Article

Ecosystem service of carbon stored in coffee plantations under shade in agroforestry systems

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Abstract

Coffee agroforestry systems (AFSs) have a high potential in carbon (C) sequestration thanks to the great diversity of woody species used as shade. The objective of this study was to evaluate the potential for carbon sequestration in aerial plant biomass, plant litter and soil matter at different soil depths in five different coffee AFSs in the coffee-growing region of Huatusco, Veracruz, Mexico. The agroforestry systems studied were: in full sun (03.PSC-MZ, 04.PSC-ZI), specialized (05.ESP-MZ, 06.ESP-MZ, 07.ESP-CH) and were compared with a cloud forest (02.BMM-CH) and a paddock (01.POT-TH). The AFS with the highest C content in aerial biomass, estimated with allometric equations, was 05.ESP-MZ, with 373.75 Mg ha^{-1}, followed by 07.ESP-CH with 231.88 Mg ha^{-1}, 04.PSC-ZI with 123.96 Mg ha^{-1}, 03.PSC-MZ with 61.08 Mg ha^{-1}, 06.ESP-MZ with 45.95 Mg ha^{-1}, 02.BMM-CH 456.64 Mg ha^{-1} and 01.POT-TH 3.14 Mg ha^{-1}. Regarding the total organic C, the 05.ESP-MZ system obtained the highest value with 477.54 Mg ha^{-1} and the 06.ESP-MZ the lowest with 108 Mg ha^{-1}. The implementation and conservation of coffee AFSs is vital since it contributes to mitigating the negative environmental impact such as CO_2 emissions into the atmosphere, soil compaction and loss of biodiversity in flora and fauna that other production systems have caused.

Keywords: agroforestry, carbon, coffee.

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Introduction

Global warming and climate change are caused by the increase in the concentration of greenhouse gases in the atmosphere, mainly CO_2, also known as carbon gas, whose production and accumulation is directly or indirectly related to human activities such as deforestation and the use of fossil fuels (González *et al*., 2003). Given the growing and worrying environmental deterioration, the interest in finding schemes that allow estimating and assigning objective values to the goods and services that ecosystems provide us takes on greater importance, because only in this way will the actions of conservation and restoration of nature have the desired effect (SEMARNAT, 2004).

Productive, ecological and economically sustainable strategies such as agroforestry systems help mitigate the environmental effects derived from the exploitation and inappropriate use of natural resources, since including practices where trees or shrubs interact simultaneously or sequentially favors the optimization and diversification of production in order to achieve sustainable management (Nair, 2009; Casanova-Lugo *et al*., 2011).

The implementation of agroforestry systems offers multiple benefits, such as the protection of the soil from erosion, the addition of organic matter to the soil, biodiversity, carbon reserves in vegetation and soils are favored and maintained, promoting the recovery of degraded areas, in addition to promoting carbon storage and helping mitigate CO_2, which is one of the main gases that causes the greenhouse effect (Nair, 2009; Rügnitz, 2009; Casanova-Lugo *et al*., 2011).

Coffee farming is considered a strategic activity in the country, because it allows the integration of productive chains, the generation of foreign exchange and jobs, it is the way of subsistence of many small producers and around 30 indigenous groups and recently, of enormous ecological relevance, since more than 90% of the area cultivated with coffee is under diversified shade, which contributes considerably to conserve biodiversity and provides vital environmental services to society (Giovannucci and Juárez, 2006). Productive interventions that aim at carbon sequestration have the potential to contribute to income generation in rural communities and family producers (Rügnitz, 2009).

To achieve climate change mitigation, it is essential to have basic information on the carbon content in different reservoirs that an ecosystem can have (CONAFOR, 2008), so analyzing the carbon stored in different ecosystems of the Central Region of Veracruz, an important coffee-growing region of Mexico, is of great importance because it will contribute to broadening the panorama on carbon capture in the agroforestry systems of the region. The main objective of the present research was to estimate the carbon captured by aerial biomass by means of allometric equations and the determination of soil organic carbon (SOC) at four soil depths (0-10, 10-20, 20-30, and 30-60 cm) in seven different coffee AFSs: paddock (01.POT-TH), cloud forest CRUO (02.BMM-CH), full sun, colonia Manuel González (03.PSC-MZ), full sun conventional, Zacamitla (04.PSC-ZI), specialized oak (05.ESP-MZ), specialized with red cedar (06.ESP-MZ) and specialized CRUO (07.ESP-CH), under the hypothesis that the total organic carbon content in coffee AFSs will be lower than in the relict of cloud forest, but greater than the content in the paddock, which represents conventional agricultural systems.

Materials and methods

The study area is located in the coffee-growing zone in the state of Veracruz. The relief is mountainous from north to south and belongs to the Neovolcanic axis or Tarasco Nahua System, the ridge lines remain above 2 200 masl (INEGI, 2009a) and are located in the Papaloapan hydrological region in 96% (INEGI, 2009b). The climatic variability of the mountains is represented by six types, of which the semi-warm subhumid and the humid temperate (INEGI, 2009a) cover 57 and 20%, respectively. Average annual rainfall ranges from 1 700 to 2 000 mm (SMN, 2017). The soils are of volcanic origin and the pH varies from 5.2 to 6 and the large slopes vary from 3 to 60% (Pérez, 2004). The location of the seven agroforestry systems studied was distributed in the municipalities of Huatusco, Ixhuatlán del Café and Zentla (Figure 1).

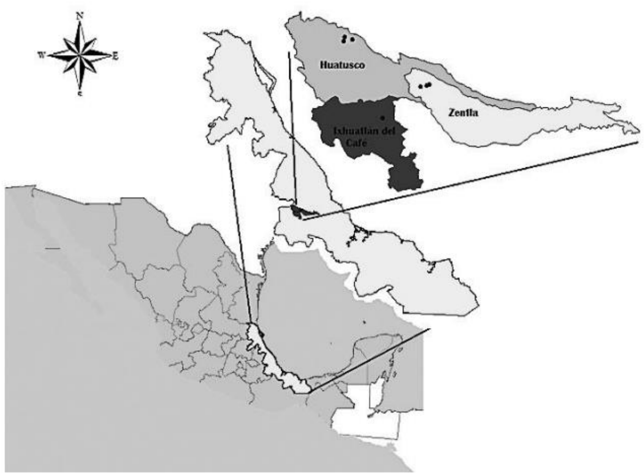

Figure 1. Geographical location of sampling sites.

Agroforestry systems evaluated (treatments)

Paddock (01. POT-TH): 90% composed of African star grass (*Cynodon plectostachyus Plinger*), with native grasses (*Axonopus* spp., *Panicum* spp. and *Paspalum* spp.), Kikuyo grass (*Penicetum clandestinum* Hochst. ex. Chiov.), white clover (*Trifolium repens* L.) and other broadleaf herbaceous plants; it includes huizaches (*Acacia pennatula* Benth.) and ocozotes (*Liquidambar styraciflua* L.) at densities less than three trees per hectare. These paddocks have been used for more than 26 years to the grazing of Holstein cows, in a semiconfined dairy system (Table 1) (Torres *et al*., 2007).

Cloud forest, CRUO (02. BMM-CH): it is located on three microrelief conditions: river plain, slope and plateau. Among the species of vascular plants existing in this relict, some stand out for their forest importance: *Lyquidambar styraciflua* L., Quiabis (*Meltosoma alba*) and aguacatillo (*Persea americana*), food species: hierba mora (*Solanum muricatum*), tepejilotle (*Chamaedorea tepejilotle*), fruit species, numerous orchids, bromeliads and ferns. In the place there are also trees of oak (*Quercus* sp.), aguacatillo (*Percea caerulea*, *Ampelocera hottlei*), ocelo (*Zyzygium* spp.), barrililloo (*Ilex quersetorum*), hincha huevos (*Comocladia engleriana* Loes), palo blanco (*Zinowiewia integerrima*), Liliana (*Eugenia* sp.), red oak (*Quercus acutifolia*) and guayabillo (*Terminalia chiriquensis* P.) (Table 1) (Escamilla *et al*., 1994).

Table 1. General characteristics of the agroforestry systems studied.

UM	Code	NL/WL	Area (ha)	Slope	Year of establishment
UM1	01. POT-TH	NL 19° 10.556’ / WL 96° 57.344’	nd	0-55%	1981
UM2	02.BMM-CH	NL 19° 10.764’ / WL 96° 58.025’	1.1	35%	1980
UM3	03.PSC-MZ	NL 19° 06.437’ / WL 96° 51.273’	nd	0-29%	2008
UM4	04.PSC-ZI	NL 19° 03.683’ / WL 96° 54.660’	1.5	0-22%	1992
UM5	05.ESP-MZ	NL 19° 06.512’ / WL 96° 50.716’	1.5	18, 32, 34 y 49%	2004
UM6	06.ESP-MZ	NL 19° 06.602’ / WL 96° 50.462’	2	2.5, 6, 7 y 8%	2008
UM7	07.ESP-CH	NL 19° 10.421’ / WL 96° 58.103’	nd	0-22%	2004

01.POT-TH= paddock; 02.BMM-CH= cloud forest; 03.PSC-MZ= full sun, Colonia Manuel González; 04.PSC-ZI= full sun conventional, Zacamitla; 05.ESP-MZ= specialized oak; 06.ESP-MZ= specialized with red cedar; 07.ESP-CH= specialized CRUO; UM=unit of sampling; NL= north latitude; WL= west latitude; nd= no data.

Full sun, Colonia Manuel González (03. PSC-MZ): coffee tree plantation (2 to 3 m high) of the ‘Costa Rica’ variety under monoculture and at full sun exposure, combined with trees of vainillo (24 m high), red cedar (0.5 m to 4 m high), ixpepe (18 m high), guarumbo and oaks (Table 1). Full sun conventional, Zacamitla (04. PSC-ZI): coffee tree plantation (1 to 1.5 m high) of the ‘Garnica’ and ‘Bourbon’ varieties at full sun exposure, combined with tesguate, vainillo, listoncillo, oak and ixpepe trees, the latter two with heights of up to 14 m (Table 1).

Specialized oak (05. ESP-MZ): coffee tree plantation (3 to 3.7 m high) that are combined with oak trees (*Quercus xalapensis*) up to 23 m high (Table 1). Specialized with red cedar (06. ESP-MZ): coffee tree plantation (2 to 2.5 m high) of the ‘Costa Rica’ variety combined with red cedar trees (*Cedrela odorata*), which reach heights of up to 17 m (Table 1). Specialized CRUO (07. ESP-CH): coffee tree plantation (1 to 3 m high) of the Colombia variety, which are mainly combined with chalahuite trees (*Inga vera* W.) which reach up to 28.

Soil sampling and biomass measurement

The design of the sampling units (UM) was systematic, three UMs were placed in a North-South direction (UM 2, 3 and 4) and one in an east-west direction (UM 1) in each study system (Figure 2). The UMs were rectangular frames of 25 x 4 m (100 m^2), Etchevers *et al*. (2005). To obtain the average value of the UMs, the values of points N and S of each of the units (UM 2, 3 and 4) and points E and O of UM1 were taken into account and thus representative samples of each of the UMs were obtained, which were used to calculate the characteristics of the plant biomass (shrub, herbaceous and plant litter) and soil at four different depths (0-10, 10-20, 20-30 and 30-60 cm) (Etchevers *et al*., 2005; Rügnitz *et al*., 2008).

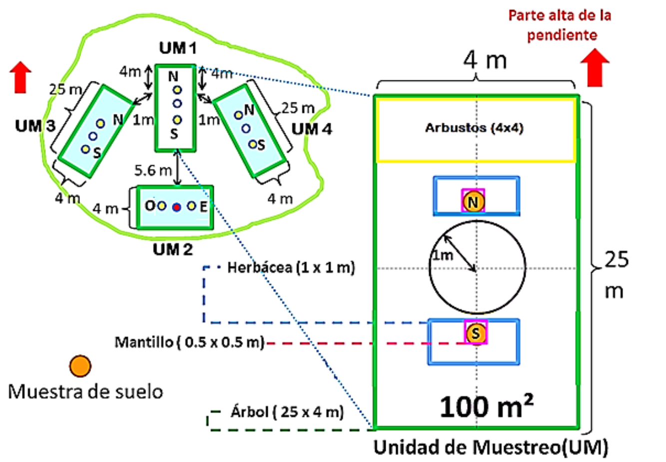

Figure 2. Schematization of the sampling unit (UM) used in the agroforestry system (Masuhara *et al*., 2015).

The measurement of edaphic C in the systems studied was carried out from soil samples from two wells per UM (Figure 3), following the methodology described by (Rügnitz *et al*., 2008; Masuhara *et al*., 2015).

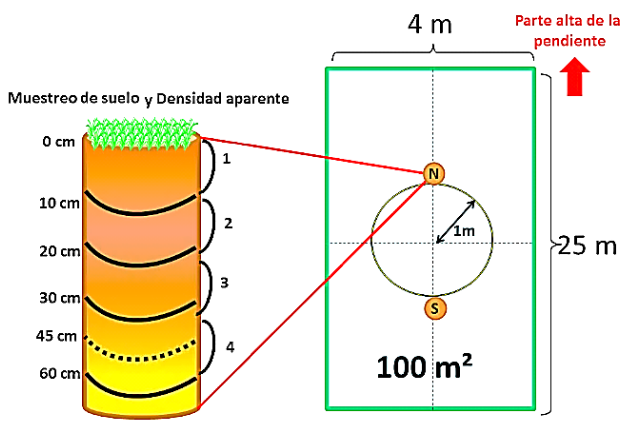

Figure 3. Schematization of soil sampling depths (Masuhara *et al*., 2015).

The bulk density (ρb) was determined according to the methodology cited by Masuhara *et al*. (2015), in each of the four depth levels (0-10, 10-20, 20-30 and 30-60 cm). To calculate the tree biomass (TB), the entire available area of the UM (25x4 m) was used, according to Etchevers *et al*. (2005); Rügnitz *et al*. (2008). For both shrub and tree species, allometric equations were used according to the species (Table 2) and kg C ha^{-1} was converted to Mg C ha^{-1}.

To estimate the biomass of fallen logs (BTC)> 5 cm in diameter and >50 cm in length, the corresponding allometric equation was used (Table 1). To calculate the amount of biomass per ha, the biomass of all the measured fallen logs was added up (1). BTC (Mg ha^{-1})= BAC x 10-4 1). Where: BAC= total biomass (g) in the UM of 25 x 4 m (Hairiah *et al*., 2001). To evaluate the herbaceous biomass (BH), a frame of 1x1 m (1 m^2) was used, placed 1 m from the center of the UM and within a sub-quadrant of 4 x 4 m, the formula used was: BH= ((PSM/PFM x PFT) x 0.01.

Where: BH= herbaceous biomass; dry matter (Mg ha^{-1})= PSM= dry weight (g) of the collected sample, PFM= fresh weight (g) of the collected sample; PFT= total fresh weight (g) per square meter and 0.01 is used as the conversion factor.

Table 2. Allometric models used in the estimation of tree and shrub biomass in agroforestry coffee systems.

Species	Equation	Citation
Coffee	$Y= 10^{(-1.113+1.578*LOG10(D)+0.581*LOG10(D))}$	Segura *et al*. (2006)
Banana	$Y= 0.03*(D)^{2.13}$	Van Noordwijk *et al*. (2002)
Red cedar	$Y= \exp(-1.17+(2.119*\ln(D))$	Brown (1997)
Trees in general	$Y =10^{(-0.834+2.223*\log10(D))}$	Segura *et al*. (2006)
Fallen logs	Y= pi∗r2 x L x 0.43	Hairiah *et al*. (2001)
Root biomass	$Y= \exp(-1.0587+0.8836*\ln(A+a+H))$	Ayala *et al*. (2001)
Inga spp.	$Y= 10^{(-0.889+2.317*(\log10(D))}$	Segura *et al*. (2006)
Oak	$Y= 1.91*(D)^{(1.782)}$	Ayala *et al*. (2001)
Tree biomass of BMM	$Y= \exp(-2.289+2.649*\ln(D)-0.021*(\ln(D)^2)$	Brown (1997)

Y= biomass above the ground in kilograms; D= Dbh in cm at 1.3 cm (trees) and 15 cm (shrubs), $\log_{10}$= logarithm in base 10, exp= exponent; ln= natural logarithm.

The sampling of plant litter biomass (BM) was performed systematically with sub-quadrants of 0.5 x 0.5 m (0.25m^2) placed in the center of the frame for the sampling of herbaceous biomass. To estimate root biomass (BR), the calculation was made with the following equation (Cairns *et al*., 1997). BR= exp [-1.0587 + 0.8836 x ln (BAE)]. Where: BR= root biomass, dry matter (Mg ha^{-1}); exp= exponential; In= natural logarithm; and BAE= tree, shrubby and herbaceous biomass, dry matter (Mg ha^{-1}). To estimate the amount of C in the total plant biomass, the following equation was used: CBV= BVT x 0.5. Where: CBV= carbon in total plant biomass (Mg ha^{-1}); BVT= total plant biomass (Mg ha^{-1}) and 0.5 as a constant.

Statistical analysis

The data were subjected to an analysis of variance (Anova) under a completely random design and Tukey's comparison of means ($p< 0.05$) was performed with the Statistical Analysis System (SAS) program to determine the statistical difference in the AFSs.

Results and discussion

Carbon stored in trees

The behavior of the tree component stood out in the 02.BMM-CH system with a C content of 386.21 Mg ha^{-1}. Beristain (2000) describes this system as a relict of natural forest that has remained undisturbed for 32 years, serving as a natural botanical garden, in the present research this system had a greater number of trees 3 175 per hectare; that is, ten times more than in the other agroforestry systems evaluated.

In the 05.ESP-MZ system, 302.54 Mg ha^{-1} and 900 ha^{-1} trees were obtained and although the C is similar to that obtained in 02. BMM-CH, the number of trees is smaller because in a specialized system with oak, the trees are of great height and have a considerable diameter, therefore, the biomass obtained in the tree component is high. The 04.PSC-ZI system provided 95.96 Mg ha^{-1} with 1 400 trees ha^{-1}, although it has a considerable number of trees, it is necessary to emphasize that these were growing so they did not provide adequate shade to the coffee trees, hence it was taken as full sun.

Carbon stored in shrubs (coffee trees)

With 11.97 Mg ha^{-1}, the 06.ESP-MZ system was the one that obtained the highest storage of C in the shrubs, followed by 03.PSC-MZ with 8.88 Mg ha^{-1} and 05.ESP-MZ with 8.28 Mg ha^{-1}. The 02.BMM-CH was the one that showed the lowest value with 1.46 Mg ha^{-1}, which is attributed to the fact that there are no coffee trees in this system and that the 41 trees (64 m^2) considered shrubs for having a dbh< 5 cm have a biomass of 2.92 Mg ha^{-1}. The 02.BMM-CH stood out from the agroforestry systems for the density of shrubs (6 406 shrubs per hectare). Masuhara *et al*. (2015) report similar values for the cloud forest with 1.5 Mg ha^{-1} and with 6 719 shrubs per hectare and for the specialized system, they reported 2.8 Mg ha^{-1}. On the other hand, in Chiapas, Guerrero (2011) obtains 11.37 Mg ha^{-1} in monoculture under shade and reported 11.03 and 8.83 Mg ha^{-1} for natural coffee and traditional polyculture, respectively.

Carbon stored in fallen logs

The biomass of fallen logs only appears in two of the agroforestry systems studied, 03.PSC-MZ with 225 fallen logs per ha and 06.ESP-MZ with 150 fallen logs per ha, it should be noted that, in the 03.PSC-MZ system, the length of the logs was three times longer. The difference in the number of logs between the agroforestry systems can be influenced by the slope, since 02.BMM-CH has a slope of 35% and the 05.ESP-MZ system has steep slopes of up to 49%, so the logs could have rolled towards the lower part and, in systems 03 and 06, which have fallen logs, the slope does not exceed 22%.

Carbon stored in herbaceous plants and plant litter

The 07.ESP-CH system had the highest amount of C in relation to the herbaceous stratum with 4.27 Mg ha^{-1}. The 02.BMM-CH system had a zero value, this may be because the tree and shrub components prevent the adequate entry of light into the soil for the growth of herbs. The 01.POT-TH resulted with 2.06 Mg ha^{-1}, similar to that observed by Espinoza-Domínguez *et al*. (2012), who report values in the paddock of 1.7 Mg ha^{-1} and for the cloud forest 0.64 Mg ha^{-1}.

Carbon in the plant litter layer

The 05.ESP.MZ system was the one that had the most capture with 8.64 Mg ha^{-1}, followed by 02.BMM-CH, 03.PSC-MZ and 06.ESP-CH with 5.04, 5.03 and 2.95 Mg ha^{-1}, respectively, finally the 01.POT-TH and 07.ESP-CH, which were the systems where the highest amount of herbaceous plants was found and they reported the lowest C contents in the plant litter, with 0.42 and 0.05 Mg ha^{-1}, respectively. These results were higher than those reported by Delgadillo and Quechulpa (2006), for their agroforestry system, the plant litter has 1.5 Mg ha^{-1}, the improved tropical and the subtropical systems with 0.65 and 2.19 Mg ha^{-1}, respectively.

Carbon stored in the roots

The largest amount of carbon in roots was found in the 02.BMM-CH system with 64.55 Mg ha^{-1}, this is proportional to the number of trees found in this system, which is high if we compare it with the results obtained by Masuhara *et al*. (2015), who report a carbon content in roots of 48.15 Mg ha^{-1}. In the 05.ESP-MZ system, 54.23 Mg ha^{-1} was obtained, this probably due to the type of trees with which coffee is associated, since oak (it includes the amount contributed by shrubs and herbaceous plants) stores 11.36% of the carbon captured in the system in its roots.

Soil organic carbon content

In the 02.BMM-CH, they obtained 108 Mg ha^{-1} of SOC, resulting in the site of greater retention of C in the soil, the 06.ESP-MZ and 07.ESP-CH systems were the ones that report lower content with 62 Mg ha^{-1}. The results obtained in the present study can be related to those reported by Mena *et al*. (2011), who report for soil organic carbon from altitudinal floors and land use systems in Costa Rica, such as secondary forest (Bo), values of 113.1 Mg ha^{-1} and for specialized coffee agroforestry systems with laurel and poró (*Erytrina poeppigiana*) with values of 84.9 and 108.1 Mg ha^{-1}, respectively.

There are very contrasting variations in the tree carbon of AFSs (Table 3.) due in some way to the agronomic management of each coffee plantation, the density of planting and the age of the trees and shrubs, but above all to the complex heterogeneity of species present. It is worth mentioning that the paddock is subjected to a semiconfined process with cattle, in which the growth of pastures and few trees is allowed.

Table 3. Average content of organic carbon in the soil (Mg ha^{-1}).

Dep (cm)	1.POT-TH	2.BMM-CH	3.PSC-MZ	4.PSC-ZI	5.ESP-MZ	6.ESP-MZ	7.ESP-CH
0 -10	20.84 ±4.92a	33.16 ±9.33ab	18.14 ±7.07a	23.95 ±6.33ab	25.59 ±5.99a	12.67 ±3.98ab	13.55 ±3.64ab
10-20	25.12 ±9.49a	17.21 ±4.08a	23.77 ±10.63a	16.71 ±5.31a	23.65 ±7.42a	12.01 ±3.02a	16.98 ±4.68a
20-30	24.1 ±6ab	26.76 ±2.51a	22.05 ±6.57ab	15.46 ±3.98ab	26.47 ±5.65ab	11.05 ±1.38ab	10.24 ±5.26b
30-60	25.82 ±9.1a	30.84 ±4.82a	7.46 a	25.56 ±8.41a	28.06 ±8.81a	26.3 ±4.33a	21.07 ±4.59a

Dep= depth; 01.POT-TH= paddock; 02.BMM-CH= cloud forest CRUO; 03.PSC-MZ= full sun, Colonia Manuel González; 04.PSC-ZI= full sun conventional, Zacamitla; 05.ESP-MZ= specialized oak; 06.ESP-MZ= specialized with red cedar; 07.ESP-CH= specialized CRUO. Eequal letters indicate non-significant differences ($p < 0.05$).

Distribution of carbon content by system components

At the paddock site (01.POT-MF), the highest concentration of carbon stored was in the soil (0-60 cm deep), 95.89 Mg ha^{-1} were detected, which represents 96.83% of the total, followed by the C linked to the herbaceous stratum with 2.06 Mg ha^{-1} associated with C stored in the roots, which was 0.66 Mg ha^{-1}, the plant litter reported 0.42 Mg ha^{-1} (0.43%) (Table 4).

Table 4. Average carbon content stored in the aerial stratum (Mg ha^{-1}, trees, shrubs, herbaceous plants, plant litter, fallen logs and roots).

Stratum	01POT-MF	02BMM-CH	03PSC-MZ	04PSC-ZI	05ESP-MZ	06ESP-MZ	07ESP-CH
Tree	0 b	385.58 a	26.83 a	95.56 a	302.54 a	22.28 a	188.06 a
Shrub	0 c	1.46 c	8.88 ab	4.9 abc	8.28 abc	11.97 a	4.6 abc
Herbaceous	2.06 cd	0 b	0.18 b	0.17 bc	0.06 a	0.05 c	4.27 a
Plant litter	0.42 a	5.04 a	5.03 a	3.32 a	8.64 a	2.95 cbd	0.05 d
Root	0.66 b	64.55 b	8.16 a	20.02 b	54.23 b	7.80 a	34.9 a
Fallen l.	0 b	0.06 c	12.01 c	0 c	0 c	0.91 b	0 b
Soil**	95.89	107.99	85.57	79.12	103.79	62.05	61.85
Total	99.03	564.63	146.65	203.09	477.54	108	293.73

01.POT-TH= paddock; 02.BMM-CH= cloud forest CRUO; 03.PSC-MZ= full sun; Colonia Manuel González; 04.PSC-ZI: Full sun conventional, Zacamitla; 05.ESP-MZ= specialized oak; 06.ESP-MZ= specialized with red cedar; 07.ESP-CH= specialized CRUO; Fallen l.= fallen logs; **= depth from 0 to 60 cm. Equal letters indicate non-significant differences between systems by stratum ($p < 0.05$).

Conclusions

In the present study, different agroforestry systems (AFSs) of the most representative of the coffee-growing zone of Huatusco were evaluated. Agroforestry systems based on coffee cultivation capture on average 245.08 Mg ha^{-1}, they are systems with more conservationist management and with the use of perennial species that are used in their entirety, even tree residues are incorporated into the soil, which guarantees stored carbon.

Regarding the aerial biomass of coffee agroforestry systems, it was determined that they can store from 3, 45, 61, 124, 231, 373 and 456.64 Mg ha^{-1}, in 01.POT-TH, 06.ESP-MZ, 04.PSC-MZ, 03.PSC-ZI, 07.ESP-CH, 05.ESP-MZ and 02.BMM-CH, respectively. The 02.BMM-CH accumulated the largest aerial biomass because being an undisturbed, uncleared forest, it maintains the largest amount of carbon stored in its tree stratum, while the aerial biomass in the paddock (01.POT-TH) was the lowest because it does not have a tree or shrub stratum, only the herbaceous one. The agroforestry coffee systems in the Huatusco region have a high potential for carbon sequestration, which is why it is essential to provide coffee growers with basic knowledge that allows them to use the resources available in their agroforestry systems.

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