Knowledge product

Assessment of the potential of carbon capture for seven tree species in shade-grown coffee plantations in the State of Veracruz, Mexico.

1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO, 2022), one of the most widely exchanged agricultural products and consumed beverages worldwide is coffee. To illustrate this point, coffee production during the year 2008 was estimated at 8.5 million tons and increased to 10.7 million tons in 2020 (FAO, 2022; Mordor Intelligence, 2021). Moreover, 70 % of total coffee production exported in 2017 was estimated at USD 19 billion, employing 125 million people globally (Fairtrade Foundation, 2022; Panhuysen & Pierrot, 2020). In this sense, it is important to emphasize that South America contributes 80% of total coffee production worldwide (Baffes *et al.*, 2005).

Currently, coffee plantations are distributed in 12.5 million farms around the world, mostly managed by smallholder farmers in developing countries with less than 2 or 5 ha available for coffee farming, representing 73–80 % of coffee producers worldwide (Fairtrade Foundation, 2022; Panhuysen & Pierrot, 2020). Specifically, in Mexico, the area designated to coffee agricultural practices is ~665,837 ha, worked by about 479,116 farmers, half of them distributed in Chiapas and Oaxaca, where 40 % are coffee smallholder farmers with less than 0.5 ha available for coffee farming (Nestel, 1995). A special case arises in the Veracruz state, where farming communities dedicated to coffee production top the list at the national level, producing 23 % of the national overall output (Nestel, 1995); however, due to the high deforestation rate in this state, erosion has become a problem on 40 % of the territory, mainly attributed to the loss of vegetation cover (García-López, 2009).

Changes in environmental conditions, including but not limited to soil erosion, negatively affect coffee production considering that this crop depends on specific conditions of temperature, humidity, and rainfall conditions, triggering phenological changes during coffee growth. Also, due to low coffee prices, many farmers no longer use the land they had set aside for growing coffee and instead use it to grow corn or engage in intensive cattle-raising (Beer *et al.*, 1998; Davidson, 2004; Adugna & Struik, 2011).

Agroforestry systems based on perennial native tree species have been an alternative to mitigate the outcomes mentioned above as well as providing fruit and/or timber when coffee prices are low. Since biodiversity preservation and the enhancement of coffee production are the two main targets in the agroecological management of coffee; these two factors should be taken into consideration when choosing tree species for shade diversification. As a result, our effort concentrated on both choosing native tree species with the most useful characteristics and studying their physiological processes in the field. Finally, the main goal of this investigation was to provide reliable scientific evidence on the amount of carbon captured by the selected species that are useful for coffee growers.

2. Methods and study area

The selection criteria were carried out applying a socio-environmental algorithm specifically devised for this assessment. the selection of 50 native tree species with the best qualities for use as shade biodiversity in the Coatepec-Huatusco coffee region, i.e., species that are a part of the natural flora, quick-growing, and useful for a variety of purposes; excluding species used as firewood or fuel, preventing the release of greenhouse gases into the environment. The species selection was based on the most recent and comprehensive list of tree species that have been published to date, which lists 2885 native tree species in Mexico, divided into 612 genera and 128 families with a 44 % endemism rate (Tellez *et al*., 2020). The list of 50 prioritized species was then submitted to the communities through two interactive community workshops, the first one in Teocelo, and the second one in Ixhuatán del Café, Veracruz. The selection was based on their first-hand traditional and cultural experience, meeting the shade needs for the rustic production of coffee and representing species that have several diverse uses. From the 15 species chosen through the participatory workshops, eight species were selected for their potential to have the greatest impact on communities. Subsequently, these species were screened for their selection process and status, those species that come from domestication and cultivation processes were discarded, as is the case of *Persea americana* Mill. (Hass Avocado) which was discarded, and subsequently, the next species on the list was used. As a result, the seven species selected for further studies are listed in Table 1.

Table 1. Ranking of coffee-associated shade trees chosen for *in-situ* assays.

Ranking	Species	Selection Process/Status[1]
1	*Inga jinicuil* Schltdl. & Cham. Ex G. Don	Wild/Cultivated
2	*Inga vera* Willd.	Wild/Cultivated
3	*Inga punctata* Willd.	Wild/Cultivated
4	*Erythrina americana* Mill.	Wild/Cultivated
5	*Psidium guajava* L.	Wild/Cultivated
6	*Persea schiedeana* Turcz.	Wild
7	*Heliocarpus appendiculatus* Nees	Wild

[1] Source: CONABIO (https://enciclovida.mx, accessed on 21th September 2022).

Field assays were carried out in two farms located in the municipality of Coatepec, Veracruz-Llave, Mexico, during October and November 2022. Measurements were performed in farms with coordinates: 19° 23' 36'' N, 96°59'9.4'' W, at an elevation of 1117 m.a.s.l. and 19° 25' 23.5'' N, 96° 55' 42.6'' W, at an elevation of 1053 m.a.s.l., for shaded and unshaded conditions (only coffee plants), respectively. Both farms have average minimum and maximum temperatures of 10 and 29 °C, respectively. The distances between the coffee farms ensured little variation in weather conditions.

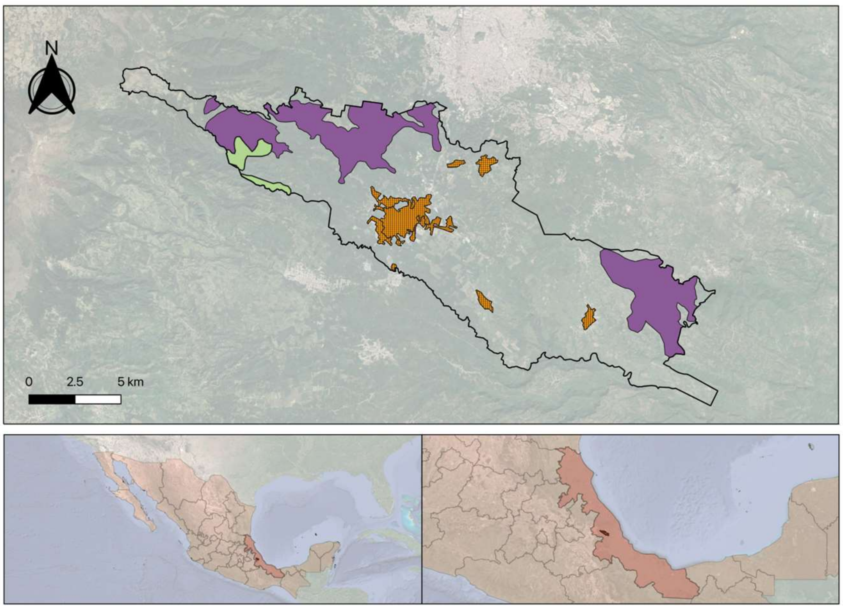

Figure 1. Municipality of Coatepec, Veracruz-Llave, Mexico. In the upper box are shown the cloud forest area (green), the area corresponding to cultivated grassland (purple), the region designated for coffee agriculture (orange), and the area of urban settlements (grid), which overlaps with the coffee agriculture area.

The field assays in the coffee plantation comprised the measurement of two dendrometric parameters of the seven chosen shade trees species:

1. diameter at breast high (DBH, at 1.30 m), and
2. height.

Using this data, reported allometric equations *ad hoc* for the different tree species were applied to determine above-ground biomass (AGB) for each tree (Rojas-García *et al*., 2015) (Table 2).

The AGB is referred to as the mass of living organic matter and represents the approximated value of the weight of that portion of the tree found above the ground surface, this parameter is linked to ecosystem functioning qualities as well as climatic change, due to implications of biomass on carbon cycles (Liang & Wang, 2020; Araza *et al*., 2022). Biomass values were transformed into biomass carbon stock by multiplying AGB by 0.47, the value assigned by the Intergovernmental Panel on Climate Change (IPCC) to the fraction of carbon that corresponds to the calculated biomass; this value relates to the tree's potential to store carbon and its capacity to develop into new cells (IPCC, 2006). Subsequently, 10-year carbon stocks were calculated for the seven selected species of shade trees associated with coffee.

Gas exchange analyses were conducted around midday using the Infrared Gas Analyzer (IRGA) coupled with a fluorometric cell for photosynthetic analysis. Six stomatal and photosynthetic parameters were measured on individual shade tree leaves localized on the first plagiotropic branches near the understory:

1. maximum quantum yield (Fv/Fm, quotient between the variable fluorescence and the maximum fluorescence),
2. photosynthesis,
3. stomatal conductance,
4. transpiration,
5. intercellular CO_2 (Ci), and
6. photosynthetically active radiation (PAR).

For comparative purposes, the same parameters were measured from shaded and unshaded coffee plants Oro Azteca variety, which is characterized for its resistance against coffee rust (leaf infection by the fungus *Hemileia vastatrix*) and for having been developed and registered in Mexico by Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP).

The branch where the leaves used for photosynthetic and stomatal analysis were located was cut and collected for analytical test. The branches were dried in a botanical press immediately after cutting. The analyses were performed during the first two days following *in-situ* sampling and drying. Humidity and nitrogen contents were determined from sample leaves of unshaded and shaded coffee plants. Gravimetric methods, which include weight measurement and the relationship between weight before and after drying, were used for humidity content determination.

Nitrogen contents were assayed by the Kjeldahl method, which comprises sample digestion and determination of organic nitrogen and ammoniacal nitrogen content. The analysis was assessed in the dried leaf material using micro - Kjeldahl Nitrogen apparatus. All measurements were performed by triplicate.

3. Results and discussion

As the main objective of this work, seven selected species were studied by their potential as a carbon sink to mitigate the impacts of global warming through carbon capture and sequestration and its further assimilation as part of their tree biomass. With this purpose, two dendrometric parameters, i.e., diameter at breast height and total height were measured, followed by their application in allometric equations for above-ground biomass (AGB) and carbon stock per tree at 10 years of age. Additionally, it is crucial to note in this context that studies of plant physiology often make use of the fluorescence and gas exchange of chlorophyll *a* to assess plant development and responses to environmental stimuli; this type of assay is both rapid and non-destructive, as it involves efficiently measuring the photosynthetic apparatus's conversion of light energy into organic molecules, as well as promoting plant growth and responses to environmental factors that affect photosynthesis, such as water and nutrition availability (Sakshaug *et al*., 1998; Roháček, 2002).

The highest AGB values were observed for *E. americana*, followed by *P. schiedeana*, *H. appendiculatus*, *I. jinicuil*, *I. vera*, *P. guajava,* and finally *I. punctata* (Table 2). These results, however, because each tree age varied—for example, while individuals of the species *E. americana* had an average age of around 40 years, some individuals of the species *P. guajava* had barely reached the age of six—these results were normalized to 10 years of age for all species for the calculation of the carbon stock. Carbon stock calculation indicates that *P. schiedeana* has the highest carbon fraction, which corresponds to the calculated biomass during the first ten years, this means that this species has the highest potential for carbon assimilation, considering its higher photosynthetic and stomatal conductance values, and despite its lower transpiration values, which could be explained by gas exchange measurements in young, not fully developed leaves; the same response has been observed previously in *P. guajava* leaves (Nava *et al*., 2009). Another result that needs to be addressed is the one observed in *I. jinicuil*, which ranks 4th place in carbon stock stored as biomass and was ranked 1th place during species selection, this species (and all *Inga* species studies during this work) has the highest number of characteristics that benefit farmers as well as coffee plantations. During its first ten years *I. jinicuil* could store 28 %, 56 %, and 78 % of the total carbon stock incorporated as the biomass of *P. schiedeana*, *E. americana,* and *H. appendiculatus*, the first three places in the rank. The incorporation of *I. jinicuil* into coffee agroforestry systems can lead to carbon sequestration of 198 Mg C ha^{-1}, while the association with other *Inga* and *Erythrina* species, and other Musaceae species, the sequestration can amount to 15.5 Mg C ha^{-1} and finally in areas with *Inga* spp. and forest strata, carbon sequestration could reach 91.64 Mg C ha^{-1} (Haber, 2001). In coffee plantations, shade species like *Inga* spp. have carbon sequestration values of 24.3 Mg C ha^{-1} at 20 years of age (Kursten & Burschel, 1993).

The values of Fv/Fm ≥0.75 of the seven tree species and shaded coffee plants indicate normal functioning of the photosynthetic apparatus (Table 3). Fv/Fm ratio, i.e., the potential quantum efficiency of photosystem II (PSII), is a widely used parameter of chlorophyll fluorescence, and it is used to estimate the maximum efficiency of PS II when all its reaction centers are opened. Fv/Fm ratio values between 6.5–8 suggest normal non-stressed plant photosynthesis; while values below 6.5 are related to photosynthesis downregulation and/or photoinhibition (Maxwell & Johnson, 2000; Silva *et al*., 2017), this downregulation is usually triggered by temperature and environmental stress (Larcher, 1994; Roháček, 2002)

Photosynthesis, stomatal conductance, and transpiration values were different between species. In this sense, it was observed that *Psidium guajava* had the highest values of photosynthesis (11.76 μmol CO_2 m^2/s), and therefore a higher biochemical and physiological potential for carbon fixation; while *Erythrina americana*, *Persea schiedeana*, *Heliocarpus appendiculatus,* and *Inga punctata* rank 2nd (values ranged from 6.55 to 5.57 μmol CO_2 m^2/s) and finally followed by *Inga jinicuil* and *Inga vera* in 3rd place (3.23 and 2.45 μmol CO_2 m^2/s, respectively). Concerning stomatal conductance (Table 3), we observed that *P. schiedeana* had the highest values (0.41 μmol CO_2 mol^{-1}) followed by *P. guajava* and *H. appendiculatus* (≈0.22 μmol CO_2 mol^{-1}) and finally followed by the group formed by *I. jinicuil*, *I. vera*, *I. punctata* and *E. americana* (values ranged from 0.19–0.14 μmol CO_2 mol^{-1}). Transpiration values follow the same tendency as stomatal conductance, except for the case of *P. schiedeana*, species in which a high value of stomatal conductance and a low transpiration value were observed. Stomatal conductance and photosynthesis are closely related due to the photosynthetic rate being limited by stomata closure, which in turn imposed a large limitation on the rate of CO_2 assimilation.

Intercellular CO_2 (Ci) (Table 3) was higher for the group formed by *I. jinicuil*, *I. vera*, *I. punctata*, *E. americana*, and *H. appendiculatus* (≈437.4 μmol CO2 mol^{-1}); while *P. guajava* and *P. schiedeana* had lower Ci concentrations (3.74 and 331.8 μmol CO_2 mol^{-1}, respectively); however, this difference between Ci concentrations of the seven species was not statistically different. Stomatal conductance and Ci values, the reduction of CO_2 concentration is linked with stomatal closing, reducing in turn, the availability of this substrate for photosynthesis, affecting carbon assimilation and fixation of atmospheric CO_2. High photosynthesis rates imply a high biochemical and physiological potential for a high carbon fixation capacity (Gulmon & Chu, 1981). Shaded plants adapt their leaves to become thinner and bigger to boost their carbon-fixing capability (Friend, 1984; Fahl *et al*., 1994). These changes enable them to capture and use the light energy available, increasing the amount of dry matter they produce more effectively. On the other hand, low CO_2 assimilation is related to drought stress and reduced growth rates (Maxwell & Johnson, 2000; Simonin *et al*., 2012; North *et al*., 2013). Stomatal conductance is a measure of the gas exchange through the stomata; that is, it indicates the molar flow of either water vapor, H_2O, or CO_2. The stomatal response is related to the air temperature and the difference in vapor pressure between the leaf's interior and the atmosphere, leading to stomatal aperture/closure. The Ci values are influenced by the rate of CO_2 availability to the interior of the leaf and the demand for CO_2 in the chloroplasts inside, both of which are controlled by the stomatal conductance; therefore, it would be expected that with a higher conductance, there would be greater availability of this gas in the intercellular spaces of the leaf (Nava *et al*., 2009); our observed values support this premise.

Regarding coffee plants, Fv/Fm values below 0.65 of unshaded plants (Table 3) indicate a decrease in the efficiency with which light energy is used during photosynthesis. This decrease in quantum efficiency suggests an inhibition/damage of the photosynthetic apparatus (Maxwell & Johnson, 2000; Silva *et al*., 2017). Fv/Fm values of unshaded plants were accompanied by a decrease in the values of photosynthesis, stomatal conductance, and transpiration compared to shaded coffee plants; this physiological response was expected due to higher radiation at the leaf level, i.e., 50-fold higher radiation (PAR) for unshaded coffee plants, together with an increase in air temperature. The reduction of radiation reaching the coffee canopy is the main source of the decrease in air temperature. In this context, it has been observed that the shade provided by the trees associated with the coffee plantation changes the microclimatic conditions. This microclimate amelioration helps to preserve air and soil humidity; for example, evidence shows that shade helps to buffer higher and lower air and soil temperatures in a range between 2–5 °C; also, higher evaporation rates under open conditions (Barradas & Fanjul, 1986; Adugna & Struik, 2011).

As the final stage in this research, the humidity and nitrogen levels of coffee plants of the Oro Azteca variety with and without shade were analysed and compared (Table 4). These parameters could be associated with radiation stress conditions and nitrogen assimilation. Our observed results indicate that there are significant differences in humidity and nitrogen content between both types of crops, being higher for shaded coffee plants. Coffee plants grown in shaded conditions had higher values of nitrogen and humidity content. A correlation between nitrogen content and leave colour it has been observed, at higher nitrogen concentrations, darker green colour (Titus & Pereira, 2005). Coffee leaves developed a darker green color when they were in the shade, which was related with more nitrogen accumulated inside of them. This type of leaves might be able to absorb more light, due to its chloroplasts with higher light-capturing capability can absorb lower light intensities and use them more effectively to boost their photosynthetic rate. In this context, it has been observed by Fahl *et al*. (1994) and Ramalho *et al*. (2000) that under stressed conditions increased leaf nitrogen availability stimulates the activation and support of photoprotective systems to prevent photooxidation (Fahl *et al*., 1994). Additionally, it has been found that leaf nitrogen levels and carbon absorption rates are positively correlated, allowing shaded leaves to function photosynthetically and grow more vegetatively than sun-exposed leaves. Consequently, direct sunlight coffee plants were exposed to environmental variables that are more likely to trigger plant stress responses than shaded plants.

The higher humidity content of shaded samples could be explained by the lower air temperature and reduced light intensity under shadowed conditions where relative humidity levels surrounding coffee plants tend to increase, increasing in turn the leaf water content. This atmospheric water absorption via aerial organs of plants has been considered a crucial and universal phenomenon in previous studies (Schwerbrock & Leuschner, 2017). Relative humidity levels around shaded coffee plants increased because of the reduced air temperature and light intensity in shaded conditions, decreasing in turn vapor pressure deficit (VPD), under these conditions the rate of transpiration of the leaf decreased, resulting in a higher leaf water potential. Under such low VPD, the stomatal aperture increases, increasing in turn, the CO_2 diffusion into the leaf and therefore, the intercellular CO_2 concentration. Considering the relationship between the stomatal aperture with transpiration and photosynthesis, it would be expected a greater effect of the stomatal aperture on transpiration than on photosynthesis, because stomatal resistance is the main resistance to the process of transpiration (Shimshi & Ephrat, 1975). It is worth remembering that the primary processes that underlie and govern plant growth are those that involve gas exchanges with the environment, such as photosynthesis, respiration, and transpiration (Taiz & Zeiger, 2015).

Table 2. Dendrometric parameters of coffee-associated shade trees. Values are expressed as mean three independent replicates.

Tree specie	DBH (cm)[1]	Height (m)	AGB (kg $tree^{-1}$)[2]	AGB equation	Carbon stock at 10 years (kg $tree^{-1}$)[3]
Inga jinicuil	19.84	9.33	164.27	[Exp[−1.76]*[DBH^2.26]]	77.21
Inga vera	13.00	6.33	69.34	[Exp[−1.76]*[DBH^2.26]]	17.78
Inga punctata	10.29	5.00	41.16	[Exp[−1.76]*[DBH^2.26]]	14.51
Erythrina americana	58.09	16.00	1165.58	[0.3700]*[DBH^1.9600]	136.96
Psidium guajava	10.96	6.33	62.46	[0.246689]*[DBH^2.24992]	48.93
Heliocarpus appendiculatus	40.69	16.00	417.77	[[Exp[4.9375]]*[[DBH^2]^1.0583]]*[1.14]/1000	98.18
Persea schiedeana	34.87	14.33	585.93	Exp((−3.1141)+((0.9719)*(Ln(DBH^2*H))	275.38

[1] Diameter at breast height (1.30 m)
[2] Above-ground biomass
[3] Obtained AGB were converted into carbon stock by multiplying with IPCC's (2006) default carbon fraction of 0.47

Table 3. Photosynthetic parameters of coffee-associated shade trees and unshaded and shaded coffee plants. Values are expressed as mean three independent replicates.

Parameter	*Unshaded coffee*	*Shaded coffee*	*I. jinicuil*	*I. vera*	*I. punctata*	*E. americana*	*P. guajava*	*H. appendiculatus*	*P. schiedeana*
Fv/Fm (dimensionless)	0.64	0.77	0.79	0.75	0.80	0.83	0.85	0.83	0.85
Photosynthesis (μmol CO_2 m^2/s)	1.63	6.22	3.23	2.45	5.57	6.55	11.76	6.06	6.29
Stomatal conductance (μmol CO_2 mol^{-1})	0.038	0.15	0.19	0.19	0.14	0.14	0.23	0.22	0.41
Transpiration (mmolH_2O m^2/s)	0.49	2.18	1.54	1.77	1.14	1.10	2.15	2.73	0.52
Intercellular CO_2 (μmol CO_2 mol^{-1})	388	396.4	439.1	456.3	425.2	440.3	374.1	427.4	331.8
PAR[1] understory (μmol m^{-2} s^{-1})	1150.2	23.6	40.5	62.67	26.56	128	60.67	ND	27.50

[1] Photosynthetically active radiation

Table 4. Humidity and nitrogen content from laves of unshaded and shaded coffee plants. Values are expressed as mean ± SD of three independent replicates.

Parameter	Unshaded coffee (Oro Azteca var.)	Shaded coffee (Oro Azteca var.)
Sample humidity (%)	53.97**	55.56**
Nitrogen content (%)	2.54 ± 0.02**	2.83 ± 0.06**

[1]Statistical analysis was performed using a two-tailed unpaired t-test (t (7.6) = 4 and p=0.002). The asterisk indicates significant differences between samples.

Due to coffee agroforestry systems can sequester significant amounts of carbon, both above and below ground, these ecosystems, by acting as carbon sinks, could lessen the consequences of global warming and temperature increases. Considering the above and incorporating the available literature on the number of individuals that constitute one hectare of each of the studied tree species, an approximate calculation of carbon stock at one year per hectare was performed assuming that the seven species under study make up the entire hectare (Table 5), the seven species were ranked descending according to their ability to assimilate and transform carbon into biomass, being *P. schiedeana* the species with the best ability to assimilate carbon and incorporate into new cells and I. *punctata* the specie with the lower values. At this point, it is essential to mention that the *Inga* genus species under study have the lowest values for their capacity to sequester and store carbon, they still have other qualities that are advantageous to the coffee agrosystem, such as their ease and economy of cultivation and its high growth rate. Finally, to transform our findings into knowledge that is helpful for coffee farmers, the carbon emissions from various activities were calculated and compared concerning the carbon stock at one year of each of the seven species evaluated in the field (seen as the number of trees needed to assimilate that amount of carbon) (Table 6). These data can be compared to the carbon footprint of the most common anthropogenic carbon emissions, such as transport, industry, agriculture, waste disposal, and the coffee value chain itself, among other examples.

Table 5. Carbon stock of one hectare composed of the seven shade-tree species at one year.

Specie	Carbon stock at 1 year (kg C tree^{-1})	≈Trees per hectare	Carbon stock per year per hectare (kg C ha^{-1})	Reference (Trees per hectare)
Persea schiedeana	27.54	40	1101.6	ND
Erythrina americana	13.70	40	548	Garza-Lau *et al.*, 2020
Heliocarpus appendiculatus	9.82	40	392.8	Romero-Alvarado *et al.*, 2002
Inga jinicuil	7.72	200	1544	Barradas & Fanjul, 1986
Psidium guajava	4.89	40	195.6	ND
Inga vera	1.78	200	356	Garza-Lau *et al.*, 2020
Inga punctata	1.45	100	145	Valencia *et al.*, 2014
		Total=660	Total=4283	

Table 6. Comparison between carbon emissions of different anthropogenic activities and the number of shade trees of the seven studied species needed for carbon sequestration.

Activity	CO_2eq emissions (kg)	Number of adult trees over 10 years old needed to capture carbon emissions						
		Inga jinicuil	*Inga vera*	*Inga punctata*	*Erythrina americana*	*Psidum guajava*	*Heliocarpus appendiculatus*	*Persea schiedeana*
A 329 km journey (Mexico City-Coatepec, Veracruz) in a compact car	59.22	8	34	41	5	13	7	3
Annual consumption of heating and domestic hot water for a house of 45 m^2	1708.2	222	960	1178	125	349	174	62
Annual power consumption (250 kWh)	62.5	8	35	43	5	13	7	3
Annual feeding: vegetables, fruit, bread, cereals, moderate consumption of meat and fish, eventual consumption of processed foods. The origin of food is 80% national.	2280	296	1281	1573	167	467	233	83

4. Conclusions and future perspectives

We summarize this study with the following statements:

1. All tree species and shaded coffee plants have a non-stressed condition compared with unshaded coffee plants.
2. Higher carbon storage potential has been observed for *P. schiedeana* at 10 years, while the lowest values were observed for *I. punctata*.
3. *Inga* species has complementary benefits other than its carbon sequestration potential, such as its economics and ease of cultivation, as well as its high growth rates.
4. Leaf nitrogen levels and therefore carbon absorption rates are higher for shaded coffee plants related to an ameliorated environment condition.

Until now, the different ecological investigations on the attributes of coffee agroforestry systems have emphasized the following points: (1) interactions between soil fertility and shadow on coffee production; (2) the associations between the microclimate, pathogens, and shade; and (3) the management of soil fertility, nutrient cycling, and sustainability. To fully address the benefits like the storage of carbon by tropical forests and agroforestry systems, applied research, to which this work belongs, needs to be focused on species selection, methods of propagation, determination of appropriate population densities, and planting configurations. All this is intended to protect watersheds, biodiversity, and the environment, decreasing environmental toxicity and diversifying unstable monoculture economies. Therefore, to maximize the benefits of tree-crop relationships while avoiding the drawbacks, it is vital to define precise guidelines for the selection and management of suitable shade trees ad hoc for the different ecosystems. To provide a complete understanding of the processes occurring within and between the components in shaded perennial crop plantations, future research should integrate and enhance the current knowledge. This will enable extrapolation of the site- and/or species-specific results.

In addition, as a perspective of this work and due to the lack of information, it is necessary to complement our studies in the field, both at the level of plant communities and populations of soil microflora and microfauna, to identify the limiting factors and the belowground interactions and dynamics. Finally, it is reported that studies of germination behavior at cardinal temperatures of the selected species are still in progress, due to the long germination recording times at low temperatures.

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