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Article

Carbon storage in *Coffea arabica* L. in the Sierra Madre de Chiapas

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Abstract

Carbon accumulation in coffee is a way to reduce greenhouse gases and combat climate change; nevertheless, in the Sierra de Chiapas, there is no accurate information on carbon capture in coffee plantations. Quantifying carbon is essential to value this ecosystem service and conserve coffee plantations through subsidies. For this reason, this research aims to evaluate the carbon stored in the aerial biomass of coffee in two altitudinal gradients and determine the concentration of carbon (CC) and nitrogen, with CC being an indispensable element in obtaining the carbon stored in coffee. The study was carried out at two altitudes: the first at 1 200 m and the second at an altitude of 1 500 m, in the year 2022. To estimate the carbon, first, the biomass was estimated indirectly using an allometric equation for the species, then the concentration of carbon and nitrogen was determined with a device called Thermo Scientific Flash 2000 NC Soils Analyzer, which works by complete combustion at 950 °C. Once the biomass and the concentration of carbon in coffee were obtained, they were multiplied, thus obtaining the stored carbon; for carbon dioxide, the stored carbon was multiplied by the constant 3.67. The results indicate significant differences in the range of 1 200 masl (10.72 t C ha^{-1}) and the lowest carbon storage in the range of 1 500 masl (4.74 t C ha^{-1}). This indicates that the altitude of the site influences carbon capture in coffee; the lower the altitude, the more carbon stored there will be in the coffee.

Keywords:

altitude, biomass, coffee.

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Introduction

One way to mitigate greenhouse gases (GHGs) is through carbon capture through photosynthesis, which must be sequestered for as long as possible (Espinoza *et al*., 2012). The agro-industrial crop of coffee is the main crop in the Sierra Madre de Chiapas, where producers obtain a large part of their livelihood, which is why they conserve the coffee plantations. Therefore, the carbon in coffee will always be sequestered in the air or in the soil, and it contributes to the reduction of GHGs.

The conservation of coffee allows carbon capture, so it should be proposed as an alternative to mitigate climate change through subsidies for the producer and thus further guarantee the carbon that exists in coffee plantations (Olorunfemi *et al*., 2019), so that the soil would be conserved, and greater biological nitrogen fixation and nutrient cycling would be obtained (Villa *et al*., 2020).

To obtain the carbon stored in coffee, it is necessary to obtain the biomass and the percentage carbon content. Biomass is the dry weight of the species, which can be estimated directly and indirectly. Carbon concentrations (CC) in Mexico have been studied mostly in conifers and broadleaf trees (Yerena *et al*., 2012b; Jiménez *et al*., 2013; Villanueva *et al*., 2015; Pompa *et al*., 2017), but very little for coffee. Therefore, knowing the carbon concentration in coffee would make the determination of carbon storage more accurate (Aquino *et al*., 2018).

In a study on coffee, Zavala *et al*. (2018) found that the stored carbon depends on the altitude, where the lower the altitude, the greater the carbon capture. At altitudes of 1 565 m, Andrade *et al*. (2014) conducted a study in Colombia on carbon fixation in coffee, where they recorded an average of 0.63 t C ha^{-1}. On the other hand, at altitudes below 1 200 m, the average coffee carbon in Ecuador is 4.6 t C ha^{-1} (Corral *et al*., 2013).

Given the importance and considerations mentioned above, this research aims to evaluate the carbon storage in aerial coffee biomass in two altitudinal gradients; in addition, the concentration of carbon and nitrogen was determined, with the CC being a reliable element to obtain the carbon stored in coffee.

Materials and methods

The study was carried out in two municipalities belonging to the Sierra Madre de Chiapas: The first area is located between the coordinates 15° 34’ 10.07” north latitude and 92° 20’ 6.28” west longitude, at an altitude of 1 200 m, located in the municipality of Siltepec. The second area with coordinates 15° 15’ 56.7” north latitude and 92° 17’ 55.07” west longitude, at an altitude of 1 500 m located in Motozintla (Figure 1). The land has slopes from 0 to 60%. The climates are sub-humid warm, humid warm, and humid semi-warm, with abundant rainfall in summer ranging from 800 to 1 200 mm, and an average annual temperature greater than 18 °C; the predominant soils in the area are Luvisol, Regosol, and Acrisol (García, 2004).

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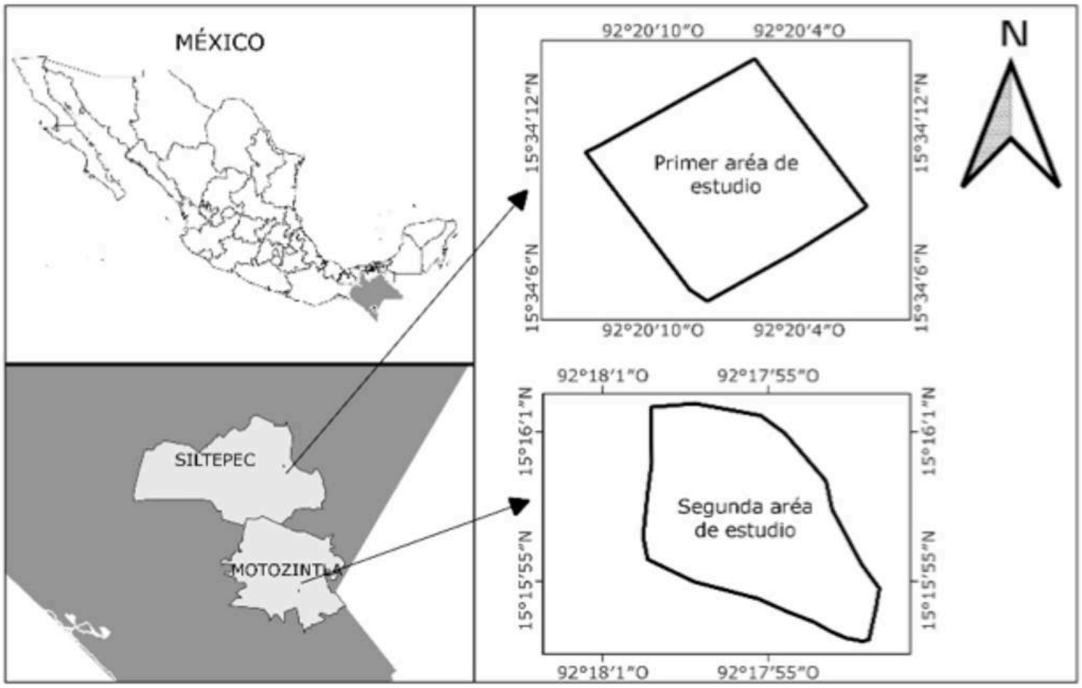
Figure 1. Location of the study area.



Sampling design

A random sampling was carried out in each of the localities, evaluating an area of 5 ha; to determine the size of sites to be inventoried, first a pre-sampling was carried out, using the following equation (1) (Ancira and Treviño, 2015).

$$n = \frac{t^2 * CV^2}{E^2_{\%}}$$

1). Where: n= sample size; t^2= value extracted from Student's t-table (p< 0.05). CV= coefficient of variation; E= percentage error. The sample size was defined from the variable of biomass. A total of 24 sites were established in both areas; the sites were rectangular 4 x 25 m (100 m^2) (Espinosa *et al*., 2012; Timoteo *et al*., 2016). At each site, all coffee individuals present were evaluated. The variables measured were normal diameter (cm), with a Forestry Suppliers 283D/5m diameter tape, and heights (m), with a tape measure (Truper FH-5ME).

Biomass estimation

Aerial biomass in coffee was estimated using the allometric model proposed by (Hairiah *et al*., 2001), which includes only one independent variable. This model (2) was applied to each coffee individual. BT= 0.2811 * DBH ^ 2.0635 2). Where: BT= total aerial biomass (kg); DBH= diameter at breast height (cm).

Laboratory tests

Once the biomass was obtained, the carbon and nitrogen concentration of coffee was calculated. For the two areas, six individuals were randomly taken; for each individual, one sample was obtained for each component (bark, leaves, and trunk) and placed in paper bags (Aquino *et al*., 2018). The samples were dried in a Blue M drying oven until they reached a constant weight, then the 18

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samples were pulverized in a Marathon Electric C20J020016 series mill, placed in polyethylene bags labeled with a code, with an average weight of 90 g each.

Thirty milligrams of each sample were then weighed on a scale to be analyzed by the equipment called Thermo Scientific Flash 2000 NC Soils Analyzer. The concentration of carbon and nitrogen was determined with the aforementioned equipment, which determines the concentrations in solid samples by complete combustion at a temperature of 950 °C; the gases produced by combustion are measured through a non-dispersive infrared detector that counts the carbon molecules contained in these gases (Yerena *et al*., 2012a).

Carbon and carbon dioxide estimation

The carbon stored in each coffee plant was estimated by multiplying the aerial biomass by the average carbon concentration of the components of the present study. Once the carbon storage was obtained, it was multiplied by the constant 3.67 (44/12), and the carbon dioxide in coffee was obtained (Zavala *et al*., 2018).

Statistical analysis

Biomass, carbon storage, and carbon dioxide in coffee were compared as independent populations through a Student's t-test to check for significant differences at different altitudes (Hernández *et al*., 2017).

The carbon and nitrogen concentration data were subjected to an analysis of variance, and when there were significant differences, Tukey's mean test ($p< 0.05$) was performed to verify the difference between the coffee components (Sáenz *et al*., 2021). The analyses were performed in the R Studio version 4.1.2 statistical program (Marroquín *et al*., 2018; R Core Team, 2022).

Results and discussion

The number of coffee plants in Siltepec was 30 individuals per site on average, having an average density of 3 014 plants ha^{-1}, while for Motozintla, there was an average of 32 individuals per site, with 3 211 plants per ha^{-1}, this density depends on the form of planting with respect to the topography of the land. For both altitudes, the planting distance was 2 x 1.5 m. The planting frame in Siltepec was a real frame, with slopes of less than 20%, and in Motozintla, it was with a triangular pattern, with slopes of more than 40%. The difference in plants is due to the topography of each altitude (Table 1).

Table 1. Number of individuals assessed per hectare.

Locality	Species	Planting distance (m)	Plants ha^{-1}
Siltepec	Coffee	2 x 1.5	3 014
Motozintla	Coffee	2 x 1.5	3 211

The planting distance in coffee is the same as that reported by (Zavala *et al*., 2018), obtaining more than 3 000 individuals of coffee ha^{-1}, while at distances of 1.3 x 1.3 m, densities > 6 250 were recorded (Medina *et al*., 2009; Jurado *et al*., 2019), which do not influence the CC with respect to the present research.

Diameters in Siltepec vary from 2.45 to 3.98 cm, reporting an average height of 2.91 m; these values estimate an average biomass of 2.49 kg per individual. For the other locality, the diameters range from 1.25 to 2.48 cm and an average height of 2.24 m, obtaining an average biomass of 0.88 kg per plant.

Sites with altitudes of 1 200 m (Siltepec) double the estimates of biomass, carbon, and carbon dioxide compared to 1 500 masl (Table 2). Based on the above, Solórzano and Querales (2010)

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Table 2. Variables obtained and estimated in coffee.

$\overline{DBH}$	$\overline{H}$	$\overline{Bt}$	$\overline{C}$	$\overline{CO_2}$
		Siltepec		
2.88	2.91	226.6	107.2	393.7
		Motozintla		
1.74	2.24	100.7	47.4	173.7

$\overline{DBH}$ = average diameter at breast height (cm); $\overline{H}$ = average height (m); $\overline{Bt}$ = average total biomass (kg site^{-1}); $\overline{C}$ = average carbon (kg site^{-1}); $\overline{CO_2}$ = average carbon dioxide (kg site^{-1}).

In a study carried out in Colombia, a coffee plant has an average biomass of 2 kg, this value is similar to that found in Siltepec, but higher than the biomass of Motozintla (Darío, 2011). Zavala *et al*. (2018) evaluated coffee at an altitude of 1 500 m, reporting an average diameter of 4.93 cm, with an average height of 1.75 m, resulting in a biomass per plant of 0.81 kg; this value was close to the biomass reported by Motozintla, although the results of diameter and height were higher than the two altitudes of the present study.

Biomass estimation

Statistical analysis using the Student's t-test indicates that there are significant differences (p< 0.001) in biomass by altitude. At altitudes of 1 500 m, the average biomass was 10.07 t ha^{-1}; for altitudes of 1 200 m, an average biomass of 22.66 t ha^{-1} is obtained (Figure 2); both results are higher than those reported by other researchers in coffee, where they record a biomass of 1.1 and 6.64 t ha^{-1} at altitudes above 1 500 m (Andrade *et al*., 2014; Jurado *et al*., 2019).

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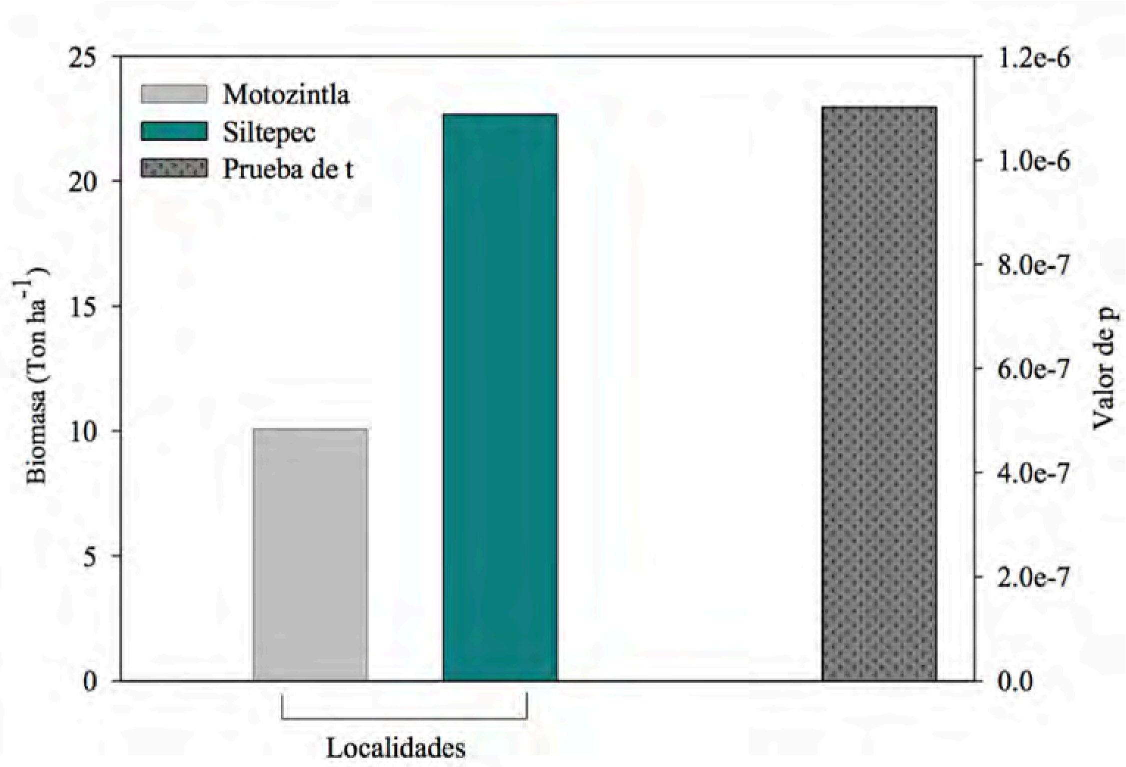
Figure 2. Estimation of biomass by locality.



Likewise, Hernández et al. (2020) conducted a study on coffee in Colombia at an altitude of 1 200 m, obtaining a biomass of 7.2 t ha-1. Corral et al. (2013) reported 9.6 t ha-1 in coffee biomass, with this value being similar to the locality of Motozintla (1 500 masl) and lower for Siltepec. Nonetheless, in Peruvian coffee plantations at an altitude of 1 500 m, Zavala et al. (2018) recorded a biomass of 51.39 t ha-1 in coffee at 10 years.

In the present study, the lowest altitude is the one that stored the highest biomass in coffee plants; these results coincide with other studies where the highest stored biomass was recorded at altitudes # 1 200 m (Mena et al., 2011; Hernández et al., 2012). Coffee plants play an important role in the accumulation of biomass as this species stores between 30 and 40% of biomass compared to an agroforestry system (Andrade et al., 2014; Terán et al., 2018). The accumulation of biomass can be attributed to crop management, such as pruning in coffee and fertilization, which contributes to better plant growth and development (Medina et al., 2009).

Carbon concentration

Total carbon concentration on by component among localities

There were significant differences ($p< 0.001$) between the components of each locality. Tukey's test($\propto$ = 0.05) indicates that the concentration of carbon in the trunk component is statistically different, with values higher than the rest of the components by locality, while the leaf and bark components of Siltepec are statistically similar, the opposite occurs for the components (leaf and bark) of Motozintla, where there was a group with intermediate values ranging from 46.18 to 47.42% (Table 3).

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Table 3. Total carbon content (%) by component between localities.

Component	Locality	Mean ± SE	Tukey grouping[1]
Trunk	Siltepec	49.25 ±0.72	a
	Motozintla	48.97 ±2.49	a
Leaf	Motozintla	47.42 ±0.9	ab
	Siltepec	46.53 ±0.76	bc
Bark	Siltepec	46.18 ±0.93	bc
	Motozintla	44.72 ±1.41	c

[1] = equal letters are statistically similar ($p \leq 0.05$). SE= standard error.

Like this study, Yerena *et al*. (2012a) presented higher values in the trunk in Tamaulipas thorn scrub sites, and in the bark sites, the values were lower than the rest of its components. The average CC was higher in the locality of Siltepec, altitude lower than in Motozintla, which is similar to the research of Hernández *et al*. (2012) in a study of carbon capture where they found that, the lower the altitude, the higher the carbon content in the total biomass.

Total carbon concentra on of the species

Through the analysis of variance, it was determined that there are significant differences between the coffee components ($p< 0.001$), so Tukey's test ($\propto = 0.05$) was performed, where the carbon concentration was divided into 3 groups. The carbon content expressed as a percentage ranged from 45.45 to 49.11%, where the bark obtained the lowest concentration of carbon, then the leaf, and finally the trunk (Table 4).

Table 4. Total carbon and nitrogen by component in coffee.

Component	Mean ± SE	Tukey grouping[1]
	Carbon	
Trunk	49.11 ±0.81	a
Leaf	46.98 ±0.54	b
Bark	45.45 ±0.84	c
	Nitrogen	
Leaf	3.03 ±0.35	a
Bark	1.68 ±0.15	b
Trunk	0.43 ±0.05	c

[1] = equal letters are statistically similar (p# 0.05). SE= standard error.

Figueroa *et al*. (2005) determined the CC in coffee, obtaining values of 41.9% in trunk and 42.3% in leaves; these percentages are lower than in the present study. The average total carbon content of this study was 47.18%; this value is similar to that recorded in Oaxaca, where they obtained 46.2% for species developed in tropical environments (Aquino *et al*., 2018), and also to that reported in broadleaf species (48.84%) and *Pinus* sp. (47.34%) by (Yerena *et al*., 2012b; Jiménez *et al*., 2013). On the other hand, the CC obtained in trees that are used as shade for coffee (40.28%) was lower than that of this research (Hernández *et al*., 2012). Regarding the above, the species have different carbon contents (41.9-49.95%); however, in most species, it is close to 0.5.

Nitrogen concentration

Coffee not only contains carbon but also nitrogen (N), mainly in the leaf component (3.03%), followed by the bark (1.68%) and finally the trunk (0.43), having an average of 1.71% in total nitrogen

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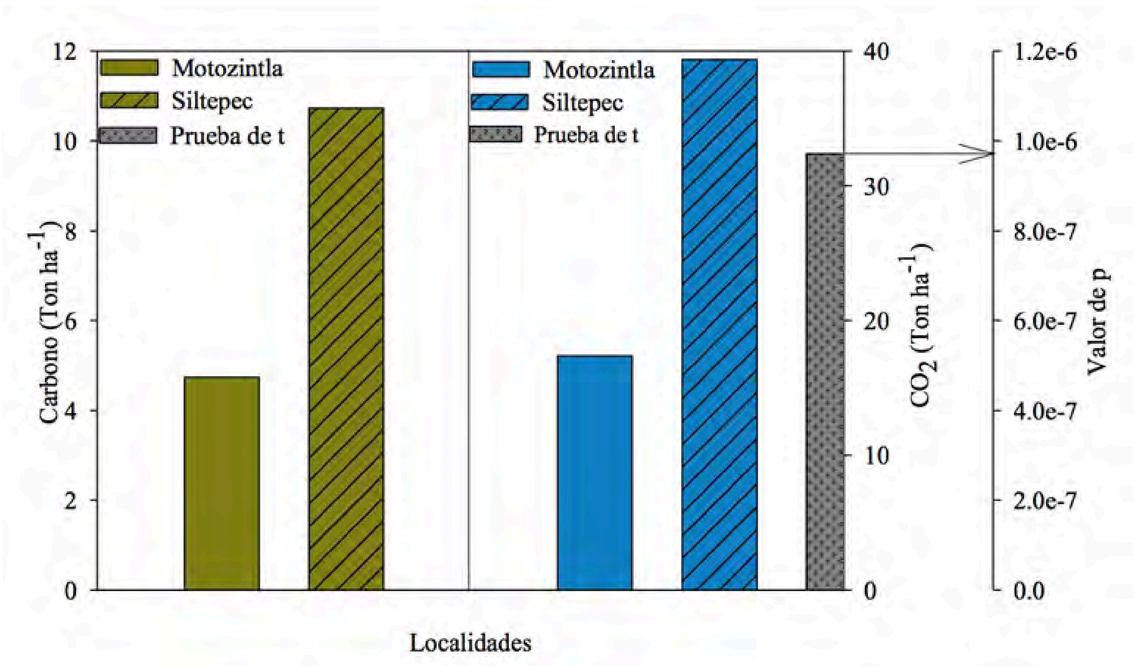
(Table 4). The average nitrogen content of this study is lower than that reported by Pérez *et al*. (2014), where values range from 2.91 to 3.09% N in coffee. Nevertheless, for tropical species in Chiapas, the nitrogen is 1.86% in a study conducted by Moreno *et al*. (2021), which is similar to this study, but lower for tropical trees in Oaxaca, with 0.48% N (Hernández *et al*., 2012). It is important to know the nitrogen in coffee plants because they serve as indicators of the plant's nutritional status. A good leaf nitrogen content in coffee allows a good yield to be obtained; a value below 2.80% N (foliar) indicates nutrient insufficiency (Pérez *et al*., 2014).

Carbon and carbon dioxide estimation

By estimating carbon (C) and carbon dioxide (CO_2) in coffee by altitude, it was determined that there are significant differences ($p< 0.001$). In the present study, coffee plants registered 10.72 t C ha^{-1} and 39.37 t CO_2 ha^{-1} at altitudes of 1 200m (Siltepec); 4.74 t C ha^{-1} and 17.37 t CO_2 ha^{-1} were obtained for altitudes of 1 500 m (Motozintla); (Figure 3).

Figure 3. Estimation of carbon and carbon dioxide in coffee.



The highest storage of carbon and carbon dioxide occurred at altitudes of 1 200 m; this statement coincides with other authors where they have found the highest carbon potential of coffee at altitudes below 1 300 m (Hernández *et al*., 2012; Paz *et al*., 2018). Terán *et al*. (2018) conducted a study on coffee in Oaxaca with altitudes of 1 200 to 1 600 m, where they found values of 2.38 t C ha^{-1} and 8.71 t CO_2 ha^{-1}; these values are lower than the altitude of 1 200 m in this research, the opposite occurs for the altitude of 1 500 m.

In a study of coffee in Veracruz with altitudes above 2 200 m, Valdés *et al*. (2022) found values of 8.88 t C ha^{-1}, different from what was reported in the present study. The results of the estimated variables of Motozintla are similar to the results of Van *et al*. (2002); Jurado *et al*. (2019); Hernández *et al*. (2020), where they found average values of 3.5 t C ha^{-1} and 12.84 t CO_2 ha^{-1}. Likewise, authors such as Zavala *et al*. (2018) reported 8.42 t C ha^{-1} and 30.90 t CO_2 ha^{-1} in coffee at altitudes below 1 500 m in Peru. Carbon storage in coffee plants depends mainly on altitude, site slope, climatic conditions, and management practices, such as pruning (Darío, 2011; Hernández *et al*., 2012; Zavala *et al*., 2018).

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Conclusions

The total carbon concentration in the aerial coffee biomass ranged from 45.45 to 49.11% in its components, obtaining an average carbon content of 47.18%. Carbon storage in the two altitudinal gradients showed significant differences, where the highest carbon recorded was at altitudes of 1 200 m with an average of 10.72 t C ha^{-1}. Altitude is a variable that influenced carbon storage in coffee plantations in the Sierra Madre de Chiapas.

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