

Arbuscular mycorrhizal fungal communities and soil organic matter in pasture and analog agroforestry systems

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ABSTRACT: Study aimed to (i) assess the impact of analog agroforestry (agrofor) on arbuscular mycorrhizal fungi (AMF), easily extractable glomalin-related soil protein (EE-GRSP), soil organic matter (SOM), and aggregate stability compared with a pasture system and (ii) investigate the chemical, physical and OM properties that explain the differences in soil microbiology between sites. The study was conducted in an agrofor and pasture area. Soil samples were collected in the dry season. A total of 12 AMF taxa were identified. Mean richness was positively correlated with soil pH, Mg²⁺, sum of bases (SB) and moisture. Mean richness and diversity were higher in the analog agroforestry site. Pasture soil had higher EE-GRSP content and spore abundance, variables that were found to be positively correlated with soil temperature, P, K⁺, and H + Al. EE-GRSP also showed a positive correlation with total organic carbon. Aggregate stability was greater in soil under analog agroforest than pasture. SOM properties did not differ between sites. It is concluded that agrofor changes the evaluated soil physical and microbiological attributes, and the microbiological attributes are influenced by the pH, Mg²⁺, K⁺, SB, P, H+Al, soil moisture and TOC.

Key words: glomalin; light-fraction organic matter; organic carbon fraction; weighted mean diameter

Fungos micorrízicos arbusculares e matéria orgânica do solo em sistema agroflorestal regenerativo análogo e pastagem

RESUMO: O estudo objetivou avaliar o impacto de um sistema agroflorestal regenerativo análogo (SAFRA) na comunidade de fungos micorrízicos arbusculares (FMAs), na proteína do solo relacionada à glomalina - facilmente extraível (PSRG-FE), na matéria orgânica (MO) e na estabilidade de agregados comparado a uma área de pastagem. Além disso, avaliar as propriedades químicas, físicas e da MO que explicam a variação dos atributos microbiológicos do solo em tais áreas. O estudo foi conduzido em uma área de SAFRA e de pastagem. As amostras de solo foram coletadas na estação seca. Foram identificados 12 taxas de FMAs. A riqueza média (RM), correlacionou-se positivamente com o pH, Mg²⁺, soma de bases (SB) e umidade do solo. Tanto a riqueza média quanto a diversidade foram maiores no SAFRA. Na pastagem, foram maiores a abundância de esporos (AE) e PSRG-FE, sendo que ambas as variáveis se correlacionaram positivamente com a temperatura do solo, P, K⁺ e H+Al. A PSRG-FE também se correlacionou positivamente com o carbono orgânico total. A estabilidade de agregados foi maior no SAFRA, e os atributos da MO não variaram entre as áreas. Conclui-se que o SAFRA altera os atributos físicos e microbiológicos avaliados, e os atributos microbiológicos são influenciados pelo pH, Mg²⁺, K⁺, SB, P, H+Al, umidade do solo e COT.

Palavras-chave: glomalina; matéria orgânica leve; frações do carbono orgânico; diâmetro médio ponderado

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Introduction

Analog agroforestry systems, in which the horizontal and vertical stratification of the plant community follows the structure of a natural forest, contribute to the recovery of degraded Atlantic Forest fragments within four years of implementation (Souza & Piña-Rodrigues, 2013). These systems aim to restore environmental functions and increase biodiversity and agricultural and forest productivity (Souza et al., 2016). A recent investigation showed that, in comparison with pasture systems, analog agroforests not only enhance soil fertility, but also the complexity of the soil faunal community, as evidenced by an increase in the total abundance, mean and total richness, evenness, and diversity of soil taxa (Camara et al., 2020). However, few studies have examined the influence of natural succession in analog agroforestry systems on soil organic matter fractions, aggregate stability, arbuscular mycorrhizal fungi (AMF) (Martins et al., 2019), and easily extractable glomalin-related soil protein (EE-GRSP).

AMF play an important role in forest regeneration, with root colonization intensity and soil spore density progressively decreasing during ecological succession from pasture to mature forest (Zangaro et al., 2012). There is a possible positive relationship between AMF richness and plant species composition in different environments during ecological succession. The beneficial action of AMF on soil aggregation may be the result of glomalin production and particle approximation by external mycelia (Liu et al., 2020). Glomalin is a glycoprotein with well-described cementing effects on soil aggregates. AMF respond to changes in land use and promote carbon sequestration via GRSP, which represents 4 to 5% of the soil carbon stock (Singh et al., 2017). These observations demonstrate that AMF are important components of the soil biota and have great value as biological indicators of soil quality.

Soil organic matter (OM), in turn, is important in maintaining soil quality and sustainability (Costa et al., 2013). Its physical fractionation (particulate organic carbon and mineral-associated organic carbon) contributes to the acquisition of soil quality indicators, since it supports to distinguish carbon compartments subject to the influence of land use and management systems (Balin et al., 2017). OM influences the soil chemical properties, such as the supply of nutrients to plants, and the complexation of toxic elements and micronutrients. Influence also on the soil physical properties, such as aggregate stability, which in turn interfere on bulk density, porosity, aeration, water retention and infiltration, which are essential for soil productivity (Costa et al., 2013).

The purpose of this study was to evaluate the impact of an 11-year analog agroforestry system on AMF abundance and diversity and EE-GRSP content, assess the relationship of soil microbiology with soil chemical and physical properties, and determine the influence of analog agroforestry on soil organic matter and aggregate stability compared with an adjacent field of managed pasture (the former land use type of the agroforestry site).

Materials and Methods

Study sites and sampling procedures

The study was conducted at the agroecological farm of Seropédica, Rio de Janeiro State, Brazil (22°44'38" S 43°42'27" W, 26 m elevation). The predominant climate is of the Aw type (Köppen classification), characterized by dry winters and wet summers. The average annual precipitation is 1213 mm, with rainfall occurring mostly between November and March, and the average annual temperature is 23.9 °C. The primary vegetation is semideciduous tropical rainforest.

Two sites were selected for this investigation: a pasture on Argissolo Vermelho-Amarelo and an analog agroforest on Planossolo. The pasture site, composed of *Megathyrus maximus* (syn. *Panicum maximum*) and *Urochloa brizantha*, surrounds the 6000 m² (200 × 30 m) agroforestry system, which was established in February 2005. The agroforest was previously covered by *M. maximus* and underwent floristic changes over the years (see Martins et al., 2019). At the time of installation, the entire agroforestry site was planted with 36 tree species at a spacing of 1.0 × 1.0 m in addition to the following short cycle crops and green manure species: pigeon pea (*Cajanus cajan*, spacing of 1.0 × 0.3 m), sunflower (*Helianthus annuus*, 1.0 × 0.5 m), squash (*Cucurbita* sp., 3.0 × 3.0 m), banana (*Musa* sp., 3.0 × 3.0 m), sugarcane (*Saccharum officinarum*, 3.0 × 3.0 m), pineapple (*Ananas comosus*, 1.0 × 0.4 m), and cassava (*Manihot esculenta*, 1.0 × 0.5 m). *Tectona grandis* seedlings were planted in April 2009. In January 2010, invasive grasses were removed, part of the canopy (10-15%) was pruned, and the agroforest community was enriched with seedlings of *Euterpe edulis*, *Apuleia leiocarpa*, *Erythroxylum pulchrum*, *Cedrela fissilis*, and *Plathymenia foliosa*. Seedlings of *Spondias* sp. were planted in April 2010. Spontaneous occurrence of *Eriotheca candolleana*, *Erythroxylum pulchrum*, *Anadenanthera* sp., *Mimosa bimucronata*, and *Eugenia brasiliensis* was observed between April 2008 and May 2010 (Camara et al., 2020).

Data on soil physical and chemical properties and microclimate (gravimetric moisture content and soil temperature) in the 0-5 cm depth layer (Table 1) were previously published by the authors (Camara et al., 2020). Correlations between these parameters and the results of the present study were investigated.

Disturbed soil samples were collected for chemical, physical, and microbiological analyses in October 2016 (end of the dry season). In the 11-year analog agroforestry site, tree individuals predominated, and short-lived crops had been completely replaced by other plant species. A total of 10 composite samples were collected at a depth of 0-5 cm from randomly distributed points at each site. Each composite sample comprised three subsamples. The material was evaluated for particulate organic carbon and mineral-associated organic carbon (Cambardella & Elliott, 1992), light-fraction organic matter (Anderson & Ingram, 1989), EE-GRSP, and AMF community structure. In addition to disturbed soil samples, five discrete undisturbed samples were collected

Table 1. Soil physical and chemical properties, total organic carbon (TOC), gravimetric moisture content (W_g), and temperature (T) in the 0-5 cm depth layer in pasture and analog forestry sites in Seropédica, Rio de Janeiro, Brazil.

Site	W_g (g g ⁻¹)	T (°C)	Sand	Clay	Silt
			(g kg ⁻¹)		
Pasture	4.89 B	27.4 A	635.7 A	241.4 A	122.9 A
Analog agroforest	9.98 A	24.1 B	700.8 A	181.6 A	117.6 A
Site	pH in H ₂ O	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺
Pasture	4.25 B	1.74 B	1.77 B	0.10 A	0.02 A
Analog agroforest	5.29 A	2.10 A	2.35 A	0.07 B	0.02 A
Site	SB (cmol _c dm ⁻³)	H + Al	TOC	N	P
Pasture	3.63 B	9.29 A	31.02 A	0.42 A	17.12 A
Analog agroforest	4.53 A	4.74 B	26.02 B	0.38 A	6.06 B

Different letters indicate significant differences between sites by the parametric Student's t-test or the nonparametric Mann-Whitney test ($p < 0.05$). SB, sum of bases. Source: adapted from Camara et al. (2020).

from the 0-5 cm depth layer for analysis of the weighted mean diameter of soil aggregates (Donagemma et al., 2011).

Evaluation of AMF community structure

AMF spores were extracted from 50 g of soil from each composite sample by wet sieving (Gerdermann & Nilcoson, 1963), centrifugation in water, and, subsequently, centrifugation in 45% sucrose. Spores were counted in a grooved plate under a stereoscopic microscope, and species were identified under an optical microscope on the basis of morphological characteristics (Oehl et al., 2011) and data from the International Culture Collection of (Vesicular) Arbuscular Mycorrhizal Fungi website.

After AMF species identification, we calculated the mean species richness and the Margalef diversity index using the following equation: $I = [(n - 1)]/\ln N$, where I is the Margalef diversity index, n is the number of species, and N is the total number of individuals from all species. Then, we estimated the relative frequency of AMF species (F_i), determined as the number of samples in which species i was identified divided by the total number of samples. Species were classified according to their dominance on the basis of F_i values (Zhang et al., 2004), as follows: dominant ($F_i > 50\%$), very common ($30\% < F_i \leq 50\%$), common ($10\% < F_i \leq 30\%$), and rare ($F_i \leq 10\%$). The degree of similarity between AMF communities of study sites was assessed using the Sørensen index, calculated as $S = 2j/(a + b)$, where j is the total number of AMF species, a is the total number of species in the pasture site, and b is the total number of species in the analog agroforestry site.

Determination of GRSP

Glomalin was quantified as GRSP. EE-GRSP was obtained by autoclave extraction (121 °C, 30 min) using 1 g of soil and 8 mL of 20 mM sodium citrate solution (pH 7.0). After autoclaving, the material was centrifuged at 4000 rpm for 10 min and the supernatant removed. Protein quantification was carried out by the Bradford method using bovine serum albumin as

standard (Wright et al., 1996). EE-GRSP concentrations were transformed to mg g⁻¹ soil considering the total supernatant volume and soil dry weight.

Data analysis

Homogeneity of variance was assessed by Levene's test. When the assumption of homoscedasticity was met, means were compared by the parametric Bonferroni test and, when not, means were compared by the nonparametric Mann-Whitney test. Pearson correlations were determined between replications of spore abundance, EE-GRSP, AMF richness, presence/absence of AMF species and soil physical and chemical properties and microclimate. Statistical analyses were performed using Statistica version 8.0. Significance was set at $p < 0.05$. All variables, except weighted mean diameter (which had a different number of replications), were subjected to principal component analysis using PAST version 2.17c.

Results and Discussion

Twelve AMF morphospecies were identified (11 at the species level and 1 at the genus level), distributed in four families (Acaulosporaceae, Archaeosporaceae, Glomeraceae, and Gigasporaceae) and five genera (Table 2). The genera *Glomus* and *Acaulospora*, represented by five and three species, respectively, were dominant, accounting together for about 67% of the total species richness. *Ambispora*, *Gigaspora*, *Racocetra*, and *Scutellospora* contributed to species richness (33%) with one species each.

Eight morphospecies were found in the pasture site and nine in the analog agroforestry site. Of these, five morphospecies (*Acaulospora mellea*, *Glomus tortuosum*, *Glomus macrocarpum*, *Glomus clavisporum*, *Glomus microaggregatum*) were common to both areas (Table 2). The Sørensen index (0.58) revealed an intermediate similarity (<61.5%) (Carrenho & Gomes-da-Costa, 2011) between

Table 2. Relative frequency (F_i) and dominance (Do) of arbuscular mycorrhizal fungal species in pasture and analog agroforestry sites in Seropédica, Rio de Janeiro, Brazil.

Family and species	Pasture		Analog agroforest	
	F_i	Do	F_i	Do
ACAULOSPORACEAE				
<i>Acaulospora tuberculata</i>	-	-	10	R
<i>Acaulospora mellea</i>	10	R	20	C
<i>Acaulospora foveata</i>	10	R	-	-
ARCHAEOSPORACEAE				
<i>Ambispora leptoticha</i>	-	-	40	VC
GLOMERACEAE				
<i>Glomus tortuosum</i>	20	C	20	C
<i>Glomus macrocarpum</i>	90	D	90	D
<i>Glomus clavisporum</i>	10	R	60	D
<i>Glomus microaggregatum</i>	10	R	50	VC
<i>Glomus glomerulatum</i>	-	-	60	D
GIGASPORACEAE				
<i>Gigaspora</i> sp.	10	R	-	-
<i>Racocetra persica</i>	-	-	10	R
<i>Scutellospora scutata</i>	10	R	-	-

AMF communities in pasture and analog agroforestry sites. This result might be a reflection of differences in floristic composition, biomass generation, and diversity of functional plant groups between the study sites (Goomaral et al., 2019). In addition, the influence of the different soil chemical and microclimate characteristics of these two systems (Tabela 1) can be considered.

Glomus was dominant and *Acaulospora* common in both sites, whereas *Ambispora* was very common in the analog agroforestry site and absent in the pasture site (Table 2). *Gigaspora* and *Scutellospora* were rare in the pasture site and *Racocetra* in the analog agroforestry site. Although there is no specificity between symbionts for the establishment of mycorrhizal association, environmental conditions can influence the presence of host plants and, as a consequence, alter AMF community composition. Thus, some AMF species may be ubiquitous and others rare (Winagraski et al., 2019).

Ambispora leptoticha was common and exclusive to the analog agroforestry site (Table 2). Its occurrence was significantly ($p < 0.05$) and positively correlated with soil moisture content ($r = 0.51$), pH ($r = 0.51$), Ca^{2+} ($r = 0.66$), and sum of bases ($r = 0.46$); these parameters were highest in the agroforestry site (Camara et al., 2020). On the other hand, *A. leptoticha* was negatively correlated with soil temperature ($r = -0.49$) and K^+ ($r = -0.49$), which were lowest in the analog agroforestry site (Camara et al., 2020). *A. leptoticha* seems to occur more frequently in environments occupied by plant communities with a forest-like structure (such as secondary Atlantic Forest fragments and *Eucalyptus* plantations) and in areas with low disturbance levels (such as Cerrado regions) (Teixeira et al., 2017). The species is uncommon in areas lacking tree vegetation or with higher levels of anthropogenic disturbances, such as in rocky environments or areas under post-iron mining revegetation with *Melinis minutiflora*, as seen in the municipality of Sabara, Minas Gerais, Brazil (Teixeira et al., 2017).

G. clavisporum, although detected in both sites, was dominant in the analog agroforestry site and rare in the pasture site (Table 2). It was significantly ($p < 0.05$) and positively correlated with pH ($r = 0.47$) and Mg^{2+} ($r = 0.52$). *G. clavisporum* was among the four species with the lowest frequency (4-8%) in an AMF community of 50 species in a highly disturbed semideciduous seasonal forest fragment in Maringá, Paraná, Brazil (Santos & Carrenho, 2011).

G. glomerulatum was dominant and exclusive to the analog agroforestry site (Table 2). Significant ($p < 0.05$) and positive correlations were observed between the species and soil moisture content ($r = 0.46$), pH ($r = 0.70$), Ca^{2+} ($r = 0.57$), and sum of bases ($r = 0.59$), and negative correlations with soil temperature ($r = -0.58$), K^+ ($r = -0.57$), and H + Al ($r = -0.63$), which were lowest in the agroforestry site (Camara et al., 2020). A previous study showed that *G. glomerulatum* spores were more abundant in the rhizosphere of *Talipariti elatum* and *Calophyllum antillanum* under shade conditions at 19-23 and 25-30 °C, respectively. Such conditions, as opposed to full sun exposure, imply a high soil moisture content (Torres-Arias et al., 2017).

AMF community complexity (as assessed by mean and total richness and Margalef diversity index) was higher in the analog agroforestry site (Table 3). There were significant ($p < 0.05$) and positive correlations between mean richness and pH ($r = 0.71$), Mg^{2+} ($r = 0.56$), sum of bases ($r = 0.61$), and soil moisture content ($r = 0.59$), as well as significant and negative correlations between mean richness and soil temperature ($r = -0.63$) and H + Al ($r = -0.62$). The differences in AMF diversity between land use systems might be associated with biotic and abiotic factors, including environmental conditions, soil fertility, host plant diversity, and agricultural management techniques (Winagraski et al., 2019).

Soil pH is known to influence the diversity of AMF communities (Kawahara et al., 2016), as it can alter the availability of Al, Fe, and Mn. In general, the diversity and/or richness of AMF is higher in less disturbed soils (Schneider et al., 2013) and areas with highly diverse vegetation. For instance, AMF diversity was greater in secondary Atlantic Forest fragments and soil under agroecological coffee cropping (application of green manure and rotation with other crops) than in soil under 30-year coffee monoculture (Prates Junior et al., 2019).

AMF spore abundance, in contrast, was significantly higher in the pasture site (Table 3). This result was associated with low soil moisture content and high soil temperature (Table 1) and might have been influenced by the higher density of thin roots in this ecosystem. The stressful microclimatic conditions often observed in pastureland, as opposed to Atlantic Forest sites at different stages of succession, favor the production of AMF survival structures (Silva et al., 2016). Factors such as low anthropogenic interference, high microclimate stability, and soil fertility explain the lower number of spores in the analog agroforestry site (Table 3). This pattern was corroborated by significant ($p < 0.05$) negative correlations between spore abundance and soil moisture content ($r = -0.58$), pH ($r = -0.72$), Ca^{2+} ($r = -0.55$), Mg^{2+} ($r = -0.58$), and sum of bases ($r = -0.69$) and significant positive correlations with soil temperature ($r = 0.67$) and H + Al ($r = 0.50$).

Table 3. Arbuscular mycorrhizal fungal community attributes, easily extractable glomalin-related soil protein (EE-GRSP), weighted mean diameter (WMD), light-fraction organic matter (LF-OM), particulate organic carbon (POC), and mineral-associated organic carbon (MAOC) in pasture and analog agroforestry sites in Seropédica, Rio de Janeiro, Brazil.

Parameter	Pasture	Analog agroforestry
Mean richness	1.7 B	3.6 A
Total richness	8.0	9.0
Margalef diversity index	1.08	2.45
Spore abundance (spores 50 cm ³)	649 A	26 B
EE-GRSP (mg g ⁻¹)	1.69 A	1.22 B
WMD (mm)	3.64 B	4.29 A
LF-OM (g)	0.06 A	0.06 A
POC (g kg ⁻¹)	3.05 A	2.35 A
MAOC (g kg ⁻¹)	25.03 A	22.97 A

Means within rows followed by the same letter are not significantly different ($p < 0.05$) according to the parametric Bonferroni test or the nonparametric Mann-Whitney test (spore abundance).

EE-GRSP was highest in the pasture site (Table 3) and followed the same pattern of correlations observed for spore abundance. However, spore abundance and EE-GRSP were not significantly correlated. EE-GRSP was significantly and negatively correlated with species richness ($r = -0.50$). A previous report found a positive correlation between EE-GRSP and spore abundance in areas with low degrees of disturbance; in such cases, high glomalin production is associated with the maintenance of the hyphal network in the soil (Fokom et al., 2012).

A significant ($p < 0.05$) and positive correlation was observed between EE-GRSP and total organic carbon ($r = 0.70$), P ($r = 0.80$), K^+ ($r = 0.54$), H + Al ($r = 0.71$), and soil temperature ($r = 0.67$). However, a significant and negative correlation was found between EE-GRSP and pH ($r = -0.63$), Mg^{2+} ($r = -0.65$), and sum of bases ($r = -0.62$). Similar patterns were observed in other studies, with significant positive correlations between glomalin and total organic carbon, P, and K^+ (Kumar et al., 2018) and significant negative correlations between EE-GRSP and pH (Kumar et al., 2018).

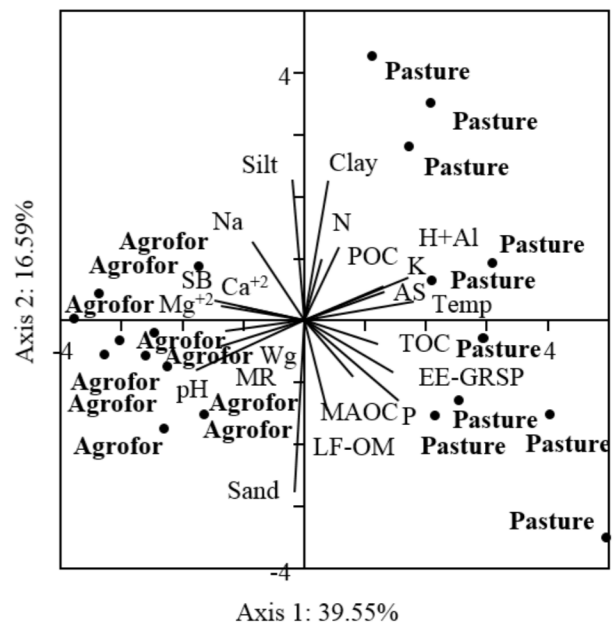
Under conditions of high soil acidity, as occurred in the pasture site, high concentrations of glomalin can be attributed to two factors. The first is the lower degradation rate of glomalin at low soil pH; such a condition is not favorable to the activity of microorganisms that participate in protein decomposition, such as Actinobacteria (Lima et al., 2013). The second refers to the greater root colonization by AMF in low pH soil, a fact that is associated with higher AMF activity and, consequently, greater production of glomalin (Ríos-Ruiz et al., 2019).

Soil aggregate stability (expressed as weighted mean diameter) was highest in the analog agroforestry site (Table 3), probably because of the greater richness of AMF and plant species. As a result, hyphae are more abundant in the soil, contributing physically and biochemically (glomalin production) to soil aggregation (Winagraski et al., 2019). This effect was observed despite the fact that EE-GRSP levels were higher in the pasture site (Table 3). Aggregate stability was also likely associated with the higher abundance and diversity of soil arthropods in the analog agroforest (Camara et al., 2020). This diverse group of organisms comprises ecosystem engineers, whose excrements compose soil aggregates and contribute to stabilization, favoring the regulation of soil porosity, density, and other properties (Coyle et al., 2017). Stable aggregates are crucial for good soil structure. Porous spaces allow root development, air and water circulation, and survival of soil arthropods (Salton et al., 2008).

Soil organic matter fractions (light-fraction organic matter, particulate organic carbon, and mineral-associated organic carbon) did not differ between sites, as assessed by univariate analysis (Table 3). Similarly, principal component analysis showed that these attributes contributed little (factor loadings < 0.6) to the variation between pasture and analog agroforestry sites (Figure 1). Principal components 1 and 2 (PC1 and PC2) accounted for 39.55 and 16.59% of the variance in the dataset, respectively.

Of the variables assessed in this study, those related to soil microbiota (spore abundance, AMF species richness, and EE-GRSP) contributed the most to the distance between sites along the PC1 axis (factor loadings ≥ 0.70). Spore abundance and EE-GRSP were more associated with the pasture site, as were chemical properties (P, K^+ , H + Al) and soil temperature (right upper and lower quadrants) (factor loadings ≥ 0.70).

On the other hand, species richness, moisture, pH, Mg^{2+} , and sum of bases were correlated with the analog agroforestry site (upper and lower left quadrants). Thus, the analysis revealed associations (positive or negative) between AMF-related parameters (richness, diversity, and EE-GRSP) and soil physical and chemical properties and microclimate (water content and temperature), corroborating the results. AMF served as indicators of the effects of 11 years of agroforestry management on soil quality.



MR, mean richness; W_g , gravimetric moisture; POC, particulate organic carbon; SA, spore abundance; Temp, temperature; TOC, total organic carbon; EE-GRSP, easily extractable glomalin-related soil protein; MAOC, mineral-associated organic carbon; LF-OM, light-fraction organic matter; SB, sum of bases.

Figure 1. Principal component analysis of soil chemical, physical, and microbiological properties at the 0-5 cm depth in sites under pasture and analog agroforestry systems (agrofor) in Seropédica, Rio de Janeiro, Brazil.

Conclusions

AMF richness and diversity were influenced differently by the chemical, physical and microclimatic properties of soils under pasture and agroforestry compared with AMF spore abundance. AMF species richness, diversity, and aggregate stability were higher in the analog agroforestry system, where the species *A. leptoticha*, *G. clavisporem*, and *G. glomerulatum* were found to occur exclusively. These parameters were positively associated with pH, sum of bases, and soil moisture. Spore abundance and EE-GRSP levels were higher in the pasture site, attributed to the higher soil

temperature, P, K⁺, and H + Al. EE-GRSP correlated positively with total organic carbon. Physical fractions of organic matter did not vary significantly between the study sites. Aggregate stability was greater in soil under analog agroforest than pasture. Thus, analog agroforest changes the soil physical and microbiological attributes evaluated, and the microbiological attributes are influenced by pH, Mg²⁺, K⁺, SB, P, H+Al, soil moisture and TOC.

Compliance with Ethical Standards

Author contributions: Conceptualization: RC, MGP; Data curation: CFS, RC, GLS, GSA, CSS, HGF; Formal analysis: CFS, RC; Funding acquisition: MGP, EMRS; Investigation: CFS, GLS, GSA, CSS, HGF; Methodology: CFS, MGP, RC; Project administration: RC; Resources: MGP, EMRS; Supervision: RC, MGP; Visualization: CFS, RC, MGP; Writing - original draft: CFS, RC; Writing - review & editing: MGP, EMRS

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