Coffee agroforestry system has effects on microclimate and soil chemical and microbial characteristics

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Research Article

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Abstract

Understanding the effects of agroforestry systems of coffee plants on microclimate, microbial and chemical soil properties, on coffee bean yields and soil quality is important for decision making regarding tree species choice and crop management. The aim of this study was to evaluate the effects of shading of coffee plants (*Coffea arabica*) using tree species: *Croton floribundus, Moringa oleifera* and *Senna macranthera* compared to full sun cultivation, on the interaction of microclimate, soil microbial and chemical properties. The tree species provided a favorable microclimate for coffee crops, as they reduced the maximum temperatures in the hottest periods and provide high minimum temperatures in the cold dawns, with emphasis on the *C. floribundus* and *S. macranthera* species due to the higher shade density. The interaction between microclimate and soil microbial community demonstrates that higher soil moisture rates and lower soil and air thermal amplitudes found under shaded coffee tree agroforestry systems improve soil quality. Coffee agroforestry systems provided positive effects on the soil microbial community due to the effects of shading and the greater amount of phytomass generated by trees, which outcomes greater diversified substrate, improving biological and enzymatic activity and nutrient supply.

Highlights

Shaded coffee provides favourable microclimatic conditions for coffees tree.

Coffee agroforestry systems provide positive effects on the soil microbial.

There is interaction between microclimate and soil properties in shaded coffee.

Introduction

One of the main challenges of contemporary agriculture is to produce without the negative environmental impacts being amplified. Studies show that with Climate change has effects on both the production and the quality of coffee are affected by great impacts, especially the *Coffea arabica* species (Läderach et al., 2017). Agroforestry Systems (AFS) increase energy efficiency and land use, in addition to having the potential to reduce pesticides (Clark and Tilman, 2017) and to provide shading (Baggio et al., 1997) what improve microclimate conditions and deep water drainage compared with unshaded coffee (de Carvalho et al., 2021). The shaded AFS have high potential to sequester carbon (C) and nitrogen (N) from the atmosphere (Chen et al., 2017), which provides greater stocks of organic C (Guo et al., 2020; Zaro et al., 2020)d in the soil. In addition to mitigating climate adversities by maintaining balanced systems (de Carvalho et al., 2021), AFS can bring many other benefits to coffee farming, including increasing the quality of the drink, reducing inputs, stability in production, generating additional income for the farmer, especially in organic agriculture.

Coffee crop reacts differently to shade at the cultivar level (Koutouleas et al., 2022) and AFS have the potential to promote improvements in soil quality, due to factors such as greater biodiversity and tree component, in addition to contributing to the cycling of nutrients and the continued supply of organic

material (Dollinger and Jose, 2018). In the region on the border of Eastern Uganda and Western Kenya, coffee growers integrate trees to provide shade and improve the soil fertility, for example using species capable of fixing nitrogen, but also for the associated cross-functional benefits that meet needs and protect the environment (Sebuliba et al., 2022).

Although coffee field management has significant effects on coffee roots fungal communities structure (Sternhagen et al., 2020), on soil microbial, fauna and food web structure (Lammel et al., 2015; Sauvadet et al., 2019), there are few previous studies on soil microbiota under agroforestry systems, for instance in China using Ginkgo (*Ginkgo biloba*) and tea (*Camellia sinensis*) (Tian et al., 2013) in Brazil using cacao (*Theobroma cacao*) (Zaia et al., 2012)

To our knowledge, there is a lack of information related to the interaction between the microclimate and the soil microbial community under shaded coffee plants AFS conditions. Thus, the aims this study was investigated the interference of tree species on the microclimate, coffee productivity and microbial and chemical attributes of the soil and, as well as their interactions under agroforestry systems of coffee trees.

Material and Methods

2.1 Experimental area

The study was carried out at the experimental station of the Instituto de Desenvolvimento Rural do Paraná – IAPAR-EMATER (IDR–Paraná), in Londrina, PR, Brazil (23º21'. 27S; 51º09'O; 573 m). The soil is classified as Rhodic Eutrudox (Soil Survey Staff, 2014) clayey Tipic Harplorthox, containing in g kg^{-1} 760 of clay, 150 of sand and 90 of sand. The climate according to Köppen is *Cfa* (Alvares et al., 2014) with an average annual temperature of 21°C, with the average of the hottest month (January) of 24°C and the average of the coldest month (June) of 17°C. The average annual rainfall is 1639 mm; the rainiest months are December, January and February and the driest months are June, July and August (IDR-Paraná, 2020).

The long-term field experiment of Arabica coffee (*Coffea arabica* L.) cv IPR 98 in agroforestry systems (AFS) consisted the following treatments: i) full sun (FS), ii) *Moringa oleifera*, iii) *Croton floribundus* and, iv) *Senna macranthera*, in a randomized block design with four replications. In April 2012, one coffee seedling per hole was planted at a spacing of 2.50 m between rows and 0.60 m between plants. In May 2012, with one tree for every 11 coffee plants, in the same line, arranged in quincunx was done. Each plot consisted of dimensions of 19.80 m x 22.50 m and a useful dimension of 10.0 m x 10.20 m. The spacing of trees was 2.50 m between rows and 7.20 m between plants, totalling 555 trees ha^{-1}. Each plot with full sun cultivation had 6666 plants ha^{-1}while each plot in the AFS had 6111 plants ha^{-1}.

In September 2015, eight trees per plot were removed (40%), reducing to 222 plants ha^{-1}. The annual soil fertilization was based on the chemical analysis of the soil using urea, single superphosphate and

potassium chloride, according to the recommendations for the crop (Chaves, 2002). The weeding was done with a brush cutter. For pests and diseases, there was no control.

2.2 Microclimate measurements

Photosynthetically active radiation (PAR) was measured with a Quantum Flux ceptometer (ref. com. Apogee Instruments), in each randomly chosen plot of each treatment. In each plot, four randomly selected plants placed in different rows were evaluated. Measurements were carried out monthly from July to November 2020, with the instrument positioned above the coffee trees, on cloudless days, at 9 am, 12 pm and 3 pm. The daily average of the PAR was calculated which represented the value of the month. The percentage of shading of the AFS was calculated based on the PAR of the full sun treatment.

Air temperatures and relative humidity were monitored from June 2019 to October 2020 using an automatic weather station fixed in the middle of each experimental plot. The sensors were installed in the coffee trees located next to the stations. Air temperature was monitored in three positions: above the coffee tree canopy, at 2 m in height, using a sensor model HMP45C Campbell Scientific®; 1.5 and 0.5 m from the surface, using copper-constant thermocouples, placed in the line of coffee trees between two plants, with the aid of a wooden support and protected from direct exposure to the sun with polyvinyl chloride tubes cut in half lengthwise, 10 cm long and 5 cm in diameter. Leaf temperature was monitored with copper-constant thermocouple sensors, fixed with wooden clamps to the leaf on the abaxial surface of a branch facing the south face of the plant and located in the middle portion of the coffee tree, corresponding to the second pair of leaves of the plant plagiotropic branch from the apex.

Soil temperature was measured using thermocouple sensors buried in the row, between two coffee trees, in the crown projection, at a depth of 0.10 m. The relative humidity of the air above the coffee tree canopy, at 2 m height, was monitored using sensor readings that were taken every second and averaged daily every 15 min and stored on a digital data collector (Campbell Scientific®, Datalogger CR1000).

The ten-day sequential water balance was calculated considering an available water capacity of 100 mm according to Thornthwaite and Mather (1955), using rainfall and air temperature data from the automatic weather stations of Paraná Environmental Technology and Monitoring System (SIMEPAR) located 200 m from the experimental area and the graphs was plotting according to Rolim et al. (1998).

2.3 Soil chemical and microbial analysis

In May 2019, soil sampling was carried out in the projection of the coffee tree canopy at 0.0-0.1 m, 0.1–0.2 m and 0.2–0.4 m layers to determine chemical variables according to Pavan et al. (1992). The soil pH was determined using a soil-to-$CaCl_2$ solution (0.01 mol L^{-1}) ratio of 1:2.5. Potential acidity (H^{+1}+Al^{+3}) was determined using the single-buffer (SMP) method (McLean, 1982). The organic carbon (C_{org}) content in the soil was measured by the Walkley–Black potassium dichromate–sulphuric acid oxidation method (Nelson and Sommers, 1982). Phosphorus (P) and potassium (K^+) were extracted with the Mehlich-1 method, and their concentrations were determined colorimetrically in a UV–visible spectrophotometer and

a flame photometer, respectively. Calcium (Ca^{+2}) and magnesium (Mg^{+2}) were extracted with a non-buffered solution of KCl (1.0 mol L^{-1}) and measured with an atomic absorption spectrophotometer.

In August, 2019 (winter) and in January, 2020 (summer), soil samples were collected at 0-0.1 m layer, between the rows distanced at 0.7 m and 1.0 m apart from the coffee plants trunk, which were kept fresh at temperature of 6 ± 2°C, until the microbial analysis. Soil moisture was determined using an oven at 105 ^{o}C. The soil microbial biomass of C (MBC) was determined by the fumigation-extraction method according to Vance et al. (1987) using a correction factor (Kc) of 0.33 (Sparling and West, 1988). The soil microbial biomass of N (MBN) also was determined the fumigation-extraction method and calculated using 0.54 as conversion factor (Brookes et al., 1985). Basal soil respiration (BSR) was determined in soil samples incubated at 26 ± 2°C for a period of 10 days (Jenkinson, 1976). Soil metabolic quotient (qCO_2) was calculated by dividing basal respiration by the C of the microbial biomass according to Eq. 1.

$$qCO_2 = \frac{BSR}{MBC * 10^{-3}}$$

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qCO_2 = Metabolic quotient (mg C-CO_2 g^{-1} MBC h^{-1})

BSR = basal soil respiration (mg C-CO_2 kg^{-1} soil h^{-1})

MBC = microbial biomass of C (mg C kg^{-1} soil)

The acid phosphatase (AcP) [E.C. 3.1.3.2] at pH 6.5 and alkaline phosphatase (AlP) [E.C. 3.1.3.1] at pH 11.0 activities were determined in field fresh soil samples (Tabatabai, 1994). All microbial (MBC, MBN, BSR, qCO_2, AcP and AlP) data were expressed on a dry soil basis.

2.4 Coffee bean yield

The coffee bean yield was carried out in 2018 and 2019 by harvesting the beans on the cloth and weighing the fruits of each useful plot. The estimated average bi-annual (2018/2019) productivity of processed coffee was calculated by the proportion of the total mass of the fruits of each plot in relation to the respective sample of processed beans.

2.5 Statistical analysis

Data were evaluated for normality by the Shapiro-Wilk test and homogeneity by the Bartlett test. Analysis of variance was performed and the means were compared by Tukey's test ($p \leq 0.05$). Multivariate Principal Component Analysis (PCA) were also performed using RStudio® software.

Results and Discussion

3.1 Microclimate

The monthly minimum temperatures varied according to the height of measurement, it was observed lowest values closer to the ground surface (0.5 m), increasing gradually with height (Fig. 1).

This happened due to the thermal inversion, in which on cold autumn/winter nights, in conditions of atmospheric stability, without clouds, low air humidity and absence of winds, intense radiative losses from the surfaces occur. As the cold air is denser and with continuous cooling, temperatures remain lower in the air layers closer to the soil surface (Caramori et al., 1999; Morais et al., 2006).

The temperature measurement points closer to the canopy showed greater differences between treatments, especially in the coldest months (May to August). However, at the height of 2.0 m the differences between treatments were lesser. This may have occurred due to the limited size of the plots, which may have diluted the effect of the shading of the trees with the penetration of external air inside the evaluated plots. Furthermore, the measurement height of 2.0 m may have been too high to assess the environment inside the plantation, being more subject to interference from outside air. In this sense, the temperature of the leaves and at 0.5 m better represent the cooling that occurs inside the canopy.

The minimum leaf and air temperatures at 0.5 m in the autumn/winter (May-August) months of 2020 were higher in coffee under AFS, compared to full sun, indicating the potential of this cultivation practice to protect plants under conditions of sub-optimal temperatures (Fig. 1). Trees provide this effect because on cold nights, when the surface progressively loses heat, mainly influenced by radiation and conduction processes, their crowns intercept the radiation emitted by the surface, maintaining a warmer environment.

During an episode of weak frost, on August 21 and 22, 2020, it is observed during the cold dawn, that the air temperatures at 0.5 m of the coffee trees cultivated at full sun were lower than those of the coffee trees under AFS, mainly from 00:15 (Fig. 2a).
Comparing the AFS, in coffee trees under the species *C. floribundus*, the highest temperatures were recorded, being this the species that presented the densest canopy (63%). A study during frost nights showed that coffee leaf minimum temperatures were higher when cultivated in a bracatinga (*Mimosa scabrella*) system than in open-air coffee plants (Caramori et al., 1996). In our study, coffee trees cultivated under *C. floribundus* reached a temperature of 3.9 ºC higher than those cultivated under full sun. These results confirm that tree species have an effect of retaining heat inside the canopy, preventing the drop in temperatures and protecting coffee trees in extreme low temperature events. It should be noted that, even if infrequent, just one frost event, depending on the intensity of the phenomenon and the age of the plant, is enough to damage coffee plants, reduce productivity or even cause plant death (Caramori et al., 1996).
Regarding maximum temperatures, a greater effect was observed when temperatures were higher during the spring (Sep-Dec, 2020) and summer (December-March) seasons (Fig. 2b). It was found that the species *S. macranthera* and *C. floribundus*, with leafy canopies and high levels of shading, attenuated the maximum temperatures throughout the period, providing a more suitable environment for coffee

cultivation. On the other hand, coffee trees cultivated in consortium with the species *M. oleifera* presented the highest values of maximum temperatures, even higher than the treatment full sun, in most of the evaluated period. This occurred because this species remained practically leafless, with only 7% of solar radiation intercepted, also associated with the limited and reduced size of the plots, which cause heat transport by convection from the adjacent plots.

The temperatures of coffee leaves on October, 7, 2020 were extremely high during the day, reaching 46 ºC at full sun and shaded with *M. oleifera* (Fig. 2c). In the AFS with *C. floribundus* and *S. macranthera*, softened the temperatures of the coffee leaves up to 7.9 ºC and 7.7 ºC, respectively. Coffee plants do not tolerate high temperatures for prolonged periods, which can cause damage to the leaves and photosynthetic apparatus and, if they occur in the flowering phase, it causes abortion of flower buds and poor flower formation.

The minimum soil temperatures under coffee trees grown in full sun recorded the lowest averages in the cold months, showing a greater thermal amplitude in soil temperatures (Fig. 3a).
Soils under AFS retained more heat, especially in July 2019, when soils under *M. oleifera*, *C. floribundus* and *S. macranthera* had averages of 14.4°C, 15.3°C and 16.6°C, respectively, while the coffee trees in full sun registered an average maximum temperature of 9.1°C. Note that the shading density did not affect soil temperature, since there were no pronounced differences between the shading species.

The soil of coffee trees cultivated at full sun showed the highest values of maximum temperature and highest thermal amplitude during almost the entire period of the evaluation (Fig. 3b). Comparing the coffee plants under AFS, it is noted that the values of maximum soil temperature were proportional to the shading density, thus, the more shaded the coffee plants, the lower the maximum temperatures. The soil under shaded coffee trees had lower average maximum temperatures throughout the period, with values of 20.4°C for *C. floribundus*, followed by the species *S. macranthera* with 21.5°C and *M. oleifera* with 23.3°C. Soils under coffee trees in full sun reached an average maximum temperature of 29.3°C. The large difference in maximum soil temperatures of coffee trees in full sun and under AFS shows the important role of trees in mitigating the coffee microclimate within the soil profile.

The global warming forecast issued by the Intergovernmental Panel on Climate Change (IPCC, 2014) has caused great concern for the coffee agribusiness. The use of afforestation would be one of the agricultural techniques of mitigation for the possible scenario of global warming as highlighted in some studies. For instance, in coffee crops intercropped with pigeon pea (*Cajanus cajan*), leucena (*Leucaena leucocephala*), gliricidia (*Gliricidia sepium*), and macadamia nuts (*Macadamia tetraphylla*) (Coltri et al., 2019), with rubber trees (*Hevea brasiliensis*) (Assad et al., 2020; Zaro et al., 2020), which indicates the potential of this agricultural practice to reduce the effects of global warming on the crop to mitigate high temperatures.

Overall, there was a variability in relative humidity throughout the period, which is associated with the rainfall index, number of days with rain, winds, cloud cover and air temperature (Fig. 4a).

Overall, there was an increasing in the relative humidity of the air as the rainfall index increases. It is noted that throughout the period there were no great variations between treatments, with values of 44% – 45%. Regarding soil moisture, it is observed that in August, 2019 the soils with *M. oleifera* species stood out with greater moisture than the others at both distances. In January, 2020, regardless of the distances (0.7 and 1.0 m) of coffee tree trunk sampling, there was no difference between treatments (Table 2).

In August, 2019, the soil was in water deficit, showing that under intercropped coffee trees the *M. oleifera* species had the potential to retain moisture on the soil surface in periods of drought (Fig. 4b). In contrast, at the beginning of January, 2020, the soil was in excess of water and showed no differences between treatments. Studies with arabica coffee (Morais et al., 2006) and conilon coffee (Guimarães et al., 2014) showed that under AFS there is higher soil water content than in full sun crops.

3.2 Interaction between PAR and coffee bean yields

The species *C. floribundus* and *S. macranthera* with 63% and 58% of shading, respectively, presented higher mean values than *M. oleifera* (7%), due to the denser crowns, with leaves present throughout the year, which vigorously intercepted solar radiation by reflection and absorption, while the latter species had few leaves in the canopy throughout the experimental period. In all treatments, *the* photosynthetically active radiation (PAR) increased as the months progressed from winter to spring, due to terrestrial declination (Data not shown). For each species, there was variability in PAR in the different months due to changes in leaf area and canopy density. There were no major differences in PAR between coffee trees at full sun and under *M. oleifera*, this was maybe due to the small amount of leaves observed in this species, unlike the other trees (Fig. 5a).

In 2017/2018 growing season, coffee beans grown in full sun had the highest yield (3576 kg ha^{-1}), while in the AFS with *M. oleifera* (3006 kg ha^{-1}) and *C. floribundus* (2128 kg ha^{-1}) had intermediate yields without significant differences, however when with *S. macranthera* had the lowest production (1881 kg ha^{-1}) (Fig. 5b). There is a high positive correlation between solar radiation and coffee productivity, which suggests that the amount of radiation that hit coffee trees under denser shading indirectly decreased grain production (Fig. 5c). From an agronomic point of view, AFS with *S. macranthera* and *C. floribundus* should be managed with greater spacing between the trees and/or more pruning to have greater solar radiation in the coffee trees.

In Mexico, shading of coffee plants up to a limit of 50% did not reduce coffee productivity (Soto-Pinto et al., 2001). For small Peruvian producers, Arabica coffee in the shading system with trees shows no negative relationship with economic performance, possibly due to revenue from other products, such as timber, which provides these farmers with an extra source of income (Jezeer et al., 2018). For both fertilizer and weed suppression functions, Staver et al. (2001) suggested that shade tree stratum in coffee plantations should have at least two tree species of contrasting phenology to maintain shade levels within the desirable range of 35 to 65% for most coffee regions. Shading of Arabica coffee trees combined with altitude might improve bean quality (Tolessa et al., 2017). Coffee trees in shaded cropping systems with attenuation of approximately 20% of global solar radiation did not produce negative effects

on coffee production (Caramori et al., 1996; Siles et al., 2010). It is worthwhile to note that in India, there was a positive effect of shade tree diversity on both coffee (*Coffea canephora*) production and quality (Nesper et al., 2017).

3.3 Soil chemical and microbial indicators

Coffee cultivation in full sun had the lowest concentrations soil carbon and the most acidic pH when compared to shaded crops with trees, while under shaded with *C. floribundus* and *M. oleifera* showed the highest values of Ca^{2+} and Mg^{2+} and base saturation, indicating that they are having an efficient management (Table 1).

Table 1
Soil chemical properties in the 0-0.10 m, 0.10–0.20 m and 0.20–0.40 m depth under coffee trees using agroforestry systems (AFS) and full sun.

Treatments	[a]pH	C_{org}	P	K	H + Al	Ca	Mg	BS
		–g kg^{-1}–	–mg kg^{-1}–	——————Cmolc kg^{-1} soil——————				–-%–-
	0-0.10 m depth							
Full sun	5.45	18.65	14,65	0.90	4.45	5.15	2.55	65.67
M. oleifera	5.83	18.75	9.00	0.82	3.76	6.27	3.20	73.10
C. floribundus	5.70	19.91	12.80	0.88	4.22	6.30	3.22	70.85
S. macranthera	5.50	19.21	17.30	0.90	4.78	5.30	2.34	64.00
	0.1–0.20 m depth							
Full sun	5.18	18.50	11.23	0.87	5.17	4.44	2.04	58.60
M. oleifera	5.58	18.24	9.13	0.69	4.39	5.15	2.56	65.52
C. floribundus	5.33	19.04	9.35	0.73	4.54	4.50	2.27	62.12
S. macranthera	5.28	18.85	14.08	0.83	4.61	4.82	2.13	62.74
	0.2–0.40 m depth							
Full sun	4.90	14.80	6.73	0.71	5.46	3.48	1.59	51.38
M. oleifera	5.15	15.13	5.03	0.52	4.64	4.00	1.96	57.86
C. floribundus	5.00	15.61	4.55	0.59	5.29	3.65	1.79	53.21
S. macranthera	5.15	15.41	6.13	0.62	4.44	3.82	1.78	58.27

Note: pH in $CaCl_2$ (0.01 mol L^{-1}); C_{org} (total organic carbon) by Walkley-Black method; P and K^+ (HCl 0.05 mol L^{-1} Mehlich-1; H + Al in SMP; Ca^{2+}, Mg^{2+} and Al in KCl 1 mol L^{-1}; BS (base saturation).

The soil under coffee cultivated with tree shading had higher concentrations of organic carbon (C_{org}), especially the species *C. floribundus* and *S. macranthera*, which increased 3% and 7% in relation to full sun. This result indicates the potential of AFS to increase C_{org}, which allows the supply of nutrients along the coffee tree with the mineralization of organic matter, in addition to maintaining soil moisture.

Overall, microbial biomass C (MBC) values from sampling in August, 2019were higher than those from January 2020. In August 2019, for MBC, there were no significant differences between treatments. In contrast, in January 2020, soil microbial carbon biomass was higher ($p < 0.05$) at 0.7 m than at 1.0 m (Table 2).

Table 2 Effect of agroforestry systems (AFS) and soil sampling in the 0.10 m layer between the coffee tree row, at locations (L) at 0.7 m and at 1.0 m away from the coffee tree trunk on soil microbial biomass C (MBC) and N (MBN) in µg g^{-1} soil; microbial C and N (C/N) ratio, acid phosphatase (AcP) and alkaline phosphatase (AlP) in µg of *p-nitrophenol* (PNP) g^{-1} h^{-1}); basal soil respiration (BSR) in mg de C-CO_2 kg^{-1}solo h^{-1}, metabolic quotient (qCO_2) in µg C-CO_2 μg^{-1} MBC h^{-1} and soil moisture (Moi) in %.

AFS	L (m)	MBC	MBN	C/N	AcP	AlP	BSR	qCO_2	Moi
					August, 2019				
Full sun	0.7	299	41	7.2	357.7	32.69b	0.83a	2.61a	20.0b
	1.0	301	36	8.4	303.5	33.06a	0.43b	1.16b	19.3b
M. oleifera	0.7	321	38	8.4	348.5	35.85a	1.21a	3.50a	24.5a
	1.0	314	32	9.7	338.5	33.88a	1.14a	3.44ab	23.8a
C. floribundus	0.7	343	29	11.8	323.0	32.38b	1.13a	3.61a	19.0b
	1.0	419	36	11.5	334.5	34.49a	1.11a	3.71a	19.6b
S. macranthera	0.7	352	34	10.4	359.0	33.56a	0.71a	2.49a	20.3b
	1.0	308	36	8.4	346.3	33.23a	0.66ab	2.51ab	18.9b
Means	0.7	329	36	9.2	347.1A	33.62A	0.97A	3.05A	21.0
	1.0	335	35	9.5	330.7A	33.66A	0.84A	2.70A	20.4
ANOVA									
AFS		ns	ns		ns	*	*	*	*
Locations (L)		ns	ns		ns	ns	ns	ns	ns
AFS x L		ns	ns		*	*	ns	ns	ns
CV (%)		23.87	11.27		7.08	3.82	38.18	41.18	6.07
					January, 2020				
Full sun	0.7	211A	29	7.4	319.9a	66.88	0.94	4.46a	22.9
	1.0	222A	30	7.3	325.6b	63.15	1.39	6.66a	21.9
M. oleifera	0.7	263A	30	8.7	334.1a	70.26	1.48	5.86a	22.2
	1.0	201A	39	5.10	334.2ab	67.97	0.93	4.71a	22.3
C. floribundus	0.7	265A	29	9.2	336.5a	70.52	1.68	6.50a	23.4
	1.0	197A	30	6.6	358.6ab	69.66	2.35	14.07a	23.4
S. macranthera	0.7	230A	20	11.3	338.2a	69.14	2.38	10.58a	23.7
	1.0	186A	39	4.8	367.1a	72.06	2.33	13.92a	23.6
Means	0.7	242A	27	9.0	332.2B	69.2	1.62	6.85	23.0
	1.0	201B	35	5.8	346.4A	68.2	1.75	9.84	22.8
ANOVA									
AFS		ns	ns		*	ns	ns	*	ns
Locations (L)		*	ns		*	ns	ns	ns	ns
AFS x L		ns	ns		ns	ns	ns	ns	ns
CV (%)		19.77	23.87		5.07	6.2	40.26	41.18	4.28

ns and * indicate non significance and significance by F ($p<0.05$), respectively. Different lowercase within each soil sampling location (0.7 or 1.0 m) and different capital letters among different soil sampling locations in the same AFS indicate differences by Tukey's test ($p=0.05$). C.V = Coefficient of variation.

This was possibly due to the greater proximity of the root system and also to the greater self-shading of the coffee trees, whose milder temperature condition favoured microbial growth. In both season, winter (August, 2019) and summer (January, 2020), the microbial biomass of N was not altered by shading or by the soil sampling site (Table 2).
In previous study in this same clayey soil, the microbial carbon biomass was greater in the projection of the coffee tree canopy than in the inter-row of the plants (Andrade et al., 1995). Coffee trees cultivated in full sun showed lower amounts of microbial biomass C when compared to shade cultivation (Guimarães et al., 2017). However, for the coffee-araucaria agroforestry system it did not affect the distribution of the microbial groups, microbial biomass carbon, microbial activity and metabolic quotient in soil (Melloni et al., 2018). In the agroforestry system, the tree provided soil protection keeping the soil temperature more stable and at milder and more suitable levels for the growth of microorganisms in the soil.

Overall, basal soil respiration (BSR) and metabolic quotient (qCO_2) at both sampling locations of (0.7 and 1.0 m) were higher in January 2020 than in August 2019 (Table 2). This increase might occur due to the higher temperature and rainfall rates that favour a higher phytomass in the system and consequently higher BSR and qCO_2. In August 2019, for BSR, there was only a significant difference at location of 1.0 m away from the coffee tree trunk, in which the lowest value was in full sun. In January 2020, regardless of the sampling site (0.7 m or 1.0 m), there was no difference in BSR. Possibly, there was the influence of weeds in the coffee inter-row in all treatments which provides greater nutrient cycling through the addition of organic material, greater protection of the soil from solar radiation, increasing biological activity and soil resilience. In organic coffee cropping systems, soil microbial activity and qCO_2 in summer were higher due to higher temperatures and precipitation (Pimentel et al., 2011).

In August 2019, for acid phosphatase activity, there was no difference with shading of the coffee tree. while in January 2020, at a distance of 1.0 m, this enzyme had higher activity in all shaded coffee crops than in the soil in full sun. In January, 2020, regardless of the coffee shading treatment, acid phosphatase activity showed lower rates in soil samples at 0.7 m than at 1.0 m from the coffee tree trunk. In August, 2019, the alkaline phosphatase activity had lower values at 0.7 m in the full sun and with *C. floribundus* (Table 2). Overall, coffee AFSs positively influenced soil microbial activity, improving soil characteristics, as the increase in organic residues favoured the diversity and functional microbial structure.

3.4 Soil chemical, microbial and microclimate correlation

In August, 2019, in the PCA correlation plane between chemical and microbial variables, treatments with *C. floribundus* and *M. oleifera* showed high values of the variables that most contributed to PC1. While in January, 2020 soil sampling, the first two PCs show the position of AFS with *S. macranthera* in the negative coordinate of the x and y axes, which indicates a lower correlation of the variables that contributed most to the PC2. Most of the microbial variables grouped in the quadrant in which it was placed the coffee AFS with *C. floribundus* (Fig. 6a).

In January, 2020, the hottest and rainy season, a greater correlation between the variables in the treatment with *C. floribundus* was also observed, with the acid phosphatase enzyme variables (0.7 m and 1.0 m) having a strong correlation with the C_{org} variable in a more isolated way, different from that observed in the dry season, in August, 2019 (Fig. 6b). Coffee shaded with *C. floribundus* have more favourable conditions for the development of soil microbial community possibly because they promote a greater contribution of organic material deposited on the soil, in addition to providing plant substrates in different degrees of decomposition.

In August, 2019 sampling, in the correlation between the microclimatic and microbial variables, the first two PCs of the analysis are presented, the *M. oleifera* and *C. floribundus* AFS presented high values of the variables that most contributed to the PC1. The systems in full sun and AFS with *S. Macranthera* showed low values of the variables of greater availability for PC1, that is, less interaction with air maximum temperature; basal soil respiration at 0.7 and 1.0 m; qCO2 at 0.7 and 1.0 m; air minimum temperature and acid phosphatase enzyme at 1.0 m(Fig. 6c).

The microbial variables most correlated with the 1st axis were, in descending order, qCO2 at 1.0 m; acid phosphatase enzyme at 0.7 m; basal soil respiration at 1.0 m; MBC at 1.0 m; MBN at 0.7 m and qCO_2 at 0.7 m. In the second axis, the MBN at 1.0 m stood out. The microclimate variables that most correlated with the 1st axis were, in descending order, air maximum temperature, soil maximum temperature and air average temperature. For the 2nd axis, air maximum temperature at 2.0 m stood out. The position of the treatments, in full sun and with *S. Macranthera*, in the negative coordinate of the x and y axes indicates a lower correlation of the variables that most contributed to the PC2 obtained in the PCA. However, it can be observed that the variables air minimum temperature at 2.0 m, air average temperature at 2.0 m, soil moisture at 0.7 and 1.0 m, and MBN at 1.0 m were influenced by these treatments in the driest and coldest season, in August 2019 (Fig. 6c).

In January 2020, the position of the AFS with *S. macranthera* and *C. floribundus* in the negative coordinate of the x- and y-axes indicates a lower correlation of the variables that most contributed to the PC2 obtained in the analysis. Most of the microbial variables that correlated with the 1st axis was in descending order, acid phosphatase at 0.7 m; basal soil respiration at 0.7 m and 1.0 m; and MBC at 1.0 m. In the second axis, MBN at 0.7 m stood out. The microclimate variables that most correlated with the 1st axis were in descending order air average temperature at 2.0 m, soil minimum temperature, and coffee leaf minimum temperature. For the 2nd axis, air maximum temperature stood out (Fig. 6d). The interaction between microclimate and soil microbial community demonstrates that higher soil moisture rates and lower soil and air thermal amplitudes found in agroforestry systems can improve better soil quality.

Conclusion

In both winter and summer seasons, there is interaction between microclimate factors, soil chemical and microbial features under shaded coffee tree agroforestry systems. The shaded agroforestry coffee

systems, especially with the species *C. floribundus* and *S. macranthera*, positively influences the soil microbial community, due to the highest of shading density and the greater amount of phytomass generated, which results in a greater amount of diversified substrate for the growth of microbial biomass and enzymatic activity.

Declarations

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References

1. Alvares, C. A., J. L. Stape, P. C. Sentelhas, J. L. de Moraes Gonçalves and G. Sparovek (2014). Köppen's climate classification map for Brazil. Meteorologische Zeitschrift **22**(6): 711-728. https://doi.org/10.1127/0941-2948/2013/0507.
2. Andrade, D. S., A. C. Filho, M. A. Pavan, E. L. Balota and J. C. D. Chaves (1995). Atividade microbiana em função da calagem em um solo cultivado com cafeeiro Rev Bras Ci Solo **19**: 191-196.
3. Assad, E. D., L. C. Costa, S. Martins, M. Calmon, R. Feltran-Barbieri, M. Campanili and C. A. Nobre (2020). Role of ABC plan and planaveg in the adaptation of brazilian agriculture to climate change. Working Paper.
4. Baggio, A. J., P. H. Caramori, A. Androcioli Filho and L. Montoya (1997). Productivity of Southern Brazilian coffee plantations shaded by different stockings of *Grevillea robusta*. Agrofor Syst **37**(2): 111-120. https://doi.org/10.1023/A:1005814907546.
5. Brookes, P. C., J. F. Kragt, D. S. Powlson and D. S. Jenkinson (1985). Chloroform fumigation and the release of soil nitrogen: The effects of fumigation time and temperature. Soil Biol Biochem **17**(6): 831-835. http://dx.doi.org/10.1016/0038-0717(85)90143-9.
6. Caramori, P. H., A. Androcioli Filho and A. C. Leal (1996). Coffee shade with *Mimosa scabrella* Benth. for frost protection in southern Brazil. Agrofor Syst **33**(3): 205-214. https://doi.org/10.1007/BF00055423.
7. Caramori, P. H., A. C. Leal and H. Morais (1999). Temporary shading of young coffee plantations with pigeonpea (*Cajanus cajan*) for frost protection in southern Brazil. Rev. Bras. de Meteorol **7**(2): 195-200.
8. Chaves, J. C. D. (2002). Manejo do solo: adubação e calagem, antes e após a implantação da lavoura cafeeira. Londrina, IAPAR.

9. Chen, C., W. Liu, X. Jiang and J. Wu (2017). Effects of rubber-based agroforestry systems on soil aggregation and associated soil organic carbon: Implications for land use. Geoderma **299**: 13-24. https://doi.org/10.1016/j.geoderma.2017.03.021.
10. Clark, M. and D. Tilman (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ Res Lett **12**(6): 064016. https://doi.org/10.1088/1748-9326/aa6cd5.
11. Coltri, P. P., H. S. Pinto, R. R. d. V. Gonçalves, J. Zullo Junior and V. Dubreuil (2019). Low levels of shade and climate change adaptation of *Arabica coffee* in southeastern Brazil. Heliyon **5**(2): e01263. https://doi.org/10.1016/j.heliyon.2019.e01263.
12. de Carvalho, A. F., E. I. Fernandes-Filho, M. Daher, L. d. C. Gomes, I. M. Cardoso, R. B. A. Fernandes and C. E. G. R. Schaefer (2021). Microclimate and soil and water loss in shaded and unshaded agroforestry coffee systems. Agrofor Syst. **95**(1): 119-134. https://doi.org/10.1007/s10457-020-00567-6.
13. Dollinger, J. and S. Jose (2018). Agroforestry for soil health. Agrofor Syst **92**(2): 213-219. https://doi.org/10.1007/s10457-018-0223-9.
14. Guimarães, G. P., D. S. E. Mendonça, R. R. Passos and F. V. Andrade (2014). Soil aggregation and organic carbono of Oxisols under coffee in agroforestry systems. Rev Bras Cienc Solo **38**(1): 278-287. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-06832014000100028.
15. Guimarães, N. d. F., A. d. S. Gallo, A. Fontanetti, S. P. Meneghin, M. D. B. d. Souza, K. P. G. Morinigo and R. F. d. Silva (2017). Biomass and microbial activity in different systems of coffee cultivation (in Portuguese) Rev Cienc Agrar **40**(1). https://doi.org/10.19084/RCA16041.
16. Guo, J., B. Wang, G. Wang, Y. Wu and F. Cao (2020). Afforestation and agroforestry enhance soil nutrient status and carbon sequestration capacity in eastern China. **31**(3): 392-403. https://doi.org/10.1002/ldr.3457.
17. IDR-Paraná, I. d. D. R. D. P.-I.-E.-. (2020). "Médias históricas em estações do IAPAR." Retrieved May, 16, 2021, 2021, from http://www.idrparana.pr.gov.br/Pagina/Dados-Meteorologicos-Historicos-e-Atuais.
18. IPCC, I. P. o. C. C. (2014). AR4 GCM data.
19. Jenkinson, D. S. (1976). The effects of biocidal treatments on metabolism in soil-IV. The decomposition of fumigated organisms in soil. Soil Biol Biochem **8**: 203-208. http://dx.doi.org/10.1016/0038-0717(76)90005-5.
20. Jezeer, R. E., M. J. Santos, R. G. A. Boot, M. Junginger and P. A. Verweij (2018). Effects of shade and input management on economic performance of small-scale Peruvian coffee systems. Agric Syst **162**: 179-190. https://doi.org/10.1016/j.agsy.2018.01.014.
21. Koutouleas, A., T. Sarzynski, B. Bertrand, M. Bordeaux, A. S. Bosselmann, C. Campa, H. Etienne, N. Turreira-García, S. Léran, B. Markussen, P. Marraccini, J. C. Ramalho, P. Vaast and A. Ræbild (2022). Shade effects on yield across different Coffea arabica cultivars — how much is too much? A meta-analysis. Agron Sustain Dev **42**(4): 55. https://doi.org/10.1007/s13593-022-00788-2.

22. Läderach, P., J. Ramirez–Villegas, C. Navarro-Racines, C. Zelaya, A. Martinez–Valle and A. Jarvis (2017). Climate change adaptation of coffee production in space and time. Clim Change **141**(1): 47-62. https://doi.org/10.1007/s10584-016-1788-9.
23. Lammel, D. R., L. C. B. Azevedo, A. M. Paula, R. D. Armas, D. Baretta and E. J. B. N. Cardoso (2015). Microbiological and faunal soil attributes of coffee cultivation under different management systems in Brazil. Braz J Biol **75**: 894-905. https://doi.org/10.1590/1519-6984.02414
24. McLean, E. O. (1982). Soil pH and lime requirement. Methods of Soil Analysis A. L. Page, R. H. Miller and D. Keeney. Madison, American Society of Agronomy. **2:** 199-234.
25. Melloni, R., N. R. Costa, E. G. P. Melloni, M. C. S. Lemes, M. I. N. Alvarenga and J. N. Neto (2018). Agroforestry system coffee-araucaria and its effect on soil microbiota and their processes. Cienc Florest **28**(2): 784-795. https://doi.org/10.5902/1980509832392.
26. Morais, H., P. H. Caramori, A. M. d. A. Ribeiro, J. C. Gomes and M. S. Koguishi (2006). Microclimatic characterization and productivity of coffee plants grown under shade of *Pigeon pea* in Southern Brazil. Pesq Agropec Bras **41**(5): 763-770. http://dx.doi.org/10.1590/S0100-204X2006000500007.
27. Nelson, D. W. and L. E. Sommers (1982). Total carbon, organic carbon and organic matter Methods of Soil Analysis. A. L. Page, R. H. Miller and D. Keeney. Madison, American Society of Agronomy. **2:** 539-594.
28. Nesper, M., C. Kueffer, S. Krishnan, C. G. Kushalappa and J. Ghazoul (2017). Shade tree diversity enhances coffee production and quality in agroforestry systems in the Western Ghats. Agric Ecosyst Environ **247**: 172-181. https://doi.org/10.1016/j.agee.2017.06.024.
29. Pavan, M. A., M. F. M. Bloch, H. C. Zempulski, M. Miyazawa and D. C. Zocoler (1992). Manual de Análise Química de Solo e Controle de Qualidade. Circular. Londrina, PR, Instituto Agronômico do Paraná -.IAPAR**:** 40
30. Pimentel, M. S., H. De-Polli, A. M. d. Aquino, M. E. F. Correia and J. R. C. Rouws (2011). Bioindicators of soil quality in coffee organic cultivation systems. Pesq Agropec Bras **46**(5): 546-553.
31. Rolim, G. d. S., P. C. Sentelhas and V. Barbieri (1998). Planilhas no ambiente EXCEL TM para os cálculos de balanços hídricos: normal, sequencial, de cultura e de produtividade real e potencial. Rev. Bras. Agrometeorol **6**: 133-137.
32. Sauvadet, M., K. V. den Meersche, C. Allinne, F. Gay, E. de Melo Virginio Filho, M. Chauvat, T. Becquer, P. Tixier and J.-M. Harmand (2019). Shade trees have higher impact on soil nutrient availability and food web in organic than conventional coffee agroforestry. Sci Total Environ **649**: 1065-1074. https://doi.org/10.1016/j.scitotenv.2018.08.291.
33. Sebuliba, E., J. G. M. Majaliwa, P. Isubikalu, N. Turyahabwe, G. Eilu and A. Ekwamu (2022). Characteristics of shade trees used under Arabica coffee agroforestry systems in Mount Elgon Region, Eastern Uganda. Agrofor Syst **96**(1): 65-77. https://doi.org/10.1007/s10457-021-00688-6.
34. Siles, P., J.-M. Harmand and P. Vaast (2010). Effects of *Inga densiflora* on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica. Agrofor Syst **78**(3): 269-286. https://doi.org/10.1007/s10457-009-9241-y.

35. Soil Survey Staff, U. S. D. o. A. U. (2014). Keys to Soil Taxonomy. Washington, DC, United States Department of Agriculture Natural Resources Conservation Service.
36. Soto-Pinto, L., Y. Romero-Alvarado, J. Caballero-Nieto and G. Segura Warnholtz (2001). Woody plant diversity and structure of shade-grown-coffee plantations in northern Chiapas, Mexico. Revista de biologia tropical **49**(3-4): 977-987.
37. Sparling, G. P. and A. W. West (1988). A direct extraction method to estimate soil microbial C: calibration in situ using microbial respiration and ^{14}C labelled cells. Soil Biol Biochem **20**: 337-343. https://doi.org/10.1016/0038-0717.
38. Staver, C., F. Guharay, D. Monterroso and R. G. Muschler (2001). Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. Agrofor Syst **53**(2): 151-170. https://doi.org/10.1023/A:1013372403359.
39. Sternhagen, E. C., K. L. Black, E. D. L. Hartmann, W. G. Shivega, P. G. Johnson, R. D. McGlynn, L. C. Schmaltz, R. J. Asheim Keller, S. N. Vink and L. Aldrich-Wolfe (2020). Contrasting patterns of functional diversity in coffee root fungal communities associated with organic and conventionally managed fields. Appl Environ Microbiol **86**(11): e00052-00020. https://doi.org/10.1128/AEM.00052-20.
40. Tabatabai, M. A. (1994). Soil Enzymes. Methods of Soil Analysis: Part 2 Microbiological and Biochemical Properties. R.W. Weaver, S. Angle, P. Bottomley et al., SSSA Book Series. **2:** 775-833. https://doi.org/10.2136/sssabookser5.2.c37.
41. Tian, Y., F. Cao and G. Wang (2013). Soil microbiological properties and enzyme activity in Ginkgo–tea agroforestry compared with monoculture. Agroforestry Systems **87**(5): 1201-1210. https://doi.org/10.1007/s10457-013-9630-0.
42. Tolessa, K., J. D'heer, L. Duchateau and P. Boeckx (2017). Influence of growing altitude, shade and harvest period on quality and biochemical composition of Ethiopian specialty coffee. J Sci Food Agric **97**(9): 2849-2857. https://doi.org/10.1002/jsfa.8114.
43. Vance, E. D., P. C. Brookes and D. S. Jenkinson (1987). An extraction method for measuring soil microbial biomass Soil Biol Biochem **19**(6): 703-707. https://doi.org/10.1016/0038-0717(87)90052-6.
44. Zaia, F. C., A. C. Gama-Rodrigues, E. F. Gama-Rodrigues, M. K. S. Moço, A. G. Fontes, R. C. R. Machado and V. C. Baligar (2012). Carbon, nitrogen, organic phosphorus, microbial biomass and N mineralization in soils under cacao agroforestry systems in Bahia, Brazil. Agroforestry Systems **86**(2): 197-212. https://doi.org/10.1007/s10457-012-9550-4.
45. Zaro, G. C., P. H. Caramori, G. M. Yada Junior, C. R. Sanquetta, A. A. Filho, A. L. P. Nunes, C. E. C. Prete and P. Voroney (2020). Carbon sequestration in an agroforestry system of coffee with rubber trees compared to open-grown coffee in southern Brazil. Agrofor Syst **94**(3): 799-809. https://doi.org/10.1007/s10457-019-00450-z.

Figures

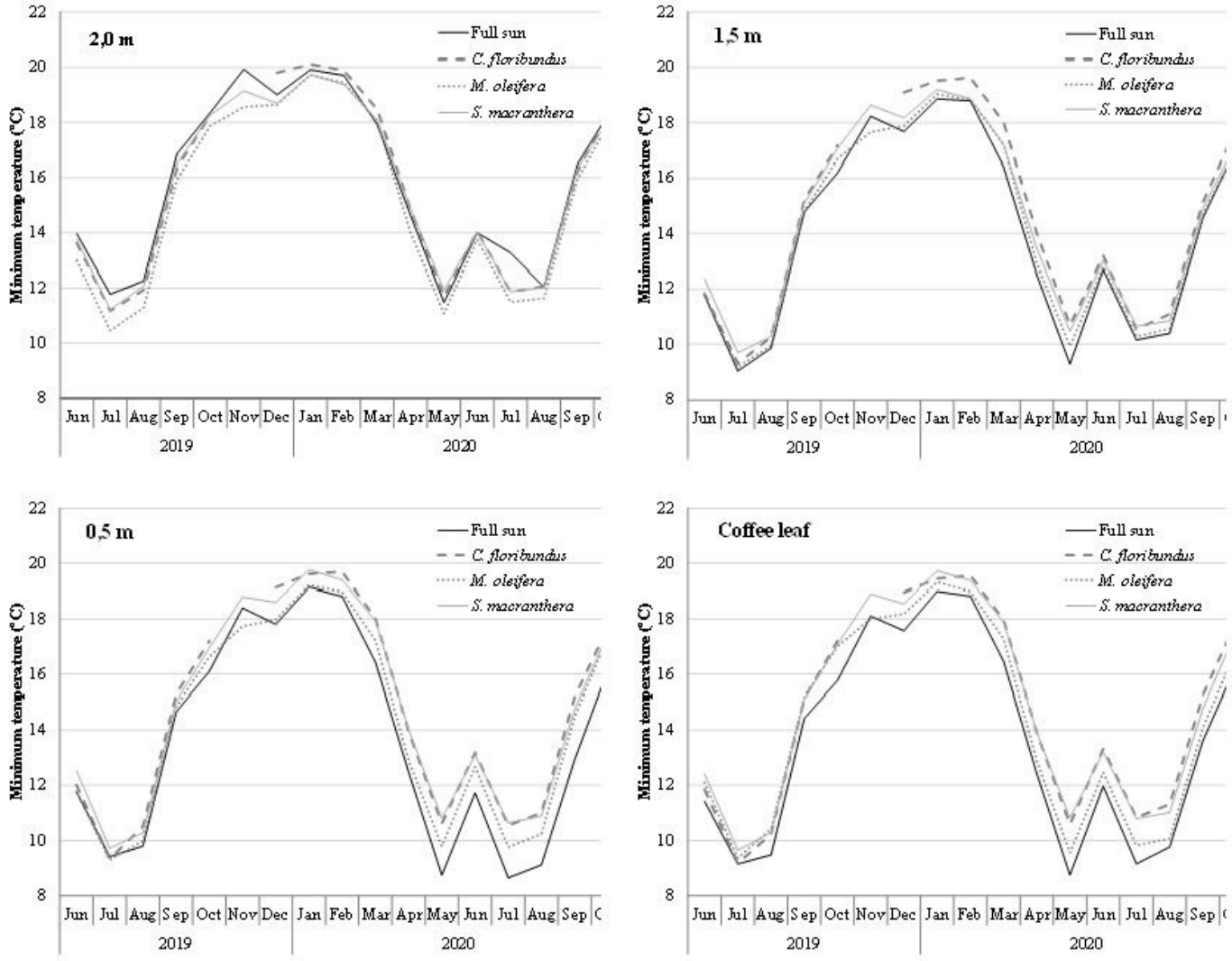

Figure 1

Monthly minimum temperature at height of 2.0 m, 1.5 m and 0.5 m and at leaf height in coffee trees in agroforestry systems with tree and full sun. From June 2019 to October 2020.

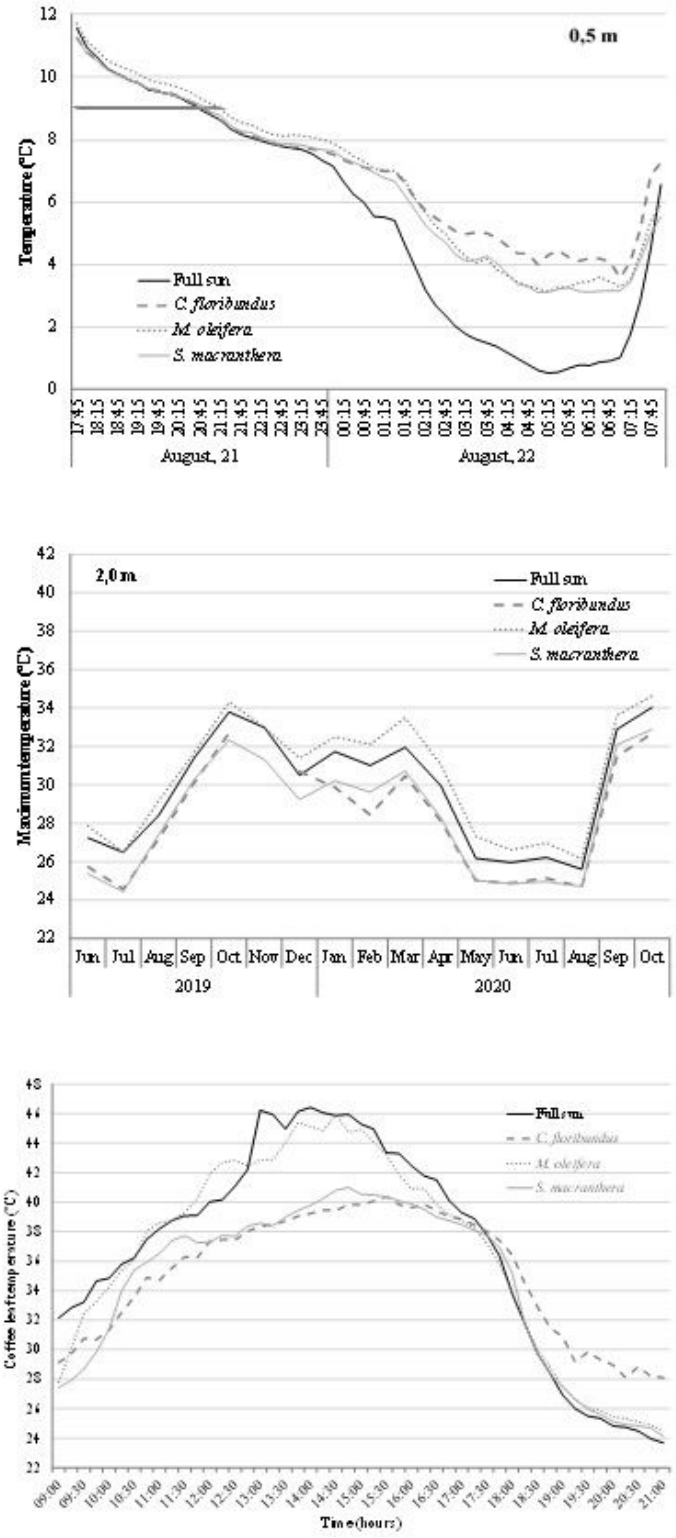

Figure 2

Effects of coffee agroforestry systems with tree and full sun on: **a)**air temperature at 0.5 m above soil surface. Measures taken on August 21, 2019 and August 22, 2019; **b)** mean monthly maximum air temperature at 2.0 m in coffee trees from June 2019 to October 2020 and **c)** coffee leaf temperature in October 7, 2020.

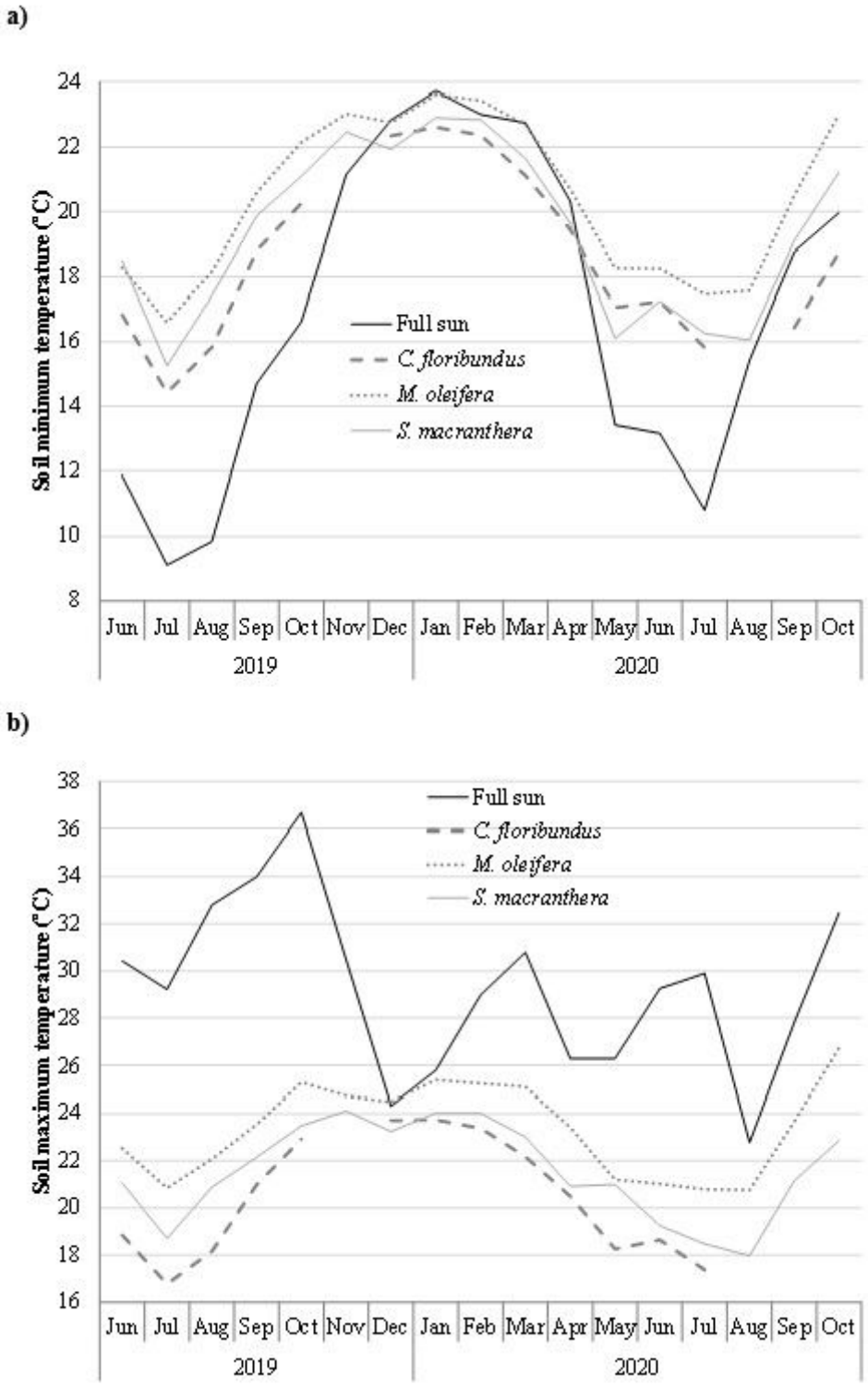

Figure 3

Monthly average of soil temperature in the 0.1 m layer under coffee trees agroforestry systems and in full sun from June 2019 to October 2020. **a)**minimum temperature and **b)** maximum temperature.

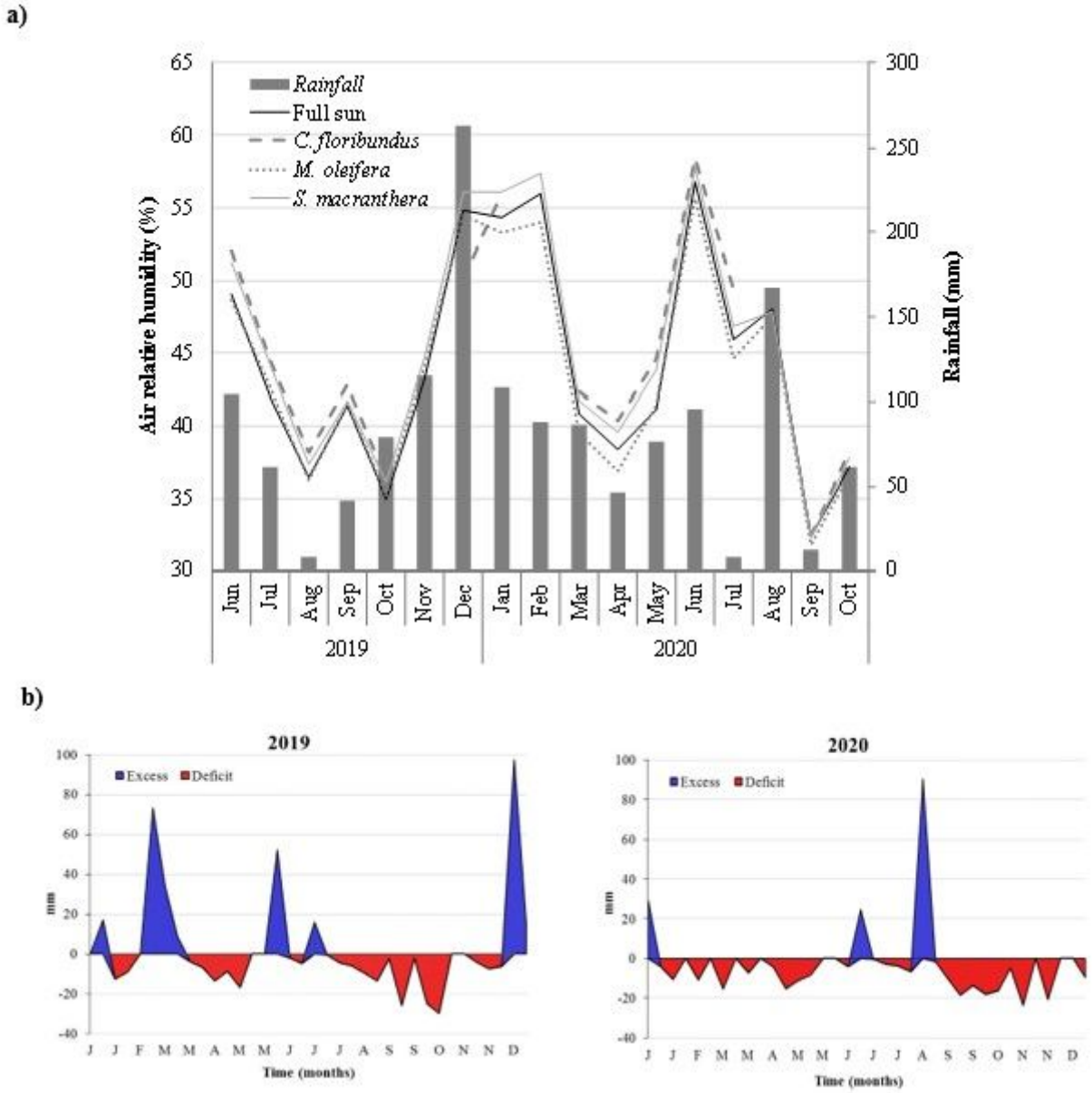

Figure 4

Effects of coffee agroforestry systems with tree and full sun on: **a)**monthly average air relative humidity at 2.0 m from June 2019 to September 2020 and, **b)** ten-year soil water balance in the experimental area of coffee trees agroforestry systems and in full sun.

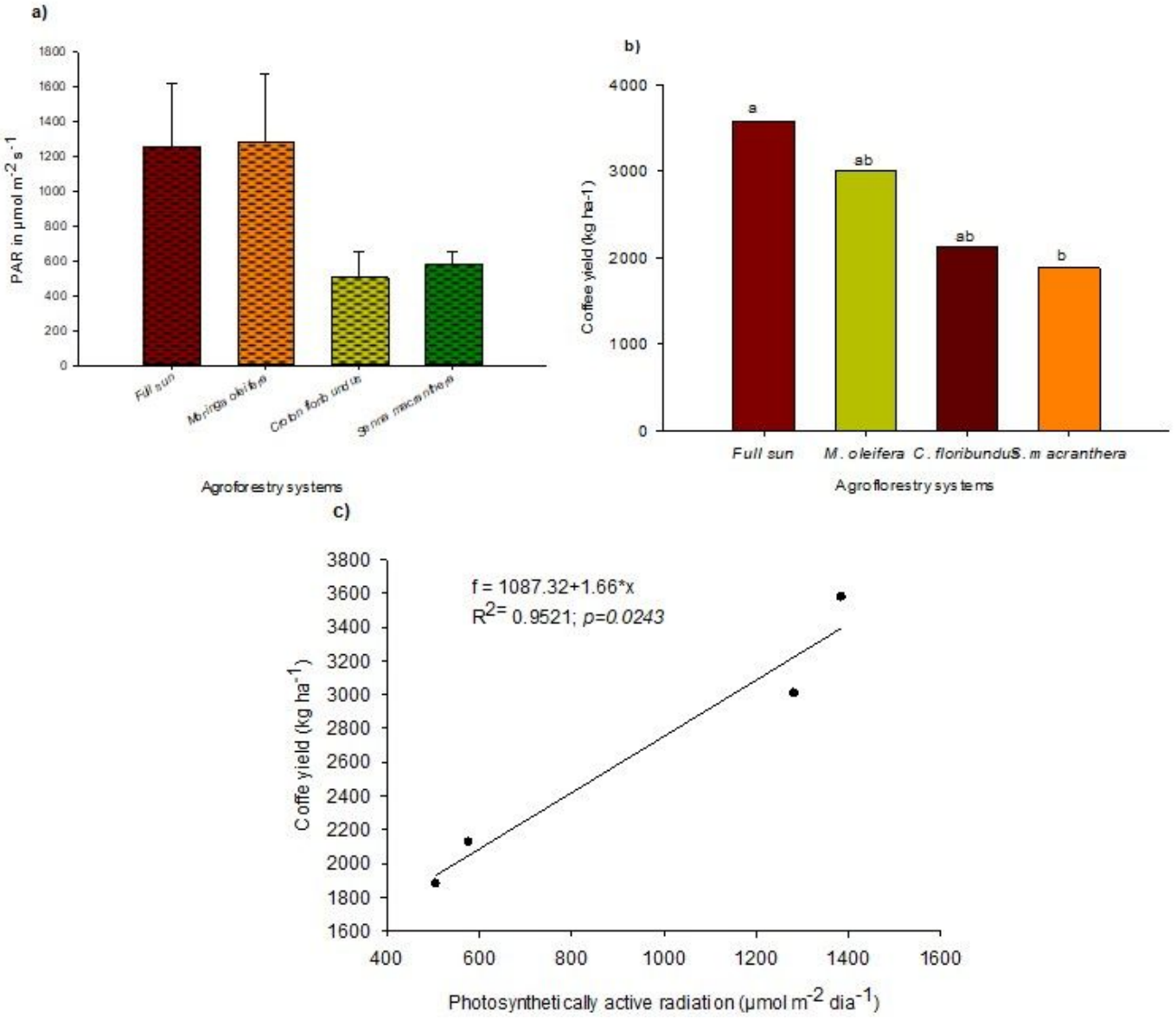

Figure 5

Effect of coffee tree agroforestry systems on: **a)** photosynthetically active radiation (PAR), **b)** coffee bean yields (means of the 2018 and 2019 harvests), and **c)** correlation between coffee bean yields in kg ha^{-1} and PAR in µmol m^{-2} s^{-1}. Bars are means from July to November 2020. Equal letters on the bars do not differ from each other by the Tukey's test (p=0.05).

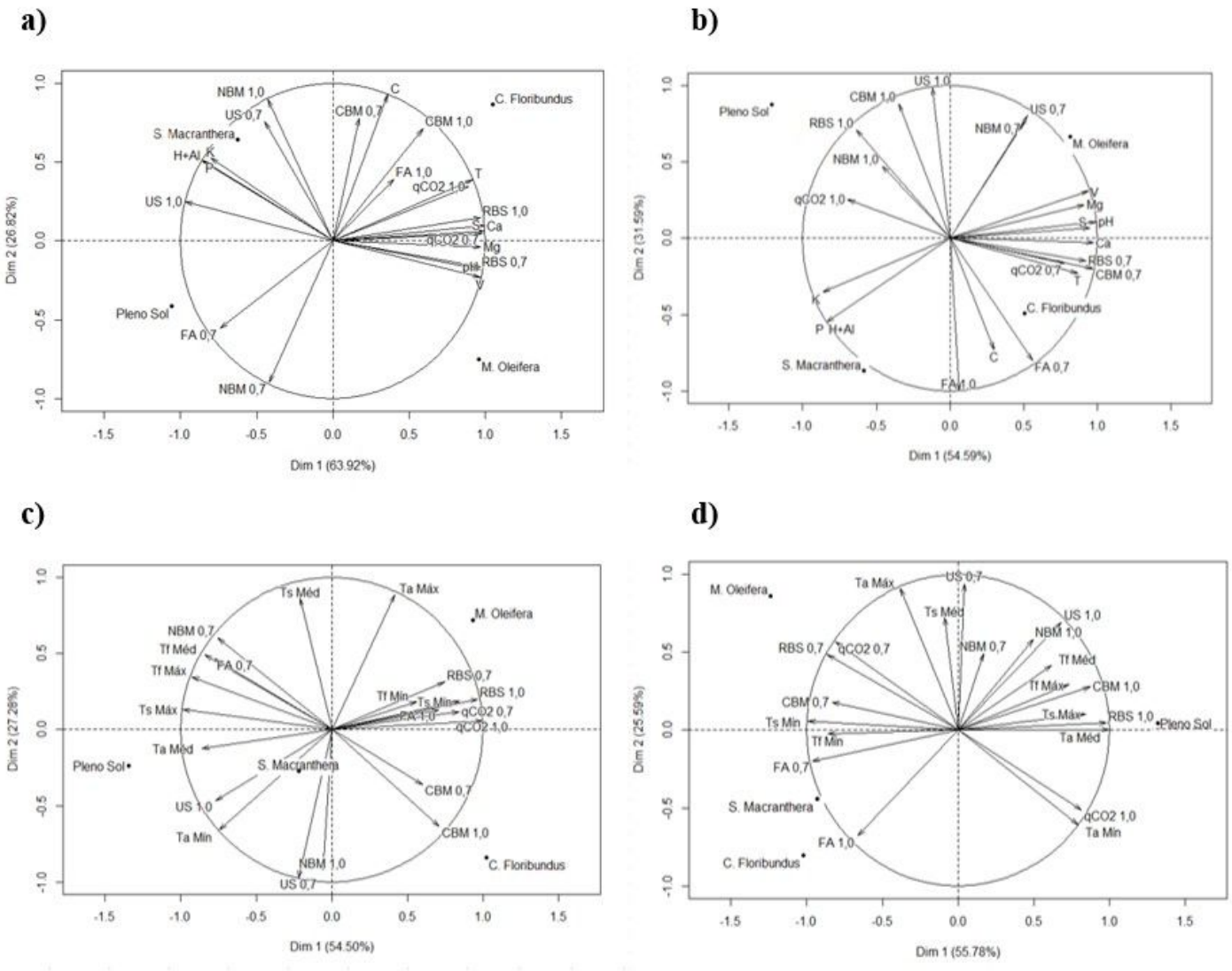

Figure 6

Principal component analysis (PCA) of soil microbial and chemical variables at 0.7 m and 1.0 m from coffee tree trunk in agroforestry systems coffee and full sun: **a)** August, 2019; **b)** January, 2020 and of soil microbial and microclimate variables: **c)** August, 2019 and **d)** January, 2020.

Legend: Pleno sol=full sun; (0.7, 1.0)= location of soil sampling; CBM=microbial biomass of C; NBM= microbial biomass of N; FA=acid phosphatase enzyme; RBS=basal soil respiration; qCO_2=metabolic quotient; US=soil moisture; P: phosphorus; C=organic carbon; Ca=calcium; Mg=magnesium; K=potassium; S= base sum; T= cation exchange capacity; V=base saturation. TaMax, TaMéd and TaMín= air maximum temperature, average temperature and minimum temperature, respectively, at 2.0 m; TfMáx, TfMéd and TfMín=maximum temperature, average temperature and minimum temperature, respectively, of coffee leaf; TsMáx, TsMed and TsMín=soil maximum temperature, soil average temperature and soil minimum temperature, respectively, in the 0.1 m layer.