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Converting Low-Productivity Pasture to Well-Managed Pasture and Silvopastoral System Cause Relevant Changes in Soil Chemical and Microbiological Characteristics

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Abstract: This study evaluated the chemical and microbiological soil attributes in a silvopastoral system compared to well-managed pasture, degraded pasture, and Cerrado vegetation in Brazil. A randomized design with four replications was employed to collect soil samples at seven depths. These samples were analyzed for carbon (C), nitrogen (N), pH, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and cation exchange capacity (CEC). Soil microbial attributes were also evaluated at three depths during the dry and wet seasons. Carbon stocks in the evaluated systems varied (0–100 cm), with the highest stocks found in well-managed pasture (MP) (129.5 Mg C ha^{-1}), followed by the silvopastoral system (SPS) (106.6 Mg C ha^{-1}), and the lowest values in native vegetation (NV) (84.8 Mg C ha^{-1}) and degraded pasture (DP) (63.4 Mg C ha^{-1}). Higher pH and base sum were observed in MP. Soil microbial biomass (Cmic) did not differ between treatments during the wet season but was generally higher in MP and lower in DP during the dry season. MP effectively regulated the chemical and biological quality of the soil. The SPS demonstrated that it is possible to combine the cultivation of trees and pastures in the same area, contributing to the improvement of the chemical and biological attributes of the soil in the Brazilian Cerrado.

Keywords: microbial biomass; fertility; Cerrado; climatic seasons

1. Introduction

Soil management has proven to be a viable option for soil organic carbon (SOC) sequestration and mitigating greenhouse gas (GHG) emissions [1–3]. However, the complex interactions between the soil chemical, physical, and biological attributes, which influence SOC dynamics, need to be better understood, aiming for the development of strategies for climate change mitigation by C sequestration in agricultural areas [4]. Accordingly, soil management can interfere with nutrient dynamics and modify SOC, microbial biomass, and basal respiration rate, thus compromising the decomposition processes of soil organic matter (SOM) and C losses [5].

Microorganisms (e.g., bacteria and fungi) make up 90% of the total microbial biomass of the soil, being responsible for SOM formation and decomposition [6]. Therefore, alterations in microbial community composition due to varying management practices likely exert a significant influence on soil organic carbon (SOC) dynamics and the long-term retention of carbon in the soil environment [4,7].

The diversity of the soil microbial community is influenced by different land use and management systems [8,9]. In pastures, the main land use in Brazil [10], often at some level of degradation and productivity loss [11,12], the soil microbial community is directly related to the content of SOC, nitrogen, phosphorus (P), and cations in the soil [13]. Thus, in pastures, soil microbial activity is also influenced by the intensity of grazing [14]. Regarding soil tillage, the proportion of soil microbial biomass tends to increase with less soil disturbance [15], specifically in no-tillage and integrated systems (e.g., integrated crop–livestock (ICL) and silvopastoral systems).

Proper pasture management, such as rotational grazing, stocking rate control, reseeding, soil correction, and fertilization, contributes to greater production of aerial and root biomass of grasses. Adequate forage production reduces the occurrence of exposed soil, which can cause erosion processes and consequently loss of soil quality and greater emission of greenhouse gases. Additionally, greater biomass production in high-productivity pastures contributes to the formation, storage, and stabilization of carbon, structuring the soil (improving aggregation, pore formation, and reducing compaction), improving water storage and favoring biological activity (increase in microbial biomass carbon and enzymatic activity), and nutrient cycling (greater availability of macronutrients and micronutrients for plants). Studies have shown that pastures under appropriate management practices contribute to improving soil quality indicators and can promote an increase in soil carbon content [4,13].

Integrated systems are studied as a production alternative associated with conservation practices [16] to simulate the characteristics of natural ecosystems [17] and those that notably improve the soil chemical, physical, and microbiological properties [18,19]. Currently, the adoption of integrated systems in Brazil is extremely important for several reasons. These systems combine different agricultural and livestock activities in a synergistic way, promoting a more efficient use of natural resources, greater productivity, and profitability for producers, in addition to contributing to environmental conservation [20]. Specifically, silvopastoral systems have been widely adopted across the Brazilian Cerrado, with multiple benefits, i.e., soil and water conservation, regularization of the hydrological cycle, biodiversity, and carbon sequestration. Furthermore, the production of wood for the market minimizes the pressure to use native wood and contributes to reducing deforestation [21,22].

In this context, studies have shown that integrated production systems result in greater physical [23], chemical [24], and biological soil quality [25] compared to pastures and monocropping. Given the above, the objective of this study was to evaluate the soil C and N stocks and chemical and microbiological attributes in areas cultivated with pasture and silvopastoral systems in the Brazilian Cerrado.

2. Materials and Methods

2.1. Site Description

The experiment was carried out at Fazenda Buritis, located in the municipality of Montes Claros (16°42′25″ S and 44°04′36″ W), in the northern mesoregion of the state of Minas Gerais, Brazil (Figure 1). The climate in the region according to the Köppen classification is of the Aw type (tropical savannah), characterized by concentrated rainfall in the between October and April with an average annual precipitation of 945 mm and an average temperature of 24.1 °C [26]. The average elevation of the region is 653 m, with undulating topography and Cerrado vegetation. The soil in the study area was classified as an Oxisol of medium texture. The areas of the evaluated systems were previously occupied by low-productivity pastures for over 13 years.

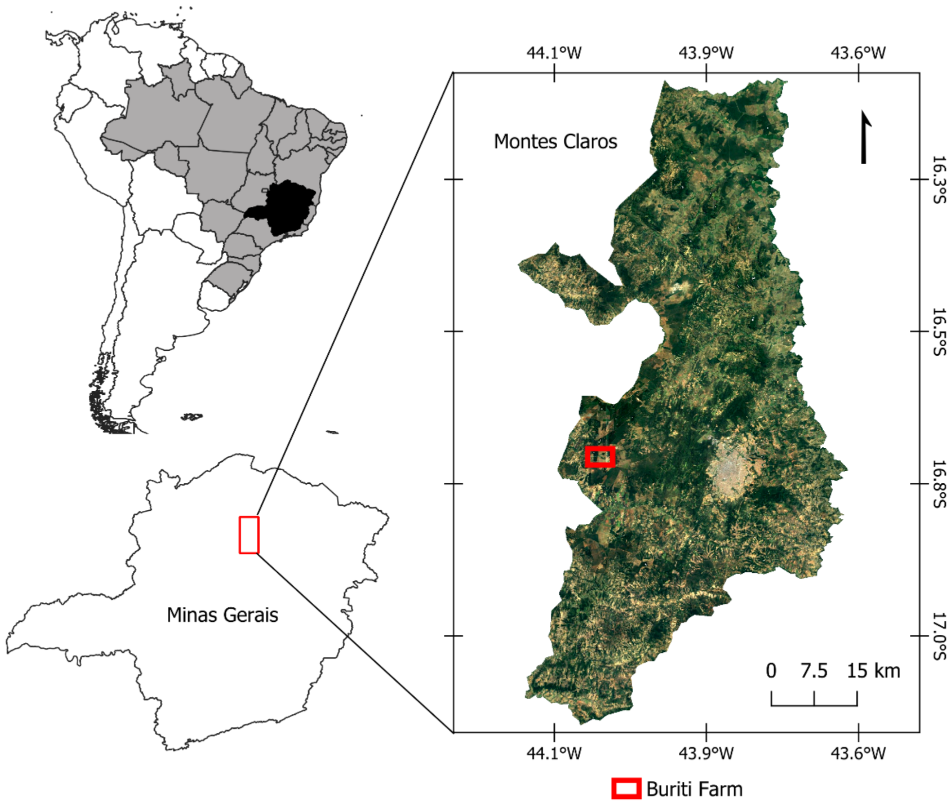

Figure 1. Location of the experimental area in the municipality of Montes Claros, Minas Gerais State, Brazil.

2.2. Experimental Design

The experimental design employed a completely randomized design (CRD) with four treatments (land use systems) and four replications across different land use systems. Soil samples were collected from four distinct land use systems within the sampling region, i.e., native vegetation (NV), degraded pasture (DP), managed pasture (MP), and a silvopastoral system (SPS). Soil analyses determined particle size, density, and nutrient content at seven different depths (0–5, 5–10, 10–20, 20–30, 30–50, 50–75, and 75–100 cm) [27]. Samples were obtained via trench excavation in each land use system, with the silvopastoral system samples considering both forestry and forage components, resulting in four composite samples (n = 4). For NV, DP, and MP, soil collections were performed in four samples (n = 4), spaced 50 m apart. Microbiological assessments were conducted exclusively in the surface layers (0–5, 5–10, and 10–20 cm) during both dry and wet seasons.

This comprehensive soil analysis set the stage for understanding the management and development of eucalyptus (*Eucalyptus urograndis* [*E. urophyla* × *E. grandis*]) plantations and pastures (*Brachiaria brizantha* cv. Marandu) within the silvopastoral system (SPS [with arrangement 3.2 × 1.5 inside the double rows of trees and 12 m between double rows]). The eucalyptus areas have been subject to cutting every 4/5 years, currently in their third cutting cycle. Recent observations revealed significant stress on Marandu grass within the SSP areas, likely due to recent droughts. In the exclusive pasture area (MP), primarily composed of Marandu grass, rotational grazing was practiced with an estimated carrying capacity of 0.8 AU ha^{-1} $year^{-1}$. There has been no recent nutrient replenishment or lime topdressing. Notably, the only liming occurred a decade ago during pasture establishment, using 2 tons per hectare of calcined dolomitic limestone. The DP system consisted of an area converted from Cerrado vegetation and cultivated with Marandu grass, lacking defined soil correction, nutrient replacement, and grazing management history, resulting in a reduction in biomass production. An area of native vegetation (VN), classified as Cerrado (similar to savanna), adjacent to the study areas, was used as a reference treatment.

2.3. Determination of Soil Carbon and Nitrogen Stocks and Chemical Attributes

Soil samples were air-dried and passed through a 2 mm mesh to remove roots. Subsequently, the samples were crushed and passed through a 0.150 mm mesh. Soil bulk density was determined using the core method (stainless steel rings—∅ 5 cm) for all samples [27]. Soil C and N contents were determined by dry combustion using an elemental analyzer (TruSpec, LECO Corporation, St. Joseph, MI, USA), estimating C content by infrared absorption and the total N by thermal conductivity. Soil C and N stocks were determined for consolidated depths of 0–10, 0–30, 0–50, and 0–100 cm by multiplying the C or N content by the soil density and respective soil depth according to Equation (1).

$$\sum(SOC \times BD \times E) \quad (1)$$

where *SOC* = soil organic carbon; *BD* = bulk density; and *E* = layer thickness.

Chemical analysis of the soil to determine pH (H_2O), organic matter (OM), Ca^{2+}, Mg, and P Mehlich, remaining P, H + Al, and K were all carried out according to Embrapa [28]. The sum of bases (BS), potential cation exchange capacity (pH = 7) (CEC_p), effective cation exchange capacity (CEC_e), base saturation (V%), and Al saturation (m%) were also calculated (Table S1).

2.4. Determination of Soil Microbial Attributes

Soil samples to determine microbiological attributes were pre-incubated at 60% of the field water holding capacity for a period of nine days. Soil microbial biomass carbon (Cmic) was determined by the fumigation-extraction method [29], and the Cmic was calculated by the difference between the values of the fumigated and non-fumigated samples, using a correction factor that represents the extraction efficiency (Equation (2)).

$$Cmic = FC \times k_c^{-1} \quad (2)$$

where *Cmic* is the carbon of microbial biomass (mg C microbial kg^{-1} soil), *FC* is the flux obtained from the difference between the amount of C (mg kg^{-1}), and K_c is the correction factor, which is equal to 0.33 [30].

Microbial activity was assessed through the determination of soil basal respiration (SBR), which was derived by incubating soil samples for nine days and quantifying the CO_2 absorbed using NaOH [31] according to Equation (3).

$$SBR = \left(\frac{(Vb - Va) \times M \times 6 \times 1000)}{Ps}\right)/T \quad (3)$$

where *SBR* is carbon originating from basal soil respiration (mg C kg^{-1} soil); V_b (mL) is the volume of hydrochloric acid used in titrating the control solution (blank); V_a (mL) is the volume spent on sample titration; M is the exact molarity of HCl; P_s (g) is the mass of dry soil; and T is the sample incubation time in hours.

The qMIC index was obtained by the ratio between *Cmic* and *SOC*, and the qCO_2 index by the ratio between *SBR* and *Cmic* according to Anderson and Domsch [32] and Reis Júnior and Mendes [33] and is described in Equation (4).

$$qCO_2 = \frac{SBR\left(mgC - CO_2\, g^{-1}Cmic\, h^{-1}\right)}{Cmic\left(mg\, C\, kg^{-1}\, solo\right) \times 10^{-3}\Big)} \quad (4)$$

where *SBR* is soil basal respiration rate (mg C-CO_2 g^{-1} Cmic h^{-1}) and *Cmic* is the microbial biomass carbon (mg C kg^{-1} soil).

2.5. Statistical Analysis

The Shapiro–Wilk test was used to verify whether the values of each variable satisfied a normal distribution, while the Bartlett test was used to verify the homogeneity of variances.

Once the data were validated, we performed an analysis of variance (ANOVA) followed by the Tukey test ($p \leq 0.05$) using the *Agricoloae* library (from Mandiburu and Simon [34]) of the statistical software R (version 4.2.3) [35].

To select explanatory variables in order to discriminate the different land use systems in the sampling region, we performed a principal component analysis (PCA) considering the average values for the 0–20 cm and 0–100 cm layers for the microbiological and other attributes, respectively.

3. Results

3.1. Soil Carbon and Nitrogen Stocks

Carbon stocks were highest in SPS and MP systems and lowest in NV and DP. Considering the evaluation of the soil profile (0–100 cm), C stocks in the evaluated systems differed from each other ($p \leq 0.05$), with the highest C stock in the MP system (129.5 Mg C ha^{-1}), followed by SPS (106.6 Mg C ha^{-1}), and the lowest values in NV (84.8 Mg C ha^{-1}) and DP (63.4 Mg C ha^{-1}). The MP system was more efficient, storing 46.1 Mg C ha^{-1} more than the other systems (Figure 2).

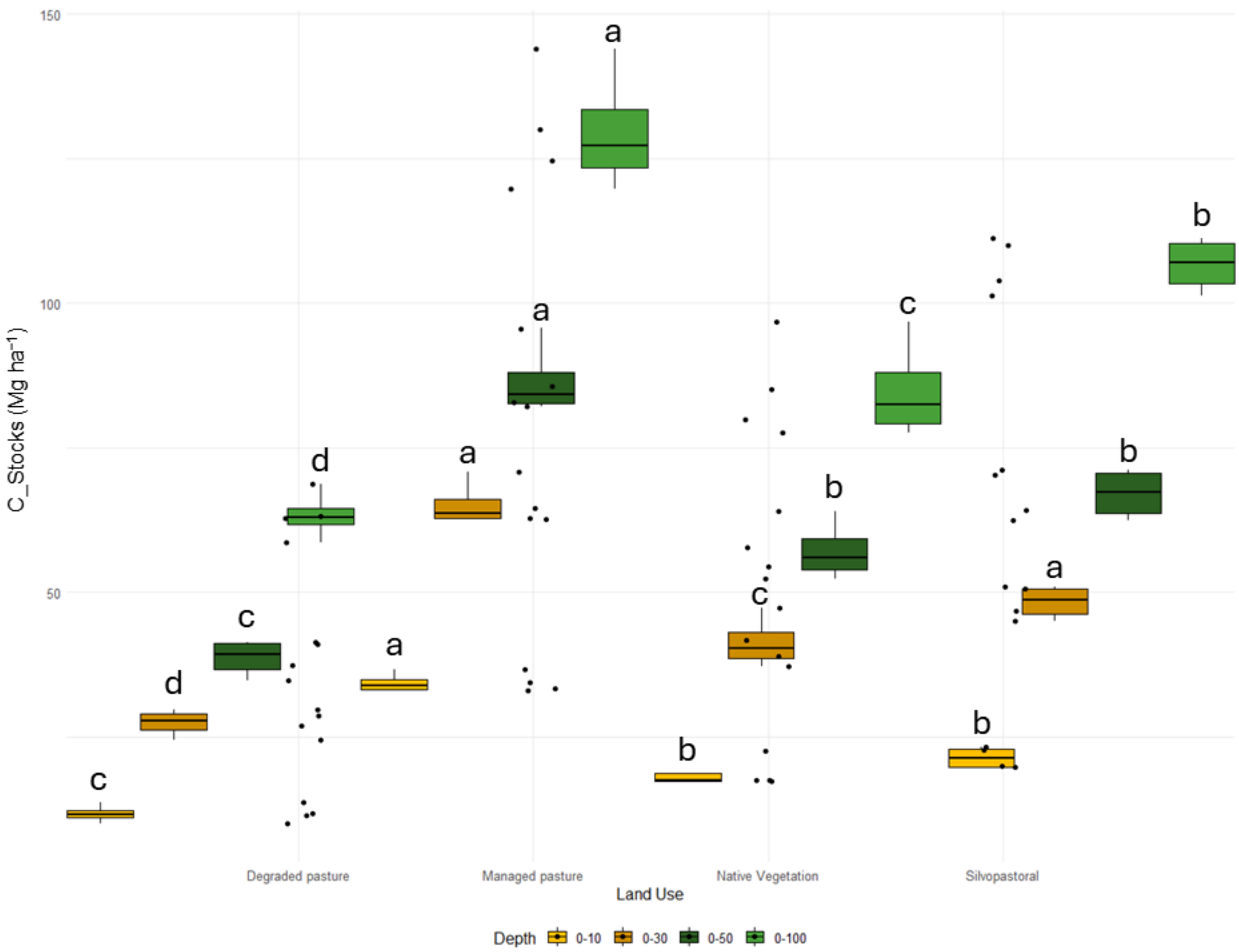

Figure 2. Soil carbon stocks (Mg C ha^{-1}) under land-use systems in the southeast of Brazil. Bars with the same letter for each depth do not differ significantly by the Tukey test ($p \leq 0.05$).

Nitrogen stocks showed a similar pattern to C stocks when considering the profile (0–100 cm), with the highest value allocated in the SPS system (34.3 Mg N ha^{-1}) representing an increase of 12.9 Mg N ha^{-1} compared to the other systems. The lowest N stock values were observed in the NV (6.5 Mg N ha^{-1}) and DP (5.1 Mg N ha^{-1}) systems, which showed no statistical difference ($p \leq 0.05$) (Figure 3).

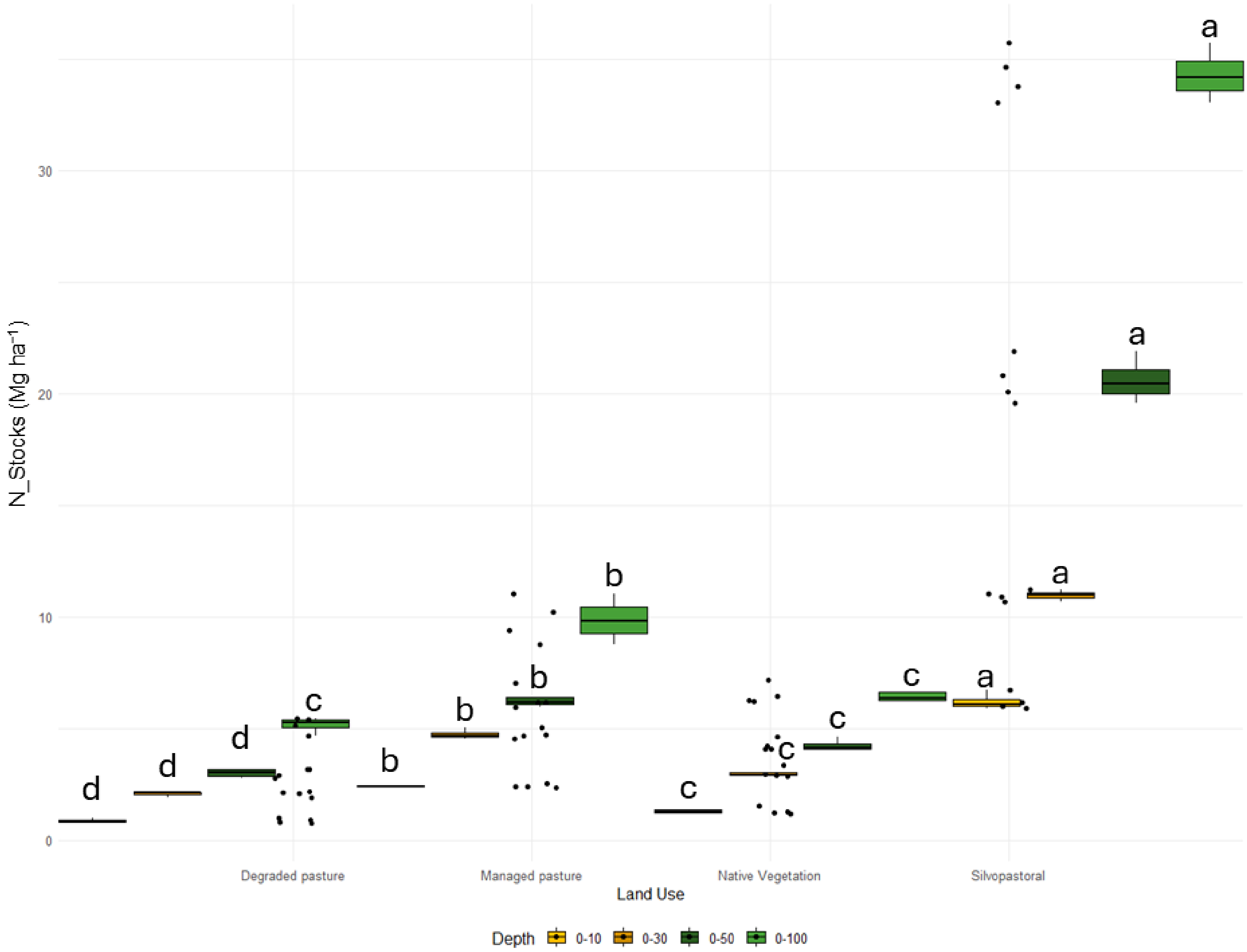

Figure 3. Soil nitrogen stocks (Mg N ha^{-1}) under different land-use systems in the southeast of Brazil. Bars with the same letter for each depth do not differ significantly by the Tukey test ($p \leq 0.05$).

3.2. Soil Microbial Changes

The Cmic in the different land use systems showed lower variations in the depths evaluated. In the dry season, the Cmic values at a depth of 0–5 cm varied from 104 to 200 mg C kg^{-1} (Figure 4A), with the highest Cmic value observed in the MP, which presented higher values when compared to NV, DP, and SPS, with DP reducing the Cmic by 23.5% in relation to the control (NV). In the 5–10 cm layer, the Cmic was higher in MP compared to DP, and no significant difference was observed between the NV and SPS systems. In the 10–20 cm layer, Cmic was higher in MP compared to DP and SPS, and no significant difference was observed between the NV, SPS, and DP systems. In the wet season, Cmic values ranged from 130.2 to 256.6 mg C kg^{-1}, but no significant difference was observed between treatments ($p \leq 0.05$) (Figure 4B).

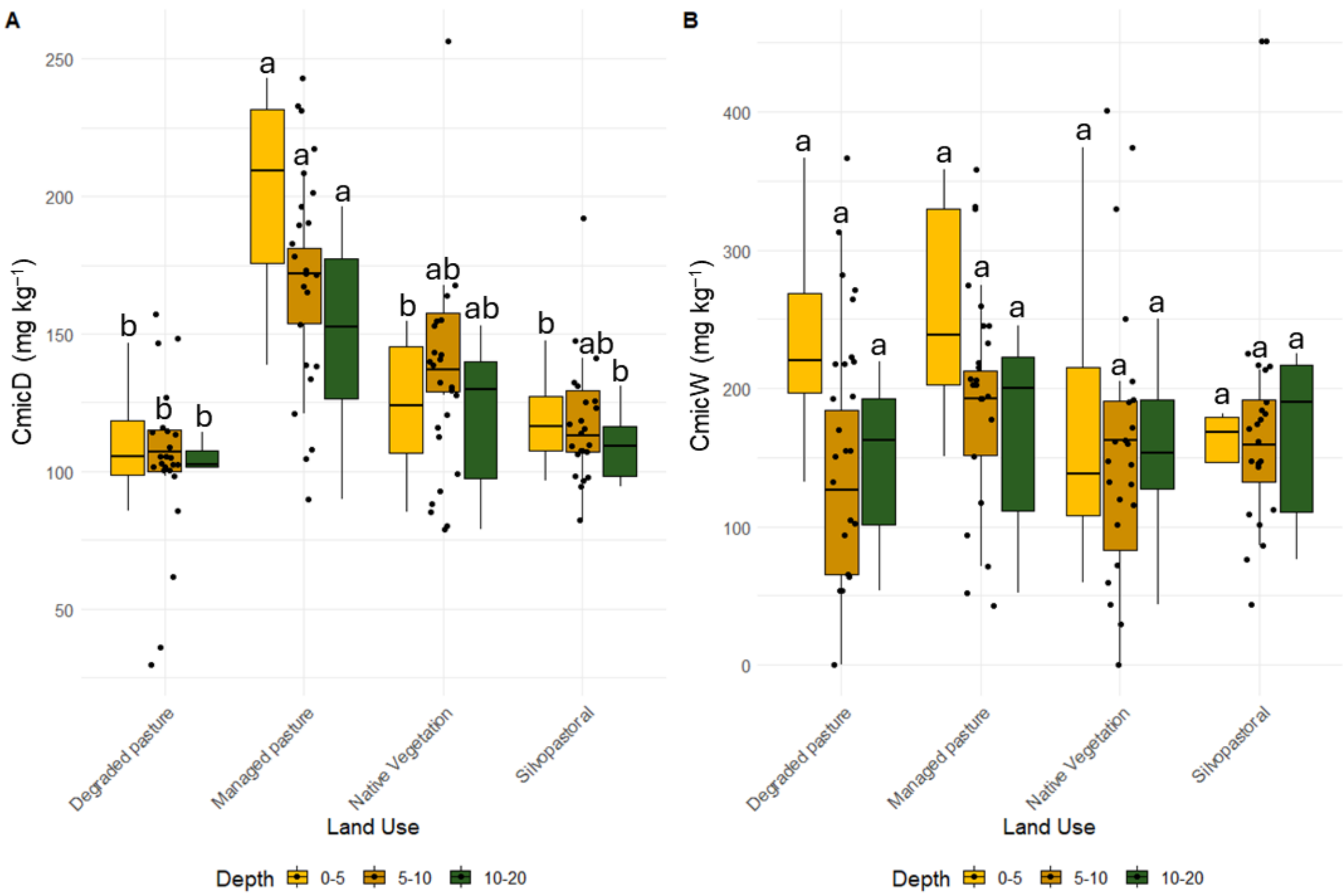

Figure 4. Soil microbial carbon (Cmic) under different land-use systems in the southeast of Brazil. Bars with the same letter for each depth do not differ significantly by the Tukey test ($p \leq 0.05$). (**A**) Wet season and (**B**) dry season.

Basal soil respiration (SBR) values ranged from 0.44 to 0.63 mg C–CO_2 Kg^{-1} h^{-1} in the dry season and from 0.65 to 1.06 mg C–CO_2 Kg^{-1} h^{-1} in the wet season but did not differ between the evaluated treatments ($p \leq 0.05$) at all evaluated depths (Figure 5A,B). In relation to the metabolic quotient (qCO_2) (Figure 6A,B), the values ranged from 2.85 to 7.31 in the dry season and from 4.84 to 9.53 in the wet season. A statistical difference was observed only in the 10–20 cm layer of the dry period (Figure 6A). For the aforementioned layer, the MP system presented the lowest qCO_2 in relation to the SPS and values equal to the other systems, while NV, SPS, and DP did not show significant differences between them ($p \leq 0.05$).

The microbial quotient (qMIC) in the dry season varied from 0.6 to 1.02% in the 0–5 cm layer (Figure 7A) but did not statistically differ from each other. This pattern was not observed in the 5–10 cm layer, where qMIC values varied from 0.73 to 1.25%, with higher qMIC in DP when compared to MP. For this same layer (5–10 cm), the qMIC did not differ between NV, DP, and SPS, and it was also possible to observe that NV, MP, and SPS presented similar qMIC. For the 10–20 cm layer, the qMIC variation was 0.67 to 1.17%, with results similar to those found in the upper layer (5–10 cm).

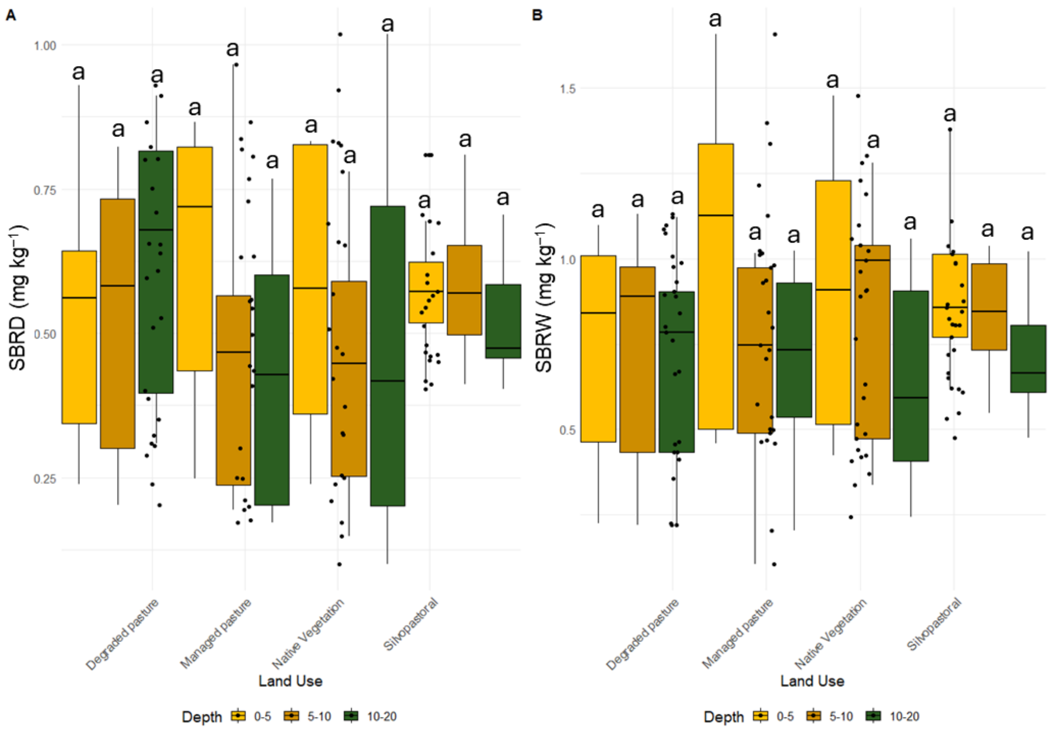

Figure 5. Soil basal respiration (SBR) under different land-use systems in the southeast of Brazil. Bars with the same letter for each depth do not differ significantly by the Tukey test ($p \leq 0.05$). (**A**) Dry season and (**B**) wet season.

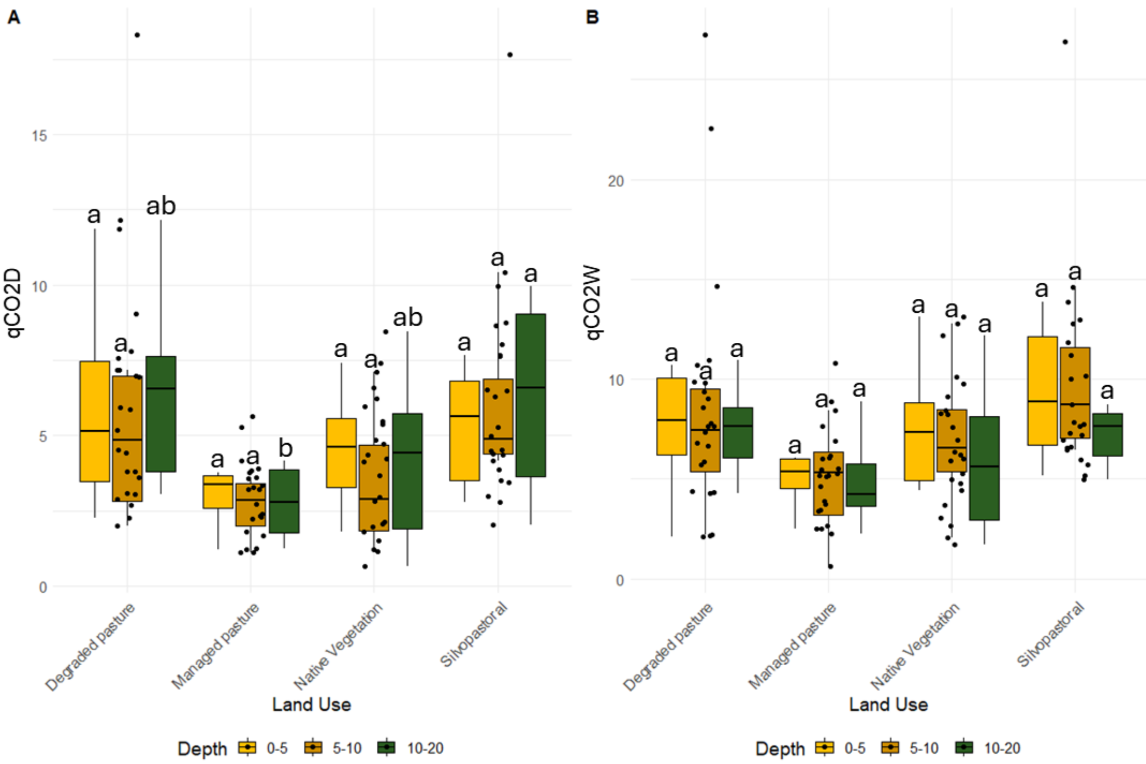

Figure 6. Metabolic quotient (qCO_2) under different land-use systems in the southeast of Brazil. Bars with the same letter for each depth do not differ significantly by the Tukey test ($p \leq 0.05$). (**A**) Dry season and (**B**) wet season.

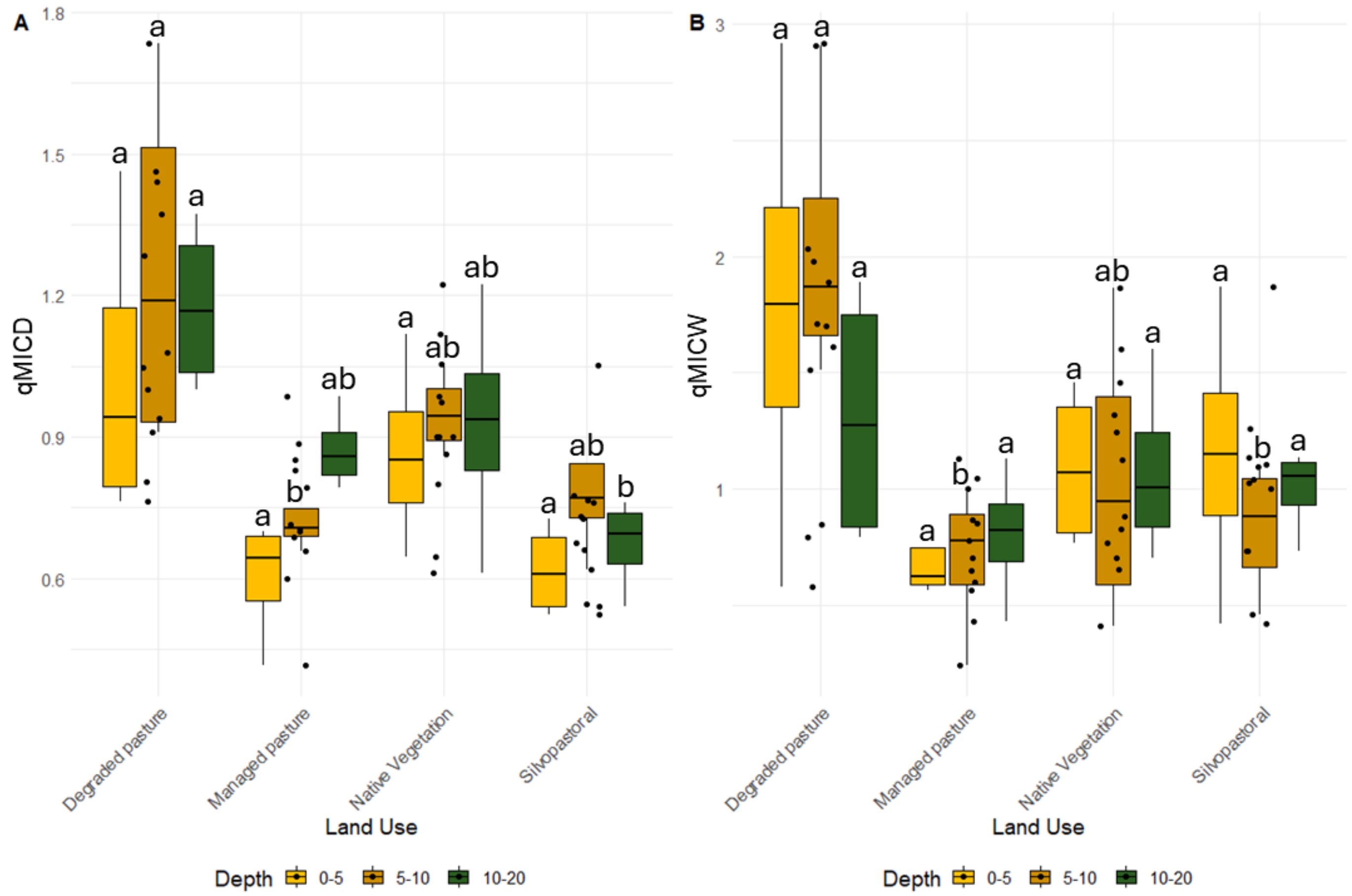

Figure 7. Microbial quotient (qMIC) under different land-use systems in the southeast of Brazil. Bars with the same letter for each depth do not differ significantly by the Tukey test ($p \leq 0.05$). (**A**) Dry season and (**B**) wet season.

The qMIC in the wet season (Figure 7B) varied from 0.71 to 1.77% in the 0–5 cm layer, but we did not observe any statistical difference between the systems evaluated ($p \leq 0.05$). In the 5–10 cm layer, qMIC values varied from 0.70 to 2.04%, with DP presenting a value equal to NV and higher in relation to the MP and SPS systems, while NV, MP, and SPS did not show a significant difference from each other. For the depth of 10–20 cm, qMIC values varied from 0.8 to 1.3%, but no statistical differences were observed between the systems.

3.3. Exploring Multidimensional Relationships: Biplot PCA Analysis

The biplot in Figure 8 visually depicts how different systems relate to the measured variables. In this analysis, the first two axes of the PCA captured 48.4% of the variation in these variables across the evaluated systems. Specifically, MP exhibited greater separability from the other systems, responding positively to the increments of carbon stocks, nitrogen stocks, pH, V%, BS, CEC_e, P Mehlich, remaining P, and K but a negative response to the increasing m values. On the other hand, both the NV and DP systems exhibit a similar pattern of response, with a mixed response to DIM1, though leaning toward a response opposite to that of MP, especially with a positive reaction to increasing m and qMICW values. In contrast, the SP system, although sharing similarities with NV and DP, was the most heterogeneous in its response to the soil characteristics, showing both a positive and a negative response to variables associated with DIM1 and DIM2. Notably, it showed a positive trend with increasing values of H + Al in the soil.

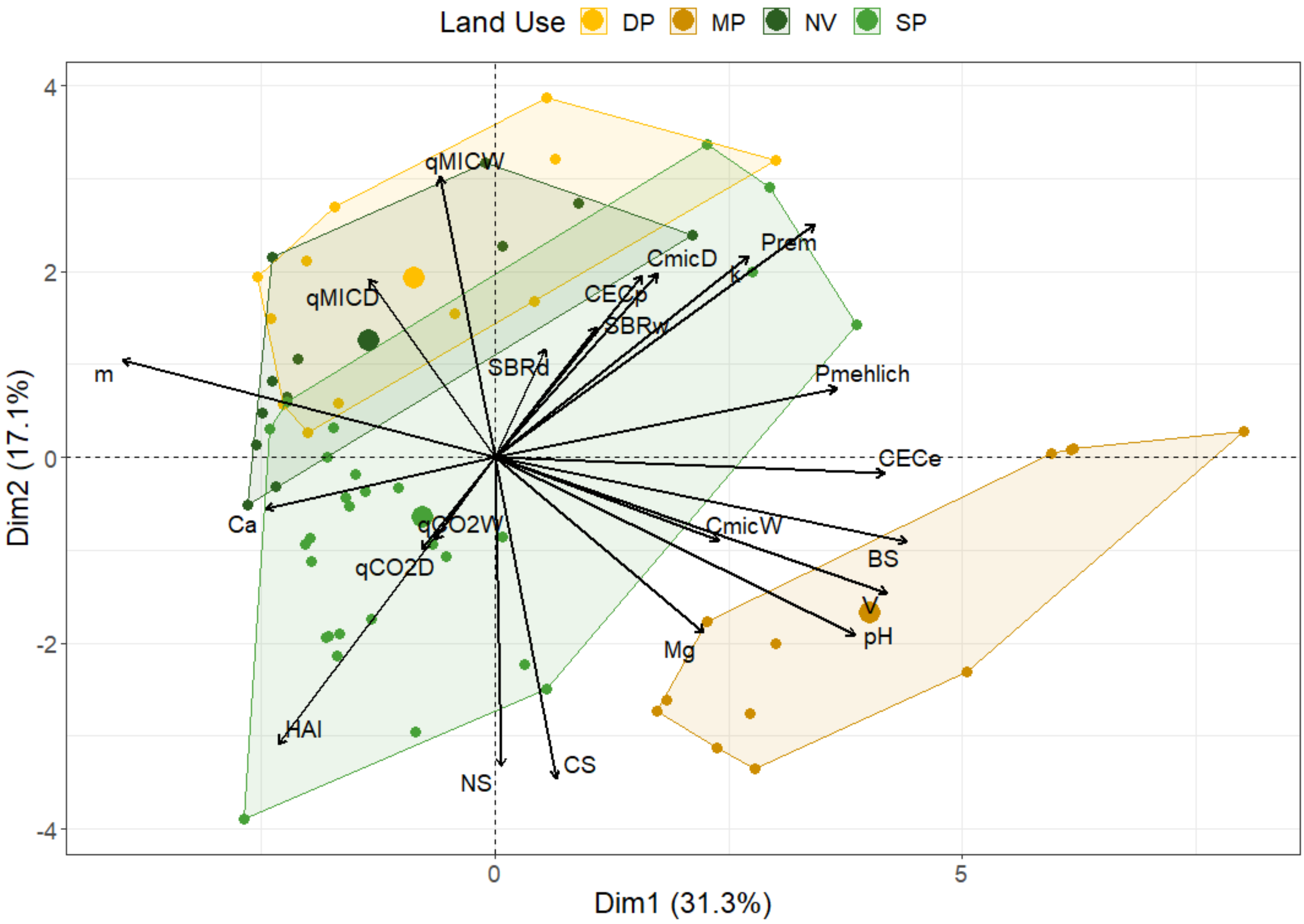

Figure 8. Biplots of analysis of main components in the different systems of use in southeast Brazil. DP = degraded pasture; MP = management pasture; NV = native vegetation; SP = silvopastoral; CS = carbon stocks; NS = nitrogen stocks; SBRw = soil basal respiration wet; SBRd = soil basal respiration dry; qMICW = microbial quotient wet; qMICD = microbial quotient dry; qCO_2W = metabolic quotient wet; qCO_2D = metabolic quotient dry; CmicD = microbial biomass dry; CmicW = microbial biomass rain; Pmehlich = P Mehlich; Prem = remaining P; CECp = potential cation exchange capacity (pH = 7); CECe = effective cation exchange capacity; V = base saturation; BS = sum of bases; m = Al saturation.

4. Discussion

4.1. C and N Stocks under Different Land Use and Management Systems

The increases in C and N stocks observed in SPS and MP in this study are consistent with findings from other studies that have evaluated the efficacy of various land use systems in carbon (C) and nitrogen (N) storage [36–39]. This rise in C stocks is only achievable through management systems that mitigate soil organic matter (SOM) decomposition while enhancing C inputs [40], thereby also augmenting N stocks within the soil-plant system [41]. Moreover, the forest component within the integrated crop–livestock–forest (ICLF) system serves as a significant C sink, capable of accumulating substantial amounts of C in woody biomass [42]. These contributions enter the system via cultural residues present on the soil surface and an increased volume of residue provided by pastures and trees in the deeper soil layers [36].

In Brazil, the adoption of integrated production systems, such as SPS, has demonstrated effectiveness in soil C storage, comparable to or even surpassing levels observed in native vegetation (NV) [43]. This efficacy is attributed to the use of tropical grasses that facilitate soil coverage, straw production, and soil structuring [44,45]. Well-managed pastures also show promise in promoting greater C and N storage in the soil due to reduced soil disturbance and the fasciculated root system of C4 grasses covering these pastures [36,46]. The lower C stock values found in NV and DP are likely attributed to reduced litter input and the loss of physical protection of SOM [37]. Thus, the decline in C stocks may be associated with prolonged overgrazing of pastures, leading to intensified soil C losses. Furthermore, the conversion of forests to low-productivity pastures exacerbates C losses due to heightened microbial activity resulting from decreased SOM inputs to the soil surface [47].

Addressing the effect of cattle manure droppings and the approximate amount of C entering the soil via such a route is crucial in understanding the dynamics of C cycling within these systems. Scientific literature has documented the significant contribution of bovine excrement to the soil carbon cycle. For instance, a study conducted by Smith et al. [48] estimated that approximately 15–30% of the carbon contained in bovine manure is incorporated into the soil after application. This input of carbon from bovine excrement plays an important role in nutrient cycling and promoting soil health in agricultural systems.

4.2. Soil Microbiological Activity

Our results for Cmic in the wet season (Figure 4B) showed no difference between treatments, but the values found were higher than those reported by Silva et al. [49] and Sousa et al. [50]. These results suggest that soil microbial activity tends to remain constant in both low-productivity pasture areas and managed areas [39], or that, when the microbiota is subjected to new environmental conditions, the response to practices conservation management systems (e.g., SPS and MP) can be slow over time [51]. Regarding the seasonality, our results corroborate those found by Oliveira [52], who also indicated higher Cmic values in the wet season (from 997 to 1108 mg C Kg^{-1}).

The highest results found in the dry season in MP (Figure 4A) are in line with those reported by Stieven et al. [53] and Mattos et al. [54], who reported that the more intensive input of SOM on the surface of well-managed pastures from grasses maximizes the performance of microbiota in the soil, thus allowing greater accumulation of organic residues in the surface layer (0–5 cm) and contributing to the rise of the Cmic. The similar Cmic values between MP, SPS, and NV also indicated that these systems can improve microbial development (5–10 cm).

The lack of significant differences in SBR (Figure 5) at the depths of the treatments evaluated suggests a uniformity in microbial activity among the different use systems evaluated. The same pattern was observed for qCO_2 in the wet season (Figure 6B), where it was not possible to observe a significant variation across the different uses, which may be associated with similar efficiency in the use of organic compounds by microorganisms at the sampled depths of the systems in our study, indicating similar loss of CO_2 per unit of biomass in all evaluated systems. Nonetheless, MP contributed to reducing qCO_2 in the dry season (Figure 6A). Thus, as the soil microbiota becomes more efficient, less SOC is lost as CO_2 through respiration, and a significant fraction of C is incorporated into the microbial tissue [55]. Similar results were also observed by Lourente [56], with small microbiological changes in different management systems in the Cerrado region.

Lower CO_2 losses are desirable, as they indicate the incorporation of C into the microbial tissue. In this sense, it is important that values are compared for the same type of soil [57,58], as carried out in this study. According to Alvarenga et al. [59], the absence of the effect of soil use and management systems on the values of this variable implies no change in the ecological balance of the soil, in relation to the non-anthropized Cerrado ecosystem.

The qMIC values (Figure 7) indicated that different sampling conditions (e.g., wet and dry season) tend to interfere with the balance of soil microbiota, as observed in this study. Thus, values below 1% may occur due to the existence of factors limiting the activity of soil microorganisms, with values varying from 1% to 2% of the SOC, which corroborate the results found by Abreu et al. [42], where they find qMIC values ranging from 1% to 4% of the SOC. High qMIC values mean that SOC is more accessible to soil microbiota [60]. In our study, there was a greater occurrence of values lower than 1% in the dry season at all depths, a different pattern from that observed in the rainy season where qMIC values were generally greater than 1, which was probably due to the decrease in microbial activity in the soil in the dry season.

Thus, in line with our results, some studies reported improvements in soil quality with the insertion of conservation practices; for example, the insertion of perennial species tends to promote an increase in the decomposition capacity of organic substances rich in carbohydrates due to the activity of the microbiota, maximizing the input of nutrients into the soil, favoring an increase in C and N stocks, in addition to increasing soil fertility, and minimizing the output of C in the form of CO_2 to the atmosphere catalyzed by the use of fertilizers [61,62].

5. Conclusions

Our study reinforces the previously reported general observation that Cerrado Oxisols exhibit relatively high soil organic carbon (SOC) stocks. This finding prompted us to investigate how conservation practices, such as Sustainable Production Systems (SPS) and Managed Pastures (MP), contribute to increasing both carbon (C) and nitrogen (N) stocks in the soil, along with microbial carbon (Cmic). Our results indicate that proper management of fertilization and cultural treatments plays a crucial role in maintaining soil fertility in pasture-cultivated areas.

Moreover, our study revealed significant increases in SOC and N stocks in the SPS system compared to degraded pastures, with an increase of 46.1 Mg C ha^{-1} and 12.9 Mg N ha^{-1}, respectively. In degraded pastures (DP), we observed that microbial biomass represents 1.02 to 2.04% of soil SOC in the 0–5 cm and 5–10 cm layers, respectively. These findings shed light on the dynamics of soil microbial communities and their contributions to SOC maintenance in different soil layers.

Importantly, our results contribute to understanding the SOC storage gap and emphasize the importance of long-term monitoring to assess the effectiveness of conservation systems in storing SOC at levels equal to or higher than those observed in native vegetation. By placing our findings in this broader scientific context, we underscore the significance of sustainable land management practices in mitigating soil degradation and enhancing ecosystem resilience in Cerrado regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15061029/s1. Table S1: Chemical characteristics of soils sampled under various land use systems.

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