Bioindicators of soil quality in coffee organic cultivation systems

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Abstract – The objective of this work was to assess the effect of different coffee organic cultivation systems on chemical and biological soil characteristics, in different seasons of the year. The following systems were evaluated: coffee intercropped with one (CJ1), two (CJ2) or three (CJ3) pigeon pea (*Cajanus cajan*) alleys; coffee planted under full sun (CS); area planted with sweet pepper and snap bean in a conventional tillage system (AC); and secondary forest area (FFR). Row spacing in CJ1, CJ2, CJ3 and CS was 2.0x1.0, 2.8x1.0, 3.6x1.0, and 2.8x1.0 m, respectively. Soil samples were collected at 10-cm depth, during the four seasons of the year. The results were subjected to analysis of variance, principal component analysis, and redundancy analysis. There was an increase in edaphic macrofauna, soil basal respiration, and microbial quotient in the summer. Total macrofauna density was greater in CJ2 followed by CJ3, CS, CJ1, AC and FFR; *Coleoptera*, *Formicidae*, and *Isoptera* were the most abundant groups. There are no significant differences among the areas for soil basal respiration, and the metabolic quotient is higher in CJ1, CJ3, and FFR. Microbial biomass carbon and the contents of K, pH, Ca+Mg, and P show greater values in AC.

Index terms: *Cajanus cajan*, *Coffea arabica*, edaphic macrofauna, metabolic quotient, shading, soil microbial biomass.

Bioindicadores de qualidade do solo em sistemas de cultivo orgânico de café

Resumo – O objetivo deste trabalho foi avaliar o efeito de diferentes sistemas de cultivo orgânico do cafeeiro sobre as características químicas e biológicas do solo, em diferentes estações do ano. Foram avaliados os sistemas: consórcio do cafeeiro com uma (CJ1), duas (CJ2) ou três (CJ3) linhas de guandu (*Cajanus cajan*); plantio do café a pleno sol (CS); área de plantio convencional de pimentão e feijão-vagem (AC); e área de floresta secundária (AFS). O espaçamento entre linhas em CJ1, CJ2, CJ3 e CS foi de 2,0x1,0, 2,8x1,0, 3,6x1,0, e 2,8x1,0 m, respectivamente. O solo foi amostrado na profundidade de 10 cm, nas quatro estações do ano. Os resultados foram submetidos à análise de variância, à análise de componentes principais e à análise de redundância. Houve aumento na macrofauna edáfica, na respiração basal do solo e no quociente microbiano, no verão. A densidade total da macrofauna foi maior em CJ2 seguidos por CJ3, CS, CJ1, AC e FFR; *Coleoptera*, *Formicidae* e *Isoptera* foram os grupos mais abundantes. Não há diferenças significativas entre as áreas quanto a respiração basal do solo, e o quociente metabólico é maior em CJ1, CJ3 e AFS. O carbono da biomassa microbiana e os teores de K, pH, Ca+Mg e P são maiores em AC.

Termos para indexação: *Cajanus cajan*, *Coffea arabica*, macrofauna edáfica, quociente metabólico, sombreamento, biomassa microbiana do solo.

Introduction

Coffee (*Coffea arabica* L.) crops are highly important for Brazilian agribusiness. In 2008, nearly two and a half million tons of coffee beans were harvested in Brazil, an increase of 16% in comparison to 2007 (Instituto Brasileiro de Geografia e Estatística, 2008). Coffee originally came from the deciduous forests in Ethiopia and Sudan, and has been associated with understory conditions. Latin American countries, such as Colombia, Costa Rica, Ecuador, and Guatemala, have been using shading as a technique for a more rational and conservationist use of the soil in coffee areas (Aquino et al., 2008a; Morais et al., 2009), in accordance with the precepts of organic agriculture sustainability.

The shading technique generates additional income for the farmer and maintains a balanced system by preserving biodiversity, soil, water resources, and carbon (Morais et al., 2009). The use of cover crops is relevant for maintaining and improving the chemical, physical, and biological characteristics of the soil, allowing for the conservation of more balanced environments (Perin et al., 2003; Paciullo et al., 2007).

Rangel et al. (2008), while assessing the input of plant residues in coffee crops, observed a decrease in soil loss through erosion and an increase in soil organic carbon due to less soil tilling. Beer (1998) reported soil accumulation of up to 14 Mg ha^{-1} per year of residues originating from fallen leaves and pruned material, in dense coffee cropping. Aquino et al. (2008a), who evaluated earthworm populations in agroforestry systems with conventional and organic coffee crops, found lower earthworm density under full sun and that shading from *Erythrina* favored earthworm diversity. Therefore, conservationist practices, including better quality organic matter input, can result in greater earthworm abundance (Ortiz-Ceballos & Fragoso, 2004).

Temperature, nutrient availability, and nitrogen (N) supply are related to soil biological activity, as described by Cerri & Volkoff (1988). The study of associations between biological and chemical attributes is important for understanding the best management practices in order to improve soil quality. Moreover, soil macrofauna can act as an indicator of environment-soil changes (Lavelle, 1997), and microbial properties allied to total organic carbon content can be used to assess the sustainability of agricultural production (Ferreira et al., 2010).

The objective of this work was to assess the effect of different coffee organic cultivation systems on chemical and biological soil characteristics, in different seasons of the year.

Materials and Methods

The experiment was carried out at the experimental area of Empresa de Pesquisa Agropecuária do Estado do Rio de Janeiro (Pesagro), located at municipality of Paty do Alferes, Rio de Janeiro, Brazil (22º46'S and 43º4'W, 507-m altitude), in a Typic Hapludox (Latossolo Vermelho-Amarelo). The region has annual mean rainfall of 1,185 mm and average temperature of 20.9°C, with rainy season from November to April (Figure 1).

During the four seasons of 2002, edaphic macrofauna, microbial biomass carbon (MBC), soil basal respiration (SBR), metabolic quotient (qCO_2), microbial quotient (qMic), and soil fertility were monitored in the following systems: two-year-old organic coffee crop (Catuaí Amarelo cultivar) containing one (CJ1), two (CJ2) or three alleys (CJ3) of pigeon pea (*Cajanus cajan* L.); coffee crop under full sun (CS); area planted with pepper (*Capsicum annuum* L.) and snap bean (*Phaseolus vulgaris* L.) in a conventional tillage system (AC); and secondary fragment of the Atlantic Rainforest (FFR), contiguous to the coffee crop.

The coffee crop was established in September 2000. A randomized complete block design with four treatments and four replicates was used. The treatments with coffee plants had four combinations of row spacings: CJ1, 2.0x1.0 m; CJ2, 2.8x1.0 m; CJ3, 3.6x1.0; and CS, 2.8x1.0 m. Pigeon pea row spacing was 1.0x0.5, 0.95x0.5, and 0.9x0.5 m for CJ1, CJ2, and CJ3, respectively. The plots measured 90 m^2 (CJ1), 126 m^2 (CJ2 and CS), and 162 m^2 (CJ3), and had 15 coffee plants per row. The areas AC and FFR measured, approximately, 400 m^2 and 1 ha, respectively; both areas are located at Pesagro, at municipality of Paty do Alferes, Rio de Janeiro, Brazil.

The annual cropping area was fertilized with 1 L of chicken manure per hill and received daily irrigation and regular applications of the following agricultural chemicals: methamidophos (0,01 ppm), deltametrine (0,001 ppm), and mancozeb (1 ppm) for vegetables (Brasil, 1985), besides lime sulphur and agrobio fertilizer.

At the coffee crop planting, in 1999, the soil was plowed, disked, and corrected with 80 g of dolomitic lime per hill. A fertilizer composed of 160 g of thermophosphate, 340 g of firewood ash, and 10 L of cattle manure was also applied at planting (Brasil, 1999), using 1 L per hill.

The soil attributes of the areas with coffee crop, conventional system, and forest fragment are present in Table 1. In order to evaluate the different treatments, soil samples were collected at a depth of 10 cm in March, June, September, and December 2002, representing

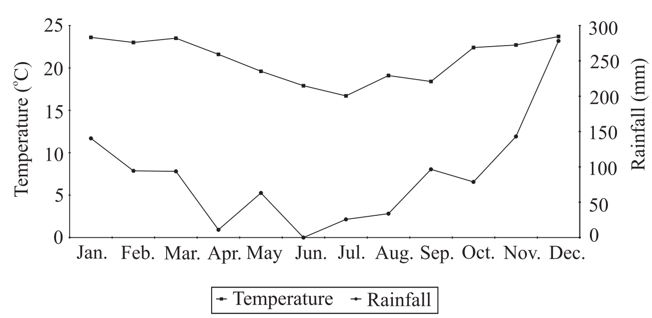

Figure 1. Monthly mean temperature and rainfall data collected at the experimental station of Avelar, in Paty do Alferes, RJ, Brazil, from March to December 2002.

summer, autumn, winter, and spring, respectively. In the coffee crop treatments, six simple soil samples per plot were collected to make a composite sample for determination of MBC, SBR, qCO_2, *q*Mic, and fertility; four monoliths per plot were randomly collected for edaphic macrofauna evaluation. In the AC and FFR, ten simple samples were collected to make a composite sample per area for determination of MBC, SBR, qCO_2, *q*Mic, and fertility; eight monoliths per area were collected for edaphic macrofauna evaluation.

Microbial biomass carbon was assessed by the fumigation-extraction method (De-Polli & Guerra, 2008), and SBR was evaluated according to Stotzky (1965). Metabolic quotient was calculated by the ratio between soil C respiration and microbial C, in a time interval (Anderson & Domsch, 1990), while *q*Mic was obtained from the relationship between soil microbial C and soil organic C (Jenkinson & Ladd, 1981).

Edaphic macrofauna sampling was done using the monolith method with a surface of 25x25 cm, recommended by Anderson & Ingram (1993). Individual macrofauna with a length greater than 10 mm was manually removed and stored in bottles containing 70% alcohol for preservation until classification into large taxonomic groups and counting under a stereoscopic microscope. For analysis of the edaphic macrofauna, the term 'group' was used to refer to a family and a class or order, within the logic of taxonomic sufficiency. Communities were characterized in terms of total density (number of individuals per square meter) and median richness (number of groups per monolith).

Soil fertility (pH, Al, Ca+Mg, P, K, and %C) was determined according to Silva (1999), and a kopeck ring was used to determine soil density. The soil was dried at 105ºC for 48 hours, and weighted.

The data were subjected to analysis of variance using the Sisvar software (Ferreira, 2008), and means were compared by the Scott-Knott test, at 5% probability. Total density, qCO_2, and SBR were transformed using the log (x) function, and median richness with root (x+0.5) function. Significant between factors interactions were determined.

Principal component analysis (PCA) and redundancy analysis (RDA) were carried out using the program Canoco version 4.5 (Ter Braak & Smilauer, 2002). Two PCA were performed for soil macrofauna and soil microbial attributes, in order to summarize the set of original chemical, physical, and biological variables, highly correlated, into a few principal components, which are linear combinations of noncorrelated original variables. Two RDA were carried out for soil macrofauna and soil microbial attributes, in order to verify the existence of the correlation between biological variables (density, richness of the edaphic macrofauna, MBC, *q*Mic, SBR, and qCO_2) and explanatory variables, corresponding to soil physical and chemical attributes: apparent density (DAP), pH, Al, Ca+Mg, P, K, and %C.

The Monte Carlo permutation test was used to evaluate the significance of the relationship between the taxonomic units of the macrofauna and the explanatory variables. The eigenvalue obtained by the RDA is the squared sum of all the canonical values, representing the greatest degree of correlation of all the variables with the axis, which indicates the relative contribution of each axis for the explanation of the total data variance.

Results and Discussion

Edaphic macrofauna, SBR, and qCO_2 were positively correlated with summer, while MBC and *q*Mic showed higher correlation with spring (Figures 2). Total macrofauna density was significantly greater in CJ2 followed by CJ3, CS, CJ1, AC and FFR (Table 2). For median richness, CJ3 and CJ1 were statistically the highest, followed by CJ2, CS, and FFR. The lowest median richness was found in AC, probably due to the absence of living perennial mulch.

With PCA, it was possible to decompose variability into two groups of explanatory variables, i.e., seasons of the year and areas. The first two principal components

Table 1. Soil attributes under coffee crop, conventional system, and secondary forest.

Soil area	Sand	Silt	Clay	Soil density	pH	Al	H+Al	Ca+Mg	K	CTC	P	C	N
	(%)			(g cm^{-3})		($cmol_c$ dm^{-3})					(mg m^{-3})	(g kg^{-1})	
Coffee	54.5	9.1	37.8	1.50	5.1	0.2	7.3	3.5	0.3	11.3	20.1	10.0	1.0
Conventional	51.7	12.7	35.5	1.54	5.4	0.0	7.1	5.5	0.4	13.0	162.0	13.0	1.4
Forest	57.6	9.5	32.9	1.40	5.0	0.8	8.7	2.8	0.2	12.5	7.8	14.0	1.6

were responsible for 70.4% of the total variance in the original data, while Y1 and Y2 explained 41.7 and 28.7%, respectively. Among the seasons, summer showed greater density for most of the groups, and strong correlation for *Formicidae* (ants) and *Isoptera* (termites). *Formicidae* and *Isoptera* were present in greater density in CJ2 and in CJ3, respectively, with correlation above 0.7, which was the limit value used to indicate strong correlation. For Y1, the areas evaluated were ordered as follows: CJ3, CJ2, CJ1, CS, FFR, and AC. For Y2, the correlations between the fauna variables and the second axis were lower than 0.7, indicating a smaller contribution of each variable to the axis, which did not allow an increase of information in the explanation by Y1.

CJ1 and CS are close to the center of Figure 2 A, while the other evaluated areas are distinct in terms of edaphic macrofauna. CJ2 and CJ3 showed greater soil fauna, due to the more effective presence of the herbaceous and shrub layer, which increases food availability for edaphic macrofauna (Souto et al., 2008). The opposite was observed for AC, which had the lowest values of edaphic macrofauna.

These results are similar to those found by Silva et al. (2006), while evaluating the following land use systems: conventional, no-tillage, crop-livestock integration, continuous pasture, and native vegetation. The authors observed that the no-tillage system showed the greatest diversity of groups. Santos et al. (2008), who assessed edaphic macrofauna under a no-tillage system, reported that the use of *Crotalaria juncea* L. favored macrofauna density. Silva et al. (2007) observed that using cover crops in a rotation system also favored macrofauna community. However, Aquino et al. (2008b), when evaluating edaphic macrofauna in a no-tillage system in the Brazilian Cerrado (tropical savanna), verified greater density and richness in the forest fragment soil.

According to Lavelle & Spain (2001), there is an association between termites and organic material with high C/N ratio. Pigeon pea, an arboreal plant rich in C, may have contributed to the higher number of termites in CJ3, i.e., in environments in which there was a greater input of ligneous material through green manure. Lima et al. (2007) found similar results for ants and termites,

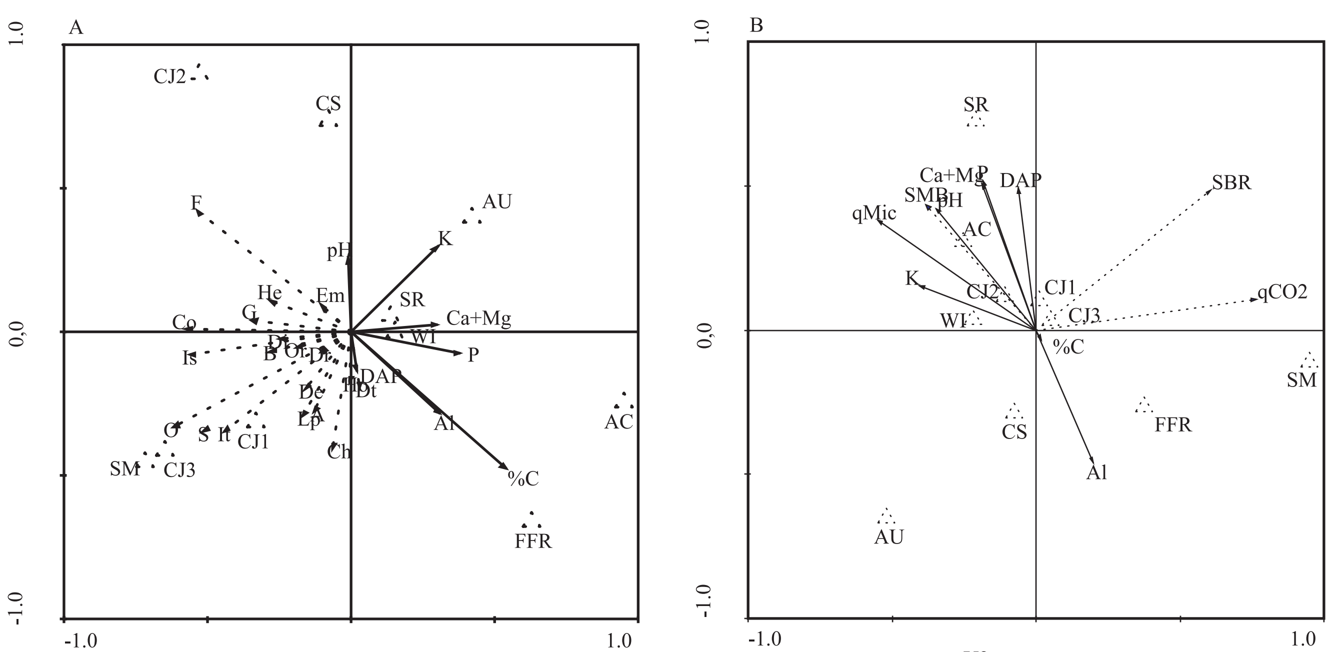

Figure 2. Principal component analysis of: A, edaphic macrofauna groups; and B, microbial biomass carbon (MBC), soil basal respiration (SBR), metabolic quotient (qCO$_2$), and microbial quotient (qMic), in the summer (SM), autumn (AU), winter (WI), and spring (SR) for coffee crop with one (CJ1), two (CJ2) or three (CJ3) alleys of pigeon pea; coffee crop under full sun (CS); annual crop soil (AC); and secondary forest fragment soil (FFR). A, *Araneae*; B, *Blattodea*; Ch, *Chilopoda*; Co, *Coleoptera*; De, *Dermaptera*; Di, *Diplopoda*; Dr, *Diplura*; Dt, *Diptera*; En, *Enchytraidae*; F, *Formicidae*; G, *Gastropoda*; He, *Heteroptera*; Ho, *Homoptera*; Is, *Isopoda*; It, *Isoptera*; Lp, *Lepidoptera*; O, *Oligochaeta*; Or, *Orthoptera*; S, *Symphyla*.

while evaluating soil macrofauna in an organic coffee management.

Huerta (2005), who studied the effect of the cover crop type on soil macrofauna, concluded that earthworm growth and reproduction rates increase with velvetbean and corn. Kitamura et al. (2008) observed an association of *Coleoptera* recovering areas, such as CJ2 and CJ3.

The area with coffee under full sun had low total density and median richness, as reported by Aquino et al. (2008a), who compared coffee crops under full sun and shaded crops with arboreal species. The presence or absence of living perennial mulch regulated the edaphic macrofauna, as demonstrated by Lima et al. (2010), when comparing soil macrofauna and chemical attributes to different systems. According to the authors, agroforestry management stimulated the occurrence of "ecosystem engineers" and promoted better soil chemical conditions. In the present study, AC showed detachment from the edaphic macrofauna (Figure 2A). Although the values of organic carbon for AC and FFR were close (13 and 14 g kg^{-1}, respectively), the conditions provided by this cropping model were not favorable to the edaphic macrofauna, possibly due to the planting system using N fertilization, agricultural implements, soil tillage, and absence of plant cover (Tanck et al., 2000), which made AC soil biologically different from the others analyzed.

For soil microbiological data, the percentage of cumulative explanation up to the second principal component was 94.6%, with Y1 and Y2 components explaining 64.3 and 30.3%, respectively. Summer showed differentiated behavior in comparison to spring, autumn, and winter (Figure 2 B).

Table 2. Total density (individuals per square meter), median richness, microbial biomass carbon (mg kg^{-1} of C), microbial quotient [Cmic (mg)/100 Corg (mg)], soil basal respiration (mg kg^{-1} ha^{-1}), and metabolic quotient (mg g^{-1} h^{-1}) for coffee crop soil with one (CJ1), two (CJ2) or three (CJ3) alleys of pigeon pea; coffee crop under full sun (CS); conventional system (AC); and secondary forest fragment (FFR)[(1)].

Atribute	CJ1	CJ2	CJ3	CS	AC	FFR
Density	547.50a	1,291.50a	733.50a	590.50a	116.30c	200.62b
Richness	4.22a	3.56b	4.97a	3.19b	1.08d	2.69c
MBC	126.70b	132.10b	125.00b	111.10b	179.70a	121.00b
*q*Mic	1.11a	1.13a	1.08a	1.07a	1.28a	0.86a
SBR	1.48a	1.59a	1.60a	1.09a	1.63a	1.55a
qCO_2	18.59a	11.78b	15.40a	11.53b	8.59b	15.31a

[(1)]Means followed by equal letters, on the same line, do not differ by the Scott-Knott test, at 5% probability. MBC, microbial biomass carbon; *q*Mic, microbial quotient; SBR, soil basal respiration; qCO_2, metabolic quotient.

Weather was also an important factor that influenced the performance of microbial attributes. In the summer, rain and temperature influenced soil microorganism activity. For Y1, qCO_2 and SBR increased and were positively correlated, showing strong (0.87) and medium correlation (0.59) with summer, respectively. Y2 positively affected qCO_2 (0.89).

The variables *q*Mic and MBC showed correlation coefficients for Y1 of -0.87 and -0.81, respectively. Microbial biomass carbon and *q*Mic were negatively correlated with SBR and qCO_2, which indicates an inverse response, a result already found in other studies (Pimentel et al., 2006). During the spring, with approximately 300 mm of rainfall (Figure 1), *q*Mic and MBC reached the highest values, indicating that, besides soil management, environmental conditions were more favorable to these attributes.

Weather influence on soil respiration was also observed by Balota et al. (1998), who reported greater values of SBR in a no-tillage system, during the summer. Soil basal respiration values were lower in autumn and winter, when the temperatures were the lowest, which confirms the correlation between SBR and environmental temperature.

The conventional system area showed significantly greater values for MBC and *q*Mic (Table 2). The secondary forest favored qCO_2 and SBR (Figure 2B). No significant differences were observed for SBR among the areas by univariate analysis, while qCO_2 was significantly greater in CJ1, CJ3, and FFR. These results differ from those of Moreira & Malavolta (2004), while evaluating soil carbon and MBC dynamics. The authors observed that the rotation forestry-pasture-cupuaçu significantly reduced both attributes.

Redundancy analyses showed significance by the Monte Carlo permutation test (p = 0.002, 499 permutations), which indicates that there is a correlation between biological variables and soil chemical attributes (Figure 3). The chemical attributes explained 42.8 and 51.1% of the variability in the edaphic macrofauna and microbiological data, respectively; 55 and 68.5% were explained on the first axis (Z1) and 27.5 and 28.4% on the second axis (Z2) (Table 3 and Figure 3).

In this study, organic carbon influenced the variability of the edaphic macrofauna, and AC and FFR soils were associated with elevated C. Greater C

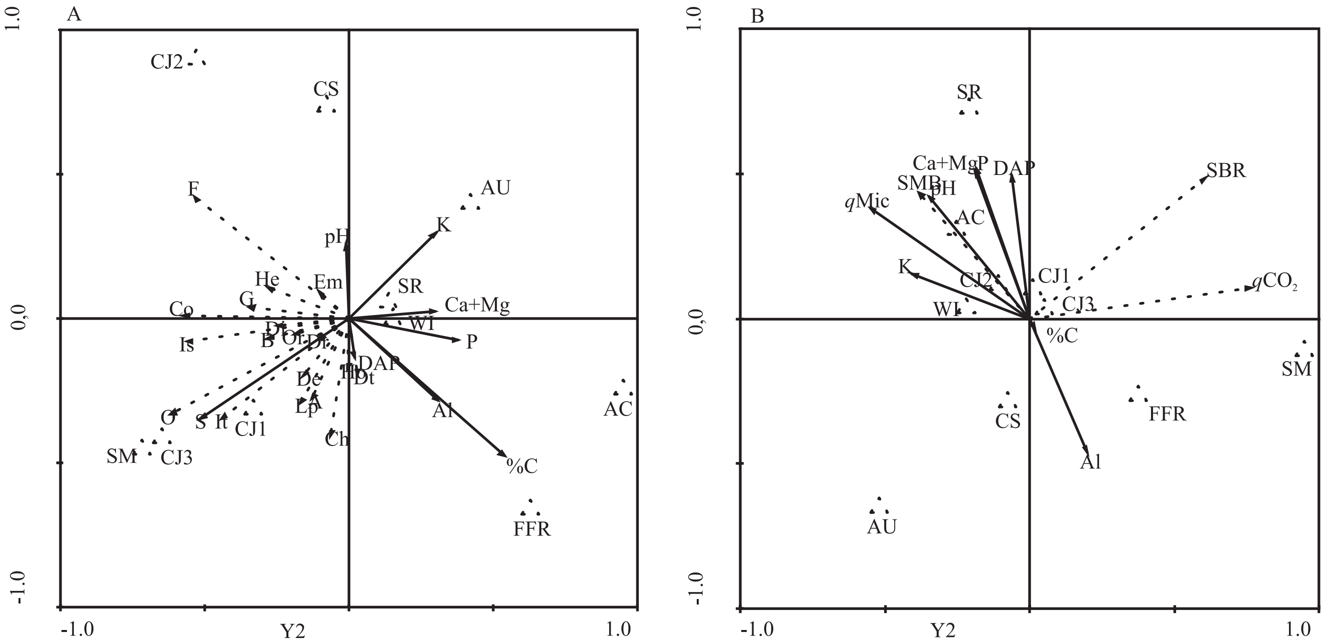

Figure 3. Redundancy analysis of: A, the edaphic macrofauna groups, organic carbon (%C), Al, K, P, Ca+Mg, pH, and DAP; and B, soil microbial biomass (SMB), soil basal respiration (SBR), metabolic quotient (qCO_2), microbial quotient (*q*Mic), %C, Al, K, P, Ca+Mg, pH, and Dap, in the summer (SM), autumn (AU), winter (WI), and spring (SR) for coffee crop with one (CJ1), two (CJ2) or three (CJ3) alleys of pigeon pea; coffee crop under full sun (CS); annual crop soil (AC); and secondary forest fragment soil (FFR). A, *Araneae*; B, *Blattodea*; Ch, *Chilopoda*; Co, *Coleoptera*; De, *Dermaptera*; Di, *Diplopoda*; Dt, *Diptera*; En, *Enchytraeidae*; F, *Formicidae*; G, *Gastropoda*; He, *Heteroptera*; Ho, *Homoptera*; Hy, *Hymenoptera*; Is, *Isopoda*; It, *Isoptera*; Lp, *Lepidoptera*; O, *Oligochaeta*; Or, *Orthoptera*; S, *Symphyla*.

Table 3. Redundancy analysis (RDA) between biological variables, considered dependent by RDA, and chemical attributes, considered independent.

RDA statistics	Fauna vs. chemical			Microbiological vs. chemical		
	1st Axis	2nd Axis	3rd Axis	1st Axis	2nd Axis	3rd Axis
Eigenvalue	0.236	0.118	0.023	0.350	0.145	0.011
Correlation	0.780	0.670	0.690	0.750	0.670	0.670
	Cumulative explained variation (%)					
Dependent variables	23.6	35.3	37.7	35.0	49.5	50.6
Dependent and independent variables	55.0	82.5	88.0	68.5	96.9	99.1

tends not to favor the density of *Coleoptera*, *Formicidae*, and *Isopoda* (Figure 3 A).

Potassium content had greater influence on the variability of biological data, and C was not related to the biological variables analyzed (Figure 3 B). Potassium content was positively correlated with *q*Mic and MBC, which were proportionally correlated with pH, Ca+Mg, P, and DAP, and inversely correlated with Al content (Z2).

Within the treatments analyzed, AC had the greatest MBC and the highest content of K, pH, Ca+Mg, and P, which was probably motivated by fertilization, liming, and irrigation, which provided favorable conditions for microbial biomass (Table 2 and Figure 3 B). Fertilization and liming, located to the left of Figure 3 B, may have favored soil microbial biomass, while Al content and C had strong correlation with FFR. In the spring, rainfall and MBC showed the highest values.

High levels of Al in forest soil has been reported in other studies (Souza et al., 2004; Longo et al., 2005). This could be attributed to FFR conditions, where there is no fertilization or liming to correct Al levels, and no soil disturbance, which allows the maintenance of the original vegetation and, consequently, carbon conservation.

Conclusions

1. Edaphic macrofauna, soil basal respiration, and microbial quotient are positively correlated with summer.

2. Total macrofauna density is significantly greater in coffee crops, mainly with two or three alleys of pigeon pea, in which *Coleoptera*, *Formicidae*, and *Isoptera* are the most abundant groups.

3. There are no significant differences among the areas for soil basal respiration, and the metabolic quotient is greater in the coffee crop with one or three alleys of pigeon pea and in the secondary forest fragment.

4. Microbial carbon biomass shows greater values in the conventional area and the highest content of K, pH, Ca+Mg, and P.

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