

Perennial rubber tree systems preserve soil microbial functioning and quality comparable to Atlantic Forest in tropical soils

Sistemas perenes de seringueira preservam o funcionamento e a qualidade microbiana do solo comparáveis à Mata Atlântica em solos tropicais

Los sistemas perennes de caucho preservan el funcionamiento y la calidad microbiana del suelo comparables al Bosque Atlántico en suelos tropicales

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ABSTRACT

Land-use change is a key driver of soil degradation in tropical ecosystems, strongly affecting microbial processes that regulate nutrient cycling and ecosystem sustainability. This study evaluated soil basal respiration (RBS), microbial biomass carbon (CBM), microbial biomass nitrogen (NBM), metabolic quotient (qCO_2), microbial quotient ($qMIC$), and chemical attributes under three land-use systems: *Brachiaria brizantha* grassland, rubber tree monoculture (*Hevea brasiliensis*), and an Atlantic Forest fragment, in a tropical soil of southeastern Brazil. Samples were collected at 0–10 and 10–20 cm depths during winter and summer. Microbial indicators responded markedly to land use. The rubber tree system showed significantly higher CBM, NBM, and Soil Quality Index (SQI) values, approaching those of the Atlantic Forest. Grassland exhibited lower microbial biomass and higher qCO_2 , indicating reduced microbial efficiency and greater physiological stress. Multivariate analysis identified CBM, NBM, calcium content, and cation exchange capacity as the main drivers of system differentiation. The SQI ranked systems as rubber tree > Atlantic Forest > grassland, demonstrating that perennial systems with continuous organic inputs and low disturbance maintain soil microbial functioning at levels comparable to native vegetation. These findings highlight the role of perennial cropping systems in sustaining soil biological quality and supporting sustainable land management in tropical regions.

Keywords: *Brachiaria brizantha*, *Hevea brasiliensis*, soil quality, perennial systems, sustainability.

RESUMO

A mudança no uso da terra é um importante fator de degradação do solo em ecossistemas tropicais, afetando processos microbianos responsáveis pela ciclagem de nutrientes e sustentabilidade ambiental. Este estudo avaliou a respiração basal do solo (RBS), o carbono (CBM) e o nitrogênio da biomassa microbiana (NBM), o quociente metabólico (qCO_2), o quociente microbiano ($qMIC$) e atributos químicos sob três sistemas de uso da terra: pastagem de *Brachiaria brizantha*, monocultivo de seringueira (*Hevea brasiliensis*) e fragmento de Mata Atlântica, em solo tropical do sudeste do Brasil, nas profundidades de 0–10 e 10–20 cm, no inverno e verão. Os indicadores microbiológicos responderam de forma significativa ao uso da terra. O sistema de seringueira apresentou maiores valores de CBM, NBM e Índice de Qualidade do Solo (SQI), próximos aos da Mata Atlântica. A pastagem exibiu menor biomassa microbiana e maior qCO_2 , indicando menor eficiência metabólica. CBM, NBM, cálcio e capacidade de troca catiônica foram os principais atributos discriminantes. O SQI classificou os sistemas como: seringueira > Mata Atlântica > pastagem, evidenciando que sistemas perenes com aporte contínuo de resíduos e baixo distúrbio mantêm o funcionamento microbiano do solo em níveis comparáveis à vegetação nativa.

Palavras-chave: *Brachiaria brizantha*, *Hevea brasiliensis*, qualidade do solo, sistemas perenes, sustentabilidade.

RESUMEN

El cambio de uso del suelo es un factor clave de degradación en ecosistemas tropicales, afectando significativamente los procesos microbianos que regulan el ciclo de nutrientes y la sostenibilidad del ecosistema. Este estudio evaluó la respiración basal del suelo (RBS), el carbono de la biomasa microbiana (CBM), el nitrógeno de la biomasa microbiana (NBM), el cociente metabólico (qCO_2), el cociente microbiano ($qMIC$) y atributos químicos bajo tres sistemas de uso del suelo: pastizal de *Brachiaria brizantha*, monocultivo de caucho (*Hevea brasiliensis*) y un fragmento de Bosque Atlántico, en un suelo tropical del sureste de Brasil. Las muestras fueron recolectadas a profundidades de 0–10 y 10–20 cm durante el invierno y el verano. Los indicadores microbianos respondieron marcadamente al uso del suelo. El sistema de caucho presentó valores significativamente mayores de CBM, NBM y del Índice de Calidad del Suelo (SQI), aproximándose a los observados en el Bosque Atlántico. El pastizal mostró menor biomasa microbiana y mayor

qCO₂, lo que indica menor eficiencia microbiana y mayor estrés fisiológico. El análisis multivariado identificó CBM, NBM, contenido de calcio y capacidad de intercambio catiónico como los principales factores de diferenciación entre sistemas. El SQI clasificó los sistemas en el siguiente orden: caucho > Bosque Atlántico > pastizal, demostrando que los sistemas perennes con aporte continuo de residuos orgánicos y bajo nivel de perturbación mantienen el funcionamiento microbiano del suelo en niveles comparables a la vegetación nativa. Estos resultados resaltan el papel de los sistemas agrícolas perennes en la conservación de la calidad biológica del suelo y en la promoción de una gestión sostenible de la tierra en regiones tropicales.

Palabras clave: *Brachiaria brizantha*, *Hevea brasiliensis*, calidad del suelo, sistemas perennes, sostenibilidad.

1 INTRODUCTION

The adoption of sustainable cropping systems has increased significantly in recent years, encouraged mainly by the public demand for better food quality that may promote less environmental impacts during its production process (Ferreira et al., 2017). Currently, there is a growing pursuit of cultivation systems capable of preserving or enhancing soil quality while ensuring food security for future generations.

Recent advances in soil microbiology have underscored biological attributes as precise indicators of soil quality changes, given their high sensitivity in detecting alterations even under minimal management conditions (Lehmann et al., 2020). Moreover, numerous biological properties of soil can serve as reliable indicators of soil quality and health, as they are highly responsive and reflect both anthropogenic management practices and the impacts of climate change (Cotrim, 2022). Mendes et al. (2012) further highlight the fundamental role of soil microorganisms as primary regulators of nutrient cycling, reinforcing their significance in sustaining the functionality of edaphic systems. Consequently, several works have been completed aiming to evaluate soil quality under different management systems (Partelli et al., 2012; Evangelista et al., 2013; Ensinas et al., 2014; Zake et al., 2015; Mazzetto et al., 2016; Ferreira et al., 2017; Oliosi et al., 2025).

Soil microbial biomass represents an important reservoir of carbon, phosphorus, nitrogen, and sulfur in the soil, essential elements for the development of plants, having also a role as catalyzers in organic matter degradation (Souza et al., 2010). The behavior and dynamics of soil can be assessed through microbiological attributes, such as microbial biomass carbon and nitrogen, basal respiration, and the metabolic quotient. These attributes serve as sensitive indicators, enabling their use in monitoring potential environmental changes (Silva et al., 2021).

The carbon cycle has been extensively investigated because soil carbon dynamics are central to biogeochemical feedbacks that influence global climate change, particularly through interactions with atmospheric CO₂ and climate system sensitivity (Varney et al., 2024). Management systems

able to preserve or increase the proportions of organic carbon in the soil may contribute to maintain the productive capability and to mitigate the increment of atmospheric CO₂ (Siqueira Neto et al., 2009). High organic carbon stocks not only preserve soil quality and local productivity but also constitute a greater permanent carbon reserve than the one in biomass (Negash & Starr, 2015).

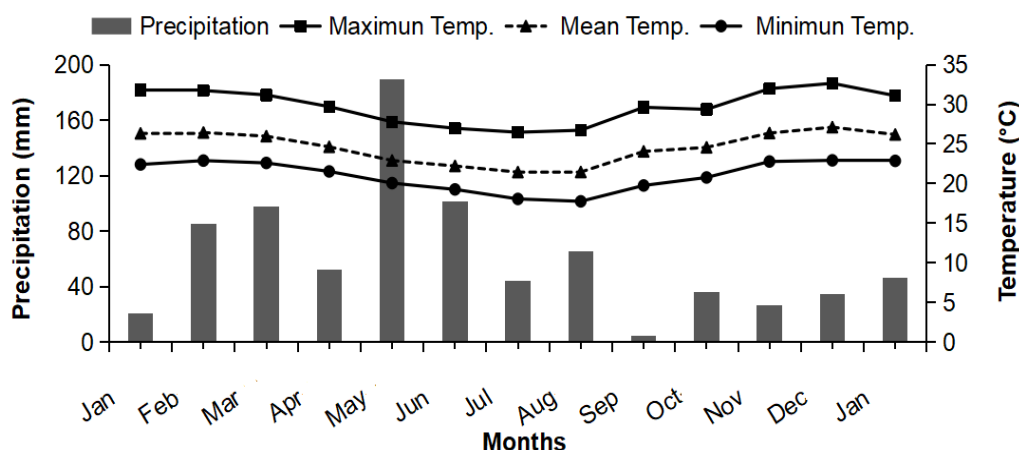
The importance of soil for global biodiversity underscores the need to preserve the integrity of ecosystems. Soil quality is essential not only for maintaining the balance of species that depend on it but also for ensuring the sustainable cultivation of agricultural crops and safeguarding global food security (Silva et al., 2021).

Despite the recognized importance of perennial cropping systems in tropical regions, significant knowledge gaps remain regarding their long-term effects on soil microbiological functioning compared to native ecosystems. Most studies have focused primarily on chemical or physical soil properties, while microbiological indicators—which are more sensitive and responsive to management-induced changes—remain insufficiently explored, particularly in rubber tree systems. Understanding these biological responses is essential for evaluating the sustainability and resilience of tropical agroecosystems under increasing environmental pressures, including climate change and land-use intensification (Fierer, 2017; Lehmann et al., 2020). Thus, the objective of this work was to evaluate the modifications in soil microbiological and chemical attributes in a grass, rubber tree and Atlantic Forest areas in different seasons.

2 MATERIALS AND METHODS

The experiment was conducted on a private farm located in the municipality of Jaguaré, Espírito Santo, Brazil (18°56' S, 39°59' W), on flat terrain at an altitude of 50 m above sea level. The soil was classified as a Dystrophic Cohesive Yellow Latosol (Santos et al., 2013), according to the Brazilian Soil Classification System. The regional climate is classified as Aw (tropical with dry winter) according to Köppen's classification (Alvares et al., 2014). During the experimental period, rainfall recorded in the summer of 2016 was below the historical average (Figure 1). Meteorological data were obtained from an automatic weather station located 31.5 km from the experimental site, which is considered representative of the regional climatic conditions.

Figure 1. Total rainfall and mean values of maximum, mean, and minimum air temperature recorded at the meteorological station in São Mateus, Espírito Santo, Brazil, from January 1, 2015, to January 11, 2016.



Source: Prepared by the authors (2026).

Total rainfall and mean values of maximum, mean, and minimum air temperature recorded at the meteorological station in São Mateus, Espírito Santo, Brazil, from January 1, 2015, to January 11, 2016. Three land use systems were evaluated: 1- *Brachiaria brizantha* grassland (P); *Rubber tree* monoculture (*Hevea brasiliensis*) (S); Atlantic Forest fragment (M). All areas were located within approximately 200 m of each other, with similar soil type, topography, and environmental conditions, minimizing variability caused by edaphoclimatic factors.

The *Brachiaria brizantha* grassland was established in 2006. Soil preparation included plowing, harrowing, and leveling. Liming was performed at a rate of 2.0 t ha⁻¹ using dolomitic limestone, and reactive natural phosphate was applied at 400 kg ha⁻¹. Sowing was performed using a seed drill followed by light compaction. During pasture establishment, weeds were controlled using herbicide, and nitrogen fertilization was applied 90 days after sowing using urea at a rate of 80 kg ha⁻¹ of nitrogen. Prior to pasture establishment, the area had been cultivated with coffee (1986–2002), cassava (2002–2004), and left fallow (2004–2006). The pasture system presented an average annual productivity of approximately 12,000 kg ha⁻¹ of dry matter and a stocking rate of 2.5 animal units (AU) per hectare.

The rubber tree monoculture was established in 1982 and was 33 years old at the time of soil sampling, representing a mature and fully productive perennial system. Tree spacing was 7.8 × 2.3 m. Prior to rubber tree establishment, the area consisted of native vegetation. Soil preparation included plowing, harrowing, and leveling, followed by manual planting. Liming was performed periodically based on soil analysis, approximately every two years. Fertilization was applied during establishment and tree formation stages, with an additional application of coffee straw in 2014. Weed control consisted of mechanical cutting every three months and glyphosate application once

per year during the rainy season. The system was rainfed and did not receive irrigation. Rubber trees exhibit complete leaf senescence during winter (May–June), followed by leaf renewal in August, resulting in substantial litter deposition and continuous organic matter input into the soil. Average dry rubber productivity was approximately 2,200 kg ha⁻¹.

The Atlantic Forest fragment served as a reference system representing native vegetation conditions. The area had not been subjected to burning during the previous 30 years, although selective logging had occurred approximately 25 years prior to sampling. This system represents a semi-conserved native ecosystem under natural regeneration.

Each land-use system was divided into four sampling plots, representing four replicates. Soil samples were collected using an auger on July 13, 2015 (winter), and January 11, 2016 (summer), at depths of 0–10 cm and 10–20 cm. These depths were selected because they represent the most biologically active soil layers and are highly responsive to management practices. Soil microbiological analyses were performed in both seasons due to their sensitivity to climatic variation, whereas chemical analyses were performed only in summer to minimize seasonal variability. Soil particle-size distribution was determined to characterize soil texture (Table 1).

Table 1. Particle-size distribution (g kg⁻¹) of soils under different land-use systems.

Evaluated Areas	Sand	Silt	Clay
	(2 a 0.05 mm)	(0.05 a 0.002 mm)	(< 0.002 mm)
G-P1	866	39	95
G-P2	879	31	90
R-P1	893	43	64
R-P2	876	44	80
F-P1	943	22	35
F-P2	940	20	40

Letters before the dash indicate land-use system and letters after the dash indicate soil depth. G: grassland; R: rubber tree; F: Atlantic Forest fragment; P1: 0–10 cm; P2: 10–20 cm. Source: Prepared by the authors (2026).

Subsamples were collected for chemical and microbiological analyses. Chemical analyses were performed by a certified laboratory according to standard procedures described by Silva (2009). For microbiological analyses, soil samples were collected near field capacity, placed in sterile plastic bags, and transported under refrigerated conditions in insulated containers to preserve microbial activity. Samples were transported to the laboratory within 24 hours after collection. In the laboratory, samples were sieved through a 2 mm mesh to remove plant residues and stones and stored at 4 °C until analysis. Microbiological analyses were performed at the Nutrient Cycling Laboratory of Embrapa Agrobiology (Seropédica, Rio de Janeiro, Brazil). All analyses were conducted in duplicate to ensure analytical precision and reproducibility.

Soil basal respiration (RBS) was determined according to the method described by Jenkinson and Powlson (1976). The metabolic quotient (qCO_2) was calculated as the ratio between basal respiration and microbial biomass carbon, following Anderson and Domsch (1990). Microbial biomass carbon (CBM) was determined using the fumigation-extraction method (VANCE et al., 1987), adopting a correction factor (kC) of 0.33 as recommended by Sparling and West (1988). Microbial biomass nitrogen (NBM) was determined using the fumigation-extraction method with a correction factor (kN) of 0.54 according to Brookes et al. (1985). The microbial quotient ($qMIC$) was calculated as the ratio between microbial biomass carbon and total organic carbon (SPARLING, 1992).

Multivariate statistical analysis was performed to evaluate differences among land-use systems. Mahalanobis distance (D^2) was used to estimate dissimilarity among systems, followed by hierarchical clustering using the Unweighted Pair Group Method with Arithmetic Mean (UPGMA). The relative contribution of each variable to system differentiation was estimated using Singh's method (SINGH, 1981). These analyses were performed using GENES software (CRUZ, 2013). Descriptive statistical analysis was also performed by calculating means and standard errors.

Additionally, soil quality index (SQI) was calculated using radar chart methodology, based on normalized microbiological attributes. Mean values of microbiological variables were converted to relative percentages using the Atlantic Forest fragment as a reference (100%), following the methodology proposed by Nunes et al. (2009). This approach allows integrated assessment of soil biological quality under different land-use systems.

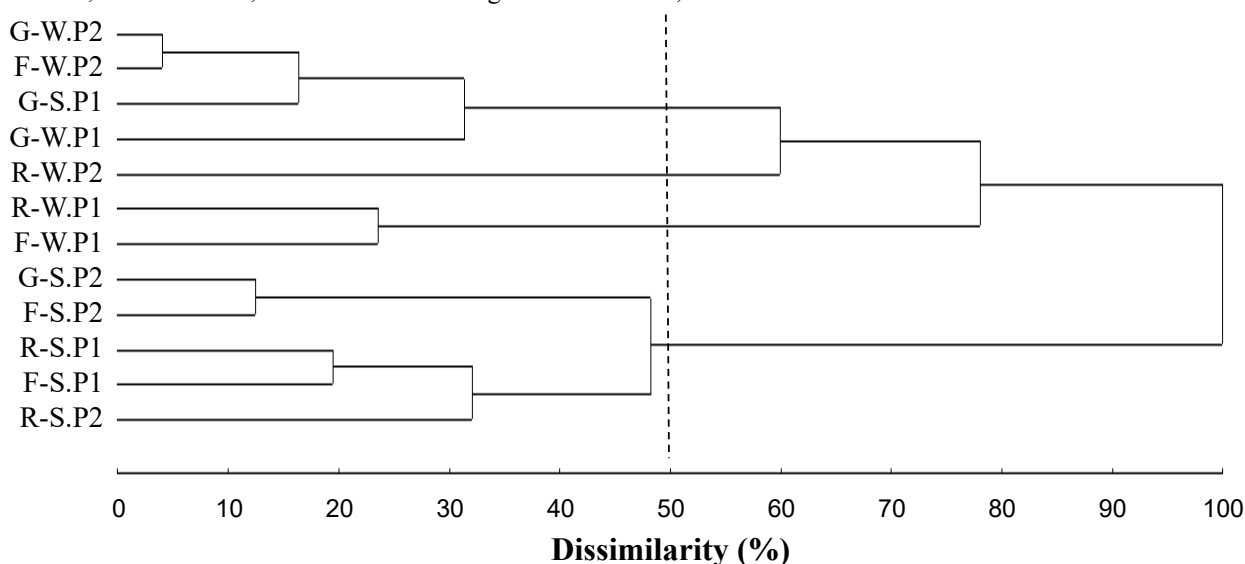
3 RESULTS AND DISCUSSION

The hierarchical clustering analysis based on microbiological attributes revealed clear differentiation among management systems and seasonal conditions, highlighting the sensitivity of soil microbial communities to land use and environmental variability (Figure 2). During the summer, most management systems clustered into a single group, indicating convergence in microbial functioning under favorable moisture and temperature conditions. In contrast, winter conditions promoted greater divergence among systems, particularly distinguishing the Atlantic Forest fragment and rubber tree monoculture at 0–10 cm depth. This seasonal divergence reflects the strong influence of abiotic constraints on microbial metabolism, especially under reduced moisture availability and lower temperatures, which selectively affect microbial growth and activity (Fierer, 2017; Lehmann et al., 2020).

Microbial biomass carbon (CBM) emerged as the primary variable contributing to system differentiation, accounting for 27.05% of total variation, followed by total organic carbon (COT)

and microbial biomass nitrogen (NBM). Variations in microbial biomass and enzyme activities across land-use systems reflect differences in substrate availability and soil functioning (Mendes et al., 2015; Oliosi et al., 2025). These results reinforce CBM as one of the most robust indicators of soil ecological functioning, as it integrates both the size and metabolic activity of the microbial pool responsible for organic matter turnover and nutrient cycling (Islam & Weil, 2000). Because microbial biomass responds rapidly to changes in organic inputs and environmental conditions, it provides an early and sensitive signal of soil quality shifts induced by management practices.

Figure 2. Dissimilarity between management systems obtained by the UPGMA clustering method, using the Mahalanobis distance, based on microbiological soil attributes. Letters before dashes are referred to the management type and letters after dashes are referred to the sampling period and finally to the soil depth. G: *Brachiaria brizantha* grassland; R: rubber tree; F: Atlantic Forest fragment. W: winter; S: summer. P1: 0-10 cm and P2: 10-20 cm.



Source: Prepared by the authors (2026).

Soil basal respiration (RBS) exhibited clear seasonal variation, with values approximately 22.3% higher in winter compared to summer (Figure 3A). This pattern may initially appear counterintuitive but likely reflects increased microbial maintenance respiration under stress conditions, rather than enhanced microbial growth. Under suboptimal environmental conditions, microorganisms allocate a greater proportion of carbon to maintenance energy requirements, resulting in higher respiration rates per unit of biomass (Anderson & Domsch, 1990). This interpretation is supported by the elevated metabolic quotient (qCO_2) observed in certain systems, which is widely recognized as an indicator of microbial stress and reduced carbon use efficiency.

The Atlantic Forest fragment consistently exhibited higher RBS values at the surface layer during winter, reflecting the presence of a more active and functionally diverse microbial community supported by continuous organic matter inputs and absence of anthropogenic disturbance. Native forest ecosystems typically maintain higher microbial activity due to greater

substrate availability, enhanced microclimatic stability, and more complex organic matter composition, which supports diverse metabolic pathways (Fierer, 2017; Lehmann et al., 2020). These conditions promote enhanced decomposition processes and contribute to the stabilization of soil carbon stocks.

The rubber tree system demonstrated particularly favorable microbial functioning, as evidenced by lower qCO_2 values across depths and seasons (Figure 3D), indicating higher microbial efficiency in carbon utilization. Lower qCO_2 values are associated with less stressed microbial communities and more efficient incorporation of carbon into microbial biomass, rather than its loss through respiration (Anderson & Domsch, 1990). This pattern suggests that rubber tree monoculture provides a relatively stable and resource-rich environment for microbial communities, likely driven by continuous litter deposition and reduced soil disturbance.

Consistent with this interpretation, CBM values were generally higher in the rubber tree and forest systems, particularly at 0–10 cm depth (Figure 3B). These results highlight the importance of organic matter inputs in sustaining microbial biomass, as litterfall serves as a primary energy and nutrient source for soil microorganisms (Zake et al., 2015). Rubber tree systems are characterized by intense seasonal litter deposition, which enhances carbon availability and promotes microbial growth, contributing to improved soil biological quality.

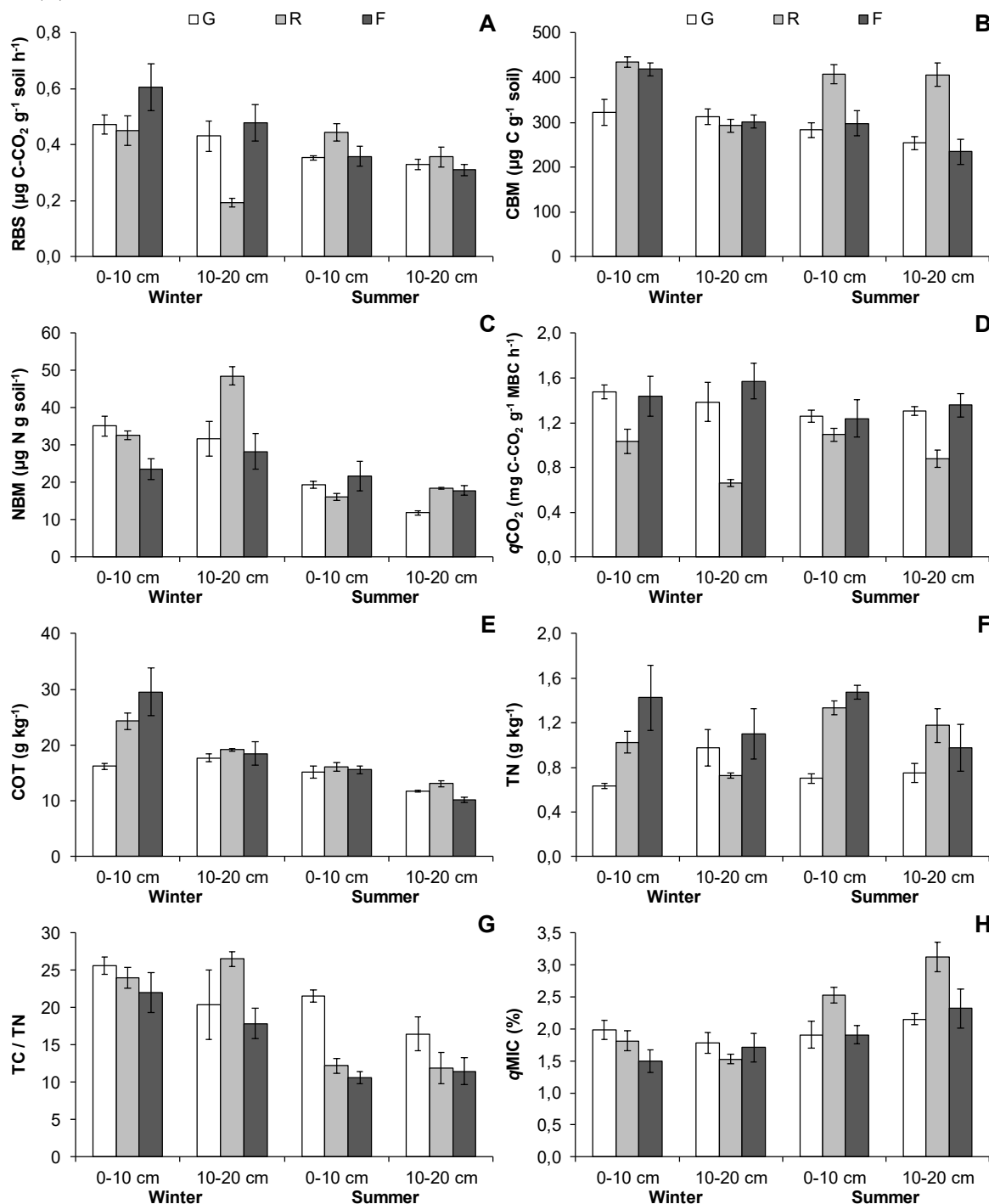
Microbial biomass nitrogen (NBM) also showed strong sensitivity to management and seasonal conditions (Figure 3C), reflecting variations in nitrogen cycling dynamics. Higher NBM values in rubber tree and grass systems suggest increased microbial immobilization of nitrogen, which is a key mechanism regulating nutrient retention and preventing nitrogen losses from the soil system. Microbial biomass functions as a transient reservoir of nutrients, regulating their availability for plant uptake and contributing to ecosystem resilience (Ding & Yu, 2025).

Total organic carbon (COT) levels were significantly higher in rubber tree and forest systems at the surface layer, reinforcing the fundamental role of vegetation cover in promoting soil carbon accumulation (Figure 3E). Increased carbon inputs from litter and root turnover enhance soil carbon stabilization through physical protection within aggregates and biochemical recalcitrance (Lehmann et al., 2020). These mechanisms contribute to long-term carbon sequestration and improved soil structural stability.

The microbial quotient ($qMIC$), which represents the proportion of total organic carbon present in microbial biomass, was higher in the rubber tree system during summer (Figure 3H), indicating greater microbial efficiency in utilizing available carbon. Higher $qMIC$ values are typically associated with biologically active and well-functioning soils, reflecting enhanced nutrient

cycling and ecosystem stability (Sparling, 1992). This finding further supports the ecological benefits of perennial vegetation systems in maintaining soil biological integrity.

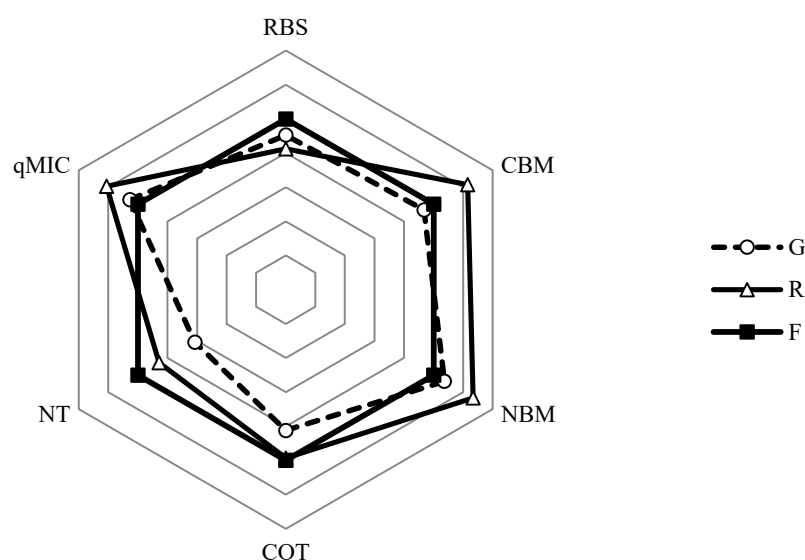
Figure 3. Soil microbiological attributes at 0 to 10 and 10 to 20 cm depth in two seasons of the year (winter and summer), in *Brachiaria brizantha* grassland (G), rubber tree (R) and forest (F) areas, where: soil basal respiration - RBS (A), microbial biomass carbon - CBM (B), microbial biomass nitrogen - NBM (C), metabolic quotient - qCO_2 (D), total organic carbon - COT (E), total nitrogen - NT (F), ratio between COT and NT - COT/NT (G), microbial quotient - $qMIC$ (H).



Source: Prepared by the authors (2026).

The soil quality index (SQI) confirmed the superior ecological functioning of the rubber tree system, which exhibited values 6% higher than the Atlantic Forest reference and substantially higher than the grass system (Figure 4). This result highlights the capacity of rubber tree cultivation to maintain soil biological quality comparable to native ecosystems. The continuous litter deposition and minimal soil disturbance associated with rubber tree systems likely promote favorable microhabitat conditions, enhance substrate availability, and support microbial diversity and functional stability (Zake et al., 2015).

Figure 4. Soil quality index (SQI) in grassland (G), rubber tree (R) and forest (F) areas, where: soil basal respiration (RBS), microbial biomass carbon (CBM), microbial biomass nitrogen (NBM), total organic carbon (COT), total nitrogen (NT) and microbial quotient (qMIC).

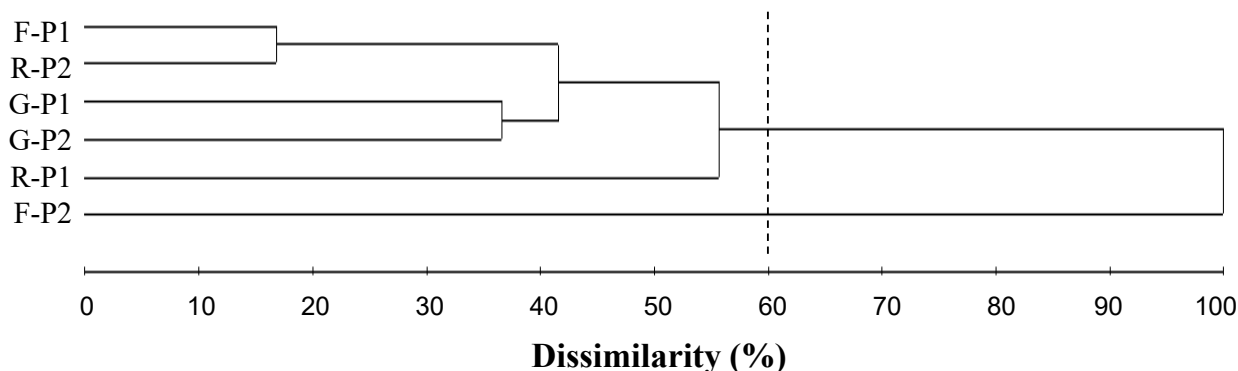


Source: Prepared by the authors (2026).

In contrast, the grass system exhibited lower SQI values, reflecting reduced organic matter inputs and less complex substrate composition. Although grass systems can contribute to soil protection and carbon input through root turnover, their lower litter deposition and simplified vegetation structure may limit microbial habitat diversity and substrate heterogeneity, ultimately constraining microbial biomass and activity (Mazzetto et al., 2016).

The Atlantic Forest fragment showed greater chemical differentiation, particularly at deeper soil layers (Figure 5). Differences in cation exchange capacity (CEC), calcium (Ca), and other chemical attributes highlight the influence of vegetation type and management history on soil fertility. Higher CEC values are associated with increased nutrient retention capacity and improved soil fertility, largely driven by organic matter content and clay mineral composition (Lehmann et al., 2020).

Figure 5. Dissimilarity between management systems obtained by the UPGMA clustering method, using Mahalanobis distance, based in the chemical attributes of the soil. Letters before dash refer to management type and after dash to the soil depth. G: *Brachiaria brizantha* grassland; R: rubber tree; F: Atlantic Forest fragment. P1: 0-10 cm and P2: 10-20 cm.



Source: Prepared by the authors (2026).

The chemical attributes presented in Figure 6 provide further evidence of the strong influence of management systems on soil fertility and chemical balance. Agricultural systems (rubber tree and grassland) exhibited higher pH, base saturation, and exchangeable nutrient levels, including potassium, magnesium, calcium, and micronutrients, compared to the Atlantic Forest fragment. These improvements are primarily attributed to liming and fertilization practices, which neutralize soil acidity and increase base availability, enhancing nutrient cycling and microbial activity.

Conversely, the Atlantic Forest fragment exhibited higher potential acidity and exchangeable aluminum levels (Figure 6), reflecting the natural acidity typical of highly weathered tropical soils. Aluminum toxicity is widely recognized as a major constraint to plant growth in acidic soils, inhibiting root elongation and severely reducing water and nutrient uptake by plants (Rahman *et al.*, 2024). The reduction of aluminum toxicity observed in agricultural systems is a direct consequence of liming, which promotes aluminum precipitation and improves root environment conditions.

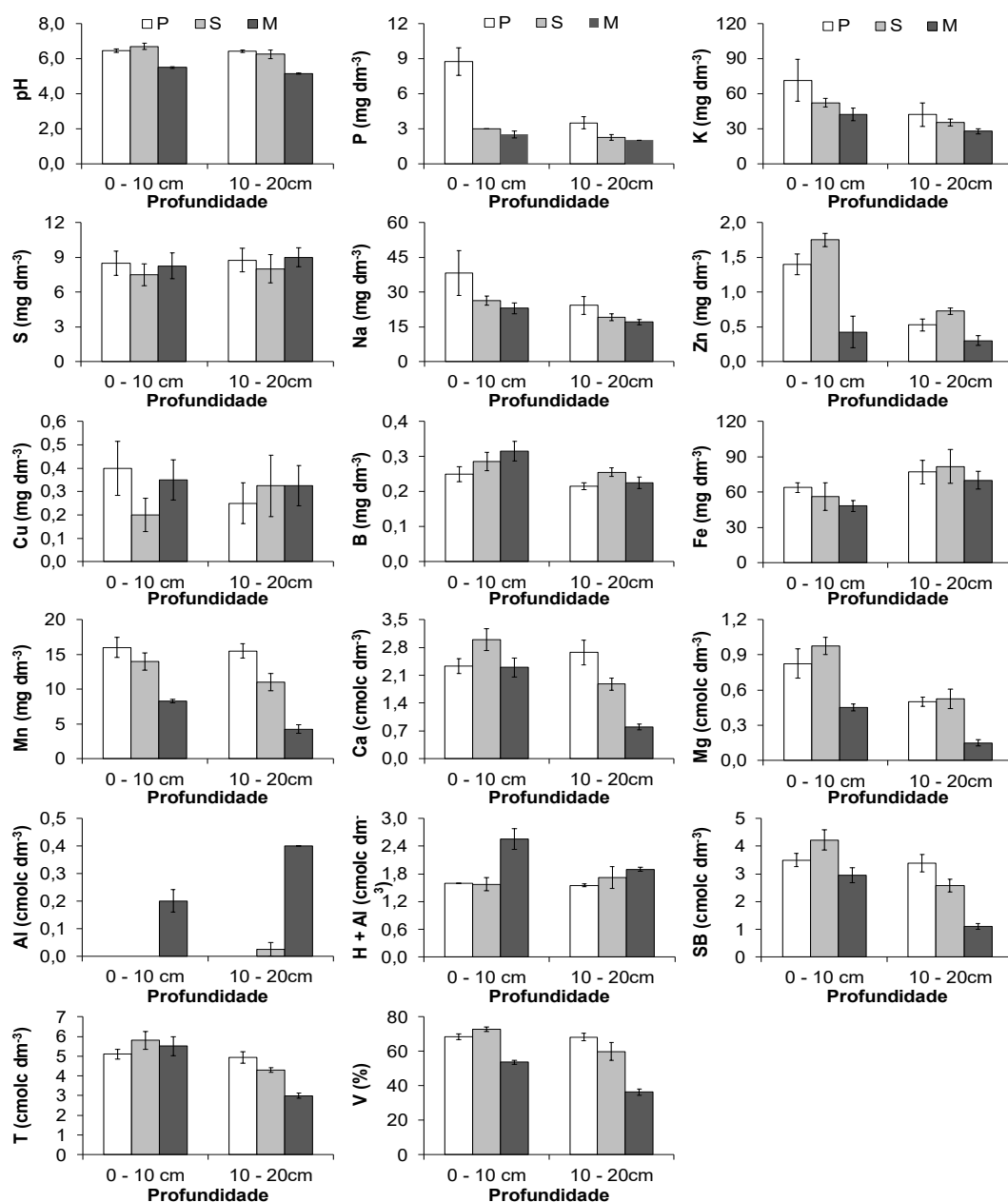
Sodium levels were slightly higher in the grassland system (Figure 6), although values remained within non-saline ranges. Soil salinity can negatively affect microbial community composition and function, inhibit enzyme activities involved in organic matter decomposition, and reduce crop yield and plant productivity (Munns & Tester, 2008; Haj-Amor *et al.*, 2022). However, the absence of salinity-related limitations in the evaluated systems indicates that management practices did not compromise soil chemical stability.

The similarity in CEC among systems suggests that organic matter played a dominant role in maintaining soil nutrient retention capacity. Organic matter contributes significantly to charge density in tropical soils, enhancing nutrient retention and supporting microbial communities

(Lehmann et al., 2020). These findings reinforce the critical role of organic matter inputs in sustaining soil fertility and biological functioning.

Overall, the results demonstrate that agricultural systems managed with perennial vegetation and appropriate soil amendments can maintain soil microbiological and chemical quality at levels comparable to natural ecosystems. The rubber tree system, in particular, showed strong potential for promoting soil biological sustainability, highlighting its relevance as a conservation-oriented production system capable of supporting both agricultural productivity and ecosystem stability.

Figure 6. Soil chemical attributes at 0 to 10 cm and 10 to 20 cm depth in grass (P), rubber tree (S) and forest (M) areas, where: acidity (pH), phosphorus (P), potassium (K), sulfur (S), sodium (Na), zinc (Zn), copper (Cu), boron (B), iron (Fe), manganese (Mn), calcium (Ca), magnesium (Mg), aluminum (Al), potential acidity (H^+Al), sum of bases (SB), CEC at pH 07 (T) and base saturation (V).



Source: Prepared by the authors (2026).

4 CONCLUSIONS

Land management systems significantly influence soil biological and chemical quality in tropical environments. The rubber tree system showed the highest Soil Quality Index (SQI), demonstrating that perennial systems with continuous litter input and low soil disturbance can maintain soil microbial functioning at levels comparable to native Atlantic Forest conditions.

Microbiological indicators such as RBS, CBM, NBM, qCO_2 , and $qMIC$ proved to be sensitive and effective for detecting changes in soil quality caused by land use. These attributes, combined with chemical properties such as cation exchange capacity and calcium content, were essential for distinguishing management systems and assessing soil functional stability.

The results confirm that properly managed perennial systems can preserve soil biological quality and contribute to ecosystem sustainability, even under agricultural use. This finding has important implications for developing sustainable production systems in tropical regions.

A limitation of this study is the absence of microbial community structure analysis and the evaluation in a single location. Future studies should incorporate molecular approaches and long-term monitoring to better understand the mechanisms governing soil microbial dynamics and resilience under different land uses.

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