Acta Scientiarum

http://periodicos.uem.br/ojs/acta
ISSN on-line: 1807-863X
Doi: 10.4025/actascibiolsci.v42i2.48620

BIOTECHNOLOGY

Effect of management (ecological and conventional) on functional groups of soil microorganisms in coffee agroecosystems with different resilience to climate variability, Colombia

Andrea Fernández Garzón[1], Laura Patricia Perdomo Rivas[1] and Lizeth Manuela Avellaneda-Torres[2*]

[1]Programa de Ingeniería Ambiental, Facultad de Ingeniería, Universidad Libre, Bogotá D. C., Colombia. [2]Instituto de Posgrados, Programa de Ingeniería Ambiental, Grupo de Investigación Tecnoambiental, Facultad de Ingeniería, Universidad Libre, Sede Bosque Popular, Carrera 70, n. 53-40, Bogotá D. C., Colombia; *Author for correspondence. E-mail: lizethm.avellanedat@unilibre.edu.co

ABSTRACT. The effect of management (ecological and conventional) on functional groups of microorganisms of soil in agroecosystems with different resilience scores reported to climate variability in Anolaima, Colombia was evaluated. Were found clustering associated with management and cellulolytic bacteria and fungi abundances. No differences found in diversity of phosphate solubilizing or nitrogen-fixing microorganisms, related to management. The diversity of microbial functional groups was affected by the climatic condition of sampling season. Management was relevant in relationships between resilience scores to climate variability and cellulolytic microorganisms; in ecological agroecosystems, biodiversity knowledge, agroecological main structure, and the participation of farmers in organizations were important.

Keywords: soil quality; cellulolytic; phosphate solubilizing; nitrogen-fixing; soil microbial diversity.

Received on July 4, 2019.
Accepted on February 6, 2020.

Introduction

In conventional agriculture, agroecosystem management is based on the use of monoculture as a means of production, the application of chemical products such as fertilizers and agrochemicals, and the use of heavy machinery, which are meant to improve productivity. This production system has led to soil acidification, a disadvantage that causes loss of fauna, erosion, deterioration of the biophysical environment, and a reduction in organic matter content (Fallas, Chacón, & Castro, 2009). In view of this, the environmental sustainability of this production system has been greatly questioned, and alternative agricultural models, such as ecological models, have been proposed.

Ecological models are characterized by the minimum use of external sources, avoiding the use of synthetic fertilizers and pesticides, and implementing practices that seek to reduce air, soil and water contamination (Sosa, Escamilla, & Díaz, 2008). Studies carried out on ecological systems in order to determine their contribution to communities' sustainability have shown the improvement of agroecosystems under these types of practices (Altieri & Nicholls, 2000; Grajales, Gómez, Quintero, & Grisales, 2006; Osorio & Alcántara, 2004).

Specifically, in coffee agroecosystems, a gradual conversion to ecological models has been implemented through systems that include different cover crops and substitution of chemical supplies, in order to reduce water stress, extend coffee crop life, reduce fruit loss, decrease the need for external sources, and protect natural resources such as soil, water, and biodiversity (Muschler, 2004). However, despite the changes in coffee management systems, few studies have addressed the impact that these agricultural practices have on soil quality and, in particular, microbiral functional groups that intervene in soil biogeochemical cycles, such as nitrogen-fixing, phosphate solubilizing and cellulolytic microorganisms.

The latter is relevant considering the relationships that are assumed to exist between agricultural models (conventional and ecological) and climate variability and change phenomena currently taking place in the planet. Therefore, our research question determines if ecological systems contribute to improving soil quality and resilience levels of agroecosystems to climate variability.

This research aimed to assess the possible relationships existing between agricultural practices, functional groups of microorganisms, and soil physicochemical properties, as a way to understand soil quality in response to the agricultural model applied. We also sought to relate the physicochemical parameters with resilience scores to climate variability, which were previously reported by Vargas and Sicard (2013) for the agroecosystems studied. This research was developed as a case study in the municipality of Anolaima, Colombia, where coffee culture is one of the main economic activities.

Material and methods

Study area

The selected study area consisted of six coffee agroecosystems (*Coffea arabica* L.)*:* three ecological and three conventional, located in the municipality of Anolaima (Cundinamarca, Colombia).

The three ecological farms are small and are managed under traditional farmer knowledge, with polyculture, cover cropping and no chemical application. Additionally, coffee crops are associated with legumes suchs as Guamo (*Inga edulis, Inga nobilis, Inga spectabilis*), Balú (*Erythrina edulis*), Muche (*Albizia carbonaria*) and the Cambrian (*Erythrina poeppigiana*). These agroecosystems are: farm E1 - El Laurel, located at 1590 m.a.s.l (4°49'25.4"N - 74°28'53.5"W) farm E2 - Los Pantanos, located at 1525 m.a.s.l (4°49'15.7"N - 74°29'46.7"W), and farm E3 - Don José, located at 1488 m.a.s.l (4°49´21.4"N - 74°29´11.1"W).

The three farms under conventional management combine several practices of the Green Revolution, such as the application of NPK-type fertilizers and chemical pesticides, with traditional farmer knowledge of agricultural practices. For this reason, these have been designated as conventional farms. These agroecosystems are: farm C1 - Don Arturo, located at 1521 m.a.s.l (4°49'19."N - 74°29'45.7"W), farm C2 - La Cajita, located at 1583 m.a.s.l (4°49'21.3"N - 74°29'10.8"W), and farm C3 - El Turista, located at 1583 m.a.s.l (4°48'37.850"N - 74°28'36.174"W).

Soil sampling

At each study agroecosystem, we collected rhizophere soil samples (0-20 cm deep) by taking five sampling points from 10m x 10m quadrants. Each sampling point was composed of five sub-samples, collected in zigzag. Thus, a composite sample was made up of five sampling points per agroecosystem. We performed two sampling events, the first in the rainy season (April, 2015) and the second in the dry season (June, 2015), based on historic precipitation data from the Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (IDEAM).

Determination of physicochemical parameters

For each one of the samples collected, we determined humidity through the gravimetric method, bulk density by the paraffin clod method, plasticity through Atterberg limits, pH by potentiometric measurement, organic carbon by the Walkley-Black oxidation method, total nitrogen was estimated from the organic carbon detected, exchangeable bases (Ca, K, Mg and Na) through extraction with ammonium acetate, exchangeable acids by extraction with 1M KCl, cationic exchange capacity was estimated by the Bray II method, microelements (Cu, Fe, Mn, Zn) through extraction with DTPA, and boron by extraction with monocalcium phosphate.

Determination of functional groups abundance and diversity

Nitrogen-fixing microorganisms. We performed counts of colony forming units (cfu g^{-1} soil) of biological nitrogen-fixing microorganisms in each of the soil samples. For this, we used Nitrogen Free Broth (NFB), reported by Avellaneda-Torres et al. (2020). Microorganisms were incubated at 28°C for 48 hours.

Phosphate-solubilizing bacteria and fungi. For colony forming units (cfu g^{-1} soil) counting of phosphate-solubilizing microorganisms, we used Sundara Rao and Sinha (SRS) medium, following the protocol reported by (Valero, 2003) and modified by Anacona (2008). This medium contains calcium phosphate salts and bromocresol purple as a pH indicator. Bacteria were incubated at 28°C for 48 hours and fungi were incubated at room temperature (19°C) for 7 days.

Cellulolytic bacteria and fungi. To determine cellulolytic microorganisms, we performed colony forming units (cfu g^{-1} soil) counting in a medium with 1% carboxymethyl cellulose (CMC), as reported by Avellaneda-Torres, Pulido, and Rojas (2014). Bacteria were incubated at 28°C for 48 hours, at pH 7.0. Fungi were incubated at room temperature (19°C) for 7 days, at pH 5.0.

For the three functional groups, we performed counts for each morphotype incubated, in order to determine the diversity of these microorganisms in each soil sample.

Relationships of microbial functional groups and resilience to climate variability

The abundance and diversity of the microbial functional groups in soil were related to the resilience to climate variability of the agroecosystems of origin. Resilience scores were obtained from previous reports by Vargas and Sicard, (2013), which indicated the biophysical and cultural characteristics of agroecosystems that determine resilience to climate variability. Vargas and Sicard (2013) carried out assessments on a scale of 1 to 5, based on 62 criteria: 4 physical, 5 soil, 4 soil management, 8 water management, 9 biological diversity, 13 social aspects, 7 economic aspects, 6 institutional aspects, 3 political aspects, and 3 technological level.

The relationships between abundance and diversity of the soil microbial functional groups and resilience scores to climate variability of the study agroecosystems were determined through multivariate analysis methods, explained in the following section.

We performed normality and homocedasticity analyses through the Shapiro-Wilks and Bartlett tests, in order to determine which soil physicochemical parameters showed statistically significant differences in relation to the factors assessed. We compared the data in order to evaluate significant differences based on the agroecosystem management (ecological and conventional) and the climate condition present at the moment of sampling (rainy and dry seasons). For this, we used the Wilcoxon test, since the variables showed a non-normal distribution.

In addition, using the program PRIMER v6 & PERMANOVA add on (Anderson, Gorley, & Clarke, 2008; Clarke & Warwick, 2001), we conducted analyses in order to observe statistically significant differences in abundance and richness data of the microbial functional groups. For this, we considered two variables: 1. Management of the coffee agroecosystems (ecological and conventional) and 2. Sampling season (rainy and wet). The statistical analyses were:

PERMANOVA analysis. The microbial abundance information belonging to each functional group was organized into a morphotype x sample matrix containing the abundance values for each microorganism in its corresponding sample. Then, we analyzed similarities in microbial composition and abundance between each sample pair using the Bray-Curtis similarity index (Clarke, 1993), previously transforming the abundance values to the fourth root. This transformation allows to reduce the weight of dominant species and increases the relative importance of rare species in the estimation of the similarity index. With the similarity matrix, we decomposed the total variation using a previously proposed linear model and a multivariate analysis based on permutations and similarity matrices (PERMANOVA) (Anderson, 2001). The number of permutations used for this analysis was 9999. We performed PERMANOVA tests in order to assess significant differences in diversity (abundance and richness) of nitrogen-fixing, phosphate solubilizing, and cellulolytic microorganisms, as well as of the total set of these functional groups.

DIVERSE. We used the DIVERSE tool of the program PRIMER v6 & PERMANOVA add on to determine diversity indexes, using richness as the analysis index.

Non-metric multidimensional scaling (MDS). We conducted non-metric multivariate scaling (nMDS) (Clarke, 1993), in order to project the similarities in the microbial structure between the soil types for each farm and sampling season. The MDS analysis is a multivariate technique of interdependence that aims to represent the existing similarity between a dataset within a geometric space of a few dimensions (Casas & Hurtado, 2012). We obtained MDS representations to visualize the behavior of the abundance of nitrogen-fixing, phosphate solubilizing and cellulolytic microorganisms, as well as the total functional groups.

Canonical analysis of principal coordinates (CAP). We performed CAP (Anderson & Willis, 2003) in order to visualize the relationships between the physicochemical parameters, scores of resilience to climate variability, and the diversity of nitrogen-fixing, phosphate solubilizing and cellulolytic microorganisms, as well as the total set of functional groups.

Results and discussion

Table 1 displays the three physicochemical parameters that showed statistically significant differences related to the ecological or conventional managements of the study farms: 1. Percentage of organic carbon (OC), 2. Soil nitrogen content, and 3. Soil boron content. Higher contents and percentages of these parameters were observed in the farms with ecological management.

The average percentage of OC obtained in the three ecological farms is 7.99% and in the three conventional farms it is 5.09%, indicating that OC percentage is very high for all farms studied (Instituto Geográfico Agustín Codazzi [IGAC], 2000). The higher OC content in the ecological farms could be associated with constant contributions of organic matter (compost, soil cover, weed maintenance) and a greater contribution of organic residues present in ecological agroecosystems, favoring an increase in soil nutrient content. This agrees with Pavan et al. (1999), who mention that, in the long term, high density coffee crops contribute to an increase in soil organic carbon, as a consequence of organic residue accumulation and higher erosion control. This is also related to litter decomposition and conservation tillage that includes zero tillage, among other traditional practices (Martínez, Chiocchio, & Godeas, 2001). Furthermore, erosion has been proposed as the main cause of OC loss, while OC gains result from contributions of organic matter from different sources (Sadeghian, 2003).

In general, there is a similar percentage of N for all farms. According to Table 1, the average percentage for the ecological farms is 0.69% and for the conventional farms it is 0.44%, indicating a statistically significant difference that could be due to a higher OC content and with the presence of legumes in association that contribute nitrogen to the soil in the ecological farms compared to the conventional farms. In other words, OC content is directly related to N content, as reported by (Sadeghian, 2003), who found variations in N content that were explained exclusively as a function of OC content.

Table 1. Averages of the physicochemical parameters assessed in ecological and conventional agroecosystems in Anolaima, Colombia. Same letter: No statistically significant difference. Different letter: Statistically significant difference by the t-Student test at 5 % of probability (the comparisons are only between cropping managements and between growing seasons). ECO: Ecological, CON: Conventional, RAI: Rainy, DRY: Dry

Factors Assessed	Management		Season	
	ECO	CON	RAI	DRY
Humidity (%)	37.25 a	45.11 a	41.74 a	40.61 a
Bulk density (Kg m^{-3})	1.031 a	1.037 a	1.035 a	1.033 a
Plasticity index	11.23 a	13.10 a	14.01 a	10.32 a
pH	5.95 a	5.70 a	5.80 a	5.85 a
OC (%)	7.99 a	5.09 b	6.37 a	6.72 a
N (%)	0.69 a	0.44 b	0.55 a	0.58 a
EA (Meq 100 g^{-1})	0.05 a	0.19 a	0.05 a	0.19 a
P (mg kg^{-1})	51.81 a	51.36 a	52.46 a	51.77 a
ECEC (Meq 100 g^{-1})	26.28 a	25.08 a	24.67 a	26.70 a
Ca (Meq 100 g^{-1})	19.357 a	18.233 a	17.657 a	19.933 a
K (Meq 100 g^{-1})	0.927 a	1.027 a	0.963 a	0.990 a
Mg (Meq 100 g^{-1})	5.875 a	5.537 a	5.905 a	5.507 a
Na (Meq 100 g^{-1})	0.070 a	0.093 a	0.085 a	0.078 b
Cu (Mg Kg^{-1})	2.38 a	2.10 a	2.50 a	1.98 a
Fe (Mg Kg^{-1})	106.17 a	129.05 a	130.63 a	104.58 a
Mn (Mg Kg^{-1})	11.71 a	12.70 a	12.55 a	11.85 a
Zn (Mg Kg^{-1})	16.52 a	9.60 a	12.74 a	13.38 a
B (Mg Kg^{-1})	0.80 a	0.55 b	0.68 a	0.67 a

According to the Sociedad Colombiana de la Ciencia del Suelo (SCCS, 1991), and Table 1, Boron (B) content was high for all farms. Moreover, we found statistically significant differences related to the management type (ecological and conventional), with a greater content found in ecological farms. This result could be attributed to the application of manure compost and other organic fertilizers as part of the agricultural practices of ecological farms, which contribute essential nutrients to the soil, including Nitrogen, Phosphorous, Calcium, Magnesium, and boron, among others. This finding agrees with the study by Alonso and Guzmán (2006), on ecological and conventional agroecosystems in Granada (Spain), where a greater B content in ecological agroecosystems was found to be a consequence of the application of organic fertilizers.

On the other hand, regarding the abundance of cellulolytic bacteria in soils of the agroecosystems studied, no statistically significant differences related to agroecosystem management were found based on the PERMANOVA analysis (Table 2). This could be due to the combined use of chemical products, such as fertilizers and pesticides, with traditional agricultural knowledge in the conventional farms, which includes practices such as cover cropping and polyculture that could be mitigating the impacts of chemical use on cellulolytic bacteria. Additionally, Table 2 shows significant differences related to the sampling season, indicating that cellulolytic bacteria abundance is affected by climate variations, which, in turn, can affect the soil and plants, by variations in the availability of nutrients associated with the carbon cycle. This is a relevant issue, considering the current global discussion on the impact of climate change on agriculture and viceversa. Finally, the interaction management x season (MAxSE) shows that these variables are independent, as there is no statistically significant relationship.

Table 2. PERMANOVA analysis of microbial functional groups abundance in soils from ecological and conventional agroecosystems in Anolaima, Cundinamarca. MA: management. SE: Season. MAxSE: Management x Season. p (perm) ≤ 0.05.

Source	Pseudo-F	P(perm)	Perm.
Cellulolytic bacteria			
MA	0.9466	0.4643	8898
SE	6.4497	0.0039	8882
MAxSE	1.5334	0.2267	8922
Cellulolytic fungi			
MA	2.9919	0.0497	8940
SE	9.7249	0.0029	8924
MAxSE	0.7400	0.5901	8948
Phosphate solubilizing bacteria			
MA	0.5815	0.7380	8906
SE	1.5793	0.1788	8873
MAxSE	2.8028	0.0330	8927
Phosphate solubilizing fungi			
MA	0.6003	0.6262	8862
SE	5.8351	0.0052	8913
MAxSE	0.1952	0.9214	8958
Nitrogen-fixing microorganisms			
MA	1.3116	0.2619	8900
SE	17.637	0.0022	8896
MAxSE	2.7731	0.0435	8866
Total set of functional groups			
MA	1.5608	0.1491	8914
SE	18.435	0.0026	8911
MAxSE	2.6436	0.0156	8913

The MDS analysis of cellulolytic bacteria abundance (Figure 1A) shows clustering among the study farms in relation to soil management. This can be understood as an early indicator of changes that are being generated by the ecological and conventional soil managements, which could be significant if these agricultural practices are maintained. Also, the data tend to group according to the sampling season, which is statistically significant based on the PERMANOVA analysis, and demonstrates the importance of climate changes on the abundance of cellulolytic bacteria in soil.

Regarding cellulolytic fungi abundance in soil, the MDS analysis (Figure 1B) shows two important criteria involved in the clustering of the data: management-related and season-related. This result is confirmed by the PERMANOVA analysis (Table 2) that identified statistically significant differences related to agroecosystem management. This finding shows that the application of chemical products in conventional farms is modifying the abundance of cellulolytic fungi and, according to Bohórquez and Pérez (2007), low cellulolytic fungi abundance leads to slower cellulose decomposition in conventional agroecosystems compared to ecological agroecosystems. Furthermore, this is associated with differences in organic matter content in the study soils, suggesting that organic matter application in ecological farms favors the abundance of cellulolytic fungi that are fundamental in the transformation of cellulose into glucose as an energy source for plants and microorganisms.

Similarly, statistically significant differences were observed between cellulolytic fungi abundance in relation to the season (rainy – dry), indicating that microorganisms associated with the carbon cycle are intermittently available to crop plants and soils, as a function of the season, and this finding demonstrates the importance of climate change and variability on these microorganisms. This analysis also established that the variables management and season are independent, since the interaction MAxSE is not statistically significant.

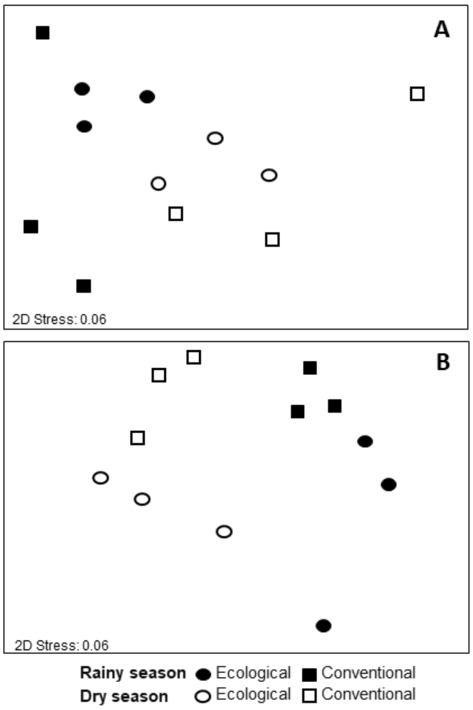

Figure 1. (A) MDS of cellulolytic bacteria abundance in soils of ecological and conventional agroecosystems in Anolaima, Cundinamarca. (B) MDS of cellulolytic fungi abundance in soils of ecological and conventional agroecosystems in Anolaima, Cundinamarca.

In terms of the abundance of phosphate solubilizing bacteria, the MDS analysis (Figure 2A) shows no evident clustering related to agroecosystem management, which is also confirmed by the PERMANOVA analysis (Table 2), since no statistically significant difference was observed. This could be attributed to polyculture, cover cropping, and traditional farm practices applied to the coffee crop in conventional farms, which attenuate the impacts caused by agroproducts application. The results shown here contradict the findings of Tao, Tian, Cai, and Xie (2008), found in their study on phosphate solubilizing bacteria in subtropical soils, which show significant differences related to management (ecological and conventional) ($p < 0.05$).

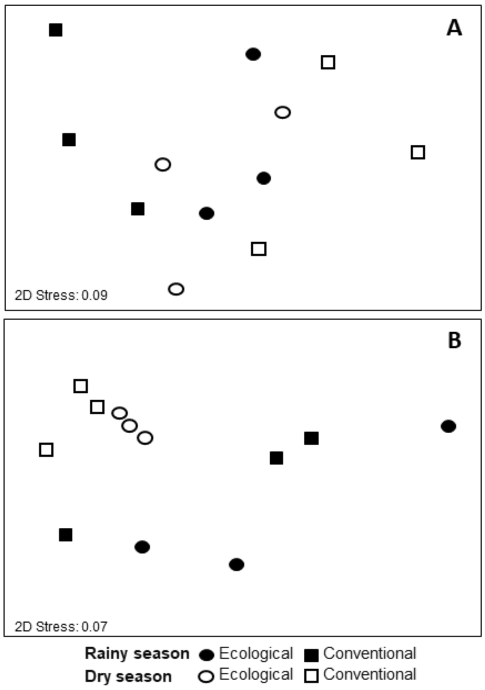

Figure 2. (A) MDS of phosphate solubilizing bacteria abundance in soils of ecological and conventional agroecosystems in Anolaima, Cundinamarca. (B) MDS of phosphate solubilizing fungi abundance in soils of ecological and conventional agroecosystems in Anolaima, Cundinamarca.

The MDS analysis shown in (Figure 2A) does not show a clear clustering of phosphate solubilizing bacteria related to the sampling season, and no statistically significant difference was observed from the PERMANOVA analysis (Table 2). Thus, the climate conditions during the sampling season did not affect the abundance of this functional group. On the other hand, we found a statistically significant interaction between management and season, meaning that these two factors are dependent. This indicates that climate variability and agroecosystem management modify the abundance of microorganisms involved in releasing inorganic phosphorus from total soil phosphorus through solubilization.

The MDS analysis (Figure 2B) does not present associations between phosphate solubilizing fungi and agroecosystem management. This agrees with the PERMANOVA analysis (Table 2), where no statistically significant difference was observed in relation to management type. Although conventional agroecosystems adopt practices established in the Green Revolution, such as fertilizer and pesticide application, the results found here could be attributed to the incorporation of traditional knowledge-based practices such as polyculture and different cover crops that mitigate the effects of chemical applications on the abundance of this microbial functional group.

On the other hand, the MDS analysis (Figure 2B) shows a relationship between phosphate solubilizing fungi and the sampling season, which is confirmed by a statistically significant difference found in the PERMANOVA analysis (Table 2). This demonstrates that phosphate solubilizing fungi abundance is affected by the rainy and dry seasons, so it is fundamental to consider climate changes that can cause modifications to the microbial abundance. We also found no interaction between management and season (MAxSE) in the abundance of phosphate solubilizing fungi, indicating that these variables are independent.

As for nitrogen-fixing microorganisms, the MDS analysis (Figure 3A) shows that the ecological farms tend to cluster, although the PERMANOVA analysis (Table 2) shows no statistically significant difference in nitrogen-fixing bacteria abundance related to farm management.

The MDS analysis shown in (Figure 3A) also demonstrates that nitrogen-fixing bacteria tend to cluster in relation to rainy and dry seasons, and this is confirmed by the PERMANOVA analysis (Table 2) that shows a statistically significant difference related to the season. This proves that climate conditions are relevant in the abundance of this microbial functional group. Furthermore, there is a statistically significant interaction between management and season (MAxSE), which suggests that climate conditions in the study farms affect the abundance of bacteria capable of reducing atmospheric nitrogen to ammonium, making it available to plants and other soil organisms (Pedraza et al., 2010).

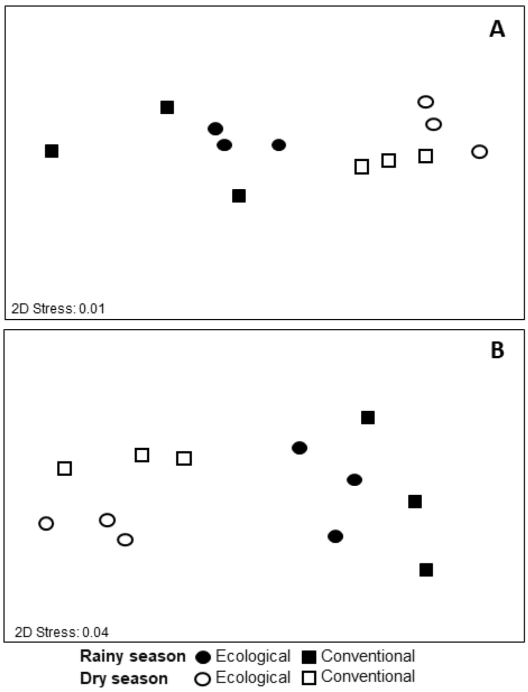

Figure 3. (A) MDS of nitrogen-fixing microorganism abundance in soils of ecological and conventional agroecosystems in Anolaima, Cundinamarca. (B) MDS of the abundance of the total set of microbial functional groups in soils of ecological and conventional agroecosystems in Anolaima, Cundinamarca.

The MDS analysis (Figure 3B) of the abundance of the total set of microorganisms shows that the ecological and conventional farms tend to cluster differentially. Although these groupings are not statistically significant, according to the PERMANOVA analysis (Table 2), they could represent an early indicator that this tendency can lead to significant differences if the agricultural management in conventional farms is maintained, including the use of chemical fertilizers and pesticides.

On the other hand, the MDS analysis (Figure 3B) shows a clear clustering tendency of the total set of microorganisms in relation to the sampling season, which is confirmed by statistically significant differences found in the PERMANOVA analysis (Table 2). This demonstrates a close relationship between microbial functional groups abundance and climate variability. Furthermore, this analysis indicates that the variables management and season are dependent, since the interaction MAxSE is statistically significant, meaning that agroecosystem management in a given season affects the abundance of microbial functional groups.

Regarding the richness of the microbial functional groups, Table 3 shows that no statistically significant differences were found due to agroecosystem management. This could be attributed to the different traditional cultural practices carried out in the conventional farms (polyculture, zero tillage, and non-use of heavy machinery), which have mitigated the effects caused the conventional practices adopted from the Green Revolution, such as chemical fertilizer and pesticide applications.

Based on Table 3, we can also observe that the richess of the functional groups during the sampling seasons (rainy and dry) does not show a statistically significant difference, except for the nitrogen-fixing bacteria. However, by comparing the total microorganisms, we found significant differences between the sampling seasons, which once again prove the existing relationship between climate conditions and diversity of soil functional groups. These microorganisms contribute to the mineralization of organic nutrients in the soils, thus, helping crop growth and development.

Table 3. Richness of each of the functional groups of microorganisms in soils of ecological and conventional agroecosystems in the municipality of Anolaima, Cundinamarca. Same letters (a): No statistically significant difference. Different letters (a-b): Statistically significant differences by the t-Student test at 5 % of probability (the comparisons are only between cropping managements and between growing seasons).

Functional group	Conventional		Total conventional	Ecological		Total ecological
	Rainy	Dry		Rainy	Dry	
Cellulolytic bacteria	19 a	19 a	38 a	16 a	20 a	36 a
Cellulolytic fungi	17 a	13 a	30 a	20 a	21 a	41 a
Phosphate solubilizing bacteria	19 a	26 a	45 a	21 a	24 a	45 a
Phosphate solubilizing fungi	8 a	13 a	21 a	6 a	15 a	21 a
Nitrogen-fixing microorganisms	11 a	18b	29 a	17 a	15 b	32 a
Total microorganisms	74 a	84 b	158 a	88 a	95 a	183 a

Regarding the relationship between the diversity of the microbial functional groups and the physicochemical parameters of the study soils, the CAP (Figure 4) showed relationships with Sodium, Copper and pH present in conventional farms. Therefore, these parameters are associated with a greater diversity of microbial functional groups in conventional farms. On the other hand, in ecological farms, diversity is related to plasticity, Magnesium, and exchangeable acids.

In terms of the sampling seasons, we observed correlations between the total set of microbial functional groups and important chemical parameters in soil quality. For the rainy season, there are correlations between pH, magnesium, and plasticity and the microbial functional groups of the study farms, indicating that rainy seasons provide conditions that favor the relationships between these physicochemical parameters and the diversity of functional groups. Meanwhile, for the dry season, no clear correlation can be observed, as only two study farms show a tendency related to pH and copper; thus, indicating that this season does not provide conditions for relationships existing between microbial activities and the physicochemical parameters analyzed. Furthermore, climate variation affects these relationships, and is more evident in the rainy season.

As for possible relationships between the diversity of soil microbial functional groups and ecological and cultural parameters that define resilience scores to climate variability, the CAP (Figure 5) showed relationships with economical aspects, such as percentage of hired workers and income, in conventional farms. This indicates that a higher income and more hired workers in the agroecosystem contribute to the diversity of the total functional groups of microorganisms.

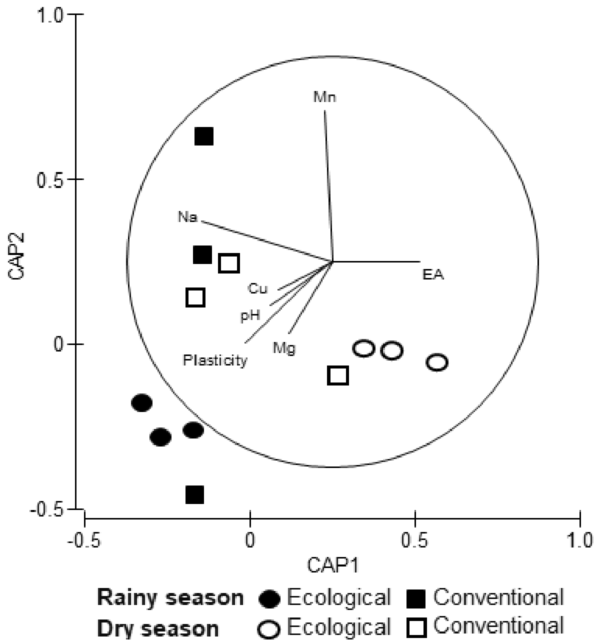

Figure 4. CAP of the relationship between physicochemical parameters and the diversity of microbial functional groups in soils of ecological and conventional agroecosystems in the municipality of Anolaima, Cundinamarca.

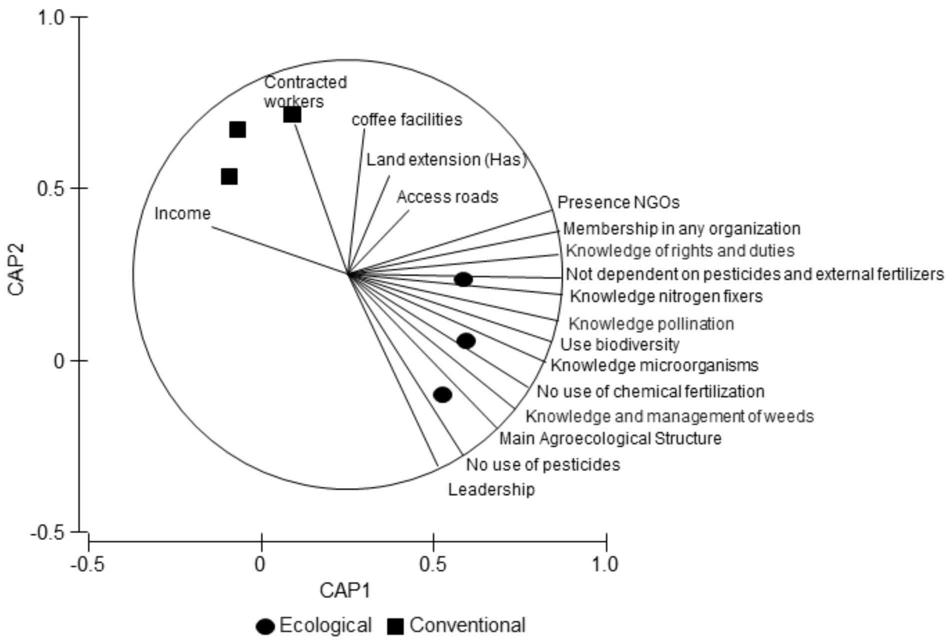

Figure 5. CAP of the relationship between the biophysical and cultural characteristics that determine resilience to climate variability and microbial functional groups in soils of ecological and conventional agroecosystems in the municipality of Anolaima, Cundinamarca.

In contrast, in the ecological farms, there are diverse factors affecting the microbial diversity of the functional groups assessed, including: knowledge of microorganisms, weed management, biodiversity use, knowledge of nitrogen fixing microorganisms and pollinators, and agroecological main structure. This indicates that, for the study farms, these parameters favor the abundance and richness of microbial functional groups. In addition, relationships with social parameters can also be observed, such as the presence of a NGO or the participation in an organization or group. This is also favorable for microorganism diversity, since those in charge of ecological agroecosystems can acquire knowledge on farm management, through these organizations, allowing them to develop activities that benefit the microbial diversity.

Likewise, we found a relationship between the microbial diversity of the ecological farms and the parameters of resilience to climate variability, such as the non-use of chemical fertilization, pesticides and external fertilizers. This demonstrates that the non-use of chemical products is contributing to the diversity of total microbial functional groups and is generating greater resilience, as mentioned by Vargas and Sicard (2013), suggesting that farmers have access to resources within their own farms that allow them to implement and face agricultural processes, providing them with greater management possibilities.

Conclusion

Were found statistically significant differences in OC, N, and B, related to the management of the agroecosystems studied, and found higher contents in ecological farms compared to conventional farms. Were found clustering associated with management and cellulolytic bacteria and fungi abundances. No differences found in diversity of phosphate solubilizing or nitrogen-fixing microorganisms, related to management. The diversity of microbial functional groups was affected by the climatic condition of sampling season. Management was relevant in relationships between resilience scores to climate variability and cellulolytic microorganisms; in ecological agroecosystems, biodiversity knowledge, agroecological main structure, and participation of farmers in organizations were important.

Acknowledgements

We especially thank the farmers of Anolaima, Colombia, who allowed us to carry out this study. We also thank C.A. Córdoba for the help provided for this research.

References

Alonso, A. M., & Guzmán, G. I. (2006). Evaluación comparada de la sostenibilidad agraria en el olivar ecológico y convencional. *Agroecología, 1*, 63-73.

Altieri, M., & Nicholls, C. I. (2000). *Agroecología: teoría y práctica para una agricultura sustentable*. México, ME: Pnuma.

Anacona, A. (2008). *Efecto del manejo agrícola sobre la composición microbiana y actividad enzimática de suelos provenientes de agroecosistemas de papa. (Solanum spp.).* Bogotá, CO: Universidad Nacional de Colombia.

Anderson, M. J. (2001). A new method for non-parametric multivariate analysis of variance. *Austral Ecology, 26*(1), 32-46. doi: 10.1111/j.1442-9993.2001.01070.pp.x

Anderson, M. J., Gorley, R. N., & Clarke, K. R. (2008). *PERMANOVA+ for primer: guide to software and statistical methods*. Plymouth, UK: Primer-E.

Anderson, M. J., & Willis, T. J. (2003). Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology. *Ecology, 84*(2), 511-525. doi: 10.1890/0012-9658(2003)084[0511:CAOPCA]2.0.CO;2

Avellaneda-Torres, L.M., León, T., Guerra, E., & Rojas, E. T. (2020). Potato cultivation and livestock effects on microorganism functional groups in soils from the neotropical high Andean Páramo. *Revista Brasileira de Ciência do Solo*, *44*, 1-25. doi: 10.36783/18069657rbcs20190122

Avellaneda-Torres, L. M., Pulido, C. P. G., & Rojas, E. T. (2014). Assessment of cellulolytic microorganisms in soils of Nevados Park, Colombia. *Brazilian Journal of Microbiology, 45*(4), 1211-1220. doi: 10.1590/s1517-83822014000400011

Bohórquez, D. M. G., & Pérez, L. I. (2007). *Aislamiento y evaluación de microorganismos celulolíticos a partir de residuos vegetales frescos y en compost generados en un cultivo de crisântemo (Dendranthema grandiflora).* Bogotá, CO: Pontificia Universidad Javeriana. Retrieved from https://repository.javeriana.edu.co/handle/10554/8296

Casas, F. M. G., & Hurtado, J. M. R. (2012). El análisis de escalamiento multidimensional: una alternativa y un complemento a otras técnicas multivariantes. *La Sociología en sus Escenarios*, 25.

Clarke, K. R. (1993). Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology, 18*(1), 117-143. doi: 10.1111/j.1442-9993.1993.tb00438.x

Clarke, K. R., & Warwick, R. M. (2001). *Change in Marine Communities: an approach to statistical analysis and interpretation*. Plymouth, UK: Primer-E.

Fallas, G., Chacón, M., & Castro, J. (2009). Sostenibilidad de sistemas agrícolas de fincas ecológicas y tradicionales en Costa Rica. *Cuadernos de Investigación UNED Research Journal, 1*(2), 151-161. doi: 10.22458/urj.v1i2.228

Grajales, G. I. C., Gómez, H. G., Quintero, A. I., & Grisales, L. N. V. (2006). Desarrollo y validación de metodología para evaluar con indicadores la sustenibilidad de sistemas productivos campesinos de la asociación de caficultores orgánicos de Colombia - ACOC. *Investigaciones de Unisarc Boletin, 4*(2), 22-46.

Instituto Geográfico Agustín Codazzi [IGAC]. (2000). *Estudio general de suelos y zonificación de tierras del departamento de Cundinamarca*. Bogotá, CO: IGAC.

Martínez, A. E., Chiocchio, V. M., & Godeas, A. M. (2001). Hyphomycetes celuloliticos en suelos de bosques de nothofagus, tierra del fuego. *Gayana. Botánica, 58*(2), 123-132. doi: 10.4067/S0717-66432001000200003

Muschler, R. G. (2004). Shade management and its effect on coffee growth and quality. In J. N. Wintgens (Ed.), *Coffee: growing, processing, sustainable production: a guidebook for growers, processors, traders, and researches* (p. 391-418). Weinheim, AL: Wiley-VCH Verlag GmbH & Co. KGaA.

Osorio, L. G., & Alcántara, H. V. (2004). Evaluación de la sustenibilidad del sistema de algodón orgánico en la zona de trópico húmedo del Perú. *LEISA - Revista de Agroecología, 19*, 47-52.

Pavan, M. A., Chaves, J. C. D., Siqueira, R., Androcioli Filho, A., Colozzi Filho, A., & Balota, E. L. (1999). High coffee population density to improve fertility of an Oxisol. *Pesquisa Agropecuária Brasileira, 34*(3), 459-465. doi: 10.1590/S0100-204X1999000300018

Pedraza, R. O., Teixeira, K. R. S., Scavino, A. F., Salamone, I. G., Baca, B. E., Azcón. R., ... Bonilla, R. (2010). Microorganismos que mejoran el crecimiento de las plantas y la calidad de los suelos. *Corpoica Ciencia & Tecnología Agropecuaria, 11*(2), 155-164. doi: 10.21930/rcta.vol11_num2_art:206

Sadeghian Kh, S. (2003). Efecto de la fertilización con nitrógeno, fósforo, potasio y magnesio sobre las propiedades químicas de suelos cultivados en café. *Cenicafé, 54*(3), 242-257.

Sociedad Colombiana de la Ciencia del Suelo [SCCS]. (1991). *Fundamentos para la interpretación de análisis de suelos. plantas y aguas para riego.* Santafé de Bogotá, CO: SCCS.

Sosa, M. L., Escamilla, P. E., & Díaz, C. S. (2008). Organic coffee. In J. N. Wintgens (Ed.), *Coffee: growing, processing, sustainable production: a guidebook for growers, processors, traders, and researches* (p. 339-354). Weinheim, AL: Wiley-VCH Verlag GmbH & Co. KGaA.

Tao, G., Tian, S., Cai, M., & Xie, G. (2008). Phosphate-Solubilizing and -Mineralizing Abilities of Bacteria Isolated from Soils. Pedosphere, 18(4), 515-523. doi: 10.1016/S1002-0160(08)60042-9

Vargas, C. A. C., & Sicard, T. E. L. (2013). Resiliencia de sistemas agrícolas ecológicos y convencionales frente a la variabilidad climática en Anolaima (Cundinamarca - Colombia). *Agroecología, 8*(1), 21-32.