

Microbial Biomass and Enzyme Activity of Soil Under Clonal Rubber Tree Plantations

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Abstract

Our study aimed to evaluate the influence of rubber tree plantations (Clones IAN 873 and FX 3864) on microbial activity, total organic carbon (TOC), and soils chemical attributes, using as reference pasture and secondary forest, in Rio de Janeiro. The plantations areas showed pH; Mg²⁺, Ca²⁺, K⁺ levels; sum of bases; base saturation, basal respiration; metabolic quotient; and arylsulfatase and FDA activities in the soil similar to or greater than the values found in the forest. In contrast, showed lower P and TOC levels; carbon and nitrogen in the microbial biomass; and β -glucosidase activity than of forest and pasture. Higher acid phosphatase and laccase enzymes activities was observed in the forest and plantations than in the pasture. Thus, we verified that the rubber tree plantations (Clones: IAN 873; FX 3864) maintain or improve the quality of some chemical and microbiological attributes of the soil regarding secondary forest and pasture.

Keywords: soil quality, basal soil respiration, acid phosphatase, β -glucosidase, arylsulfatase.

1. INTRODUCTION AND OBJECTIVES

Hevea culture is the cultivation of rubber trees for latex extraction and the subsequent production of natural rubber. It has been part of an unbalanced market considering supply and demand, a consequence of the accelerated growth of emerging countries such as Brazil, India, and China (IRSG, 2013). Areas occupied by rubber tree plantations used for latex production expanded in Brazil due to an increase in the demand for natural rubber. According to the Painei Florestal (2014), Brazil has a great potential for hevea culture expansion, since the country has areas already adequate for growing rubber tree plantations, without the need for further deforestation.

The cultivation of forest species with a long life cycle, whose economical exploitation is not associated with the

timber industry, such as rubber trees, has several advantages when compared with species with short cycles destined for timber production. For instance, the carbon stored by them remains in the vegetation for a longer period (Cotta et al., 2008). However, changes in land use must be properly managed to avoid altering the soil biota, and, consequently, plant productivity, carbon storage, nutrient cycling, and the ecosystem sustainability.

Thus, practices aiming at preserving soil quality and the quantification of changes to its attributes caused by distinct soil management systems have been widely applied to monitor soil productivity (Neves et al., 2007). Chemical, physical, and biological indicators must be characterized and analyzed according to their responsiveness to changes and disturbances caused by soil management (Carneiro et al., 2009; Silva et al., 2007). Alterations in the biological

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component that affect key functions such as the ability to cycle and store nutrients are more appropriate for the evaluation of qualitative changes in soil quality caused by exploitation when compared with chemical or physical properties (Chaer & Tótola, 2007).

Soil microorganism communities, for example, are continuously changing and adapting to environmental changes. Their natural dynamics render them potential indicators of change resulting from different soil management systems (Facci, 2008). The maintenance of ecosystem productivity, both in plantations and forests, greatly depends on the process of organic matter transformation and consequently on the microbial biomass (Gama-Rodrigues & Gama-Rodrigues, 2008). Microorganisms constitute the main source of soil enzymes, and the evaluation of enzyme activity has been reported as an effective indicator of soil quality, organic matter decomposition and nutrient availability resulting from management practices (Evangelista et al., 2012).

In this context, our study sought to evaluate the influence of rubber tree plantations (Clones IAN 873 and FX 3864) on microbial activity, total organic carbon (TOC), and chemical attributes of soils, using as reference a pasture and secondary forest in the municipality of Silva Jardim, RJ.

2. MATERIALS AND METHODS

Our study was conducted in the municipality of Silva Jardim, located in the coastal lowlands of the state of Rio de Janeiro, Brazil. The area of study is situated at coordinates 22° 39' 03" S latitude and 42° 23' 30" W longitude. According to Köppen, the region has a climate humid subtropical Cwa climate, with an annual average temperature of 23 °C and an annual average precipitation of 1,500 mm. Figure 1 shows the average values for total precipitation, highest temperature, lowest temperature, and average temperature for the years of 2012 and 2013, when the samples were collected. The soil of the region was classified as *Argissolo Vermelho-Amarelo* (Ultisol) (Santos et al., 2018). The soils in the region of study originate from sediments from the Barreiras Formation, which has a low natural fertility, especially in the superficial layer of 0-20 cm depth, with a sandier texture than that of the 20-60 cm layer, a typical characteristic of agrisols. Overall, this type of soil has a texture varying from sandy to clayey, has a yellowish color, and is found in the low Amazonian plateaus and the Atlantic Forest at the north, northeast, and east coasts of Brazil. The topography is undulating with slopes ranging from 18% to 23% and an average altitude of 45 m. The region of study is part of the morphoclimatic domain known as the Seas of Forested Hills.

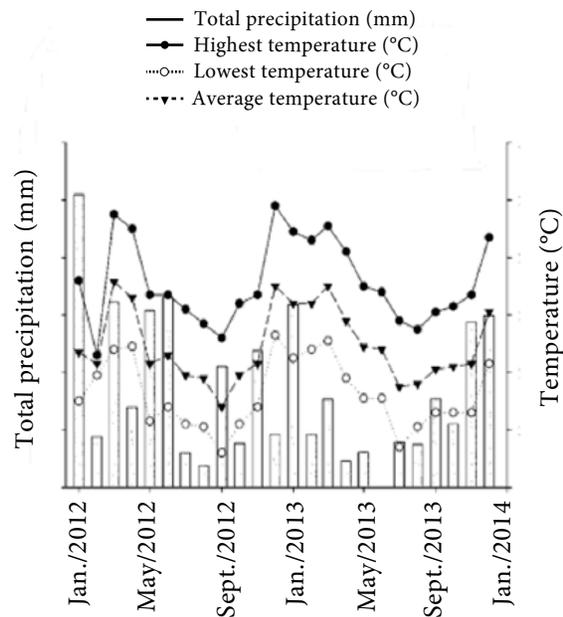


Figure 1. Average values of total precipitation, highest temperature, lowest temperature, and average temperature for the years of 2012 and 2013.

Source: Weather Stations of Arraial do Cabo and Casimiro de Abreu, RJ.

Four areas were selected for the study, as follows: two clonal rubber tree plantations (*Hevea brasiliensis*), a region of secondary forest, and a pasture. The rubber tree clones (IAN 873 and FX 3864) were planted in the mid-1980s (when the government of the state of Rio de Janeiro began subsidizing hevea culture) to produce latex in the Pedacinho do Céu property (22° 40' 22.11" S; 42° 25' 55.53" W), in Silva Jardim, RJ. This property has 4 hectares occupied by rubber trees that have been cropped for 8 years. Half of the cropping area is occupied by clone FX 3864, and the other half by clone IAN 873. The area occupied by FX 3864 has an average slope of 21% and is subjected to two or three rogues per year, with the plant waste being left on the soil surface. In contrast, the area cultivated with IAN 873 has a more pronounced average slope, of approximately 37%, being consequently subjected to only one rogue per year, in the planting line. Individuals were separated by 3.0 m, planting lines by 7.0 m, and the crop density was 500 plants per hectare. Liming and fertilization with NPK were performed at the planting stage, and no fertilization has been carried out since the rubber trees were planted.

Near the rubber tree plantations, we selected an area of secondary forest, and a pasture, in which had been planted approximately 16 years, composed mainly of *Urochloa* spp. Apart from this grass species, satintail (*Imperata brasiliensis*) and *Andropogon bicornis* L. are also found in the pasture, which is located on a plateau and subjected to grazing by

cattle during the year. Liming and fertilization with NPK were performed only at the planting stage. However, information regarding the amount of chemicals applied is not available.

To evaluate soil attributes, in each study unit, an area of 600 m² was delimited, in which samples composed of 10 single samples of soil randomly collected at a depth of 0-10 cm was made, with a total of five composite samples for each area. The physical (Table 1) and chemical attributes were analyzed according to Donagema et al. (2011). To evaluate soil microbiological properties, the samples were stored in plastic bags, protected from light and placed in thermal boxes filled with ice, and transported to the laboratory within 24 h after field collection. The samples were subsequently sieved through a 2 mm mesh and stored in plastic bags kept under refrigeration at 4 °C. For all microbiological analyses, sample humidity was corrected to 65% of their maximum water holding capacity.

Table 1. Granulometry at 0-10 cm depth from areas occupied by rubber tree plantations (clones FX 3864 and IAN 873), pasture and secondary forest, in the municipality of Silva Jardim, RJ.

Granulometry	FX 3864	IAN 873	Forest	Pasture
Clay (g kg ⁻¹)	338	308	366	290
Silt (g kg ⁻¹)	163	154	133	148
Sand (g kg ⁻¹)	500	539	501	564

The activities of acid phosphatase and β -glucosidase enzymes were analyzed using a spectrophotometer, according to Tabatabai (1994). Phosphatase activity was measured in a non-buffered medium in two replicates in test tubes containing 0.5 g soil, 1 mL H₂O and 1 mL substrate at a concentration of 50 mM. The samples were incubated at 30 °C for 1 h. The reaction was then stopped by the addition of 0.5 mL⁻¹ of 0.5 mol L⁻¹ CaCl₂ and 2 mL of 0.5 mol L⁻¹ NaOH. β -glucosidase activity was analyzed using the same procedures, but at the initial stage, the reaction was buffered with 100 mM sodium acetate at pH 5.5 and incubated at 30 °C for 2 h. Control reactions consisted of soil samples to which 2 mL⁻¹ H₂O or 2 mL⁻¹ acetate buffer was added for acid phosphatase and β -glucosidase, respectively. A tube without soil containing 1 mL⁻¹ H₂O (or acetate buffer for β -glucosidase) and 1 mL⁻¹ substrate was used as a blank. All samples were centrifuged (960 g) and read using a spectrophotometer at a 410 nm absorbance. The amount of p-nitrophenol produced in each sample was determined based on a standard curve of known p-nitrophenol concentrations, with the results expressed in μ mol p-nitrophenol g⁻¹ dry soil h⁻¹.

The arylsulfatase activity was also determined according to Tabatabai (1994), using p-nitrophenol sulfate as a substrate, which, via hydrolysis, releases sulfate and p-nitrophenol, which

can then be colorimetrically measured. The soil samples were incubated at 37 °C for 1 h, and arylsulfatase activity was expressed in μ mol pNP g⁻¹ dry soil h⁻¹. Laccase activity was evaluated based on Sinsabaugh et al. (1999), in two replicates using test tubes containing 0.5 g soil. Subsequently, 1 mL H₂O was added to each sample followed by 1 mL substrate prepared in 5 mM acetate buffer at pH 5. Then, 1 mL H₂O and 1 mL acetate buffer were added to control samples. After 1 h of incubation at 30 °C, the reaction was stopped by the addition of 1 mL sodium azide 0.6% (w/v). Finally, samples were centrifuged and analyzed using a spectrophotometer at a 460 nm absorbance. The concentration of dihydroindole-quinone-carboxylate (DIC) produced was determined based on a micromolar extinction coefficient of 1.6. Laccase activity was expressed in nmol DIC g⁻¹ dry soil h⁻¹.

Total microbial activity in the soil was quantified by measuring the hydrolysis of fluorescein diacetate (FDA) (Schürer & Rosswall, 1982). Two replicates were performed for each sample, and the results were expressed in μ mol fluorescein g⁻¹ dry soil h⁻¹. The activities of hydrolytic enzymes associated with the carbon and phosphorus cycles were colorimetrically determined based on the degradation of artificial substrates under optimal reaction conditions. The enzymes and their respective substrates were as follows: (i) phosphatase, analyzed with 4-Nitrophenyl phosphate disodium salt hexahydrate; (ii) β -Glucosidase, analyzed with 4-Nitrophenyl β -D-glucopyranoside; and (iii) laccase, analyzed with 3,4-Dihydroxy-L-phenylalanine (L-DOPA).

The carbon present in the microbial biomass (CMB) was quantified using the method of chloroform fumigation extraction (CFE) according to Vance et al. (1987). The resulting extract, in the form of a 0.5 mol L⁻¹ K₂SO₄ solution, was colorimetrically analyzed according to Bartlett & Ross (1988). The CMB values were determined applying a Kc equal to 0.35, as indicated by Anderson et al. (2008). The CMB values were expressed in mg microbial C kg⁻¹ dry soil.

The basal soil respiration rate (BR) was quantified using the method of soil incubation with NaOH traps to absorb CO₂ followed by titration with HCl (Silva et al., 2007). The respiration rate was monitored during the 10 days of incubation in 2 mL flasks hermetically sealed and kept in the dark at 25 °C. The carbon consumed by respiration was expressed in μ g CO₂-C kg⁻¹ dry soil h⁻¹, and the metabolic quotient (q CO₂) was calculated by the ratio between BR and CMB.

The results were analyzed regarding the normality of error distribution (Lilliefors test) and the homogeneity of error variance (Cochran test). Meeting the assumptions of normality and homogeneity, the average values were compared with Tukey's test at the 5% significance level ($p < 0.05$) using Sisvar statistical software. The principal component analysis was performed using PAST software.

3. RESULTS AND DISCUSSION

The areas occupied by forest or pasture presented TOC levels significantly higher than the rubber plantations (clones IAN 873 and FX 3864) (Table 2), possibly due to the larger amounts of litter observed in the forest (6.3 Mg ha⁻¹) and in the pasture (3.4 Mg ha⁻¹) and the consequent higher influx of organic matter. The rubber tree plantations have a low density of individuals (500 individuals ha⁻¹), resulting in smaller amounts of litter (FX 3864: 2.2 Mg ha⁻¹; IAN 873: 2.0 Mg ha⁻¹), which is the main source of organic matter influx in these plantations.

The TOC levels were significantly different between the rubber tree plantations (Table 2), a fact that could be explained by the soil management system used and the spontaneous vegetation, with the region that receives two rogues per year (clone FX 3864) showing higher TOC levels than the area occupied by the clone 873, which is subjected to only one rogue per year.

Regarding soil chemical attributes (Table 2), we observed that the rubber tree plantations and the pasture had increased in pH values relative to the forest. This pattern can be attributed to the higher contents of exchangeable bases and the lower Al³⁺ and H+Al levels found in the rubber tree plantations (clones IAN 873 and FX 3864) and in the pasture (Table 2). The larger amounts of litter in the soil occupied by the forest (6.3 Mg ha⁻¹) when compared with the rubber tree plantations (IAN 873: 2.0 Mg ha⁻¹; FX 3864: 2.2 Mg ha⁻¹) and the pasture (3.4 Mg ha⁻¹) contributes to a higher influx of organic matter into the soil. Furthermore, humification processes cause the formation of organic acids (fulvic acids and humic acids), presenting the dissociation of H⁺ ions at

pH levels above 3.5, being responsible for soil acidification (Mendonça et al., 2006).

The rubber tree plantations presented levels of Mg²⁺, Ca²⁺, K⁺, sum of bases (B), and base saturation (V value) similar to or higher than those observed in the area of native forest, whereas, compared with the pasture, both forest and plantations showed smaller values (Table 2). This pattern may be associated with the higher diversity of tree species that constitute the forest, with differing levels of nutrient extraction from the soil that result in a higher base extraction rate due to the greater demand for nutrients when compared with grass species. According to Davidson et al. (2007), there is greater nutrient extraction in the areas occupied by forest species due to the retention of nutrients, especially in the parts with more plant biomass such as trunks and branches. In this same area of study, Diniz (2015) found that rubber tree clones presented higher contents of N, P, K, and Ca in the litter when compared with pasture and attributed this observation both to the better extraction of nutrients from the soil relative to the grass species and to the different crop ages. The rubber tree plantation was almost twice as old as the pasture, so the rubber trees presented a more developed and deeper root system, allowing them to explore a larger soil volume and extract a greater amount of nutrients.

The lower decomposition rate of the plant material deposited on the soil may be also responsible for the existence of less nutrients in the forest soil when compared with the rubber tree plantations. Kindel et al. (2004) observed that the dynamics of litter decomposition differs greatly between rubber tree plantations (clones IAN 873 and FX 3864) and Atlantic Forest fragments, with faster decomposition in the former due mainly to their chemical characteristics (Viera et al., 2010).

Table 2. Soil chemical attributes and total organic carbon (TOC) at a depth of 0-10 cm in rubber tree plantations (clones FX 3864 and IAN 873), pasture and secondary forest in the municipality of Silva Jardim, RJ.

Chemical attributes	FX 3864	IAN 873	Forest	Pasture	CV%
TOC (g kg ⁻¹)	21.0b	18.0c	22.0a	23.0a	8.0
pH (H ₂ O)	4.3c	4.8b	4.0d	5.5a	2.8
P (mg dm ⁻³)	0.36c	0.24c	0.70b	0.90a	28.0
Mg ²⁺ (cmol _c dm ⁻³)	1.1b	0.9b	0.8c	1.8a	15.7
Ca ²⁺ (cmol _c dm ⁻³)	1.2b	1.0b	0.5c	3.2a	19.8
K ⁺ (cmol _c dm ⁻³)	0.16b	0.11b	0.13b	1.7a	28.0
Al ³⁺ (cmol _c dm ⁻³)	1.1b	1.0b	2.0a	0.7c	23.0
H+Al (cmol _c dm ⁻³)	2.8c	4.4b	12.5a	2.2c	6.8
S value (cmol _c dm ⁻³)	2.6b	2.2b	1.5c	6.7a	15.0
T value (cmol _c dm ⁻³)	5.4b	6.6b	14.0a	8.9c	6.0
V value (%)	48.1b	33.3c	10.7d	74.7a	15.0

Values followed by the same letter in a row are not significantly different according to Tukey's test at the 5% significance level. T value: cation exchange capacity; S value: sum of bases; V value: base saturation.

The higher P contents observed in the forest and pasture in comparison with other areas may result from their larger influx of plant material, contributing to a more intense humification process because, the competitive adsorption between phosphorus and organic acids for the adsorption sites in soil results in an increase of P concentration in the solution, according to Guppy et al. (2005). Moreover, high molecular weight organic acids such as fulvic and humic acids may bind to metallic cations such as Fe and Al present in the surface charge of soil colloids, reducing the number of free adsorption sites and increasing the availability of P to plants.

Regarding soil microbiological attributes (Table 3), the pasture presented higher levels of carbon in the microbial biomass (CMB) than the other areas. This observation can be explained by the distribution of the root system of the pasture, especially the fine roots in the soil profile, which increases the release of soluble compounds by exudation or root decomposition. These compounds are then utilized by microorganisms as an energy source (Kuzuyakov & Domanski, 2000). Furthermore, cattle's urine and manure are also added to the ecosystem, promoting microbial activity. Grazing, in turn, affects biomass distribution in the roots, reduces the foliar surface by removing the apical meristems, reduces nutrient stocks in the plants and changes the energy and nutrient allocation from the roots to the aerial parts, to compensate for photosynthetic tissue losses, causing, however, the death of plant roots (Corsi et al., 2001).

Root system renewal promotes the activity of soil microorganisms. Furthermore, the lower soil pH and the higher base saturation in the soil (V value) (Table 2) may have contributed to the better development of the microbial community in the pasture area.

The CMB values observed in our study agree with the results of Silva et al. (2012), who found higher CMB levels in pasture when compared with areas of forest at different successional stages. It is known that the root systems of grasses affect soil quality, including carbon incorporation (Loss et al., 2011).

The highest values of basal soil respiration (BR) were observed in the pasture area. This fact may be explained by the higher CMB levels, resulting from increased respiration due to the greater number of microorganisms present in the soil. Moreover, the pasture presented the highest metabolic quotient (qCO_2), indicating that there is lower C loss in the areas occupied by forest or rubber tree plantations, with forests being more efficient in incorporating C in the long term.

The nitrogen contents of the soil microbial biomass (NMB) were not significantly different between forest and pasture and were higher than that observed in the rubber tree plantations. The NMB levels were different between the rubber plantations, a finding that may be associated with their distinct soil management systems; clone FX 3864 showed a higher NMB, possibly being favored by the more frequent rogues and deposition of plant residues on the soil.

Table 3. Soil microbiological attributes at a depth of 0-10 cm, in rubber tree plantations (clones FX 3864 and IAN 873), pasture and secondary forest in the municipality of Silva Jardim, RJ.

Microbiological attributes	FX 3864	IAN 873	Forest	Pasture	CV%
PAC ($\mu\text{mol pNP g}^{-1} \text{ ds h}^{-1}$)	3.3b	3.1b	3.6a	2.6c	9.6
β -Glyco ($\mu\text{mol pNP g}^{-1} \text{ ds h}^{-1}$)	0.55b	0.46b	0.73a	0.67a	13.0
Aryl ($\mu\text{mol pNP g}^{-1} \text{ ds h}^{-1}$)	2.51a	2.67a	1.90a	2.0a	18.0
FDA ($\mu\text{mol of fluores g}^{-1} \text{ ds h}^{-1}$)	113.8a	105.5b	84.3c	83.7c	17.0
Laccase (nmol DIC $\text{g}^{-1} \text{ ds h}^{-1}$)	1.48b	1.43b	1.81a	1.25c	15.0
NMB (mg N-mic $\text{kg}^{-1} \text{ ds}$)	32.7b	24.5c	67.5a	69.5a	22.3
CMB (mg C-mic $\text{kg}^{-1} \text{ ds}$)	195.4c	177.0c	227.5b	308.0a	19.5
BR ($\mu\text{g CO}_2\text{-C kg}^{-1} \text{ ds h}^{-1}$)	600b	600b	602b	1,280 a	11.0
qCO_2 (mg C-CO ₂ $\text{g}^{-1} \text{ CBM h}^{-1}$)	3.75b	3.45b	2.90c	4.22a	12.7

Values followed by the same letter in a row are not significantly different according to Tukey's test at the 5% significance level. PAC: acid phosphatase; β -Glucosidase; Aryl: arylsulfatase; FDA: FDA hydrolysis; NMB: nitrogen in the microbial biomass; CMB: carbon in the microbial biomass; BR: basal soil respiration; qCO_2 : metabolic quotient; Fluores: fluorescein; ds: dry soil.

Acid phosphatase (PAC) showed higher activity in the forest, followed by rubber tree plantations, with lower activity in the pasture. The higher PAC activity in the forest may be explained by its larger amounts of litter, conferring greater levels of nutrient deposition and cycling in this environment, and increasing the organic P contents and phosphatase activity. Furthermore, this enzyme was more active in areas free from mineral fertilization. The highest value of P in solution, pH, sum of bases (S), base saturation (V value) and clay contents were found in the pasture (Table 2), an observation that may have been responsible for the lower PAC activity in that area. Balota et al. (2013) affirm that, in certain cases, enzyme activity may increase due to nutrient deficiencies or the form (organic or mineral) in which they are present in the soil, citing phosphorus and sulfur as examples. Evaluating the effects of soil use and management systems in the municipality of Eldorado do Sul (RS), Lisboa et al. (2012) observed similar phosphatase activity between an area of natural vegetation and an area of conservation planting, and higher activity in regions occupied by a conventional crop. These authors associated the elevated phosphatase activity to the increased levels of soil organic matter.

The areas of forest and pasture did not differ regarding their β -glucosidase activities, which were higher than those found in the rubber tree plantations. That higher activity is a consequence of the larger amounts of litter in the regions of forest and pasture, resulting in greater levels of organic C in the soil (Table 1), because β -glucosidase activity is associated with C cycling in the soil (Balota et al., 2013). β -glucosidase activity did not differ between the two rubber tree plantations. Higher β -glucosidase activity in areas occupied by a forest than in a pasture was also reported by Jakelaitis et al. (2008) and Silva et al. (2012). Silva et al. (2009) found higher enzymatic activity in eucalyptus plantations when compared with native Cerrado vegetation. The authors concluded that the increase in litter deposition on the soil resulted in the increase of C in the soil, thus promoting β -glucosidase activity.

Enzymatic activity of laccase, also known as phenol oxidase, was higher in forest areas due to the deposition of material richer in lignin and polyphenols such as trunks, branches, and barks. It is important to mention the fact that areas occupied by forest show higher laccase and β -glucosidase activity. These enzymes function together in the process of C cycling, with laccase acting first in the degradation of more recalcitrant compounds present in organic matter, followed by β -glucosidase acting in the degradation of more pliable material. The main source of laccase in the soil is fungi (Baldrian et al. 2008), and this enzyme catalyzes the oxidation of phenolic groups present in organic substrates such as lignin, acting in the biodegradation and transformation of the lesser labile fraction of the soil organic matter (Kellner et al., 2008).

Arylsulfatase activity did not differ among the evaluated areas. Nevertheless, the total microbial activity, represented by FDA hydrolysis, was higher in the rubber tree plantations than in the forest and pasture areas (Table 3). This finding may be associated with the chemical composition of the litter present in the rubber tree plantations, which may be promoting FDA activity in the soil. The higher FDA activity in the plantations may reflect higher rates of litter decomposition. Kindel et al. (2004) observed that the litter decomposition dynamics in the rubber tree plantations (clones IAN 873 and FX 3864) is faster than the decomposition of litter from the Atlantic Forest, possibly because of differences in litter quality as well as the higher microbial activity in rubber tree plantations. The clone FX 3864 presented a higher total microbial activity due to the management influence on these rubber tree plantations (greater addition of organic matter during the year). FDA activity refers to a group of enzymes that can hydrolyze FDA such as lipases, esterases, and proteases (Balota et al., 2013).

3.1. Multivariate analysis

Two principal components (axes 1 and 2) were created to distinguish the areas of study according to their chemical attributes, TOC, and microbiological properties (BR, CMB, NMB and qCO_2 , and arylsulfatase, acid phosphatase, β -glucosidase and FDA activity) (Figure 2). We observed that the distribution of the selected variables had an accumulated variance of 94.75% for axes 1 and 2; axis 1 explained 58.86%, and axis 2 explained 35.89% of this variance (Figure 2).

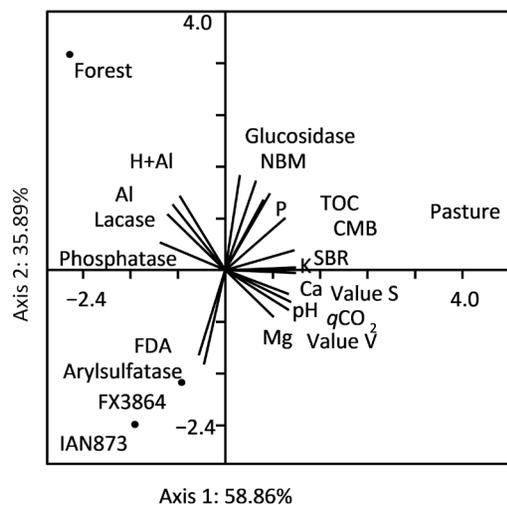


Figure 2. Principal component analysis integrating total organic carbon and the soil chemical and microbiological variables in rubber tree plantations (Clones FX 3864 and IAN 873), pasture and secondary forest in the municipality of Silva Jardim, RJ.

NBM: nitrogen in the microbial biomass; CMB: carbon in the microbial biomass; TOC: total organic carbon; SBR: soil respiration rate; FDA: fluorescein diacetate; qCO_2 : metabolic quotient.

Axis 1 separated the pasture from the forest and the rubber tree plantations. The variables that most contributed to this differentiation were pH, Ca, K, S value, V value, acid phosphatase, laccase, CMB, BR, and $q\text{CO}_2$, considering that they presented the highest coefficient of correlation with axis 1: > 0.80 (+/-) (Figure 2). The variables that most contributed to its values of axis 2 were FDA, NMB, arylsulfatase and β -glucosidase, with coefficients of correlation above 0.80 (-/+) (Figure 2). Therefore, we suggest that these variables are best suited to evaluate soil quality under the conditions of our study, being more responsive to the modifications occurring in the studied environments.

Some authors (Matias et al., 2009; Mercante et al., 2008) have identified $q\text{CO}_2$ as an efficient variable to detect changes in soil quality. Improvements in soil quality are associated with a reduction in the $q\text{CO}_2$ value, i.e., $q\text{CO}_2$ is negatively correlated with soil quality; it is, therefore, an important indicator of soil stress, disturbance or functional imbalance. An elevated quotient may reflect three situations: stress, an immature ecosystem, or a more breathable substrate (Islam & Weil, 2000). According to Kuwano et al. (2014), high $q\text{CO}_2$ values indicate that the microbial population is consuming larger amounts of C for their maintenance due to stress conditions, rendering it less efficient in energy utilization and leading to a loss of organic carbon and soil degradation. In our study, high $q\text{CO}_2$ values were more associated with the pasture, as elevated rates of basal soil respiration were observed (Figure 2). According to Islam & Weil (2000), high respiration rates may indicate an ecological disturbance in the system. Thus, the fact that the pasture presented $q\text{CO}_2$ and basal respiration higher than the forest area suggests that, in the long term, the former may be characterized by smaller C increases in the soil.

The forest area was more associated with the activities of acid phosphatase and laccase, whereas the rubber tree plantations presented higher correlation with the FDA and arylsulfatase activity variables. Thus, we verified that the forest systems promote enzymatic activity in the soil when compared with the pasture. Pereira et al. (2004) argue that soil enzymatic activity and respiration are among the variables that respond more rapidly to environmental changes when compared with the levels of organic matter in the soil. It can be observed that, in our study, even though the soil of the region under pasture presented higher TOC and CMB levels relative to the forest, it showed negative differences regarding enzymatic activity (except for β -glucosidase activity), $q\text{CO}_2$ and basal soil respiration.

4. CONCLUSION

Rubber tree plantations (clones: IAN 873; FX 3864) have potential for maintaining or improving the quality of some

soil chemical and microbiological attributes when compared with secondary forest and/or pasture. Rubber tree plantations maintain or increase pH; Mg^{2+} , Ca^{2+} , K^+ levels; sum of bases; base saturation, basal respiration; and arylsulfatase and FDA activities when compared with secondary forest. Regarding the pasture, rubber tree plantations maintain or increase cation exchange capacity, and FDA, laccase, arylsulfatase activities.

The rubber tree plantations, for a period of eight years, cannot increase the total soil organic carbon content, microbial biomass carbon and nitrogen when compared with pasture and secondary forest. On the other hand, the lower metabolic quotient ($q\text{CO}_2$) in the rubber tree plantations indicates that there is a lower loss of C in these areas, which inferred that, over time, incorporating C in soil may be more efficient than in the pasture.

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