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Soil Biological Community Structure in Coffee (*Coffea arabica* L.) Agroecosystems in Puerto Rico

David Sotomayor-Ramírez[1], Veronica Acosta-Martínez[2], Yusmary Espinoza[3], Eduardo Schröder[1], José Amador[4]

*[1]UPR – Mayagüez; Agronomy and Soils Department, Mayagüez, Puerto Rico, [2]USDA-ARS; Wind Erosion and Water Conservation Unit, Lubbock, Texas, [3]INIA-CENIAP, Maracay Venezuela, [4]Laboratory of Soil Ecology and Microbiology, University of Rhode Island, Kingston, RI * Contact author: dsotomayor@uprm.edu*

ABSTRACT.

Coffee production in the Caribbean and Latin America is an important commodity in terms of economic, ecological and social value. Coffee production in Puerto Rico was intensified in the 1960s, with a shift to higher-yield varieties, increased use of pesticides and fertilizers, increased mechanization, higher-density planting patterns, with production under full sunlight. There is concern that long-term, intensive coffee production under full sunlight may have a negative impact on agroecosystem sustainability. Soil physical, chemical and biological attributes from representative major coffee production regions in Puerto Rico under partial shade and full sunlight were quantified. Soils from secondary forests at least 25 years old were included for comparison. Soil fertility differed between forest and coffee agroecosystems with favorable soil reaction, improved nutrient reserves and availability in forested systems; coffee under shade had a tendency towards improved soil fertility. The soil physical structure was significantly affected by coffee production, with a greater proportion of large macroaggregates in forested sites than in coffee agroecosystems. Coffee under both partial shade and full sunlight had a lower proportion of macroaggregates and a higher proportion of microaggregates which may have important implications for the capacity of soils under coffee production to store C and release N for crops. Soil organic carbon and nitrogen, microbial biomass and fungal groups were negatively affected by coffee production, with few observed differences between coffee under shade and full sunlight. The soil biological community structure was negatively influenced by coffee production relative to secondary forested sites, with coffee under shade having slight improvement relative to coffee under sun.

KEYWORDS: soil biological community structure, coffee, microbial ecology, soil quality

INTRODUCTION

Technological advances promoted by the College of Agricultural Sciences of the University of Puerto Rico and the Puerto Rico Department of Agriculture brought several improvements in coffee production in the mid 20th Century, including increased yields, improved pest management practices, expansion of planting areas, and improvements in the organizational market structure (Vicente-Chandler et al. 1968). Forty years after the introduction of these practices, it is becoming important to evaluate the effects of sunlight

vs. shade coffee production management practices on coffee yields, as well as coffee quality, system sustainability and soil quality. Long-term, intensive coffee production under full sunlight may decrease orchard longevity, lower fruit quality, and increase plant pest vulnerability. Soils in coffee under full sunlight, which have lower overstory vegetative canopy cover and decreased surface litter, are more vulnerable to erosion (Smith and Abruña, 1958) and nutrient runoff losses (Semidey et al., 2002; Sotomayor-Ramírez et al., 2008), which in turn affect soil functioning and ecosystem sustainability. Coffee under shade has been suggested as a more sustainable option, but quantitative information on soil parameters related to soil quality and functioning is lacking.

Shade for coffee production in Puerto Rico has traditionally been provided by an overstory of mature forest and introduced leguminous (N-fixing) trees such as *Inga spp.* and *Gliricidia spp* (Arango et al. 2004). Trees used for shade in coffee orchards are probably an important component of N cycling, primarily through leaf litter-fall, root exudates, and N fixation (Aranguren et al., 1982). Leaf litter decomposition plays an important role in the cycling of nutrients and energy transfer between plant and soil, especially in agricultural systems with low soil fertility and low fertilizer inputs. The underlying causes of the hypothesized differences in nutrient cycling between shaded and sun coffee agroecosystems need to also be ascertained by studying the biological component, since soil functioning and its long term sustainability depends on soil biota. However, information about the size, composition and function of soil microorganisms is scant for tropical agroecosystems, especially those under coffee production. We quantified selected soil chemical, physical, biological attributes in coffee agroecosystems, coffee under partial shade and full sunlight, to explain differences in C and N cycling patterns among different agroecosystems and secondary forests.

MATERIALS AND METHODS

Study sites. Three study sites were selected based on soil order, vegetation and climatic factors within the municipalities of Las Marías, Lares, and Jayuya (Table 1). Each site had soil from a different order (Ultisol, Inceptisol, and Oxisol) which are representative of soils used for coffee production in Puerto Rico (Arango et al., 2004). Within each site, experimental plots were established in areas with coffee under partial shade (coffee shade) and coffee under full sunlight (coffee sun), as well as a secondary forest (forest) control area. Each of the agroecosystems and the control area were replicated three times, with plot sizes of about 400 m^2.

Sampling. Soil samples were collected in mid-November 2007. Soils were collected using an auger (5 cm dia.) to a depth of 0-15 cm. A portion of the sample was kept refrigerated for microbiological analyses, a second portion was dried and sieved to pass a 2mm-mesh sieve, and a third portion was dried and sieved to pass a 6mm-mesh sieve.

Physicochemical properties. Soil moisture was determined gravimetrically. Soil pH and other soil chemical properties associated with fertility were determined (Page et al., 1982) by a commercial laboratory (MDS Harris Inc.). Soil organic C (OC) and total N (TN) contents were determined on the air-dried soil (sieved to <180 μm) by automated dry combustion. Aggregate size separation was performed by wet sieving air-dried soil (100 g soil) through a series of sieves (2000, 250 and 53 μm) (Elliot, 1986; Cambardella and Elliot, 1994). Four aggregate fractions: (i) >2000 μm (large macroaggregates), (ii)

250 to 2000 μm (small macroaggregates), (iii) 53 to 250 μm (large microaggregates), and (iv) 20 to 53 μm (small microaggregates) were obtained. Aggregate mass was corrected for sand and expressed as sand-free aggregate.

Biological properties. Microbial biomass carbon (MBC) and nitrogen (MBN) were determined by the chloroform-fumigation-extraction method (Brookes et al., 1985; Vance et al., 1987). Fatty acids methyl ester (FAME) profiles were used to describe the microbial community structure and were extracted from soil samples following the MIDI (Microbial ID, Inc., Newark, DE, USA) protocol as previously applied to soil analyses (Acosta-Martínez et al., 2004a,b). In brief, soils were subjected to saponification, methylation, FAME extraction, and the extract analyzed by gas chromatography with flame ionization detector.

Statistical analyses. The treatments were arranged in the field in a randomized complete block design with three replicates. A two-way analysis of variance was performed with ecosystem and site as the two factors using the MIXED procedure on measured and estimated parameters in SAS (SAS Institute Inc., Carey, NC). Means separation was performed using the LSMEANS procedure with a significance level of $P<0.05$, unless specified otherwise, with treatment differences assessed using Tukey's test. Since the treatments and the site were previously established, the inferences are strictly observational in nature. When interaction was significant, the treatments were sliced across site using the LSMEANS option to examine treatment effects within a site. Principal component analysis (PCA) was performed for selected soil FAME markers (Frostegård and Bååth, 1996) for fungal (18:1ω9c, 18:2ω6c, 18:3ω6c and 16:1ω5c) and bacterial (15:0, *a*15:0, i15:0, *a*17:0, *i*17:0, 17:1ω9c, cy17:0, cy19:0, 10Me16:0, and 10Me17:0) populations using the PCORD statistical software (version 4) to examine treatment effects in the microbial community structure.

RESULTS AND DISCUSSION

A total of forty-five parameters were either quantified or calculated to quantify the effects of land use, soil type and their interactions. In most cases the interaction site x treatment was significant, and only the most important ones are discussed here.

Soil fertility indicators. Soil C and N in Jayuya were significantly lower in both coffee production systems (sun and shade) relative to that in forest (Figure 1A and 1B). Soil C and N in Lares were significantly lower in coffee sun relative to forest, but only total C was different between the two coffee production systems. Soil C and N were similar among the three systems in Las Marías.

Soils under forest had higher pH, significantly lower exchangeable Al, and % Al saturation than both coffee production systems in Las Marías; this pattern, although non-significant, was also observed in Jayuya soil (Figure 2A, 2B, and 2C). Soil pH, exchangeable Al, and % Al saturation values were similar among coffee production systems and forest in Lares.

Soil exchangeable NH_4^+-N was significantly higher in forest soil than in coffee production systems, with no difference between coffee production systems (Figure 3A). Soil NO_3^--N was higher in forest soil than in coffee production systems only in Lares (Figure 3B). Soil mineralizable N was significantly higher in forest than the coffee under sun in Jayuya and Lares but not in Las Marías, where it was only greater than coffee under shade (Figure 3C). Coffee under shade had significantly greater mineralizable N

than coffee under sun in Jayuya and Las Marías. Extractable inorganic N followed the order: of forest > coffee shade > coffee sun.

Soil aggregate size distribution. The site x treatment x aggregate size interaction was only marginally significant (F=1.84, $P< 0.059$) and only the treatment x aggregate size interaction was considered important (F=18.34, $P<0.01$) (Figure 4). The forest soil had the greatest proportion of large macroaggregates (>2000 μm). The proportion of large macroaggregates decreased at the expense of an increase in small macroaggregates (250 – 2000 μm) in coffee shade and coffee sun and possibly large microaggregates (<50-250 μm) in coffee shade.

Soil microbial communities. Microbial biomass C and N were lower in both coffee agroecosystems when compared to forest in all sites (Figure 5A). The MBC was higher under shade compared to sunlight coffee in Jayuya, not affected by coffee agroecosystems in Lares, and it was lower under shade compared to sunlight in Las Marías soil. The MBN was higher in coffee under shade for Jayuya soil, but it was not affected by coffee production system for the other two soils (Figure 5B). Thus, effects of coffee management on microbial biomass depended on the soil order or other climatic and management conditions within each of the different sites.

Principal component analysis was used to evaluate the microbial community composition only as a function of coffee production systems, since forest soil clearly showed higher microbial biomass and fungal populations than the agroecosystems (Figure 6). Generally, higher fungal populations were found in Jayuya and Lares under coffee production with shade, and in Jayuya with coffee production with sunlight compared to the other systems. Thus, Las Marías soil under both shade and sunlight coffee production tended to have lower fungal populations and higher bacteria populations compared to the other soils. These trends depended on comparisons based on combined data from all soils; however, two of the three soils showed higher fungal populations with coffee production under shade, mostly likely due to higher litter accumulation and substrate availability compared to sunlight production. The soil microbial community shifts to larger populations under shade were in agreement with higher C content and N mineralization compared to sunlight coffee production systems.

CONCLUSIONS

Soil fertility differed between forest and coffee agroecosystems with improved soil reaction, organic matter (C and N) and extractable ammonium-N, nitrate-N and mineralizable N in forested systems; only in some cases were these parameters influenced by the manner in which coffee is grown, with coffee under shade showing a tendency towards generally improved properties. The soil physical structure was significantly affected by coffee production as forested sites had greater proportion of large macroaggregates than coffee agroecosystems. Coffee under both partial shade and full sunlight had a lower proportion of large macroaggregates and a greater proportion of small macroaggregates, which may have important implications in the capacity of soils under coffee production to store C and release N for crops. Soil biological parameters were negatively affected by coffee production, with few differences observed between coffee under shade and full sunlight. In some cases (parameters) coffee under shade was better for the soil, but the trend was not consistent among the biological parameters measured. It was of ecological significance to find that two of three soils showed higher

fungal populations with coffee production under shade, mostly likely due to higher litter accumulation and decreased rates of C cycling compared to coffee under sunlight.

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Tables

Table1. General information from study sites.

Site	Series	Taxonomic classification [1]	Altitude above mean sea level (m) [2]
Jayuya	Los Guineos	Very-fine, kaolinitic, isothermic Humic Hapludox	789
Lares	Alonso	Very-fine, parasesquic, isohyperthermic Oxic Dystrudepts	604
Las Marías	Humatas	Very-fine parasesquic isohyperthermic Typic Haplohumults	286

1 Beinroth et al. (2003)

2 Represents the mean value of nine plots (three treatment combinations).

Figures

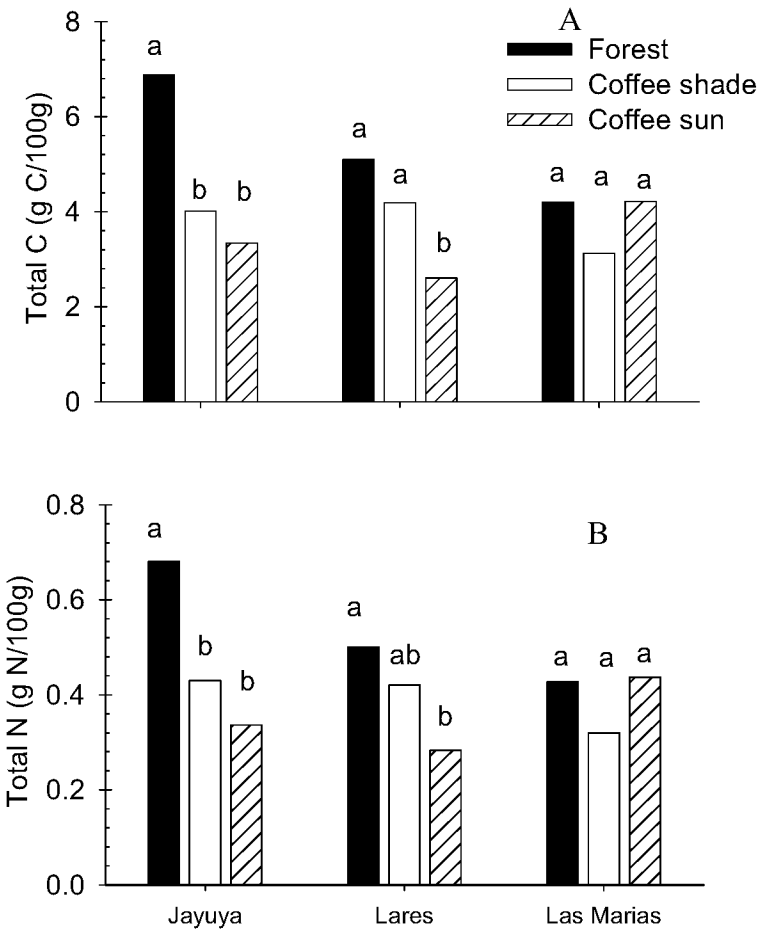

Figure 1. Soil total C (A) and total N (B) in secondary forest and in coffee production under partial shade and full sunlight in Jayuya, Lares, and Las Marías sites. Values followed by the same letter within a site were not significantly different.

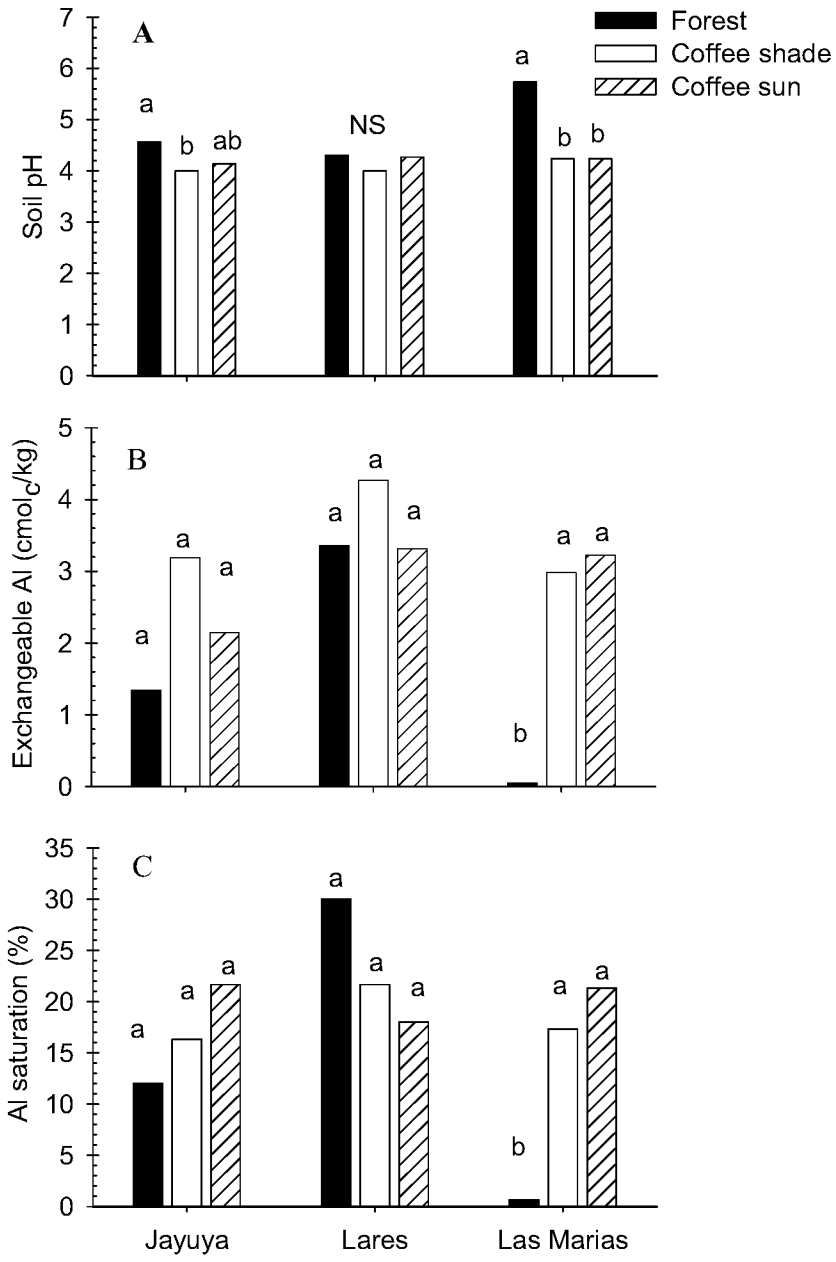

Figure 2. Soil pH (A), exchangeable Al (B), and Al saturation (C) in secondary forest and in coffee production under partial shade and full sunlight in Jayuya, Lares, and Las Marías sites. Values followed by the same letter within a site were not significantly different.

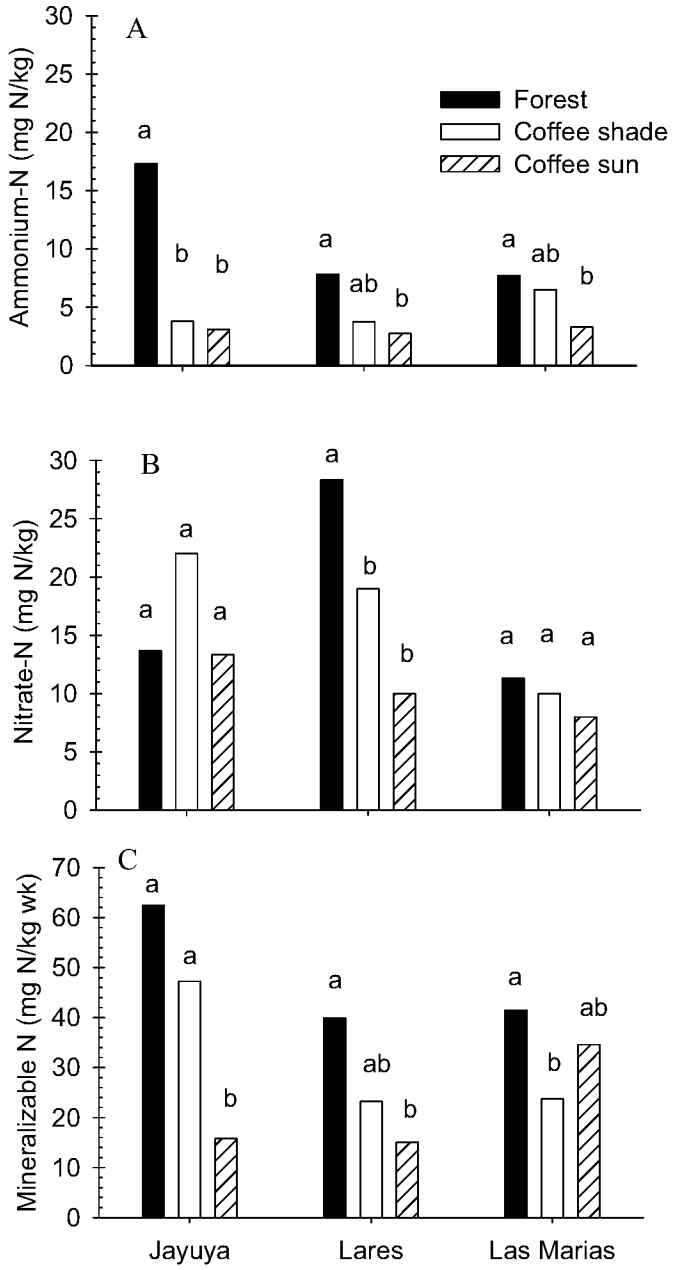

Figure 3. Soil ammonium (A), nitrate (B), and mineralizable nitrogen (C) in secondary forest and in coffee production under partial shade and full sunlight in Jayuya, Lares, and Las Marías sites. Values followed by the same letter within a site were not significantly different.

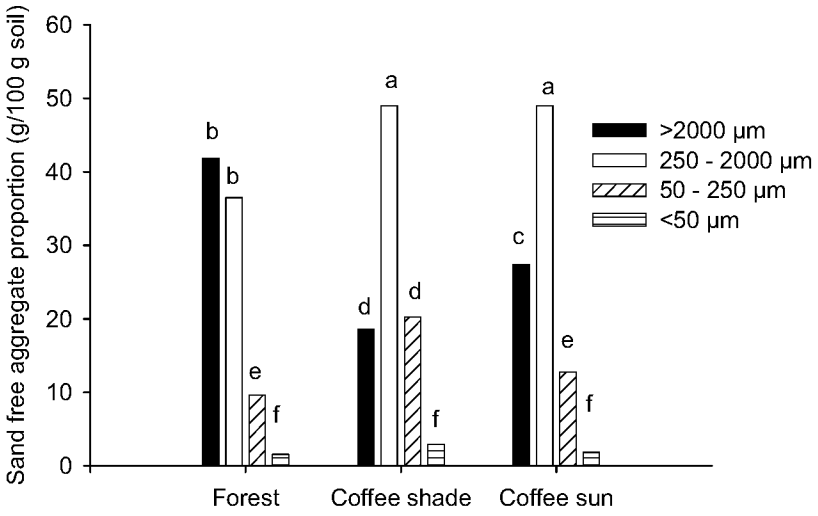

Figure 4. Aggregate size distribution as influenced by secondary forest and coffee production under partial shade and full sunlight in Jayuya, Lares, and Las Marías sites. Values followed by the same letter were not significantly different.

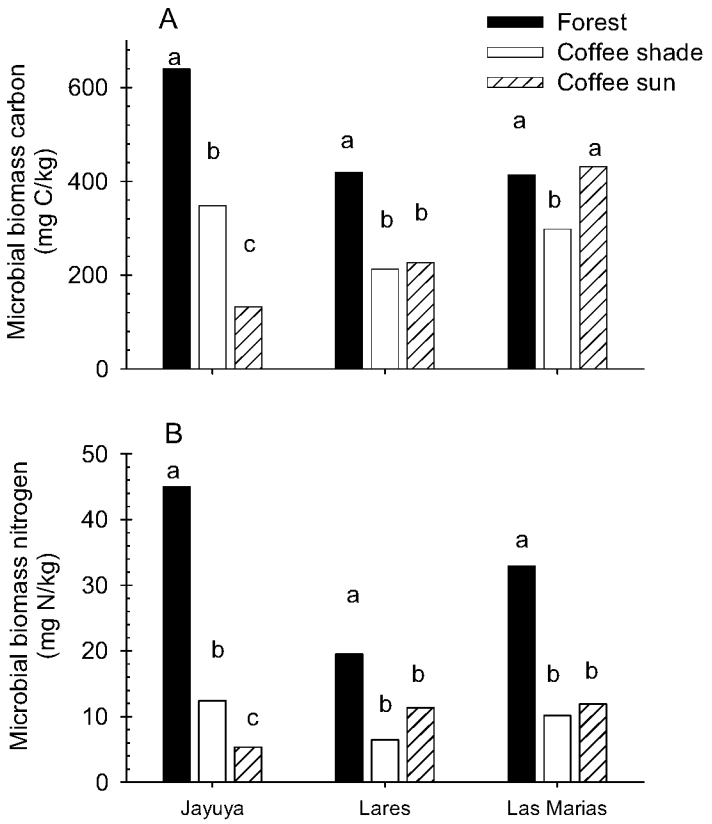

Figure 5. Soil microbial biomass carbon (A) and nitrogen (B) in secondary forest and in coffee production under partial shade and full sunlight in Jayuya, Lares, and Las Marías sites. Values followed by the same letter within a site were not significantly different.

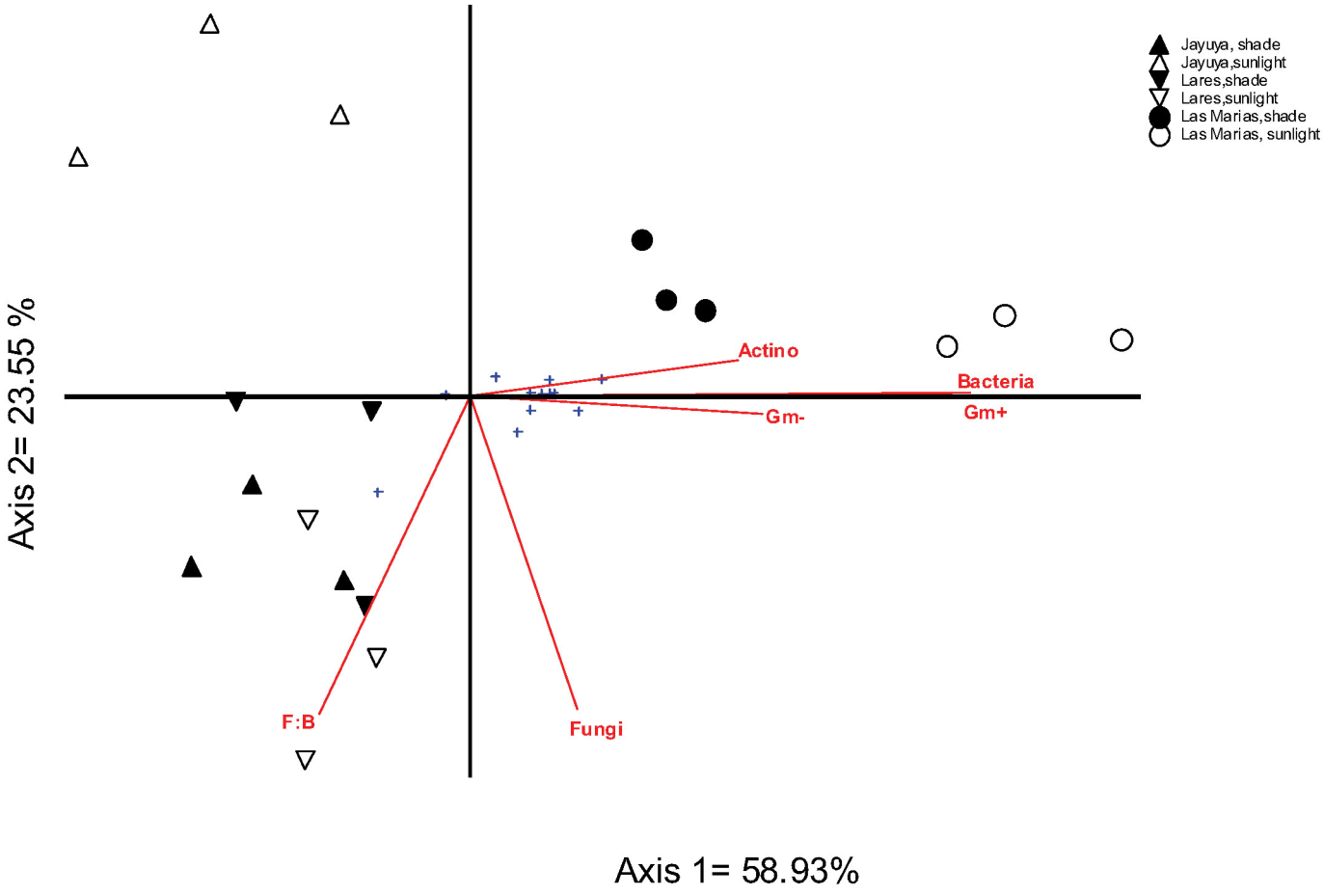

Figure 6. Principal Component Analysis (PCA) for selected soil FAME markers for fungal and bacterial populations to examine differences in soil microbial community structure in coffee under partial shade compared to coffee under full sunlight. Forest soil was not included in this analysis. In this PCA, higher abundance of fungi or bacteria populations are characterized when soil samples align to the vectors designated for those microbial groups.