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ORIGINAL RESEARCH ARTICLE

Evaluation of carbon capture in coffee production systems in the department of Nariño

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ABSTRACT

One of the biggest environmental problems that has affected the planet is global warming, due to high concentrations of carbon (CO_2), which has led to crops such as coffee being affected by climate change caused by greenhouse gases (GHG), especially by the increase in the incidence of pests and diseases. However, carbon sequestration contributes to the mitigation of GHG emissions. The objective of this work was to evaluate the carbon stored in above and below ground biomass in four six-year-old castle coffee production systems. In a trial established under a Randomized Complete Block Design (RCBD) with the treatments Coffee at free exposure (T1), Coffee-Lemon (T2), Coffee-Guamo (T3) and Coffee-Carbonero (T4), at three altitudes: below 1,550 masl, between 1,550 and 2,000 masl and above 2,000 masl. Data were collected corresponding to the stem diameters of coffee seedlings and shade trees with which allometric equations were applied to obtain the carbon variables in the aerial biomass and root and the carbon variables in leaf litter and soil obtained from their dry matter. Highly significant differences were obtained in the four treatments evaluated, with T4 being the one that obtained the highest carbon concentration both in soil biomass with 100.14 t ha^{-1} and in aerial biomass with 190.42 t ha^{-1}.

Keywords: Biomass; CO_2; Allometric Equation; Production Systems; Greenhouse Effect

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1. Introduction

Climate change has been caused by the accumulation of greenhouse gas (GHG) emissions. Of the total emissions of these gases, CO_2 constitutes approximately 70%, while about 20% corresponds to CH_4 and 9% are N_2O. Their high concentration in the environment has comprised complex relationships between climatic, environmental, economic, political, institutional, social and technological processes, thus causing a negative reaction in food production and unfavorably altering systems, decreasing their profitability[1].

One way to mitigate the effects of atmospheric CO_2, is through carbon sequestration, this process can be reflected in the soil or biomass, where it remains sequestered for a long time. In order to achieve a greater amount of captured carbon, the implementation of agroforestry systems (AFS) is considered, considering that the species to be implemented have a high potential to store carbon[2].

In addition, the biodiversity of the species in these systems can be reflected in different agroforestry designs, i.e. windbreaks, living barriers, trees in the middle of crops, among others, can be used[3].

Currently, there is a worldwide trend for the production systems of the most economically important crops to be adapted to climate change and contribute to its mitigation[4]. The development of the coffee production system is one of the main socioeconomic activities of the Colombian agricultural sector. Coffee is one of the most important and representative products when it comes to exports[5]. Despite, the extensive economic benefits, large-scale production is often focused on exports, for its contribution to local food supplies, neglecting environmental conservation[4]. Therefore, in coffee production systems, it has been proposed to increase the use of tree species for shade, as a strategy for biodiversity conservation, adaptation to climate change, food security, among other ecosystem services[4,6].

The implementation of trees in the middle of coffee cultivation (SAF-coffee), is derived as an alternative to capture and store carbon and other gases, which are sequestered through the soil and biomass[7,8]. Different studies were carried out on SAF coffee, analyzing the advantages of each component (especially coffee), which allowed us to demonstrate the greater advantages of photosynthesis, nutrition, water balance, production, etc. Compared to other systems, it is necessary to consider, among other things, the proper balance in terms of percentage of shade depending on the characteristics of the plantation area[9].

By implementing SAF-coffee, the effect that shade has in decreasing soil temperature is recorded, thus helping to have a greater potential for carbon sequestration, this allows stability in carbon flow, i.e., carbon remains stored in the soil much longer in contrast to a coffee system with free exposure[7,10,11].

In coffee cultivation, the possibility of implementing and developing efficient strategies or models in the use or capture of carbon with the potential to receive economic benefits for environmental services is becoming increasingly important. To this end, measurements of emissions and captures have been initiated to identify this balance at different stages of the production process. The evaluations carried out are of great importance, as they will later be an input that will contribute to generate alternatives and production systems that will help to make efficient use of carbon. Although at present there are not yet restrictions and requirements in terms of reducing the carbon footprint, in the future the "Carbon Footprint" component will surely be important and it will be there where the market possibilities will be analyzed for those who responsibly and voluntarily undertake actions[12]. That said, agroforestry systems of coffee in association with perennial woody plants are important carbon reserves, constituting an excellent production alternative for coffee because they contribute, apart from soil and biomass C sequestration, to the reduction of carbon dioxide emissions, the main cause of the greenhouse effect, and are an efficient strategy in the generation of ecosystem services within the framework of clean development mechanisms[13].

Additionally, in other producing municipalities of the department of Nariño, the coffee production systems evaluated under different altitudinal ranges showed highly significant differences[13]. Taking into account the above, the objective of this research was to evaluate carbon sequestration in above and below ground biomass in four coffee production systems at three altitudinal levels, located in the municipality of Sandoná, department of Nariño.

2. Materials and methods

The study was conducted in the municipality of Sandoná, Nariño, which has an approximate extension of 101 km^2; temperature ranges between 19.2 °C and 20.5 °C; rainfall of 1,091 mm per year^{-1}; and relative humidity of 80% on average. The soils have homogeneous characteristics with a silty texture and black color[14].

The experimental plots were plotted under a Randomized Complete Block (RCB) design which were defined by three altitudinal ranges, the first was located at an altitude of less than 1,550 masl at the farm called Las Delicias at coordinates 77°29′36″ E, 1°16′03″ N at 1,528 masl, the second between 1,550 and 2,000 masl called Maná located at coordinates 77°28′59″ E, 1°15′26″ N at an altitude of 1,646 masl and the third located on the La Cruz farm above 2,000 masl at coordinates 77°27′45″ E and 1°14′53″ N, at an altitude of 2,058 masl. Three experimental plots were located in each block, with an area of 10,000 m^2, where 4 treatments were established with an area of 2,500 m^2, respectively

(**Table 1**).

Table 1. Treatments evaluated in the municipality of Sandoná, Nariño

Treatment	Component	Sowing distance	Seeding system	Density (plants/ha)
T1	Coffee at free exposure	Coffee: 1.3 × 1.3 m	Triangle or tres bolillo	6,804
T2	Coffee with shady lemon	Coffee: 1.3 × 1.3 m	Triangle or tres bolillo	6,625
		Lemon: 8 × 8 m	Frame	179
T3	Coffee with shady of Guamo	Coffee: 1.3 × 1.3 m	Triangle or tres bolillo	6,663
		Guamo: 9 × 9 m	Frame	141
T4	Coffee with shady of Carbonero	Coffee: 1.3 × 1.3 m Carbonero: 12 m × 12 m	Triangle or three bolillo Square	6,725 79

The established coffee plants are of the Castillo variety and the species used as shade are: avocado *(Persea americana* Mill.), tahiti lemon *(Citrus limon (L.)* Burm), guamo (*Inga sp),* and carbonero tree (*Albizia carbonaria* Britton). The systems were established simultaneously in early 2014. Species were prioritized: Lemon (treatment 2), Guamo (treatment 3), Carbonero (treatment 4) taking into account the degree of adaptability of the species in the system.

The evaluation of carbon sequestration in coffee production systems was carried out using the non-destructive method, using the allometric equations reported by: Segura & Andrade[15], Quilio *et al.*[16], Alvarez *et al.*[17] and IPCC[18] (**Table 2**). The procedure reported by Rügnitz *et al.*[19] was used to determine biomass and soil carbon storage.

Table 2. Allometric equations used by species for biomass estimation

Allometric equation	r^2	Species	Observation	Source
BA = (0,1955 * D151,648$_{15}^{1,648}$ *1,266	0.93	Coffee *(Coffea arabica* L.)	BA = Aerial biomass (kg/tree) D_{15} = Diameter of the trunk in (cm) measured at 15 cm from the ground.	(Quilio *et al.*[16])
BA = 0.01513 * $D^{3,0054}$	0.94	Guamo *(Inga* sp.)	D = Diameter at 1.30 m (DAP)	(Quilio et al[16])
BA = exp (-1.8656 + (2.3733 * ln(D))))	0.89	Carbonero *(Albizia carbonaria* Britton).	D = Diameter at 1.30 m (DAP)	(Alvarez *et al.*[17])
BA = $10^{-1.11 + (2.64 * \log(D))}$	0.95	Lemon *(Citrus limon* (L.) Burm)	D = Diameter at 1.30 m (DAP)	(Segura and Andrade[15])
Roots = $e^{(-1.06 + 0.88 * \ln(BA))}$	0.84	Root biomass from above-ground biomass.	BA = Aerial biomass (kg/tree)	(IPCC[18])

The sampling units were determined according to Castellanos *et al.*[20]; considering the stratification and random distribution of sampling points. This methodology was chosen and adapted to the present work for which the first step consisted of dividing the area of each of the treatments into sampling units, where three points were taken at random and at each selected point three subplots nested in a concentric circle were drawn.

2.1 Variables evaluated

Evaluation of leaf litter and soil: The installation of leaf litter collection traps on the tree species and coffee plants were placed and located in three plots of 1 m^2; the sample collection was after 30 days, the total wet weight of biomass was recorded in the field and 10% of each sample was subjected to drying; after 48 hours of drying the weight was recorded again.

In the soil component, 5 sampling sites were randomly selected per treatment; 200 g per sample were collected at 30 cm depth; these were taken to the laboratory of the Universidad de Nariño; where the percentage of organic carbon was determined by applying the methodology called wet oxidation method[21].

Evaluation of the coffee trees: In the four treatments of each block, three plots of 28 m^2 were selected, obtaining a density between 19 and 22 coffee plants and the diameter value (cm) of each plant was recorded at 15 cm from the ground.

Recording information on shade trees: In coffee systems with shade trees in each lot, three plots of 250 m^2 were selected, recording the diameter (cm) of each tree at 1.30 m (DBH); a density of between 2 to 4 trees per sampling area was obtained.

2.2 Biomass and stored carbon determination

Litterfall: The determination of carbon stored in litterfall consisted of first obtaining the dry matter value of the sample by dividing the dry weight by the wet weight. Subsequently, the total dry biomass was calculated by multiplying the total wet weight, recorded in the field, by the dry matter of the sample. The carbon stock was determined by multiplying the total dry biomass by the default carbon fraction 0.5.

Coffee and shade trees: The value of the biomass of coffee and shade trees was obtained by placing the diameter value in the allometric equations for each species (**Table 2**). The equation established for lemon corresponds to the one generally used for fruit trees and for carbonero trees, the one for pre-montane rainforest tree species proposed by Álvarez *et al.*[17] was used.

To determine the amount of carbon stored in the PBS-coffee system, the value obtained from the biomass according to the allometric equation for each species was multiplied by the default carbon fraction 0.5.

Total aboveground carbon storage: The results of the estimation of leaf litter, coffee and shade tree carbon obtained in the evaluations were added together to obtain the total aboveground carbon for each of the treatments.

Roots: The determination of carbon in the root, the first step was to calculate the biomass of the tree by means of the allometric equations of each species, this value obtained was replaced in the equation for roots given in a general way by IPCC[18], then it was multiplied by the carbon fraction by default 0.5.

Soil: To calculate the amount of carbon in the soil, the sampling depth was multiplied by the bulk density, and this was multiplied by the percentage of organic carbon in the soil obtained in the laboratory.

2.3 Statistical analysis

The data were analyzed by ANDEVA under the fixed model of the Randomized Complete Block Design (RCBD) with a probability of 95%. For variables that presented significant statistical differences, Tukey's mean comparison test was applied ($\alpha = 0.05$).

3. Results and discussion

3.1 Carbon stored in aboveground biomass

Coffee and shade trees. In the coffee and shade trees component, a range of carbon fixation was determined from 11.42 to 238.8 t ha^{-1}, with the best result in the system (T4) with an average value of 190.17 t ha^{-1}, and the lowest carbon storage value in the system (T1) with 11.98 t ha^{-1} on average, as shown in **Figure 1**.

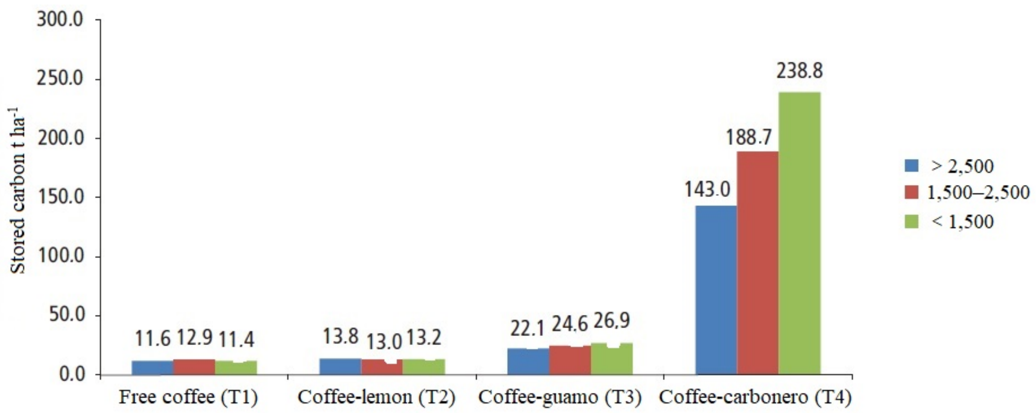

Figure 1. Carbon stored t ha^{-1} in coffee plants and shade trees evaluated at three altitudinal ranges.

Jurado *et al.*[13] estimated, like this research, the highest carbon sequestration in the coffee and carbonero production system planted at a distance of 12 × 12 with an average value of 10.77 t ha^{-1} in the municipality of Consacá, department of Nariño. While, López[22], reported the highest carbon value in systems with high density and shade trees, where tree vegetation contributes 8.86 t ha^{-1} and coffee plantations 2.59 t ha^{-1}, adding up to a total of 11.45 t ha^{-1}.

The results obtained in this research are in agreement with those obtained by Patiño *et al.*[1], who conclude that forest plantations and agroforestry systems capture large amounts of atmospheric C. Similarly, it has been shown that carbon stocks are higher in shaded coffee plantations compared to those with free exposure or with low presence of shade[23]. This indicates that coffee production systems could become payment for environmental services projects, generating extra income for coffee farmers and contributing to climate change mitigation[24].

Leaf litter. In the leaf litter component, a range of carbon fixation was determined between 0.17 and 0.42 t ha^{-1}, with the best result in the system (T3) with an average value of 0.38 t ha^{-1}, and the lowest carbon storage in the system (T1) with an average value of 0.18 t ha^{-1} as shown in **Figure 2**.

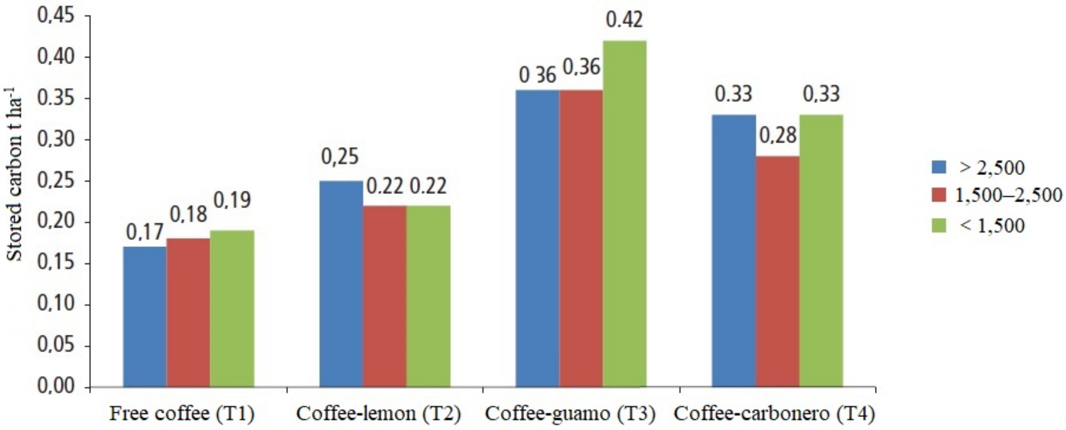

Figure 2. Carbon stored t ha^{-1} of leaf litter in the production systems evaluated at three altitudinal levels.

Cabrera *et al.*[25] reported an average concentration of 0.93 t ha^{-1} in 32 coffee agroforestry systems with diversified shade, a value that is above that found in this research; low carbon storage in leaf litter may be related to topographic, climatic and altitudinal conditions as well as planting density, type of established trees and decomposition capacity of organic matter[26]. However, the carbon in the leaves, when decomposed, becomes part of the soil, carbon dioxide that returns to the atmosphere and organic matter. In that order 58% of its dry weight of organic matter is carbon, and represents another opportunity for long-term sequestration[27].

The low accumulation of leaf litter in the system (T1) could be due to its faster decomposition, considering the direct exposure of the soil to the sun. According to Bonilla *et al.*[28], the high temperatures reached by the soil surface, when exposed to direct sunlight combined with the humidity characteristic of coffee production areas, produce a greater decomposition of organic matter. Similarly, Valenzuela and Visconti[29], who state that the wetting index is significantly higher in warm climates, regardless of the use and depth, has a greater capacity to decompose, mineralize and wet organic matter, which represents an important capacity to be CO sinks.

Total aboveground carbon storage. The system (T4) obtained the highest value of total carbon stored in aerial biomass with an average value of 190.42 t ha^{-1} , and the lowest carbon storage was observed in the system (T1) with an average value of 12.12 t ha^{-1} as shown in **Table 3**, in general a range of carbon fixation was determined from 11.57 to 239 t ha^{-1}; these results do not differ from those found by Andrade and Segura[30], in their research related to coffee production systems; where they demonstrated that the rate of carbon fixation in the total aerial biomass varies between 13.12 and 245.6 t ha^{-1}.

There are significant statistical differences in the four treatments evaluated, being the system (T4) the one with the highest average obtained with a carbon storage of 190.42 t ha^{-1} as shown in **Table 3**. These results are in accordance with what was reported by Vásquez *et al.*[31] who obtained higher carbon accumulation averages in an *Inga jinicuil* system with coffee (157.6 Mg ha^{-1}), than in coffee with free exposure. Similarly, Criollo *et al.*[32] projected for the species *Albizia carbonaria* a carbon sequestration of 143.73 Mg ha^{-1} and taking into account that 84.22% of its total aerial mass is carbon. Accordingly, carbon stocks are higher in shaded coffee production systems than in coffee plantations with free exposure or little shade[22].

Table 3. Total carbon stored t ha^{-1} in aboveground biomass in the production systems evaluated in three altitudinal levels

Range	Treatments											
	Free coffee (T1)			Coffee-lemon (T2)			Coffee-guamo (T3)			Coffee-carbonero (T4)		
>2,000	CTC	LC	BC	CTC	LC	BC	CTC	LC	BC	CTC	LC	BC
	11.6	0.17	11.77	13.75	0.25	14	22.14	0.36	22.5	143.02	0.33	143.35
1,550–2,000	12.92	0.18	13.1	13.01	0.22	13.23	24.56	0.36	24.92	188.68	0.28	188.96
<1,550	11.42	0.19	11.61	13.19	0.22	13.41	26.87	0.42	27.29	238.8	0.33	239.13
Average	11.98	0.18	12.16^{B}	13.31	0.23	13.54^{B}	24.52	0.38	24.90^{B}	190.17	0.3	190.48^{A}

CTC = coffee and tree carbon; LC = litter carbon; BC = biomass carbon. Statistically significant differences $p = 0.002$. Similar letters (B) do not show statistically significant differences.

The system (T2) is the second in presenting the second highest values in carbon sequestration with an average of 24.46 t ha^{-1}; results similar to those reported by Carvajal *et al.*[33] where the average value of aerial carbon assimilated in lemon trees is 22.3 t ha^{-1}. A relevant factor is the vegetative development that the lemon tree reaches throughout its life, becoming more lush trees, with greater leaf area and, therefore, with greater carbon sequestration capacity.

The system (T3) presented 22.49 t ha^{-1} of carbon stored. When considering that three species are established in the system, these results are below those reported by Odar[34] who states that trees such as Guamo, captures up to 19.7 t ha^{-1} of carbon in polycultures with little shade; and from that reported by Vásquez *et al.*[31] who conclude that carbon constitutes approximately 40.8 % of the woody biomass of *Inga jinicuil,* which was estimated to store 64.3 Mg C ha^{-1}.

The carbon stored in the system (T1) presents an average of 12.12 t ha^{-1} being this a low result in relation to that obtained in the other treatments evaluated in this research. The above does not differ with what was reported by Odar[34] and Cabrera *et al.*[26] who obtained average values between 10.3 and 12.81 t ha^{-1}, respectively. And it is above that obtained by Díaz *et al.*[35] where the use of free exposure land with coffee plants obtained averages of 2.35 t C ha^{-1}.

3.2 Carbon stored in below-ground biomass

Roots. The highest amount of carbon stored in the root component was obtained in the system (T4) with a value of 21.45 t ha^{-1}; and the system with the lowest carbon storage was (T1) with a value of 3.43 t ha^{-1} as shown in **Figure 3**.

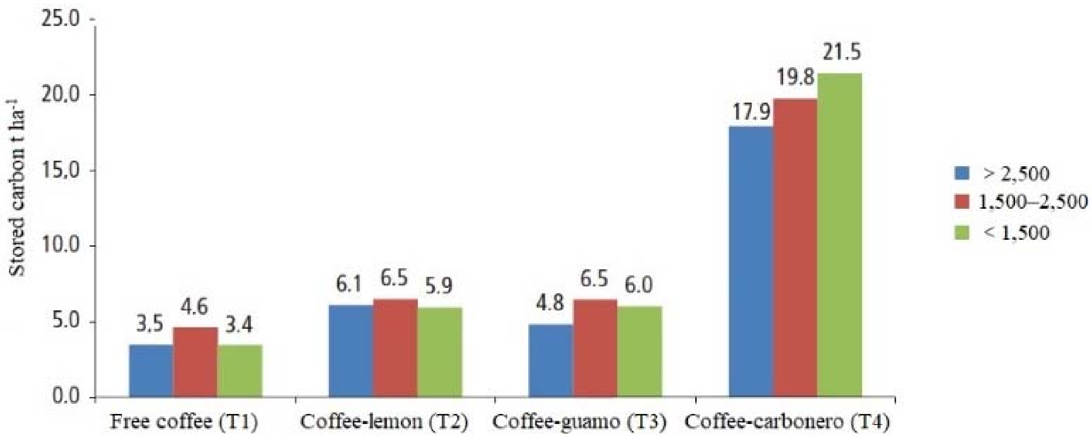

Figure 3. Carbon stored t ha^{-1} in the root component of the production systems evaluated at three altitudinal levels.

This variability is due to the spatial heterogeneity of root system development, which depends on the interactions of genetic and environmental factors of the species; in the case of the system (T4) the presence of the tree component promotes different environmental conditions due to the planting distance and morphological characteristics that influence the pattern of spatial variability[11,36,37].

Soil. The highest amount of carbon in the soil was obtained at an altitude of 2,058 masl in the system (T4) with a value of 109.22 t ha^{-1}; while the system that presented the lowest storage was (T1) with a value of 53.44 t ha^{-1} at an altitude of 1,528 masl (**Figure 4**). The results suggest that in coffee agroforestry systems with perennial woody legumes have higher soil carbon stocks than coffee monoculture[26,38]; the results may also be due to the influence of the tree component in reducing soil temperature, enhancing microbial activity and promoting greater stability of carbon flow, i.e., carbon remains stored in the soil much longer than in a free-exposure coffee system[10,11].

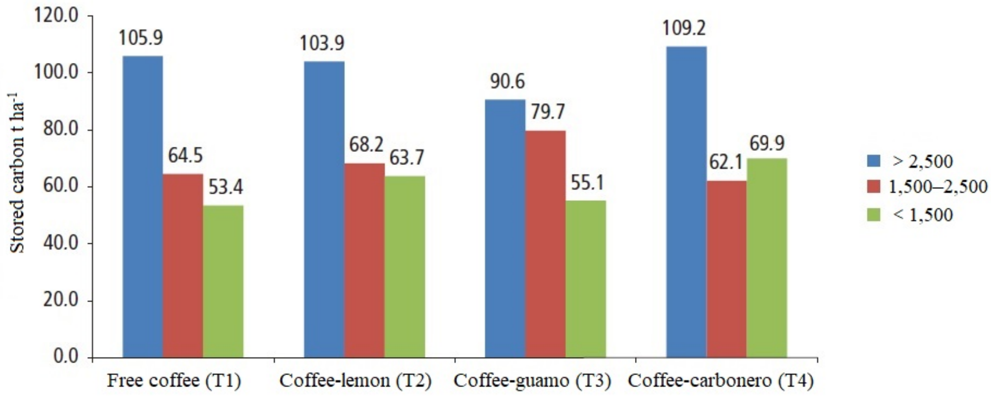

Figure 4. Carbon stored t ha^{-1} in the soil component of the production systems evaluated at three altitudinal levels.

Total carbon storage under the soil. The total carbon stored in the soil biomass was higher in the system (T4) with a value of 127.15 t ha^{-1} at an altitude of 2,058 masl; contrary to the system T1 which presented the lowest concentration with 56.87 t ha^{-1} at an altitude of 1,528 masl (**Figure 5**). These results show that carbon storage had higher values in systems with trees, attributable to the leaves, foliage and dead roots from shade trees and coffee that incorporate organic matter into the soil[39].

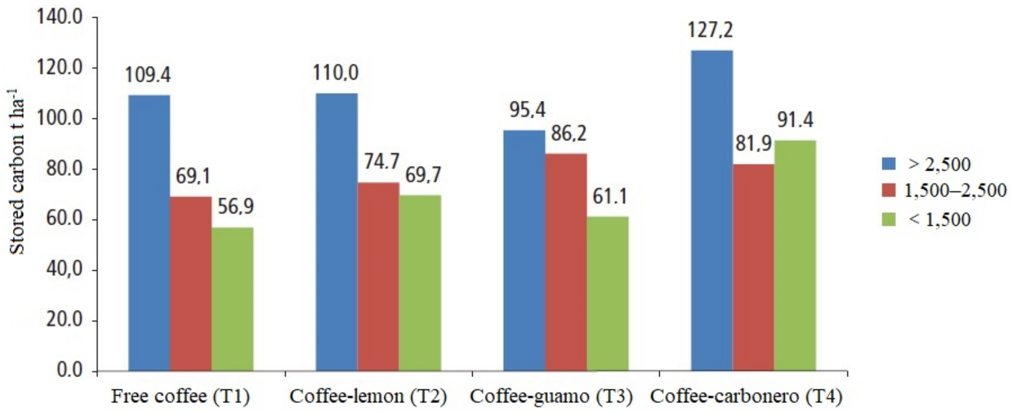

Figure 5. Carbon stored t ha^{-1} in below-ground biomass of the production systems evaluated at three altitudinal levels.

In diversified systems such as (T4) the movement or disarrangement generated by soil preparation, favors carbon metabolism, because it exposes it to the action of edaphic microorganisms with the congruent emission of CO_2, which can grow if, in addition, plant species that provide easily decomposable residues are established[40].

Total carbon stored in above and below ground biomass. There were significant statistical differences (P = 0.0001) in the treatment (T4) in amounts ranging from 270.45 to 330.38 t ha^{-1} (**Figure 6**), data similar to that reported by Espinoza *et al.*[41], where the carbon stored in an agroforestry system with coffee ranges from 254.36 to 345.2 t ha^{-1}. The system with the lowest carbon storage was (T1) with values from 68.44 to 121.07 ha^{-1} (**Figure 6**); this difference may be related to the low presence of leaf litter in the soil, since there is only one species that provides this material within the system[7].

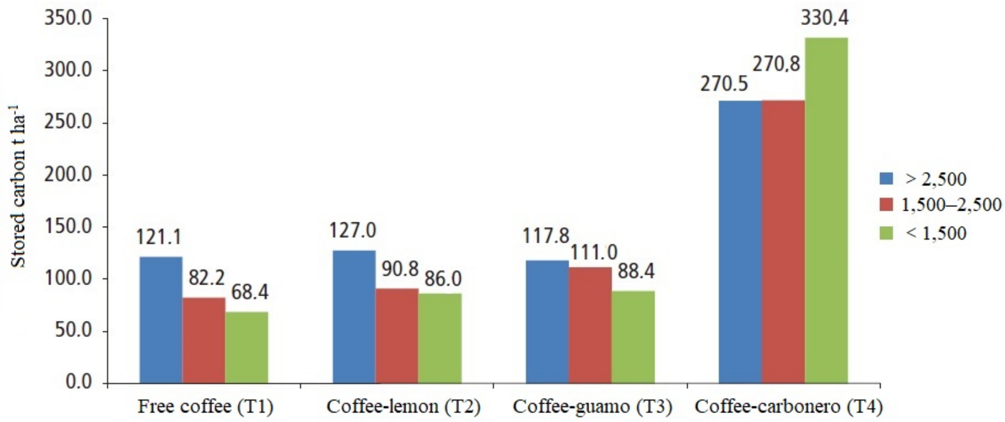

Figure 6. Carbon stored in t ha^{-1} in above and below ground biomass in the production systems evaluated at three altitudinal levels.

The highest rate of carbon stored was produced in the T4 system that includes large canopy trees, these can retain carbon in their wood for a long time; carbon sequestration in trees is due to the silvicultural management provided to each individual, allowing the development of large stems, as in the case of the carbonero species established in the system (T4); similarly it has been found that trees with large dimensions both in height and diameter, carbon storage is higher than those that are smaller[42–44].

4. Conclusions

Carbon storage in aerial biomass and soil was higher in coffee production systems with shade trees at an altitude of 2,058 meters above sea level.

The highest rate of carbon stored was produced in the PBS-coffee, where the implementation of the carbonero and guamo species (T4) obtained significant statistical differences, exceeding the result in all the components evaluated, both in aerial biomass and soil, demonstrating that carbon stocks are higher in shaded coffee production systems than in free exposure coffee plantations.

The results indicate the environmental importance of coffee FFS in the mitigation of climate change, since productive systems with a greater diversity of species store a greater amount of total carbon, due to the greater presence of living biomass, as opposed to coffee systems established in monoculture with free exposure.

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Conflict of interest

The authors declare that they have no conflict of interest.

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