomitic limestone, 150 kg ha⁻¹ of NPK (06-30-06) and 110 kg ha⁻¹ of NPK (22-00-22) were applied. The integrated livestock-forest (IPF) system was formed by the intercropping of eucalyptus and *Brachiaria brizantha* grass. Eucalyptus was planted in 2011, with 2 m spacing between plants in three rows and 3 m and 30 m between rows, using MA-2000 clones. A total of 2 t ha⁻¹ of dolomitic limestone, 150 kg ha⁻¹ of NPK (06-30-06) and 110 kg ha⁻¹ of NPK (22-00-22) were applied. In this system, rotational grazing with Nellore cattle with a stocking rate of 1 UA ha⁻¹ year⁻¹ for 15 days in each paddock was adopted. The Cerrado area is composed of herbaceous, shrub, arboreal vegetation and vines typical of this biome, especially trees with tortuous stems.

The soil attributes were analyzed after the end of the rainy season, and four subsamples were collected to compose a composite sample from the 0.0-0.10 m layer, with five replications for each management system.

Total organic carbon (TOC) was quantified by wet organic matter oxidation (Yeomans & Bremner, 1988). To determine the total nitrogen (NT) contents, soil samples were subjected to sulfuric digestion, and N levels were dosed by Kjeldhal distillation (Bremner, 1996). The microbial biomass carbon (CMIC) was determined by the irradiation-extraction method (Islam & Weil, 1998; Ferreira, Camargo, & Vidor, 1999).

The microbial respiration (MR) was determined according to the methodology of Alef and Nannipieri (1995). The ecophysiological indices, such as the microbial quotient (qMIC), the ratio between CMIC and TOC,

and the metabolic quotient (qCO_2), which is the ratio between MRI and CMIC (Anderson & Domsch, 1993), were determined.

The total enzymatic activity of the soil was determined by fluorescein diacetate hydrolysis (FDA), which was carried out according to Chen, Hoitink, Schmitthenner and Tuovinen (1988). To determine the activity of β -glucosidase, urease and acid phosphatase, the methods described by Eivazi and Tabatabai (1988), Kandeler and Gerber (1988), and Tabatabai and Bremner (1969), respectively, were used.

The results were subjected to analysis of variance, and the means were compared by the Tukey test. Pearson correlation analyses were also performed between the studied variables. In addition, the results were submitted to multivariate analysis by principal component analysis (PCA). Analyses were performed using SAS software (Statistical Analysis System [SAS], 2014).

Results and discussion

The total levels of organic carbon were higher in the CEE and IPF systems than in the other management systems, although they were not significantly different from those in the PAS system (Table 2).

Table 2. Total organic carbon (TOC), nitrogen (NT) contents and biological attributes in the 0.0-0.10 m layer of the soil under different management systems, Regeneração-PI, 2017.

| Management systems | Variables | | | | | |
|--------------------|------------------------------|-----------------------------|-------------------------------------|---|-------------|--|
| | TOC (g kg ⁻¹) | NT (g kg ⁻¹) | CMIC (μ g g ⁻¹) | MR (μ g CO ₂ g ⁻¹ day ⁻¹) | qMIC (%) | qCO ₂ (μ g CO ₂ μ g CMIC g ⁻¹ day ⁻¹) |
| CN | 21.9 b | 1.2 b | 432.4 a | 8.7 b | 2.0 a | 0.02 c |
| PD | 23.8 b | 2.2 a | 199.3 c | 18.5 a | 0.8 b | 0.09 a |
| PAS | 26.9 ab | 0.95 b | 261.7 bc | 20.5 a | 0.9 b | 0.08 ab |
| CEE | 31.82 a | 0.99 bc | 302.8 b | 18.9 a | 0.9 b | 0.06 b |
| IPF | 31.44 a | 0.65 b | 269.4 b | 20.6 a | 0.8 b | 0.07 ab |
| CV (%) | 14.6 | 29.8 | 12.2 | 14.9 | 16.2 | 19.7 |
| DMS | 7.5 | 0.7 | 67.9 | 4.9 | 0.03 | 0.02 |

Means followed by the same letter in the column do not differ from each other according to the Tukey test at 5% probability. CMIC: microbial biomass carbon; MR: microbial respiration; qMIC: microbial quotient; qCO₂: metabolic quotient; CN: native Cerrado; PD: no-tillage; PAS: pasture; CEE: exclusive eucalyptus cultivation; IPF: integrated livestock-forest integration; CV: coefficient of variation; DMS: significant minimum difference.

The high TOC values in the CEE, IPF and PAS systems can be attributed to the high input of organic residues from eucalyptus and grasses. Moreover, these systems present no soil tillage, which might have also contributed to an increase in TOC levels. This result demonstrates that these systems contribute satisfactorily to the increase in soil organic matter in the Cerrado region, which is higher than the increments promoted by the CN system. It is noteworthy that the lowest values in the CN can be associated with its high biomass and high microbial activity, contributing to the fast decomposition of organic matter, which may explain the low TOC in the soil under native forest (Cardozo Junior et al., 2016).

These data differ from the results obtained by Oliveira, Carvalho, Lange, Wruck, and Dallacort (2015). These authors studied integrated production systems in the Cerrado of Mato Grosso, Brazil, and did not find differences in the TOC values in eucalyptus monoculture when compared with the forest area. These authors attributed this behavior to the short time of eucalyptus forest implantation, only three years. This period is not sufficient to promote increases in the contents of TOC. Thus, it is inferred that the high values of TOC in the eucalyptus management systems in the present study are attributed to both the high input of organic residues as well as the long implementation time of these systems.

Eucalyptus forests usually have a dense litter layer as a consequence of the continuous deposition of plant residues during their cycle, which contributes to the increase in TOC. Wu et al. (2013) reported that eucalyptus tree tops and litter are important factors in the protection of the soil surface and contribute considerably to the conservation of organic matter, favoring the accumulation of carbon over time, especially in surface layers.

The nitrogen contents varied among the soil management systems, and the highest values were observed in the PD system. These results can be attributed to soybean residues implanted in the area, since this crop presents high biomass production (up to 2.4 Mg ha⁻¹), according to data estimated by Teodoro, Ribeiro, Oliveira, Correa, and Torres (2015). This high phytomass production contributes to the increase in N contents in the soil.

Regarding CMIC and qMIC, it was observed that the CN system outperformed the others. Nevertheless, the CEE and IPF systems presented higher values than the PD system for CMIC and qMIC. The CN system presented a high content of CMIC. This finding can be explained by the maturity of the forest, which, even

with increased stability, may be less productive. This finding can also be associated with the high biomass and high microbial activity in this system, contributing to the rapid decomposition of organic matter, which may explain the reduced TOC in the forest soil under CN in relation to that under anthropogenic interference management systems (Cardozo Junior et al., 2016).

The high values of CMIC and qMIC in the CN system can be explained by the increased diversity of the organic substrate produced and their input at the site, which results in the supply of different carbon sources to different soil microorganism groups (Campos, Etchevers, Oleschko, & Hidalgo, 2014).

In this sense, soils with native vegetation constitute a very favorable environment for the establishment of microbial biomass, which can be remarkably reduced when native vegetation is removed for planting crops. According to Ferreira et al. (2017), the soil microbial biomass was reduced by up to 60% when native forest was converted to soybean and maize crops in Red Latosol in the Cerrado area of Goiás, Brazil.

Microbial biomass activity, expressed by MR and qCO₂, varied in relation to the different soil management systems, with an increase ($p \leq 0.05$) in microbial respiration in relation to that in the CN system. Nevertheless, no differences were observed ($p \leq 0.05$) among the other systems. For qCO₂, a low value was found in the CN. Among the managed systems, it was observed that the PD stood out in relation to the CEE, while it did not differ from the others. The low values of MR and qCO₂ in the CN system indicated that the microbial biomass was close to stability, evidencing the most efficient rates of use of C by the edaphic microbiota.

On the other hand, the high values of MR and qCO₂ in managed systems such as PAS might be due to degradation processes, indicating that the microbial biomass is under stress conditions. Under these conditions, there is a reduction in the energy required to maintain the metabolic activity in relation to the energy required for biomass synthesis (Bonetti et al., 2018). Cardozo Junior et al. (2016) found similar results when studying the impact of pasture systems compared with agroforestry and native forest systems on soil microbial biomass. The authors found high respiration and qCO₂ values in the pasture area, indicating increased microbial activity in this system and showing that this microbial biomass is subjected to some stress.

The lower CMIC and higher qCO₂ values in the PD system than in the CEE, IPF and CN systems can be attributed to the low substrate availability for soil microorganisms and the unfavorable conditions for microbial growth. In addition, the short adoption time of the system might also have contributed to these results, given that the PD under study was in the transition phase of the conventional system and did not yet present characteristics of no-tillage consolidated with the formation of straw to cover the soil.

Generally, microbial biomass is favored by the no-tillage system, which provides a constant supply of organic C to the microbial soil biomass, in addition to providing improved aggregation and stabilization of the aggregates and microbiota habitat (Balota et al., 2014). Given this, it can be deduced that the no-tillage system in the present study still does not have favorable characteristics for the establishment of soil microbial biomass due to the short time of adoption. Thus, further studies should be carried out in this system to provide a better understanding of the evolution of environmental conditions in these areas over time.

Regarding the enzymatic activity, variations were found as a function of different soil management systems (Table 3).

Table 3. Enzymatic activity in the 0.0-0.10 m layer of the soil under different management systems, Regeneração-PI, 2017.

| Management systems | Variables | | | |
|--------------------|-------------------------------------|--|--|---|
| | FDA ($\mu\text{g FDA g}^{-1}$) | Acid phosphatase ($\mu\text{g PNP g}^{-1} \text{h}^{-1}$) | β -glucosidase ($\mu\text{g PNP g}^{-1} \text{h}^{-1}$) | Urease ($\mu\text{g NH}_4 \text{Ng}^{-1} \text{h}^{-1}$) |
| CN | 27.7 b | 197.6 ab | 54.5 b | 476.5 a |
| PD | 20.7 c | 183.0 bc | 65.0 b | 260.6 b |
| PAS | 24.6 bc | 174.6 c | 129.8 a | 361.0 ab |
| CEE | 29.9 b | 210.5 a | 53.2 b | 354.9 ab |
| IPF | 48.41 a | 173.3 c | 142.9 a | 378.4 ab |
| CV% | 9.7 | 5.3 | 7.9 | 20.8 |
| DMS | 5.6 | 18.9 | 13.3 | 44.9 |

Means followed by the same letter in the column do not differ from each other according to the Tukey test at 5% probability. FDA: fluorescein diacetate hydrolysis. CN: native Cerrado; PD: no-tillage; PAS: pasture; CEE: exclusive eucalyptus cultivation and IPF: integrated livestock-forest system; CV: coefficient of variation; DMS: significant minimum difference.

For fluorescein diacetate hydrolysis, the IPF system showed the highest activity, which was much higher than that in other systems due to the input of organic residues. Cardozo Junior et al. (2016) found similar behavior when studying soil microbiological indicators in agroforestry systems and pastures compared with native

vegetation. The authors found high FDA values in the native vegetation and agroforestry systems, which were attributed to increased deposition of organic residues and, consequently, high levels of organic matter.

Regarding acid phosphatase, the CEE and CN systems presented higher values ($p < 0.05$) than the other systems, in which PAS and IPF had the lowest values. However, the CN did not differ from the PD. The high acid phosphatase values in the CEE system might be associated with the high efficiency of eucalyptus in the use of soil nutrients, such as P, which may have led to a reduction in available P levels and CN due to the low P availability in soil stimulating acid phosphatase activity (Balota et al., 2014). According to Singh (2016), phosphatase activity may be dependent on P availability in soils. When the content of soil-available P is low, the supply of this element to plants occurs through the transformation of organic P into inorganic P. This process, resulting from microbial activity, which promotes the extrusion of the phosphatase enzyme in the soil, increases the P content (Conte, Anghinoni, & Rheinheimer, 2002). In addition, the high availability of easily decomposing organic carbon, represented by a large amount of organic P and P from microbial biomass, also promotes an increase in phosphatase activity (Gatiboni, Kaminski, Rheinheimer, & Brunetto, 2008). Thus, the availability of P in the soil under native forest occurs through microbial activity by the release of phosphatases, transforming P from organic to inorganic forms and conditioning the growth of plants to the recycling of organic P from litter. Regarding β -glucosidase, the IPF and PAS systems presented the highest values, surpassing the PD, CEE and CN, which did not differ among themselves.

This behavior can be attributed to the high TOC values observed in these systems. The higher the organic carbon content is, the higher the β -glucosidase enzyme values (Zago et al., 2016). In addition, the values of β -glucosidase in the IPF and PAS systems might be strongly related to the presence of grasses, since these plants usually have a dense root system that is mostly formed by fast-decomposing thin roots. This phenomenon can increase the levels of organic C in the soil and stimulate the activity of this enzyme, as found by Silva et al. (2012) when studying the enzymatic activity in soils under a conventional tillage system, and high values of β -glucosidase were found in the *Brachiaria decumbens* pasture.

Regarding urease, differences were observed between only CN and PD, in which high values of this enzyme activity in CN and small values in PD were observed (Table 3). A possible explanation for this behavior is the large amount of plant species in CN and, consequently, the larger root system than that in agricultural systems, which increases the rhizosphere by stimulating the activity of microorganisms at these sites. In addition, there are permanent inputs of organic residues in relation to the cultivated areas. Similar to β -glucosidase, urease also correlates with TOC values, indicating that organic matter can protect this enzyme against the action of proteolytic enzymes naturally present in the soil, maintaining the activity potential of urease. Cardozo Junior et al. (2016) reported similar results when studying the biological indicators of the soil in agroforestry systems and pastures when compared with native forest, in which high values of urease were found in the native forest. On the other hand, the low urease values found in the PD system might be associated with high NT contents, since the activity of this enzyme is highest in low N soils.

The TOC) was significantly correlated ($p < 0.05$) with RM, qMIC and β -glucosidase (Table 4).

Table 4. Correlation coefficient (r) between soil attributes in the 0.0-0.10-m layer. Values of r followed by an asterisk represent significance at the 0.05 probability level.

| | TOC | NT | CMIC | RM | qMIC | qCO ₂ | FDA | FA | β GI | UR | P |
|------------------|-------|--------|--------|--------|--------|------------------|-------|--------|------------|--------|---|
| TOC | 1 | | | | | | | | | | |
| NT | -0.51 | 1 | | | | | | | | | |
| CMIC | -0.5 | -0.51 | 1 | | | | | | | | |
| RM | 0.91* | -0.2 | -0.72* | 1 | | | | | | | |
| qMIC | 0.64* | -0.24 | 0.94* | -0.9* | 1 | | | | | | |
| qCO ₂ | 0.34 | 0.36 | -0.98* | 0.82* | -0.97* | 1 | | | | | |
| FDA | 0.31 | -0.64* | 0.15 | 0.21 | 0.06 | -0.01 | 1 | | | | |
| FA | 0.11 | -0.03 | 0.32 | -0.23 | 0.25 | -0.27 | -0.2 | 1 | | | |
| β -GI | 0.73* | -0.54 | -0.22 | 0.6* | -0.36 | 0.29 | 0.57 | -0.75* | 1 | | |
| UR | 0.51 | -0.53 | 0.9* | -0.67* | -0.89* | -0.86* | 0.48 | 0.04 | 0.01 | 1 | |
| P | 0.09 | 0.69* | -0.89* | 0.42 | -0.72* | 0.81* | -0.23 | -0.06 | 0.2 | -0.72* | 1 |

Values of r followed by an asterisk represent significance at the 0.05 probability level. TOC: total organic carbon; CMIC: microbial biomass carbon; MR: microbial respiration; qMIC: microbial quotient; qCO₂: metabolic quotient; FDA: fluorescein diacetate hydrolysis; FA: acid phosphatase; β -GI: β -glucosidase; UR: urease; P: phosphorus.

This correlation indicates that these soil microbiological parameters increase as the TOC level increases (Table 3). The correlation between TOC and β -glucosidase shows that the greatest activity levels of this

enzyme occur in soil management and use systems with high inputs of organic residues. Acid phosphatase showed a low correlation with phosphorus levels in the soil (Table 4), confirming that the activity of this enzyme is stimulated when the contents of available P decrease to the critical levels for microbial and plant growth, indicating the importance of these enzymes for the supply of P to plants in the native Cerrado (Balota et al., 2014). The correlation between urease and NT was not significant, but it was negative (Table 4), indicating that the higher the soil N content is, the lower the activity of this enzyme.

For example, consider the levels of N in PD. This soil management system presents high N contents and, consequently, low values of the urease enzyme, as shown in Tables 2 and 3, respectively.

From the multivariate analysis of principal components, it was found that the first two components explained 76.5% of the variability presented by the data (Table 5).

Table 5. Correlation between variables and principal components of the soil attributes.

| Variable | CP1 | CP2 |
|---------------------|--------|--------|
| TOC | -0.54 | -0.45 |
| NT | 0.07 | 0.86* |
| CMIC | 0.86* | -0.35 |
| MR | -0.90* | -0.04 |
| qMic | 0.94* | -0.08 |
| qCO ₂ | -0.91* | 0.29 |
| FDA | -0.22 | -0.79* |
| Acid phosphatase | 0.50 | 0.13 |
| β-glucosidase | -0.61* | -0.55 |
| Urease | 0.47 | -0.58 |
| Total variance | 50.20 | 26.3 |
| Cumulative variance | 50.20 | 76.5 |

Values of *r* followed by an asterisk represent significance at the 0.05 probability level. TOC: total organic carbon; CMIC: microbial biomass carbon; MR: microbial respiration; qMIC: microbial quotient; qCO₂: metabolic quotient; FDA: fluorescein diacetate hydrolysis.

Principal component 1 (CP1) represented 50.20% of the total variability of soil microbiological indicators and was positively correlated with CMIC, qMIC and acid phosphatase and negatively correlated with MR, qCO₂, β-glucosidase and TOC. Principal component 2 (CP2) explained a smaller amount of the data variance (26.3%) than CP1, correlating positively with NT and negatively with FDA.

A distinction between the studied management systems promoted by the correlations between the microbiological indicators of the soil was observed. CN was clearly far from the cultivated systems and was influenced by acid phosphatase, CMIC and qMIC (Figure 1).

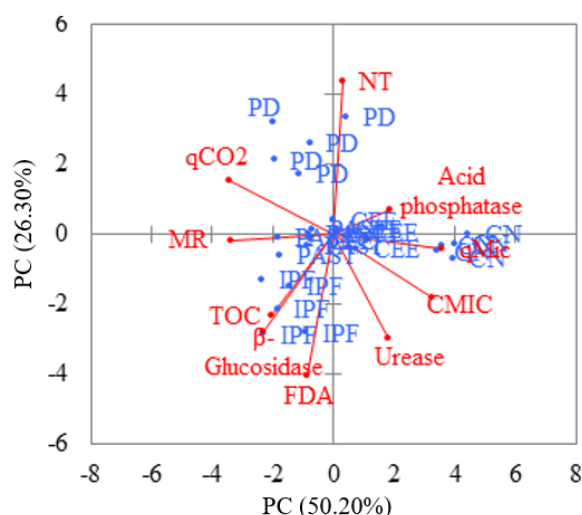


Figure 1. Projection diagram of the microbiological attribute vectors and ordering diagram of the principal components in the different management systems. CN: native Cerrado; PD: no-tillage; PAS: pasture; CEE: exclusive eucalyptus cultivation; IPF: integrated livestock-forest system; TOC: total organic carbon; CMIC: microbial biomass carbon; MR: microbial respiration; qMIC: microbial quotient; qCO₂: metabolic quotient; FDA: fluorescein diacetate hydrolysis.

Additionally, CP2 promoted a separation of IPF from other land use systems, as well as the distinction of PD from the other systems. In addition, there was similarity between the PAS and CEE systems (Figure 1).

Multivariate analysis showed that the biological indicators of the soil presented distinct behaviors among the studied land use systems. The isolation of CN was determined by the high microbial biomass and activity levels of the enzymes urease and acid phosphatase. This finding might be related to the high amount of plant material deposition in this system. This high deposition promotes the incorporation of organic matter in the soil, which might also promote increased biological activity, represented by microbial biomass (CMIC, qCO_2 , $qMIC$) and enzymes (acid phosphatase and urease).

This scenario reaffirms that the transition from CN to agricultural areas causes changes in the soil microbiological indicators and that these changes are still perceived several years after the anthropogenic intervention, indicating that even with the adoption of conservation systems, it was not possible to reestablish the soil microbial biomass.

On the other hand, the IPF and CEE systems with the highest TOC levels showed that these systems have characteristics of conservation systems, as they benefit from the lack of soil tillage and the reduced water erosion promoted by increased soil cover from eucalyptus, thus contributing to the sequestration of C in the soil surpassing even the values in the CN.

The distancing of the PD system from the other systems with the contribution of the high values of qCO_2 in both evaluated periods demonstrates that the microbial biomass was considerably altered by the soil turnover that occurred in previous years. Thus, the edaphic microbiota is subjected to a stressful environment, considering that the PD system in the present study is in the transition phase of conventional planting, with no well-established no-till farming.

Conclusion

The IPF integrated production system promotes improvements in microbiological indicators of soil quality and is considered an environmentally sustainable agricultural production system.

The transition from CN to agricultural areas causes changes in the soil microbiological indicators, and these changes are still perceived several years after anthropogenic intervention, indicating that even with the adoption of conservation systems, it was not possible to reestablish the soil microbial biomass.

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