ORIGINAL PAPER

Biological and chemical attributes of soils under forest species in Northeast Brazil

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Abstract Timber forests contribute to the sustainable development of the biomes in tropical regions. The aim of this study was to evaluate the biological and chemical properties of the soil as a consequence of the cover with native and non-native species in the Acaraú basin, a transition area from the coast to the Brazilian semi-arid region. Areas planted with four native species (*Anadenanthera colubrina*, *Astronium fraxinifolium*, *Handroanthus impetiginosus*, *Colubrina glandulosa*) and three exotic species (*Acacia mangium*, *Casuarina equisetifolia*, *Eucalyptus urophylla*) plus a non-forested agricultural area were evaluated for organic carbon contents, and microbial and chemical soil properties. The levels of soil organic carbon were highest in *A. colubrina* and *C. equisetifolia* plantations. Low basal soil respiration was observed but the microbial biomass was particularly low in the non-forested area. In the *C. equisetifolia*, *E. urophylla*, *and H. impetiginosus* plantations, elevated soil metabolic quotients were found. The *A. colubrina* and *H. impetiginosus* plantations had the highest levels of easily extracted-glomalin related soil protein. Tree species affect concentrations of essential nutrients and the biological quality of the soil in different ways. They can also improve the biological and chemical properties of the soil in the coastal plains of tropical regions.

Keywords Soil quality · Brazilian timber species · *Eucalyptus* · *Acacia* · *Casuarina*

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Introduction

Brazil has large areas of forest and the greatest diversity of plants (Beech et al. 2017). Reforestation has recently reached 7.8 million hectares (Moreira et al. 2017), the wood from which is used in the pulp and paper and energy industries. The plantations are concentrated in the Atlantic Forest region and in the Cerrado biome, where species of *Eucalyptus* (5.7 million ha), *Pinus* (1.6 million ha) and other genera (0.6 million ha) (IBÁ 2017) have been planted. There was practically little use of native species. The success of these plantations is linked to favorable environmental conditions for intensive forestry, the adaptability of the introduced species and the abundance of available land.

In the Brazilian northeast where the Caatinga biome (dry tropical forest) is found, there is significant anthropogenic pressure to transform land into agriculturally productive, non-forested areas (Silva et al. 2018). The region has low soil organic carbon stocks (Bernoux et al. 2002), making these productive areas vulnerable to soil fertility loss

(Ferreira et al. 2014). This has led to recommendations that conservation practices should be adopted to aid regeneration (Medeiros et al. 2017) using tree plantations, including native species such as *Handroanthus impetiginosus* (Mart. ex DC.) Mattos (Fonseca Filho et al. 2017), *Anadenanthera colubrina* (Vell.) Brenan (Monteiro et al. 2006), and other hardwood species (Lucena et al. 2007; Ramos et al. 2008; Fernandes et al. 2017). Forest coverage enables changes in the physical (Martinkoski et al. 2017), chemical and biological attributes of soil (Gomes et al. 2012; Silva et al. 2015; Chandra et al. 2016; Medeiros et al. 2017), and can modify microenvironments (Joly et al. 2017), thus affecting the sustainability of forest ecosystems.

Chemical indicators and soil organic carbon (SOC) (Li et al. 2018a), in addition to biological indicators such as microbial biomass activity (Cheng et al. 2013; Liu et al. 2018), and glomalin-related soil protein (GRSP) (Silva et al. 2014), have been successfully used in the evaluation of soil quality in forest ecosystems. Soil microbial biomass (SMB) plays an important role in biogeochemical cycles, as it is a significant source of enzymes responsible for the transformation of soil organic matter (SOM) (Medeiros et al. 2017). Although it is only a small proportion of SOM, it constitutes an important labile fraction functioning as an early indicator of changes in soil organic carbon stability resulting from alterations in land use and management (Li et al. 2018b). It is believed that modifications in soil microbial biomass could be the result of alterations in organic matter inputs and the immobilization of C and N during the decomposition process (Plaza et al. 2004; Li et al. 2018a).

Glomalin is a glycoprotein produced by arbuscular mycorrhizal (AM) fungi, (components of cellular walls of hyphae and spores) (Wright et al. 1996; Rillig 2004; Driver et al. 2005), liberated in the soil after the decomposition and senescence of these fungi (Driver et al. 2005). There is a direct relationship between GRSP, organic carbon content, and the stability of soil aggregates (Gispert et al. 2013; Rotter et al. 2017), and this affects nutrient cycles, water flow, microbial activities and plant development (Six and Paustian 2014) contributing to the sustainability of agroecosystems.

In light of the interest of public and private reforestation institutions, and the need for sustainable management of plantations on coastal plains in the semiarid tropics, four native species and three introduced species were evaluated in this study to determine their impact on soil biological and chemical attributes in the Acaraú basin, a transition area from the coast to the Brazilian semiarid region. Productive areas in the coastal zone are often vulnerable to soil degradation (Cunha et al. 2010; Mota and Valladares 2011), and forest plantations could be a viable option for agribusinesses in the region.

Materials and methods

Study area and description of the species

The study of the seven species was carried out on an experimental area (3.6 ha) in the Lower Acaraú basin, approximately 30 km from the Atlantic coast (coordinates 3°27′06″S and 40°08′48″W). According to the Köppen climate classification system, the climate is Aw (tropical, with a dry winter) (Alvares et al. 2014). Annual rainfall reaches nearly 950 mm, with more intense rainfall between the months of February and June; annual evaporation may exceed 1500 mm. Due to irregular rain distribution and high temperatures during the year (Fig. 1), plants may easily experience hydric stress.

Analysis of the soil profile under *Acacia mangium* Willd. shows Dystrophic Sandy Gray Argisol developed from the 'Formação Barreiras' (Tertiary-Quaternary) formed by pre-littoral tableland sediments, with a Master Bt (iluvial mineral horizon with concentration of clay translocated from the upper horizons) below 1.3 m (Table 1). It may be assumed that this type of soil occurs under the other canopies evaluated here, and it is notable that Grayish Argisol has been reported in the coastal tablelands of Brazil's northeast (Bezerra et al. 2015), as well as some agricultural areas of the Acaraú basin.

Planting of all the species occurred between October 2010 and March 2011; the saplings were 6 years old at the time of soil sampling. Each species with about thirty trees occupied 270 m^2 (9 m by 30 m), and rectangular spacing was used, making 3 m between rows and 2 m between trees in the same row. At the time of planting, saplings were fertilized with 120 g NPK (10:28:20) and 30 g of FTE Br-12 (composition per kg: 18 g of B, 8.0 g of Cu,
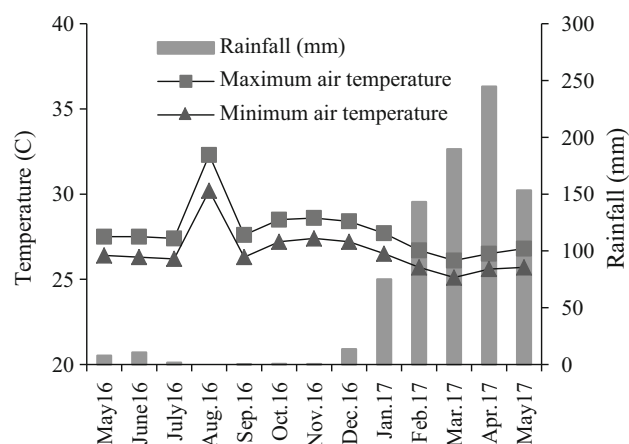

Fig. 1 Average air temperatures and monthly rainfall recorded in the Lower Acaraú Basin, State of Ceara (Brazil), during the forest soil evaluation period

Table 1 Morphological description of horizons, granulometric aspects and chemical analyzes of the Dystrophic Sandy Gray Argisol

Horizons	Depth (m)	Morphological descriptions	
		Munsell chart color	Observation
Ap1	0–0.10	Very dark grayish brown (2.5Y 3/2)	Sand, very friable, slightly plastic and non-sticky, smooth and clear transition
Ap2	0.10–0.27	Dark grayish brown (2.5Y 4/2)	Sand, very friable, non-plastic and non-sticky, smooth and gradual transition
EA	0.27–0.49	Light olive brown (2.5Y 5/3)	Sand, very friable, non-plastic and non-sticky, smooth and gradual transition
E1	0.49–0.87	Light olive brown (2.5Y 5/3)	Sand, very friable, non-plastic and non-sticky, smooth and gradual transition
E2	0.87–1.15	Light yellowish brown (2.5Y 6/3)	Loamy sand, very friable, non-plastic and non-sticky, wavy and gradual transition
BE	1.15–1.29	Pale yellow (2.5Y 7/3)	Sandy loam, very friable, slightly plastic and slightly sticky, irregular and abrupt transition
Bt1	1.29–1.84	Light gray (2.5Y 7/2)	Sandy loam, very friable, slightly plastic and slightly sticky, smooth and gradual transition
Bt2	1.84–2.05+	Light gray (2.5Y 7/2)	Sandy loam, very friable, slightly plastic and slightly sticky

		Granulometry (%)			Clay dispersed in water (%)
		Sand	Silt	Clay	
Ap1	0–0.1	92.44	1.87	5.69	3.47
Ap2	0.1–0.27	93.54	0.57	5.89	5.19
EA	0.27–0.49	90.75	2.09	7.16	7.24
E1	0.49–0.87	89.08	1.58	9.33	8.57
E2	0.87–1.15	85.75	2.25	12.00	11.56
BE	1.15–1.29	79.43	2.25	18.32	17.40
Bt1	1.29–1.84	79.58	1.86	18.56	16.84
Bt2	1.84–2.05+	77.72	2.91	19.37	17.02

		pH in water (ratio 1:2.5)	Sorption complex ($mmol_c$ kg^{-1})				SOC (g kg^{-1})
			Ca^{2+}	Mg^{2+}	K^+	Na^+	
Ap1	0–0.1	5.4	15.1	6.3	0.5	0.5	9.1
Ap2	0.1–0.27	5.8	6.3	3.3	0.5	0.4	2.9
EA	0.27–0.49	6.3	5.2	2.8	0.8	0.6	1.8
E1	0.49–0.87	6.1	3.6	3.9	0.4	0.5	1.1
E2	0.87–1.15	5.2	2.2	3.4	0.6	0.7	1.4
BE	1.15–1.29	4.8	1.3	1.2	1.2	1.8	5.4
Bt1	1.29–1.84	4.6	0.7	0.6	0.6	1.4	2.5
Bt2	1.84–2.05+	4.4	0.8	1.0	0.8	0.6	4.8

30 g of Fe, 30 g of Mn, 1.0 g of Mo and 90 g of Zn) per plant. At six months, all plants received a supplement of NPK (50 g $plant^{-1}$) with the aim of promoting establishment. The plants were not provided additional fertilizer in order to ensure that the conditions were those of the natural fertility of the soil. At 3 years, some of the smaller trees were removed, leaving 30 trees in each plot.

It was assumed that the soil profile under *Acacia mangium* would be similar for the other species evaluated. Fine roots were common along the surface horizons (Ap) but rarer in the Master Bt horizon. The E horizon represents the

eluviation of clay material, while the master Bt is an alluvial clay horizon. Analytical procedures used to determine pH, exchangeable nutrients and SOC contents are described by Silva (2009). Based on growth and uniform size, seven experimental plots were selected, consisting of Brazilian timber species: (1) *Anadenanthera colubrina*, (2) *Astronium fraxinifolium*, (3) *Handroanthus impetiginosus*, and (4) *Colubrina glandulosa*; and three exot species: (5) *Acacia mangium* Willd., (6) *Casuarina equisetifolia* L., and (7) *Eucalyptus urophylla* S. T. Blake (clone GG-702). The control area was not forested here, and had been previously planted to food crops; grasses native to the Acaraú basin grew there during the rainy season.

Soil sampling

Twelve to fifteen soil samples were taken from the upper layer (up to 10 cm deep) at a minimum of one meter from the tree trunk in the plot. The samples were collected following a zig-zag path. Soil samples were collected between the 8th and 10th of August and November 2016, and February and May 2017. The samples were sieved (2 mm mesh) to remove leaf litter and large aggregates. One portion of the sample was refrigerated ($\pm$ 4 °C) and then subjected to an analysis of respiratory activity and of microbial biomass carbon. Other portions of the samples were air-dried and subjected to chemical analyses.

Measurement of organic carbon and microbial properties

The soil organic carbon (SOC) content was measured using the wet dichromate oxidation method (Silva 2009). Basal soil respiration (BSR) was measured by incubating 50 g of dry soil in jars containing NaOH for the capture of CO_2, followed by titration with HCl (Silva et al. 2007). The rate of respiration was measured after ten days of incubation in 2 L jars kept at room temperature (22–25 °C) in the dark. Carbon from the soil microbial biomass (SMB) was measured using the fumigation-extraction method (Vance et al. 1987) in which the differences in carbon concentration between fumigated and non-fumigated extracts are converted into microbial carbon (C-mic) using the Kc of 0.33 as suggested by Sparling and West (1988). Using the microbial properties and the SOC, the following were measured: metabolic quotient (qCO_2, relationship between BSR and SMB) (Silva et al. 2007), microbial quotient of the soil (qMic ratio between SMB and SOC) (Tótola and Chaer 2002), and the mineralization quotient of the soil organic matter (qMin ratio between BSR and SOC) (Rasid et al. 2016).

Other fractions of dry soil were used for the analyses of easily extractable-glomalin related soil protein (EE-GRSP) and total-glomalin related soil protein (T-GRSP) according to Wright and Upadhyaya (1998) and Rillig (2004), with modifications in the extraction process (1 g dry soil) with sodium citrate (20 mM at pH 7.0 for EE-GRSP and 50 mM at pH 8.0 for T- GRSP). The Coomassie Brilliant Blue Bradford Assay (Wright et al. 1996) was used to measure the two protein fractions.

Chemical analyses of the soil

Fractions of dry soil were used for the analysis of chemical properties except for the analysis of the hydrogen ionic potential (pH) of the soil. The procedures of Silva (2009) were used to determine the of pH in water (proportion 1:2.5) and the extraction of the elements P, K, Na, Fe, Cu, Mn and Zn (extractor Mehlich-1), Ca and Mg (extractable by KCl at 1.0 mol L^{-1}). A spectrophotometer (λ = 660 nm) determined available phosphorus while exchangeable K and Na contents were determined in a flame photometer. The Ca, Mg, Fe, Cu, Mn and Zn contents were measured by atomic absorption spectroscopy. Total nitrogen content was determined using the Dumas Nitrogen Analyzer (NDA 701) apparatus, in accordance with Ribeiro (2010).

Statistical analysis

Soil property data were subjected to a descriptive statistical analysis, measuring averages, maximums and minimums (95%), asymmetric measures, kurtosis, and W values on the Shapiro–Wilk test ($p \leq 0.05$), which indicated abnormal data distribution. In addition, for a better understanding of the soil attributes data, a multivariate analysis was carried out. Hierarchical clustering was analyzed (*Agglomerative Hierarchical Clustering*, AHC) according to dissimilarities or similarities. The Spearman dissimilarity (matrix) was used to examine properties with non-normalized data, and as an agglomeration technique of unweighted pair-groups (*Unweighted Pair-Group Average*, UPGM) with centralized and reduced data. The principal components analysis (PCA) was from Spearman analysis (Abdi and Williams 2010), enabling atypical properties to be identified through their average values and the separation of forest cover and the non-forested area among the principal components. The calculations and the graphics were generated by the XLSTAT © program version 2016.1 (Addinsoft Inc., Brooklyn, NY, USA).

Results and discussion

From the descriptive statistical analysis data (Tables 2 and 3), it was inferred that timber species (*A. colubrina*, *A. fraxinifolium*, *H. impetiginosus*, *C. glandulosa*, *A. mangium*, *C. equisetifolia*, *E. urophylla*), cultivated for 6 years, changed the biological and chemical attributes of the soil in different ways. This Argisol soil, which is predominantly sand (ranging from 93% sand near the surface to less than 78% along the horizon at 2 m deep), can be advantageous for forest ecosystems. Tree roots may reach considerable depths, enabling a more efficient capture of water when rainfall is scarce, a situation favored by the presence of a horizon with an accumulation of clay (Bt—Table 1) which retains moisture in the soil. Argisols are common in Brazil's northeast (Cunha et al. 2010), particularly in the coastal tablelands (Bezerra et al. 2015). Plantations for timber production could help producers reduce or even end deforestation in the dry tropical forest. This would, however, require adaptation of soil and plant management practices, as well as the definition of objectives specifically for planted forests (Chazdon et al. 2016) and also considering the naturally low fertility of this type of soil (Table 1).

Based on measurements of dispersion, asymmetry and kurtosis, the majority of soil properties had a normal data distribution (insignificant W values ($p \leq 0.05$) in the Shapiro–Wilk test) (Table 2). There were exceptions for the following parameters, which showed high values of kurtosis and significant W-values indicating an abnormal distribution of the data: pH (3.90) and qCO_2 (3.57) under *E. urophylla*; SMB (3.93) and qMic (3.88) under *A. mangium*; qMin (3.69) planted with *A. colubrina*; and T-GRSP (3.99) in the area with *H. impetiginosus*. There were differences in the formation of leaf litter under these canopies (data not shown here), which possibly contributed to an increase in spatial variability of soil properties. It would, however, be a mistake to rule out that the variability of properties might possibly be due to periods of rainfall and of drought, with the formation of different microenvironments under the canopies and in the non-forested area. Seasonal variations have been observed in Caatinga vegetation (Holanda et al. 2017), and in agroforestry systems in the northeast region (Lima et al. 2010), as well as in *Eucalyptus urophylla* x *Eucalyptus globulus* populations in southern Brazil where there is a temperate climate (Vieira et al. 2014).

In this study, the vegetative cover indicated low BSR (basal soil respiration) ranging from 0.23 µg (*H. impetiginosus*; *A. colubrina*) to 0.40 µg C–CO_2 g^{-1} h^{-1} (*E. urophylla*), which was reflection of low microbiota activity and the consequent immobilization of organic carbon. The

SMB (soil microbial biomass) was equally low in the control area and in areas planted with *C. equisetifolia*, *E. urophylla*, *H. impetiginosus*. In these sites, there were high values of qCO_2 indicating microbial stress. This could be due to low fertility, microenvironmental variations, variations in high temperatures, and/or hydric deficits in the soil. SMB is low in more arid environments (Xu et al. 2013) where there are large oscillations in topsoil temperatures without plant cover. In this study, SMB values were slightly higher under *C. glandulosa* (142. 29 µg C-mic g^{-1} soil), *A. colubrina* (117.81 µg C-mic g^{-1} soil), *A. fraxinifolium* (112.11 µg C-mic g^{-1} soil), and *A mangium* (107.8 µg C-mic g^{-1} soil), all sites with good leaf litter. These values should serve as the baseline for defining critical levels of the Argisol microbial biomass on tablelands planted with timber species, (without maintenance fertilization), as they are comparable to those observed in the Caatinga (Ferreira et al. 2014) and in plantations of *Pinus tecunumanii* and *Eucalyptus grandis* in the Cerrado biome (Silva 2009). On the other hand, in areas of the Cerrado where fertilizers and agronomic practices result in high crop productivity, the levels of edaphic respiration rates are equivalent to/or higher than 4.16 µg C–CO_2 g^{-1} h^{-1} and the SMB is 375 µg C-mic g^{-1} (Lopes et al. 2013).

Sites with *E. urophylla* and *A. fraxinifolium* and the control area indicated low levels of glomalin-related soil protein (< 2.0 mg T-GRSP per gram of dry soil). The area with *A. fraxinifolium* also had low EE-GRSP levels, while the areas planted with *A. colubrina* and *H. impetiginosus* had the highest levels of this protein fraction. The leaf litter deposition and the microenvironments in the vegetation coverage under these last two species may be favorable to AM fungi activity, microorganisms responsible for the production and deposition of glomalin in the rhizosphere. It is also possible that the quality of the leaf litter affected the decomposition rates of the organic matter, corroborating Joly et al. (2017), as well as the glomalin content (Rotter et al. 2017) in the soil. Silva et al. (2014) noted some factors which could be related to the production or deposition of this protein by the AM fungi in plantations and in non-forested areas. These include climate, soil biota, concentrations of nutrients, the diversity of AM fungi, as well as the host and its productivity (Oliveira et al. 2009; Silva et al. 2012).

Some soil attributes such as the SOC and its relationship with N and GRSP fractions (Table 2), plus soil nutrient levels (N, P, K$^+$, Ca^{2+}, Mg^{2+}, Na$^+$ Fe, Mn, Zn; Table 3), showed a normal distribution, observed with insignificant W-values by the Shapiro–Wilk test ($p < 0.05$). There was evidence of contributions of *A. colubrina* and *C. equisetifolia* to the SOC increase, mainly in relation to areas under *E. urophylla*, *A. fraxinifolium* and the control. The litter under the canopies of these last two species may have

Table 2 Biological attributes of soils under trees and non-forested control in the Lower Acaraú Basin, State of Ceara (Brazil)

Forestry area	Soil organic carbon (SOC, g kg^{-1})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	10.56	9.79	11.36	0.24	− 0.06	− 2.86	0.96	4.7
Anadenanthera colubrina	11.57	10.39	12.75	0.55	− 0.32	− 3.3	0.93	6.4
Casuarina equisetifolia	11.9	8.18	15.61	5.45	1.54	2.62	0.87	19.6
Eucalyptus urophylla	8.83	7.19	10.48	1.06	− 0.15	− 5.01	0.84	11.6
Astronium fraxinifolium	8.64	8.2	9.08	0.08	0.92	0.59	0.96	3.21
Handroanthus impetiginosus	10.95	9.28	12.62	1.1	0.12	1.1	0.98	9.6
Colubrina glandulosa	11.1	9.46	12.73	1.06	0.54	1. 21	0.97	9.3
Control	8.69	8.49	8.89	0.02	0.84	0.93	0.96	1.5

Forestry area	Total-glomalin related soil protein(T-GRSP, mg g^{-1})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	1.90	1.85	1.94	< 0.01	0.64	− 2.31	0.89	1.52
Anadenanthera colubrina	1.99	1.41	2.57	0.13	− 0.02	− 0.69	0.99	18.24
Casuarina equisetifolia	2.03	1.61	2.39	0.06	− 0.14	0.23	0.99	12.32
Eucalyptus urophylla	1.54	1.33	1.74	0.02	− 0.68	1.75	0.93	8.35
Astronium fraxinifolium	1.48	0.78	2.18	0.19	− 1.64	2.62	0.82	29.76
Handroanthus impetiginosus	2.04	1.48	2.6	0.12	1.99	3.99	<u>0.63</u>	17.24
Colubrina glandulosa	2.17	1.98	2.36	0.01	0.96	1.79	0.94	5.05
Control	1.48	1.39	1.58	< 0.01	− 0.64	1.72	0.93	4.04

Forestry area	Easily extracted-glomalin related soil protein (EE-GRSP, mg g^{-1})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	0.81	0.68	0.93	0.01	− 0.25	− 3.82	0.91	9.82
Anadenanthera colubrina	0.91	0.77	1.06	0.01	1.61	2.75	0.85	9.76
Casuarina equisetifolia	0.75	0.62	0.88	0.01	− 0.76	− 0.14	0.96	10.75
Eucalyptus urophylla	0.79	0.59	0.99	0.02	1.14	0.47	0.9	16.06
Astronium fraxinifolium	0.61	0.42	0.8	0.01	− 1.2	0.84	0.9	19.29
Handroanthus impetiginosus	0.85	0.65	1.06	0.02	− 0.45	1.08	0.98	14.75
Colubrina glandulosa	0.64	0.53	0.76	< 0.01	− 0.23	− 0.48	0.99	11.71
Control	0.75	0.65	0.85	< 0.01	− 0.16	− 2.72	0.96	8.14

Forestry area	T-GRSP:SOC ratio (/%)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	18	16.61	19.38	0.76	− 0.02	− 5.9	0.76	4.84
Anadenanthera colubrina	17.33	11.03	23.64	15.69	0.62	1.61	0.95	22.85
Casuarina equisetifolia	17.29	11.31	23.28	14.14	− 0.45	− 2.91	0.92	21.74
Eucalyptus urophylla	17.51	15.61	19.41	1.42	0.22	0.7	0.99	6.81
Astronium fraxinifolium	17.07	9.5	24.65	22.65	− 1.79	3.18	0.76	27.88
Handroanthus impetiginosus	18.76	13.38	24.14	11.43	0.76	0.47	0.97	18.01
Colubrina glandulosa	19.73	16.15	23.31	5.06	− 1.56	2.44	0.85	11.39
Control	17.12	15.88	18.36	0.6	0.75	1.05	0.97	4.53

Table 2 continued

Forestry area	EE-GRSP:SOC ratio (%)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	7.62	6.45	8.81	0.55	− 1.13	1.53	0.93	9.72
Anadenanthera colubrina	7.96	5.93	10.01	1.64	1.32	1.1	0.85	16.07
Casuarina equisetifolia	6.48	4.33	8.64	1.83	1.21	1.95	0.92	20.9
Eucalyptus urophylla	8.97	7.77	10.17	0.56	0.64	− 2.41	0.86	8.36
Astronium fraxinifolium	7.06	5.17	8.96	1.42	− 1.47	1.75	0.82	16.85
Handroanthus impetiginosus	7.82	6.46	9.2	0.73	1.33	1.18	0.86	10.97
Colubrina glandulosa	5.82	5.01	6.63	0.26	− 1.42	2.31	0.89	8.7
Control	8.63	7.58	9.68	0.43	− 0.35	− 3.97	0.87	7.64

Forestry area	Basal soil respiration (BSR, μg C–CO$_2$ g^{-1} h^{-1})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	0.32	0.22	0.42	< 0.01	0.65	− 2.17	0.9	20.1
Anadenanthera colubrina	0.23	0.13	0.33	< 0.01	− 1.71	2.55	0.85	27.4
Casuarina equisetifolia	0.26	0.12	0.41	0.01	− 0.37	− 3.9	0.85	33.9
Eucalyptus urophylla	0.4	0.15	0.65	0.03	1.44	2.39	0.88	39.7
Astronium fraxinifolium	0.25	0.05	0.45	0.02	0.08	− 5.69	0.82	49.6
Handroanthus impetiginosus	0.23	0.19	0.28	< 0.01	1.09	− 0.05	0.85	14.1
Colubrina glandulosa	0.38	0.15	0.61	0.02	− 0.93	− 0.85	0.87	38
Control	0.32	0.09	0.54	0.02	0.56	− 2.67	0.9	45.1

Forestry area	Soil microbial biomass (SMB, μg C-mic/g)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	107.8	30.52	185.08	2359.5	1.98	3.93	<u>0.68</u>	45.1
Anadenanthera colubrina	117.81	17.71	217.91	3957	0.8	− 1.54	0.88	53.4
Casuarina equisetifolia	99.47	75.76	123.19	222.13	1.86	3.59	0.76	14.9
Eucalyptus urophylla	98.53	57.69	139.37	658.62	0.49	− 2.33	0.94	26.1
Astronium fraxinifolium	112.11	40.16	184.61	2045	0.2	1	0.98	40.3
Handroanthus impetiginosus	58.99	41.38	76.59	122.41	0.39	− 2.54	0.94	18.7
Colubrina glandulosa	142.29	61.38	223.2	2585	0.81	1.23	0. 96	35.7
Control	97.99	59.47	136.51	586.06	− 0.16	1.24	0.97	24.7

Forestry area	Metabolic quotient (μg C–CO$_2$ μg^{-1} C-mic h^{-1})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	3.36	1.21	5.52	1.83	− 1.08	1.21	0.66	40.2
Anadenanthera colubrina	2.53	0.19	4.86	2.16	− 0.53	− 1.68	0.96	58.2
Casuarina equisetifolia	2.66	1.25	4.07	0.78	0.45	0.75	0.99	33.3
Eucalyptus urophylla	4.13	1.92	6.35	1.94	0.2	− 0.73	0.99	33.6
Astronium fraxinifolium	2.77	− 1.1	6.64	5.92	1.88	3.57	<u>0.75</u>	87.9
Handroanthus impetiginosus	4.16	2.25	6.05	1.42	− 0.05	− 5.36	0.85	28.7
Colubrina glandulosa	3.16	0.09	6.24	3.74	0.22	0.96	0.98	61.1
Control	3.52	0.43	6.6	3.75	0.01	− 4.72	0.89	55.1

Table 2 continued

Forestry area	Microbial quotient (%)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	10.09	3.55	16.62	16.86	1.96	3.88	<u>0.69</u>	40.7
Anadenanthera colubrina	10.35	0.75	19.94	36.34	1.16	0.36	0.88	58.2
Casuarina equisetifolia	8.43	7.18	9.68	0.78	0.88	− 0.46	0.94	9.3
Eucalyptus urophylla	11.03	8.35	13.7	2.82	1.09	0.43	0.92	15.2
Astronium fraxinifolium	12.95	4.58	21.32	27.69	0.51	1.39	0.96	40.6
Handroanthus impetiginosus	5.45	3.38	7.54	1.07	− 0.42	− 3.63	0.86	23.9
Colubrina glandulosa	13.13	3.93	22.32	33.36	1.21	1.2	0.91	43.9
Control	11.28	6.76	15.81	8.07	− 0.01	0.84	0.99	25.1

Forestry area	Mineralization quotient (%)							
	Mean	Median	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	3.02	2.96	2.04	3.99	0.38	0.23	− 4.43	0.87	20.4
Anadenanthera colubrina	1.96	2.15	1.24	2.68	0.2	− 1.91	3.69	<u>0.74</u>	22.9
Casuarina equisetifolia	2.12	2.14	1.31	3.08	0.31	0.59	1.4	0.97	25.4
Eucalyptus urophylla	4.49	4.01	2.15	6.83	2.16	1.27	0.82	0.84	32.7
Astronium fraxinifolium	2.96	2.87	0.54	5.38	2.31	0.07	− 5.56	0.81	51.4
Handroanthus impetiginosus	2.16	2.08	1.7	2.62	0.08	1.31	1.17	0.87	13.2
Colubrina glandulosa	3.42	3.62	1.34	5.5	1.71	− 0.38	− 3.79	0.87	38.2
Control	3.66	3.36	1.05	6.28	2.7	0.57	− 2.71	0.89	44.8

Underlined W-values were significant in the Shapiro–Wilk test ($p < 0.05$), indicating that the hypothesis for a normal distribution was rejected. C.V. (Coefficient of variation). Soil samplings: August and November 2016, February and May 2017

affected the carbon cycling as there was a low soil metabolic quotient in these environments (Table 2). Behera and Sahani (2003) observed an inefficient use of organic substrate from *Eucalyptus* (30-year-old trees) compared to the leaf litter from a naturally regenerated forest. It should be noted that *Eucalyptus* litter often has high cellulose: N and lignin: N ratios (Barreto et al. 2008), indicating a certain recalcitrance on leaf litter matter.

In this study, the highest levels of Mg^{2+} (9.88 mmol$_c$ dm^{-3}) and soil N (0.57 g kg^{-1}) occurred on sites with *A. colubrina* (Table 3), and differed from other coverages evaluated here. The highest levels of P (0.26 mg dm^3), Fe (2.31 mg dm^3), Ca^{2+} (26.10 mmol$_c$ dm^{-3}) and Na^+ (1.88 mmol$_c$ dm^{-3}) were found in areas with *C. equisetifolia*, *E. urophylla*, *H. impetiginosus* and *A. mangium*, respectively, which shows that tree species affect the concentrations of nutrients and biological quality of soils in different ways. In addition, there might have been some microenvironmental influence due to soil sampling periods (Fig. 1) because arbuscular mycorrhizal activity and organic matter accumulation are generally higher during the driest periods of the year. Variations in communities of AM fungi have been observed in Costa Rican forests during the rainy and

dry seasons (Lovelock et al. 2003) as well as a more intense fungal sporulation in the dry season. During the rainy season, there could also have been a leaching of nutrients and labile organic constituents, which indicates a vulnerability to soil degradation. Glomalin-related soil protein fractions (Singh et al. 2017) and soluble ions could have been leached out with the water.

Using agglomerative hierarchical clustering (AHC), three classes of vegetation cover were established using the averages of the soil properties analyzed (Fig. 2). The species of cluster 2 were very similar and consisted of two Brazilian timber species (*H. impetiginosus* and *A. colubrina*). Cluster 1 was formed of *C. glandulosa*, *C. equisetifolia* and *A. mangium*, while cluster 3 was made up of *E. urophylla* and *A. fraxinifolium* plus the control area. These latter two species of cluster 3 may require longer cultivation since natural regeneration takes at least 15 years for the organic carbon content to increase and for certain soil properties to improve (Medeiros et al. 2017). There may also have been variations in leaf litter formation which may have affected the microbial biomass (SMB) and the metabolic quotients and the mineralization of organic

Table 3 pH and chemical attributes of soils under trees and non-forested control in the Lower Acaraú Basin, State of Ceara (Brazil)

Forestry area	Soil pH (in water, ratio 1:2.5)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	5.41	5.29	5.53	0.01	0.56	0.93	0.98	1.4
Anadenanthera colubrina	6.10	5.90	6.31	0.02	1.75	3.05	0.79	2.1
Casuarina equisetifolia	5.58	5.48	5.69	0.01	− 0.06	− 5.45	0.83	1.2
Eucalyptus urophylla	5.51	4.93	6.08	0.13	1.96	3.90	0.69	6.6
Astronium fraxinifolium	5.85	5.73	5.97	0.01	− 1.73	2.99	0.80	1.3
Handroanthus impetiginosus	6.05	6.61	6.48	0.07	0.77	0.01	0.96	4.5
Colubrina glandulosa	5.81	5.48	6.15	0.04	− 1.00	− 0.01	0.92	3.6
Control	6.29	6.24	6.33	< 0.01	− 1.81	3.47	0.77	0.4

Forestry area	N-total (mg g^{-1} soil)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	0.48	0.41	0.54	0.02	− 1.76	3.23	0.81	8.5
Anadenanthera colubrina	0.57	0.27	0.88	0.03	0.0	− 3.96	0.93	33.4
Casuarina equisetifolia	0.46	0.30	0.62	0.01	0.37	− 3.53	0.90	21.5
Eucalyptus urophylla	0.32	0.18	0.45	0.01	0.98	1.98	0.92	27.4
Astronium fraxinifolium	0.43	0.26	0.59	0.01	− 0.41	0.88	0.98	23.9
Handroanthus impetiginosus	0.44	0.34	0.54	< 0.01	0.81	0.07	0.96	13.7
Colubrina glandulosa	0.47	0.38	0.56	< 0.01	0.10	− 5.42	0.81	12.4
Control	0.41	0.20	0.62	0.02	0.01	− 2.06	0.98	32.1

Forestry area	C:N ratio							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	22.12	19.67	24.66	2.32	− 0.21	− 0.47	0.99	6.5
Anadenanthera colubrina	21.64	11.89	31.39	37.52	0.38	3.14	0.92	28.3
Casuarina equisetifolia	26.07	19.59	32.54	16.53	0.21	1.33	0.97	15.6
Eucalyptus urophylla	28.68	19.07	38.29	36.47	0.04	− 2.34	0.97	21.5
Astronium fraxinifolium	20.85	12.79	28.95	25.80	1.06	2.06	0.92	24.3
Handroanthus impetiginosus	25.16	19.44	30.88	12.91	0.65	0.87	0.98	14.3
Colubrina glandulosa	23.90	17.55	30.25	15.91	1.51	1.98	0.83	16.7
Control	23.00	10.73	35.26	59.42	0.89	− 0.31	0.94	33.5

Forestry area	P (mg dm^{3}l)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	0.16	0.14	0.18	< 0.01	1.13	2.23	0.89	7.7
Anadenanthera colubrina	0.14	0.09	0.19	0.01	0.87	1.93	0.91	22.8
Casuarina equisetifolia	0.26	0.15	0.38	0.01	− 0.39	1.23	0.98	27.9
Eucalyptus urophylla	0.14	0.05	0.23	< 0.01	1.28	1.50	0.91	40.8
Astronium fraxinifolium	0.17	0.05	0.31	0.01	− 0.15	− 0.94	0.99	45.8
Handroanthus impetiginosus	0.21	0.08	0.34	0.01	− 0.18	1.44	0.96	38.5
Colubrina glandulosa	0.22	0.13	0.31	< 0.01	1.70	2.92	0.81	24.9
Control	0.14	0.08	0.19	0.01	− 1.19	1.98	0.92	24.7

Forestry area	K$^+$ (mmol$_c$.dm^{-3})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	1.64	0.71	2.58	0.34	1.19	1.57	0.58	35.6
Anadenanthera colubrina	1.34	0.61	2.08	0.21	0.48	1.63	0.94	34.4
Casuarina equisetifolia	1.75	0.88	2.63	0.30	0.38	0.95	0.98	31.3
Eucalyptus urophylla	1.06	0.75	1.36	0.03	− 0.22	− 4.60	0.86	17.8
Astronium fraxinifolium	1.11	0.37	1.85	0.22	0.51	1.58	0.95	41.60

Table 3 continued

Forestry area	K$^+$ (mmol$_c$.dm^{-3})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Handroanthus impetiginosus	1.65	0.91	2.39	0.22	0.92	0.25	0.95	28.2
Colubrina glandulosa	2.44	1.42	3.47	0.41	− 0.48	0.34	0.98	26.3
Control	2.06	1.19	2.93	0.29	− 0.94	0.52	0.73	26.4

Forestry area	Na$^+$ (mmol$_c$.dm^{-3})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	1.88	1.06	2.69	0.26	− 0.10	− 0.10	0.99	27.3
Anadenanthera colubrina	0.97	0.23	1.72	0.22	1.47	2.50	0.88	48.1
Casuarina equisetifolia	1.60	0.77	2.42	0.27	− 0.11	0.99	0.99	32.5
Eucalyptus urophylla	1.32	0.57	2.08	0.22	0.91	0.35	0.95	35.6
Astronium fraxinifolium	0.77	0.39	1.55	0.06	0.89	− 0.89	0.91	30.8
Handroanthus impetiginosus	1.09	0.64	1.54	0.07	1.19	1.50	0.93	12.3
Colubrina glandulosa	1.32	0.23	2.42	0.47	0.72	− 0.53	0.96	51.7
Control	1.13	0.85	1.40	0.03	0.01	− 5.48	0.84	15.5

Forestry area	Ca^{2+} (mmol$_c$.dm^{-3})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	19.88	16.45	23.31	4.63	0.34	− 3.59	0.47	10.83
Anadenanthera colubrina	23.59	20.59	26.59	3.55	− 0.19	− 0.84	0.99	7.99
Casuarina equisetifolia	25.28	21.32	29.25	6.21	− 0.12	− 2.01	0.97	9.8
Eucalyptus urophylla	17.54	13.46	21.61	6.54	0.08	− 2.29	0.97	14.6
Astronium fraxinifolium	19.19	15.09	23.29	6.63	− 0.39	− 0.01	0.99	13.4
Handroanthus impetiginosus	26.10	20.99	31.22	10.31	− 0.44	1.59	0.95	12.3
Colubrina glandulosa	23.80	19.16	28.45	8.52	0.98	− 0.63	0.87	12.3
Control	17.79	15.65	19.94	1.81	0.06	0.84	0.99	7.6

Forestry area	Mg^{2+} (mmol$_c$.dm^{-3})							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	7.61	6.13	9.09	0.86	0.75	− 1.79	0.33	12.2
Anadenanthera colubrina	9.88	9.03	10.74	0.28	− 1.71	2.89	0.81	0.5
Casuarina equisetifolia	8.56	5.85	11.33	2.96	0.31	− 1.40	0.98	20.1
Eucalyptus urophylla	6.86	5.01	8.72	1.36	− 0.47	1.46	0.96	17.1
Astronium fraxinifolium	7.84	6.66	9.01	0.54	− 1.65	2.61	0.80	9.4
Handroanthus impetiginosus	9.26	6.85	11.66	2.28	− 1.21	1.91	0.92	16.3
Colubrina glandulosa	8.92	6.46	11.39	2.39	0.12	− 3.66	0.93	17.3
Control	7.49	2.01	12.96	11.82	− 1.37	2.54	0.88	45.9

Forestry area	Cu (mg dm^3)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	0.27	0.23	0.32	< 0.01	− 2.00	4.00	0.63	9.0
Anadenanthera colubrina	0.03	0.01	0.05	< 0.01	− 2.00	4.00	0.63	46.1
Casuarina equisetifolia	0.24	0.04	0.43	0.01	0.54	− 2.94	0.86	51.1
Eucalyptus urophylla	0.04	–	–	< 0.01	nd	nd	nd	0
Astronium fraxinifolium	0.04	–	–	< 0.01	nd	nd	nd	0
Handroanthus impetiginosus	0.06	0.02	0.11	< 0.01	0.0	− 6.00	0.73	44.1
Colubrina glandulosa	0.17	0.10	0.25	< 0.01	0.85	− 1.29	0.86	26.9
Control	0.03	0.01	0.06	< 0.01	− 2.00	4.00	0.63	46.1

Table 3 continued

Forestry area	Fe (mg dm³)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	2.04	1.91	2.18	0.01	− 0.75	0.34	0.85	4.2
Anadenanthera colubrina	1.29	0.89	1.68	0.06	− 1.10	− 5.02	0.86	19.2
Casuarina equisetifolia	1.94	1.20	2.68	0.21	0.59	− 1.31	0.96	23.9
Eucalyptus urophylla	2.31	1.86	2.77	0.08	− 0.37	− 3.59	0.90	12.3
Astronium fraxinifolium	1.51	1.08	1.94	0.07	− 0.57	− 1.71	0.95	17.7
Handroanthus impetiginosus	1.30	0.92	1.68	0.06	− 0.29	− 3.96	0.90	18.4
Colubrina glandulosa	1.59	0.92	2.26	0.17	1.17	2.22	0.90	26.4
Control	1.04	0.45	1.63	0.13	− 0.23	− 4.51	0.87	35.5

Forestry area	Mn (mg dm³ soil)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	5.24	3.88	6.59	0.72	− 0.48	− 1.92	0.75	16.2
Anadenanthera colubrina	6.71	5.22	8.20	0.88	− 0.45	− 3.42	0.86	13.9
Casuarina equisetifolia	5.29	3.45	7.12	1.32	0.15	− 4.68	0.88	21.8
Eucalyptus urophylla	5.89	3.73	8.05	1.84	− 0.31	0.46	0.99	23.1
Astronium fraxinifolium	6.01	5.21	6.82	0.25	0.81	1.18	0.97	8.4
Handroanthus impetiginosus	6.07	4.81	7.33	0.62	− 1.17	0.39	0.86	13.0
Colubrina glandulosa	5.45	3.42	7.49	1.63	− 0.14	− 4.98	0.85	23.4
Control	4.86	2.50	7.22	2.20	0.45	− 3.44	0.86	30.5

Forestry area	Zn (mg dm³)							
	Mean	Lower 95%	Upper 95%	Variance	Skewness	Kurtosis	W	C. V. (%)
Acacia mangium	1.99	1.64	2.33	0.05	0.83	− 0.03	0.76	10.9
Anadenanthera colubrina	1.59	0.89	2.29	0.19	1.62	3.02	0.84	27.5
Casuarina equisetifolia	1.60	0.92	2.28	0.18	1.67	2.85	0.83	26.7
Eucalyptus urophylla	1.09	0.77	1.41	0.04	0.47	− 3.32	0.86	18.1
Astronium fraxinifolium	1.85	− 0.08	3.79	1.49	1.95	3.85	0.71	65.8
Handroanthus impetiginosus	1.56	0.90	2.23	0.17	1.76	3.11	0.79	26.6
Colubrina glandulosa	1.38	0.98	1.77	0.06	0.39	− 2.44	0.95	17.9
Control	1.30	0.35	2.25	0.35	1.13	1.78	0.93	45.6

The elements P, K, Na, Cu, Fe, Mn and Zn were extracted with Mehlich-1; Ca and Mg were extracted with KCl (mol L^{-1}). C.V.: Coefficient of variation Underlined W-values were significant in the Shapiro–Wilk test ($p < 0.05$), indicating that the hypothesis for a normal distribution was rejected. Soil samplings: August and November 2016, February and May 2017

matter, not allowing the separation of forest species from the control (Table 2).

Analyzing the Principal Components, F 1 explains 31.6%, F 2 25.2%, F 3 15.52%, F 4 11.05%; the other axes were irrelevant. However, only the first two components were retained, explaining almost 60% of the variance in the data set (Fig. 3). In the F 1 component, the more sensitive variables (with the largest square cosines) were: Ca^{2+} (0.842) > Mg^{2+} (0.756) > SOC (0.677) > N (0.646) > T-GRSP (0.603) > P (0.590), all with large positive factor loadings, and qMin (0.628) plus EE-GRSP:SOC (0.422) with negative loadings. In the F 2 component, the variables Na^+ (0.805) > Fe (0.635) > BSR (0.632) > Cu (0.614) > T-GRSP:SOC ratio (0.437) > C:N ratio (0.429) showed large positive loadings, while pH (0.652) and Mn

(0.312) were negative loadings. The other assessed soil properties were less sensitive to these major components.

It should be noted that several properties were related to each other as observed in the significant correlations ($p < 0.05$) of Spearman. The positive relationships were associated with the one-way movement of the axis in component analysis (Fig. 3) such as: T-GRSP versus T-GRSP: SOC (r = 0.81); T-GRSP versus SOC (r = 0.81); T-GRSP versus Ca^{2+} (r = 0.83); SOC versus Ca^{2+} (r = 0.74); BSR versus qMic (r = 0.91); P versus Ca^{2+} (r = 0.81); Na^+ versus Cu (r = 0.74); and, Ca^{2+} versus Mg^{2+} (r = 0.81). This direct relationship between the levels of glomalin and SOC has already been observed in soils under tree canopies (Vasconcellos et al. 2016; Rotter et al. 2017; Zang et al. 2017). The relationship between

T-GRSP versus exchangeable Ca^{2+} could be associated with the activity of AM fungi in the rhizosphere of the plants as well as with the Ca cycle because of the litter of *C. equisetifolia*, *A. colubrina*, *C. glandulosa* and *H.*
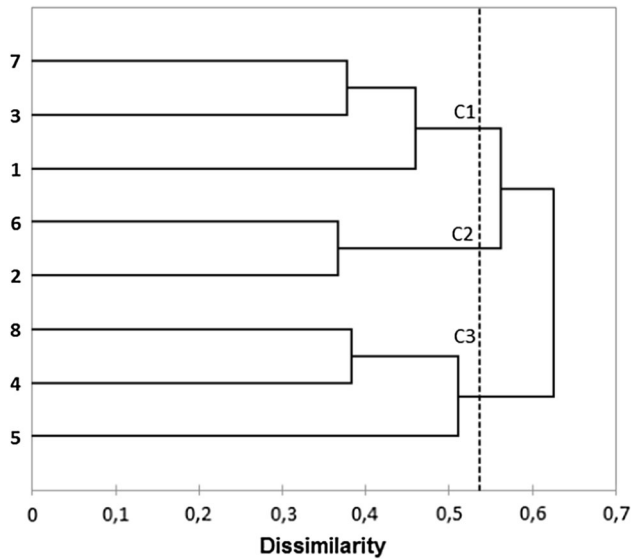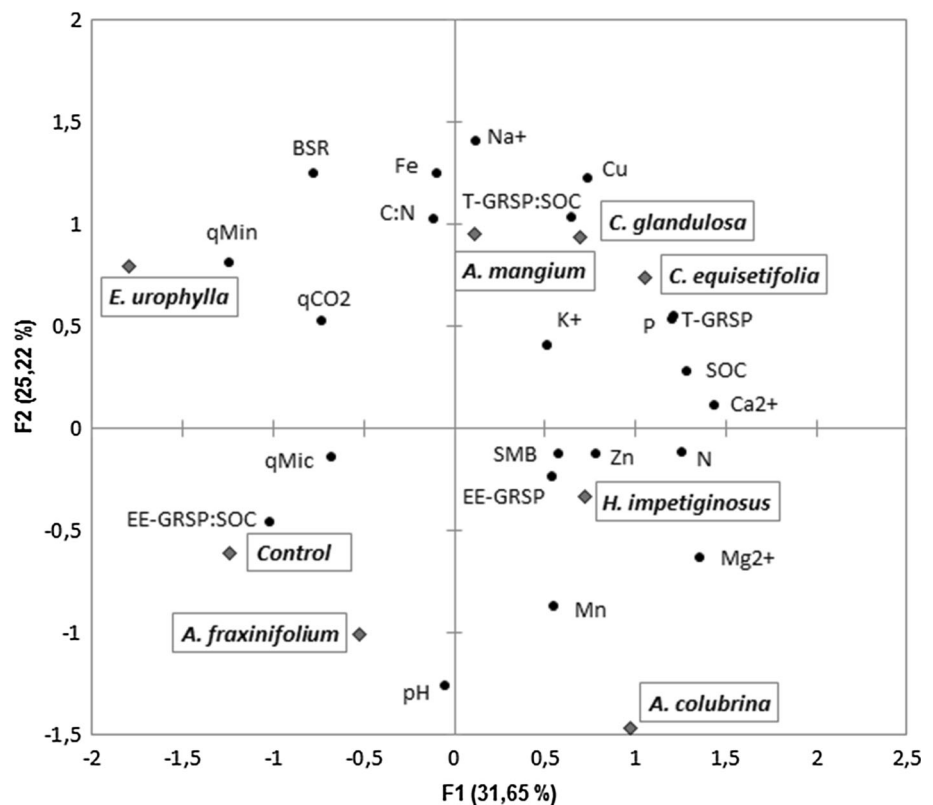

Fig. 2 Dendrogram constructed by UPGMA using the mean values of soil attributes as influenced by trees and non-forested area. Plant coverings separated by the cluster C 1 [*Colubrina glandulosa* (7), *Casuarina equisetifolia* (3), and *Acacia mangium*) (1)]; cluster C 2 [*Handroanthus impetiginosus* (6) and *Anadenanthera colubrina* (2)], and cluster C 3 [control (8), *Eucalyptus urophylla* (4), and *Astronium fraxinifolium* (5)]

impetiginosus. In these same environments, higher values of SOC and T-GRSP were detected than under the other species. The variations in these biological properties, among other chemical characteristics, may affect the growth of the trees (Table 3).

Other significant correlations between soil properties were negative and the inverse relationship between EE-GRSP and qMic ($r = -0.74$) may be associated with levels of labile fractions in the organic constituents and activity of the soil microbiota. The quality of the organic matter on the soil surface may have affected the availability of nutrients for fungi and other micro-organisms, as can be seen in the relationship between EE-GRSP:SOC versus P ($r = -0.88$) and qMin versus Mg^{2+} ($r = -0.86$). Links between pH values and the concentrations of some soil elements (pH versus Na^+ ($r = -0.74$); pH versus Cu ($r = -0.77$); pH versus Fe ($r = -0.98$) were also observed. An increase in pH could have favored the insolubility of Cu and Fe and the leaching of Na in the soil profile. This possibility should not be ruled out in the plantations of *H. impetiginosus* (pH = 6.1) and *A. colubrina* (pH = 6.1) (Table 3), which nearly reach the levels in the control (pH = 6.3), where a cover of native *Paspalum* was observed during the rainy season. We had expected to find a certain acidification of the soil in the forested areas as a consequence of the production of acids during the decomposition of organic matter. This could

Fig. 3 Principal component analysis (PCA) using the mean values of biological and chemical attributes of the soil under trees and non-forested area. Soil attributes: BSR (basal soil respiration), SOC (soil organic carbon), T-GRSP (total-glomalin related soil protein), EE-GRSP (easily extractable-glomalin related soil protein), SMB (soil microbial biomass), qCO_2 (Metabolic quotient), qMic (Microbial quotient), qMin (Mineralization quotient), minerals

have favored the bioavailability of Cu, Fe, Mn and Zn. There might also have been an imbalance of ions in the rhizosphere due to their absorption and accumulation in the biomass of the trees, particularly under *E. urophylla* where low pH (5.5) and a low level of K^+ (1.76 mmol$_c$ dm^3) were detected (Table 3). These factors may have influenced the activity of microorganisms decomposing organic substrates. Moreover, it should be noted that the exudation and respiration of roots could contribute to the acidification of the rhizosphere (Hinsinger et al. 2003). More acidic environments inhibit the production of bacterial biomass but are compensated for this, in part by the growth and production of fungal biomass (Rousk et al. 2009).

Conclusions

Reforestation using Brazilian timber species such as *Anadenanthera colubrina*, *Astronium fraxinifolium*, *Handroanthus impetiginosus*, *Colubrina glandulosa*, and the non-native species *Acacia mangium*, *Casuarina equisetifolia*, *Eucalyptus urophylla* represents an alternative way to maintain or improve the biological and chemical properties of the Argisol in coastal tablelands of the tropics.

The cultivation of these species for 6 years increases organic matter, microbial biomass and glomalin-related soil protein, as well as the concentration of phosphorus, calcium, iron and manganese in the soil. The only exception was *E. urophylla*, which led to a reduction in pH and in the level of exchangeable potassium, reflecting a degree of stress among the soil microbiota, measured by metabolic and microbial quotients and the mineralization of the organic matter.

The effects of the species on soil biological and chemical properties indicates that *H. impetiginosus* and *A. colubrina* may be planted together, as can *C. glandulosa*, *C. equisetifolia* and *A mangium*, while plantations of *E. urophylla* and *A. fraxinifolium* cannot be differentiated from the non-forested control. These findings should be taken into account when devising reforestation programs with different tree species in the coastal plains of the tropics.

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