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Soil organic carbon storage in different agroforestry systems associated with coffee in Nariño, Colombia*

Almacenamiento de carbono orgánico en el suelo en diferentes sistemas agroforestales en asocio con café en Nariño, Colombia.

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Abstract

Introduction. Anthropogenic activities are one of the causes of the increase in global temperature, which affects agro-environmental, ecological and socioeconomic processes. The contributions of agricultural production systems in the capture and storage of greenhouse gases have been little studied. Still, the literature indicates that the inclusion of trees on farms is an option to capture and store some greenhouse gases. **Objective**. To evaluate the relationship between floristic and structural diversity of coffee production systems and soil organic carbon storage (SOC). **Materials and methods.** The study was carried out during the period 2019-2020, in three localities Sandoná, San Pablo and Buesaco, Nariño-Colombia. Twelve agroecosystems with coffee were visited, where Shannon-Weiner and Simpson indices, tree density and complete soil analysis with samples at 30 cm depth were evaluated. An analysis of variance and principal components was sufficient for the analysis of the information**. Results.** The SOC was not presented statistical differences ($p>0.05$), which ranged between 38.55 Mg ha^{-1} in the full sun coffee arrangement in Buesaco and 96.63 Mg ha^{-1} in the coffee arrangement with miscellaneous in the same municipality, which presented the highest species diversity. **Conclusions.** It was proved that the coffee harvest associated with agroforestal systems (T3 and T4) with higher diversity and abundance of species, is higher than carbon accumulated in the soil compared to the monoculture arrangement (80,43 Mg ha^{-1} vs 58,32 Mg ha^{-1}, severally), this diversification give to the family and enviroment some services and goods, contributing to the mitigation of climate change.

Keywords: Ecosystem services; agroforestry, soil conservation, *Coffea*.

Resumen

Introducción. Las actividades antropogénicas son una de las causas del aumento de la temperatura global, lo que afecta los procesos agroambientales, ecológicos y socioeconómicos. Las contribuciones de los sistemas de producción agrícola en la captura y almacenamiento de gases de efecto invernadero han sido poco estudiadas, pero la literatura indica que la inclusión de árboles en las fincas es una opción para capturar y almacenar algunos gases de efecto invernadero. **Objetivo**. Evaluar la relación entre la diversidad florística y estructural de los sistemas de producción de café y el carbono orgánico almacenado en el suelo (COS). **Materiales y métodos**. El estudio se llevó a cabo en durante el período 2019-2020, en tres localidades Sandoná, San Pablo y Buesaco, Nariño-Colombia. Se visitó 12 agroecosistemas con café, donde se evaluó los índices de Shannon-Weiner y Simpson, la densidad de árboles y el análisis completo del suelo con muestras a 30 cm de profundidad. Un análisis de varianza y componentes principales fueron suficientes para el análisis de la información. **Resultados**. El COS no presentaron diferencias estadísticas ($p>0,05$), el cual varió entre 38,55 Mg ha^{-1} en el arreglo de café a pleno sol en Buesaco y 96,63 Mg ha^{-1} en el arreglo de café con misceláneas en el mismo municipio, el cual presentó la mayor diversidad de especies. **Conclusiones. Se demostró** que, el cultivo de café en asocio con sistemas agroforestales (T3 y T4) con mayor diversidad y abundancia de especies, supera el carbono acumulado en el suelo en comparación con el monocultivo de café (80,43 Mg ha^{-1} vs 58,32 Mg ha^{-1}, respectivamente); esta diversificación provee de bienes y servicios a la familia y el ambienteal contribuir lamitigación del cambio climático.

Palabras claves: servicios ecosistémicos, agroforestería, conservación de suelos, *Coffea*.

Introduction

Since ancient times earth has experienced fluctuations in climate by temperature, humidity, atmospheric pressure, and precipitation, among other phenomena; such as variations in average weather conditions, that generate an abnormal behavior of the climate within spatial scales; it can be an eventual transition as the climatic variability or conversely an extended modification denoting a non-time process such as climate change (Instituto de Hidrología, Meteorología y Estudios Ambientales [IDEAM] et al., 2015). The increase in greenhouse gas (GHG) emissions due to anthropogenic activities has grown by an average with evidence in the interannual statistics of 1,3 % (1970 and 2000) of 2.2 % (2000 and 2010) (Intergovernmental Panel on Climate Change [IPCC], 2023) becoming of world problematic that affects the socioeconomics process (diseases and pets increasing) agro-environmental (increasing of agrochemical inputs) ecologists (thaws and loss of trees area) and sociocultural (loss of culture knowledge and migrations), causing the planet's average temperature to rise by up to 2.5 °C (Andrade et al., 2022; Leonel et al., 2023).

In Colombia, El Niño-Southern Oscillation is the main phenomenon causing the interannual variability of precipitation, having a great influence on rainfall in the southwest of the country (Cerón et al., 2021). This generates a socioeconomic impact, because agriculture depends on the rainfall regime and the summer season; this imbalance in climatic timing has caused the proliferation of pests, changes in crop vegetative cycles, a decrease in crop yields and a threat to food security, among others (Canchala et al., 2022; IDEAM et al., 2015). This has led to the search for alternatives, including the adoption of agricultural practices that allow the additional accumulation of carbon in the soil, which is a natural resource that contributes to the well-being of the planet and the community through the ecosystem functions and services it provides (Burbano-Orejuela, 2016).

In Latin America, there is evidence of research in different knowledge, techniques and knowledge that can contribute to proposing mitigation and adaptation alternatives, within which the adoption of so-called carbon sinks that are represented by vegetation, soil and ocean is envisaged (Delgado-Vargas et al., 2022; Leonel et al., 2023). Among them, agroforestry stands out, recognized for the incorporation of different levels of biodiversity of tree species with the potential to be associated with different agroforestry designs, providing a variety of ecosystem services, such as soil carbon storage - SOC (Ramos-Prado et al., 2023; Somarriba et al., 2023). With the intermediation of plants and the participation of soil organisms, carbon is transformed into organic matter that accumulates in the soil for long periods (Burbano-Orejuela, 2018).

Added to this is the fact that very little research has been done on coffee production systems and agroforestry alternatives in coffee-growing areas as potential carbon sinks. Therefore, it is of great importance to develop research on this type of interaction and to know the potential of agricultural systems in association with perennials woody ones regarding the storage of carbon in the soil in different coffee production systems of Nariño. This research evaluated the relationship between floristic and structural diversity of coffee production systems and soil organic carbon storage (SOC).

Materials and methods

Study places

The research was conducted from 2019 to 2020 in the southwestern of Nariño-Colombia, in the municipality of Sandoná (N: 1°17’05”, O: 77°28’16”) in the villages of San Gabriel, Plan Ingenio, San Andrés and San Fernando; in the municipality of San Pablo (N: 1º36’06’’, O: 77º00’15’’) in the villages of El Alto and Alto Llano and in the municipality of Buesaco (N: 1°23’05”, O: 77°09”23”) in the villages of Veracruz, Hatillo Medina and Medina Espejo (Table 1). The area is located in a Premontane Moist forest – (bh – PM) (Holdridge, 1982). Soils were classified as class II - III, undulating soils with 9 %, with a moderate tendency to hydric and wind erosion, with moderate acidity, and moderately impeded drainage (Instituto Geográfico Agustín Codazzi, 2004).

Table 1. Agroclimatic conditions of the localities Buesaco, San Pablo and Sandoná, Nariño, Colombia. 2019 – 2020.

Cuadro 1. Condiciones agroclimáticas de las localidades Buesaco, San Pablo y Sandoná, Nariño, Colombia. 2019 – 2020.

Location	Altitude (meters)	Average temperature (°C)	Precipitation (mm)	Soil order	Soil taxonomy	Range of the farm area (ha)
Buesaco	1692	18	1400	Molisol	Entic Hapludolls,	
Typic Argiudolls	0.25 - 2					
San Pablo	1700	19	1998	Molisol	Entic Hapludolls,	
Typic Hapludands	0.75 – 1.8					
Sandoná	1817	18.1	1091	Molisol	Entic Hapludolls	0.75 - 7

Traditional agroforestry arrangements (AFS) with coffee were selected, taking into account the productive age (4 - 5 years); according to the methodology proposed by Somarriba et al. (2013), Pinoargote et al. (2017) and Delgado-Vargas et al. (2022); In a Randomised Complete Block design by localities; (municipalities of Buesaco, San Pablo and Sandoná) with four treatments and three repetitions: coffee in full sun (T1); coffee and banana (T2); coffee , multipurpose trees (T3) and coffee and miscellaneous (Musaceae, multipurpose trees , timber and fruit trees (T4), by a total of twelve experimental units evaluated.

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Floristic and structural diversity of the production systems

To obtain the information, complete agroforestry inventories were carried out of all the species of plants of canopy shaded per farm, and the density and floristic composition of the production system were determined. The diversity of plant species was determined too. Dasometric measurements were taken (height, diameter at breast height - DBH), basal area (at a height of 1.30 m) by type of multipurpose woody perennial (fruit trees, forage, firewood, timber, ornamentals and musaceae). The percentage of shade (visual method) and the diversity of species were determined using the Shannon-Weiner and Simpson indices.

Estimation of organic carbon storage in the soil

An area of 10,000 m^2 (100 x 100 m) was taken as an experimental plot for each treatment, according to the methodology proposed by Aguilar & Guharay (2009). For soil sampling, 10 random subsamples were taken from each treatment, at a depth of 30 cm, which were grouped to obtain a sample of 1 kg. In the laboratory, carbon content was determined using the combustion method (MacDicken, 1997) and bulk density using the "cylinder of known volume" method (Forsythe, 1975). The samples were also used to determine some physical and chemical properties of the soils in the different coffee production systems, can be appreciated in the Table 2.

Table 2. Chemical and physical variables analyzed in edaphic soil in specialized soil laboratory. University de Nariño. San Juan de Pasto, Colombia. 2020.

Cuadro 2. Variables químicas y físicas analizadas en las muestras edáficas en laboratorio especializado de suelos. Universidad de Nariño. San Juan de Pasto, Colombia. 2020.

Parameter	Method	References
Soil organic carbon	Wet digestion (Walkley-Black)	Icontec, 2006
Soil organic matter	Wet digestion (Walkley-Black)	Icontec, 2006
Total soil nitrogen	Modified Kjeldahl	IGAC, 2006
Apparent density	Graduated cylinder	Icontec, 2006
Real density	Pycnometer	IGAC, 2006
Soil texture	Bouyoucos	IGAC, 2006
Total porosity	P = 1–(Da/Dr)*100	IGAC, 2006
Fertility	Different methods	Icontec, 2006

Estas referencias no están

Statistical analysis

A design was established by completely random blocks (Buesaco, San Pablo and Sandona) with four treatments and three repetitions, where the treatments were productive systems, coffee in full sun, (T1), coffee and banana (T2), coffee, multipurpose trees (T3), and coffee and various (Musaceae, multipurpose trees, timber and fruits trees (T4). A modified Shapiro-Wilks test was used to determine the normality of the data through a variance of a one-way analysis lead to determine the significant statistical differences between treatments. Throw Tukey's test was used to separate treatment means. Principal component analysis (PCA) was used to determine possible groupings of variables and production systems with variables having a coefficient of variation (CV) greater than 30 %. R software version 4.3.0 (R Core Team, 2023) was used to process the information with 95 % probability.

Results

Floristic and structural diversity of the production systems

A total of 359 individuals of 37 species were recorded for 25 families. There was a higher density of woody tree/shrub species in T4 in the three locations, with a total of 108 individuals/ha; richness in T3 and T4 ranged between four and twelve multipurpose woody perennial species. The highest abundance was found in the species *Trichanthera gigantea* (Bonpl.) *Nees, Musa × paradisiaca* L, *Cyphomandra betacea* (Cav.) Sendtn, *Citrus limon* (L.) Osbeck, *Carica papaya* L, *Psidium guajava* L. Identifying an average of four species per coffee plantation that were classified by use as follows: 58 % fruit, 13 % forage, 13 % ornamental, 13 % timber and 1 % wood energy (firewood), as presented in Table 3.

Table 3. Diversity indices and percentage of shade in the productive systems of *C. arabica* in the municipalities of Buesaco, Sandoná and San Pablo, Nariño, Colombia. 2019 - 2020.

Cuadro 3. Índices de diversidad y porcentaje de sombra en los sistemas productivos de *C. arabica* de los municipios de Buesaco, Sandoná y San Pablo, Nariño, Colombia. 2019 - 2020.

	Buesaco				Sandoná				San Pablo			
Indexes	**T1**	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
S-W	0 (b)	0.65 (b)	1.40 (a)	2.2 (a)	0 (b)	0.61 (b)	2.1 (a)	1.85 (a)	0 (b)	0.54 (b)	1.9 (a)	1.7 (a)
S	1 (b)	0.54 (b)	0.20 (a)	0.12 (a)	1 (b)	0.58 (b)	0.12 (a)	0.21 (a)	1 (b)	0.64 (b)	0.14 (a)	0.19 (a)
J	0.13 (a)				0.18 (a)				0.15 (a)			
Shade	0 (b)	11.8 (b)	38.8 (a)	84.4 (a)	0 (b)	45.9 (b)	56.7 (a)	62.4 (a)	0 (b)	19.3 (b)	86.3 (a)	66.1 (a)

S-W means shannon-weiner index. S menas simpson's index. J means jaccard index. shade. Parameters with different letters differ statistically (p<0.05) / S-W significa índice de shannon-weiner. S significa índice de simpson. J significa índice de jacard. Shade significa porcentaje de sombra. Parámetros con letras diferentes difieren estadísticamente (p<0,05).

Higher values were presented for the diverging indices in T3 and T4, in relation to the Jaccard similarity coefficient the values found are very close to 0, presenting a decrease in species shared between municipalities. The highest percentage of shade was presented in T3 and T4, the species with the highest percentage of shade in the coffee plantation are the cajeto (*Palicourea amethystina* (Ruiz & Pav.) DC.), guayacan (*Tabebuia chrysantha* (Jacq.) G. Nicholson) and *Mangifera indica* L., with 90, 83 and 71 %, respectively for the municipalities of Sandoná and San Pablo.

Estimation of carbon stored in the soil – SOC

There were no significant statistical differences in the production systems with the concentration of SOC (p>0.51) (Table 4). There was a tendency for a greater accumulation of carbon in the T4 treatment corresponding to coffee, banana, fruit trees, and leguminous plants, which ranged between 66.63 Mg ha^{-1} and 86.83 Mg ha^{-1}. Similarly, there was a tendency to a lower accumulation in T1 which ranged between 38.55 Mg ha^{-1} and 76.14 Mg ha^{-1}.

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Table 4. Total carbon stored in the soil in the production systems of *C. arabica* in the municipalities of Buesaco, Sandoná and San Pablo, Nariño, Colombia. 2019 - 2020.

Cuadro 4. Carbono total almacenado en el suelo en los sistemas productivos de *C. arabica* de los municipios de Buesaco, Sandoná y San Pablo, Nariño – Colombia. 2019 - 2020.

Treatments	SOC (Mg ha^{-1})	N (kg·ha^{-1})	OM (%)
T4	80.43[a]	7.24[a]	4.75[a]
T2	71.57[a]	6.07[a]	4.43[a]
T3	68.56[a]	5.53[a]	3.85[a]
T1	58.32[a]	5.02[a]	3.52[a]

Principal component analysis

The Principal Component Analysis (PCA) made it possible to form four large factors to explain 81% of the total variation evaluated (Table 5). The first factor explains 28% of the variability and is mainly composed of the variables boron (-72.84), phosphorus (-70.5), Shannon (-52.96), and shade (-49.05). This shows that the lack of the tree component that casts shade on the coffee makes the soil present greater phosphorus retention, due to the traditional tillage management. The second factor, which explained 50% of the variability observed, was mainly composed of the variables total trees per hectare (-50.10), organic matter (-36.93), and diameter at breast height (-25.068), where bulk density and pH stood out. The third factor, which explained 69% of the total variation related to cation exchange capacity CEC (-57.82), soil potassium content (-31.38), shade (-30.37), and Shannon index (-30.31). Finally, the fourth factor showed an 81% explanation of the variability with the highest contribution of organic matter (-51.55) in this component (Table 6).

Table 5. Total variability of the different components of the production systems of *C. arabica* in the municipalities of Buesaco, Sandoná, and San Pablo, Nariño, Colombia. 2020.

Cuadro 5. Variabilidad total de los diferentes componentes de los sistemas productivos de *C. arabica* de los municipios de Buesaco, Sandoná y San Pablo, Nariño – Colombia. 2020.

Component	Value	Percent	Cumulative (%)
C1	3.3337	3.3340	28
C2	2.6732	6.0070	50
C3	2.3056	8.3130	69
C4	1.3654	9.6780	81
C5	1.0599	10.7380	89
C6	0.6804	11.4180	95
C7	0.2625	11.6810	97
C8	0.1561	11.8370	99
C9	0.1003	11.9370	99
C10	0.0473	11.9840	100
C11	0.0156	12.0000	100

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Table 6. Relative contribution of variables to different components of *C. arabica* production systems in the municipalities of Buesaco, Sandoná and San Pablo, Nariño, Colombia. 2019 - 2020.

Cuadro 6. Contribución relativa de las variables a los diferentes componentesde los sistemas productivos de *C. arabica* de los municipios de Buesaco, Sandoná y San Pablo, Nariño, Colombia. 2020.

	Components			
Variable	**C1**	**C2**	**C3**	**C4**
pH	12.6629	41.2917	-21.7935	-17.90954
OM	-0.0515	-36.9307	-5.6915	-51.55449
Phosphorus	-70.5330	13.5905	4.8983	0.34569
CEC	22.0365	-1.7344	-57.8151	11.64876
Magnesium	30.3755	16.6955	-26.2119	11.0904
Potassium	-1.9272	1.6961	-31.379	-2.66205
Boron	-72.8396	4.2052	0.3492	0.03514
DBH	-2.2276	74.2125	-1.4609	-2.18829
Shadow	-49.0486	-0.2291	-30.3069	2.54917
Total trees	-1.0475	-50.1029	-12.4585	-5.3115
Shannon	-52.9596	1.5612	-30.3703	-2.86928

pH: Indication of the acidity or alkalinity of soil; OM: Organic matter; CEC: Cation exchange capacity; DBH: Diameter at breast height. / pH: medición de la alcalinidad o acidez del suelo; MO: materia orgánica; CIC: capacidad de intercambio catiónico; DAP: diámetro a la altura de pecho.

The principal component analysis ordination (Figure 1) showed a slight clustering of the variables Shanon-Weiner Index, amount of shade and boron content represented in the systems coffee with fruit trees and coffee with Musaceae. Similarly, total trees, OM, pH, bulk density and DBH had a strong influence on component 2.

Hierarchical classification analysis

The hierarchical classification analysis allowed the identification of three hierarchical groups or clusters, characterized by the similarity between them and by their differences with the accessions that formed the groups (Figure 2).

Cluster one groups coffee farms with various crops (coffee, bananas, fruit trees, legumes) In this cluster there is a significant contribution of boron and phosphorus equal to or higher than the average 0.41 and 60 ppm respectively. Compared to the overall average of 0.24 and 20.88 ppm respectively. In cluster two the free exposure coffee systems are agglomerated, which presents low variability due to the presence of only one component (coffee), there are no woody plants that contribute to the DBH and there is no shade. The variables of this system present mean values lower than the general mean in the Shannon index, DBH and shade index variables. This correlates with the low amount of organic matter accumulated and therefore the low capacity of this production system to accumulate carbon. In cluster three, the largest number of production systems is found. These farms contain coffee systems with bananas and coffee with fruit trees, they are the farms with average values in all the indices. They have an OM percentage of 4.14 %, pH of 5.6, boron of 0.24, P of 20 ppm, and bulk density of 0.97, among others.

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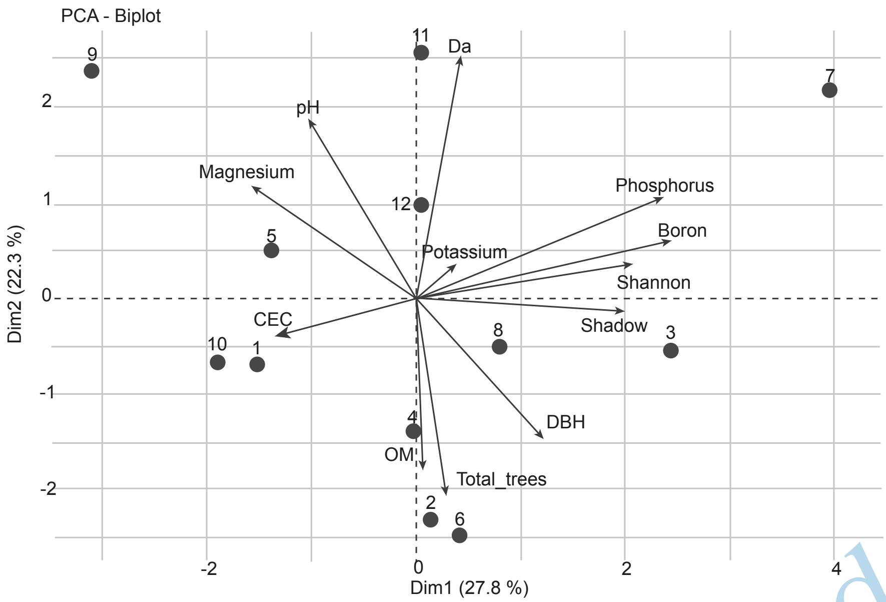

Figure 1. Principal Component Analysis (PCA) between the physical and chemical properties of the soil, Diameter at breast height, shade canopy and total trees associated with the types of productive systems of *C. arabica* production systems in the municipalities of Buesaco, Sandoná and San Pablo, Nariño, Colombia. 2019 - 2020.

pH: Indication of the acidity or alkalinity of soil; OM: Organic matter; CEC: Cation exchange capacity; DBH: Diameter at breast height.

Figura 1. Análisis de componentes principales (PCA) entre las propiedades físicas y químicas del suelo, Diámetro a la altura de pecho, dosel de sombra y total de árboles asociado a los tipos de sistemas productivos de *C. arabica* de los municipios de Buesaco, Sandoná y San Pablo, Nariño, Colombia. 2020.

pH: medición de la alcalinidad o acidez del suelo; MO: Materia orgánica; CIC: Capacidad de intercambio catiónico; Total_arb: Total trees; DAP: Diámetro a la altura de pecho; Da: Densidad aparente; Total árboles/ha; sombra: shade.

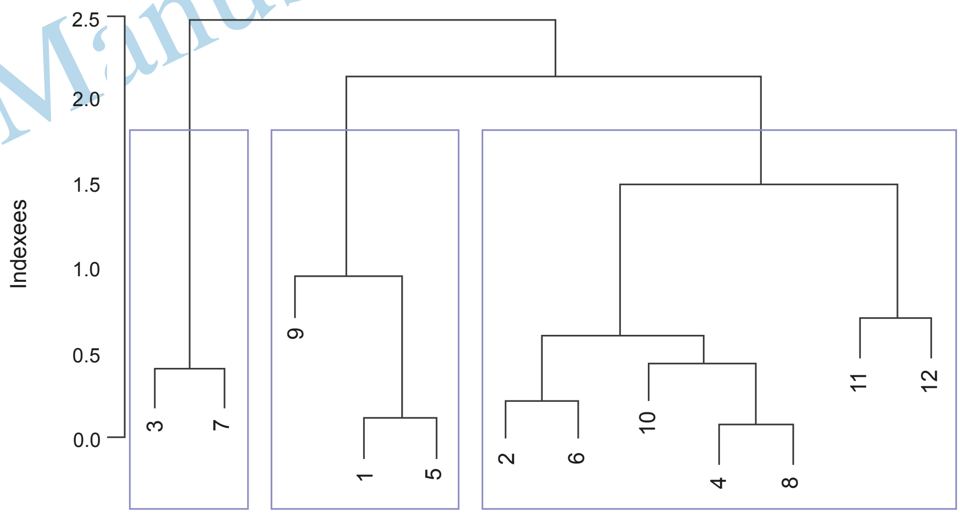

Figure 2. MCL dendrogram of the variables evaluated in the production systems of *C. arabica* production systems in the municipalities of Buesaco, Sandoná and San Pablo, Nariño, Colombia. 2019 - 2020.

Figura 2. Dendograma MCL de las variables evaluadas en los sistemas productivos de *C. arabica* de los municipios de Buesaco, Sandoná y San Pablo, Nariño – Colombia. 2020.

Discussion

The department of Nariño has two agroecological zones of warm climate with similar agroclimatic characteristics, corresponding to ecotopes 220A and 221A, where there is evidence of Entic Hapludolls and Typic Argiudolls soils, being characteristic of the order of molisols, which are mineral soils (sediments and organic residues), with high clay content, rich in cations that form bases and nutritive salts (Gómez et al., 1991; Criollo et al., 2016). In the stratified agroforestry system in association with coffee, a higher carbon/nitrogen ratio was evidenced compared to conventional coffee (T4 11.10 and T1 11.61), when the C/N ratio is 10 to 14, the proliferation of microorganisms that decompose organic matter is favored, because they have enough carbon to use it as a source of energy and nitrogen to synthesize their proteins, which stimulates the mineralization of that element to be used by the plant components of the system (Gamarra Lezcano et al., 2018). An average bulk density of 0.97 gm/cm^3 is presented, which is below the ideal range (1.3 - 3 gm/cm^3), without, there is no affectation of root growth, adequate drainage, aeration and nutrient flow is evidenced (Alvarado & Forsythe, 2005; Alvarado et al., 2013).

Increasing the diversity of plant species in the coffee system induces a greater accumulation of carbon stored in the soil (Somarriba et al., 2023). This positive interaction between biodiversity indices, organic matter and Soil Organic Carbon (SOC) stocks is indispensable for ecosystem functioning and largely determines soil health, water cycle regulation and climate change mitigation (Delgado-Vargas et al., 2022; Laban et al., 2018). Therefore, the SOC is correlated with the abundance of perennial woody, which results in the contribution of litter, and roots, among others, factors that increase the carbon stored in the soil and therefore the organic matter, which contains more than $1.4x10^{12}$ Mg ha^{-1}, which is almost twice the C of the atmosphere (Food and Agriculture Organization of the United Nations, 2002; Villanueva et al., 2023).

Land use and management is a determining factor in the behavior of stored carbon, which is evident in the variability found between the different production systems (treatments) in this study, associated with characteristics such as species present, botanical composition, plant biodiversity and soil cover. For soil variables such as organic matter content and carbon storage, although they represented an influence on variability, they had low values, so no significant differences were found in carbon storage reports (Somarriba et al., 2023). Them, agroforestry is presented as an alternative, for the incorporation of multipurpose woody perennials (arboreal/shrubby) within productive systems, which allows the promotion of diversity, looking for a system resilience in the medium and long term; therefore, the variables: Shannon Index, Simpson Index and absolute abundance of species, show a great contrast in treatments 2, 3 and 4, compared to the monoculture system T1 (Burbano-Orejuela, 2018; Orozco et al., 2014).

Diversity increases as the system is established and reaches a certain maturity; while other theories suggest that the incorporation of species into the system and, therefore, the increase in diversity depends on the experience of producers, and the technical accompaniment that the projects carry out helping the fulfillment of productive objectives (Somarriba et al., 2023). In agroforestry systems (AS) with higher biodiversity (Shannon-Weaver 1.9 and Simpson 0.2) with various perennial woody, but with low abundance, which may represent a diversity of products, So, it is important to plan and design agroforestry to optimize and direct the coffee system to a production of differentiated quality (Delgado-Vargas et al., 2022).

In AS carbon storage rates depend on agro-climatic factors such as plant density, fertility, soil type, site climatic characteristics, age and forestry management of the production system (Rousseau et al., 2021). When estimating the storage of SOC in coffee production systems under agroforestry systems (AS with coffee and nut, AS with banana and coffee in full sun exposure) no statistical differences between AS in the first 30 cm of soil, with an average carbon storage between 33.6 and 72.3 Mg ha^{-1} (Alvarado et al., 2013). Besides, coffee cultivation in association with *Eucalyptus deglupta* and *Erythrina poepiggiana* at different ages, with sampling at 30 cm of soil, showed carbon storage of 66.2 and 87.3 Mg ha^{-1} respectively (Ávila et al. 2001).

The difference between the storage values may be associated with the life zone where the systems are established and sometimes the sampling depth, since soil C is mainly stored in the surface layer with a tendency to decrease towards the lower layers (Carvajal et al., 2009), in addition to soil processes over time, mainly to litterfall, as well as mortality and exudation of fine roots, which depends on their distribution and activity (Alvarado et al., 2013). Finding a wide range of carbon accumulation in soils between 3.9 Mg ha^{-1} and 90.0 Mg ha^{-1} (Poveda et al., 2013). On the Ecuadorian coast in two agro-ecological zones found between 66.9 Mg ha^{-1}; 72.0 Mg ha^{-1} and 78.8 Mg ha^{-1} in AS with coffee and *Schizolobium parahybum*, coffee and *Guadua spp*, and coffee and *Cordia alliodora* respectively (Hernández et al., 2023). In seven-year coffee plantations in PBS with *Inga densiflora* of 25.2 Mg ha^{-1} and in coffee monocultures of 9.8 Mg ha^{-1} (Hergoualc'h et al., 2012).

It is important to note that fine roots (diameter <2mm) are the main source of SOC accumulation due to senescence at depths of 0-15 cm, decreasing progressively as the soil depth increases (Delgado et al., 2016), with up to 75 % of fine roots, similar trends are reported by Siles et al. (2010), Goçalves et al. (2023) and Villanueva et al. (2023) when evaluating the dynamics of SOC in other production systems in the tropics. Which is directly proportional to the biological productivity of the system in the first 30 cm of soil (Alvarado et al., 2013; Rodríguez et al., 2022). It is verified that the selection of tree species can significantly affect the ability of agro-ecosystems to capture and store atmospheric carbon and maintain nutrient cycles; therefore, the agroforestry planning and the farm plan for its management is prevalent for the coffee grower, the family organization and the commitment to carry out the practices for the optimization of the agroforestry system (Leonel et al., 2023). A careful selection of species could optimize the provision of ecosystem services (Ontong, et al. 2023); similarly, it is corroborated that various agroforestry systems can´t to store more carbon than monocultures (Xiang, et al. 2022).

Conclusions

There was evidence of greater diversity and abundance of species in the multi-stratum agroforestry system (semiannual crops, timber trees, fruit trees, mosses and firewood) in association with coffee (T4), which correlates with a greater accumulation of organic carbon in the soil compared to the coffee monoculture (80.43 t C ha^{-1} vs. 58.32 t C ha^{-1} respectively), such diversification in tree cover is promising for carbon capture and storage intentions, contributing to climate change mitigation.

The principal component analysis allowed the establishment of four factors or components, which explain 81 % of the total variability in the production systems evaluated. The variables that contributed the most were P and B content, Shannon index, number of trees, density, IC, and organic matter, which are related to diverse agroforestry systems that allow for greater soil dynamics, which improves soil structure and fertility, the microclimate for coffee cultivation allowing for greater accumulation and carbon cycling.

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