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Carbon footprint and carbon storing capacity of arabica coffee plantations of Central America: A review

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ABSTRACT

Knowing the carbon footprint of agricultural systems will allow us to create mitigation and carbon capture strategies to mitigate environmental impacts. Here we reviewed the available literature about the carbon footprint associated with the cultivation of Arabica coffee in Central America region, ranging from traditional polycultures to unshaded monocultures. Subsequently, we reviewed the carbon storage data about different C stocks of a coffee plantation (*i.e.* living biomass, litter and soil). Finally, actions to mitigate emissions at the farm level are suggested. The major findings of this review were: i) the carbon footprints vary from 0.51 kg $CO_{2eq}/kg_{cherry\ coffee}$ in traditional polycultures to 0.64 kg $CO_{2eq}/kg_{cherry\ coffee}$ in unshaded monocultures. ii) Nitrogen fertilization is the main factor contributing to the carbon footprint. iii) The amount of carbon stored in living biomass varies from 53.6 Mg/ha in traditional polycultures to 9.7 Mg/ha in unshaded monocultures. The adequate use of fertilizers, periodic monitoring of soil fertility, the incorporation of functional trees (*e.g.* shade trees and/or nitrogen fixers) to plantations, soil conservation practices and the use of biofertilizers are some of the recommended actions to mitigate the carbon footprint associated with coffee plantations.

Key words: *Coffea arabica*; carbon dioxide; nitrous oxide; climate change; carbon sequestration.

1 INTRODUCTION

Arabica coffee is one of the main crops in Central America. Per cycle, this region produces around 1,200,000 Mg of green coffee (fifth global production), being Honduras the largest producer, followed by Mexico, Guatemala, and Nicaragua (International Coffee Organization - ICO, 2020). From a social perspective, coffee cultivation represents the main living-income for more than half a million producers in Mexico, and more than three million people are involved and depends on the coffee economic sector (Cámara de Diputados LXIII LEGISLATURA - CEDRSSA 2018). In a similar way, one million people (Instituto Hondurenho do Café - IHCAFE, 2017) depends on the coffee industry in Honduras, and in Costa Rica, around 43 thousand people are coffee producers (Instituto del Café de Costa Rica- ICAFE, 2017).

Coffee production success in the region is mainly due to its location. Since the so-called "*Coffee belt*" combines the ideal temperature and precipitation conditions required for this crop [i.e. temperature between 18-21° C; rainfall 1,500 – 2,200 mm per year, (Teketay, 1999)], this intertropical region is considered perfect for coffee production. However, anthropogenic climate change threatens the continuity of these conditions and, with it, the production of coffee in the region and the world. Some models indicate, that should the global warming trend continue as it does today, a reduction of 50% in the globally suitable area for coffee production by 2050 has been predicted (Bunn et al., 2015). Regarding the "*Coffee belt*" region here reviewed, local models predict a production decrease of 16 up to 60%, being El Salvador the country with the highest vulnerability in the region, meanwhile Mexico was considered the least vulnerable (Gay et al., 2006; Laderach et al., 2010; Baca et al., 2014).

The decrease in coffee production will mainly be driven by the rise of temperatures and by the increase of the intra-seasonal climatic variation (Schroth et al., 2009; Bunn et al., 2015). These factors will affect the phenological cycle of coffee trees, which is expected to affect their relationship with pollinating organisms (Peters; Carroll, 2012). Another factor that will affect the performance of coffee plantations will be an increase in diseases like coffee rust (*Hemileia vastatrix*) and coffee berry borer (*Hypothenemus hampei*). Both species usually thrive with the rise of temperatures and the drought stress to which coffee trees will be exposed (Schroth et al., 2009). As a current example, in Mexico, coffee rust is a severe problem for farmers who produce coffee using traditional varieties as Bourbon, Typica, Mondo Novo, and Caturra. It is estimated that this disease caused a 50% shortage in *C. arabica* production from 2012 to 2016 (Escamilla 2016) and around 16% in the rest of Central America (Avelino et al., 2015).

On the other hand, it is also envisaged that, to maintain the current coffee production, coffee productive regions should migrate to areas located at higher altitudes and latitudes (Magrach; Ghazoul, 2015). However, this implies different ecological and socio-economic problems, for example, many areas where *C. arabica* can be grown are currently covered with forests. The transformation of these forests to shaded coffee plantations would generate global carbon emissions of the order of 6 million of Mg of CO_{2eq}, or even up to 16 million Mg of CO_{2eq} if they were converted to unshaded plantations (Magrach; Ghazoul, 2015). Moreover, it is expected that moving the coffee production area will cause the loss of 35% of threatened vertebrates worldwide, with significant impacts on Costa Rica, Nicaragua, Panama, and Mexico (Magrach; Ghazoul, 2015).

Having this into consideration, it is required knowledge about greenhouse gas emissions related to coffee plantations. These emissions can be quantified through the carbon footprint, which consists of the sum of all gases emitted with global warming potential (GHG) expressed in units of CO_{2eq} per functional unit (*e.g.* crop mass unit; Ecuation 1) (van Rikxoort et al., 2014; Alhajj et al., 2016; International Panel of Climate Change - IPCC, 2019).

Equation 1: Carbon footprint calculation, adapted from Alhajj et al. (2016).

$$\text{Carbon footprint}\left(\frac{kgCO_{2eq}}{\text{kg coffee}}\right)=\frac{\text{Total GHG}\left(\frac{kgCO_2}{ha}\right)}{Coffee\ yield\left(\frac{kg}{ha}\right)} \quad (1)$$

Determining the carbon footprint of coffee plantations in Central America could help improve existing management practices and detect "hot spots" of CO_{2eq} emissions. These data will allow to suggest specific corrective strategies for the type of plantation, which will reduce the carbon footprint of this economic activity.

Even when the evaluation of carbon footprint in Arabica coffee plantations in Central America is difficult because of the heterogeneity of management systems, these can be categorized as follows: i) traditional polyculture (coffee + various species of fruit or timber trees), ii) commercial polyculture (coffee + another main crop that provide shade, e.g. *Musa paradisiaca*), iii) shaded monoculture (coffee under a permanent tree shade, e.g. *Inga* spp.), and iv) unshaded monoculture (Van Rikxoort et al., 2014). Thus, the first goal of this review was to summarize the available knowledge about carbon footprint in those management systems (Table 1) in Central America.

Coffee management systems are intrinsically related to their ecological importance. It has been observed that shaded coffee plantations maintain diverse forest-specific ecosystem services, such as being a biodiversity reservoir, soil conservation, and carbon sink (Cerda et al., 2017; Meylan et al., 2017); on the other hand, unshaded monocultures have low ecosystem-services prevalence. Carbon sequestration is attractive in agricultural systems, due to its capacity to mitigate greenhouse gas emissions (Soto-Pinto et al., 2010). Therefore, the second goal of this review was to summarize the available information on the carbon capture and storage potential in the different coffee plantation systems in Central America.

2 MATERIAL AND METHODS

For the estimation of the carbon footprint of the different coffee plantation systems considered in this review, we reviewed the articles found by the Google Scholar search engine (period 2000-2020) through the keywords: i) carbon footprint ii) *Coffea arabica* iii) coffee plantation and iv) coffee greenhouse gas emissions. Only for the geographic area of Central America. For the estimation of the carbon storing capacity of these coffee plantations, the same search engine and period mentioned above was used, but with the following keywords: i) coffee ecosystem services ii) carbon sequestration in coffee plantations iii) carbon stored in coffee plantation soil and iv) carbon stored in coffee biomass. Obtained data reported of the reviewed articles were tabulated and it was checked that methodologies were comparable and based on the IPCC guidelines.

When the functional units of the reported carbon footprint were not the same, they were transformed to $kgCO_{2eq}$/ kg $_{\text{Cherry coffee}}$, using a conversion ratio of 5.4:1 (fresh cherry coffee:green coffee) and the conversion values of the (International Coffee Organization – ICO, 2011). Subsequently, an average of the homogenized data was obtained, and this value was used as representative by type of productive system (e.g., traditional polyculture), both for

Table 1: Average planting densities by management system for Mexico and Central America considered in this review.

Management system	Coffee trees per hectare	Shade or functional trees per hectare	Input use
Traditional polyculture	3002	351	Very low
Commercial polyculture	5626	377	Low
Shaded monoculture	2357	229	Medium
Unshaded monoculture	5925	0	High

Average values obtained from: Soto-Pinto and Aguirre Dávila (2015); Van Rickxoort et al. (2014); Rahn et al. (2014); Ortiz-Ceballos et al. (2020); Schmitt-Harsh et al. (2012); Pinoargote et al. (2016); Richards and Méndez (2013) and Goodall et al. (2014).

carbon footprint and plantation carbon storage capacity (MgC/ha). In this review, only GHG emissions related to the coffee plantations management were considered, i.e., CO_2 and NO_2, and converted to CO_{2eq}. These emissions were reported for the following categories: application of pesticides/herbicides, application of fertilizers, and emissions from burning fossil fuels. Our system boundaries were from the beginning of the production cycle (1 year = 1 cycle) until the arrival of harvested cherry coffee at the coffee mill. The sum of all of emissions converted to CO_{2eq}/kg $_{\text{Cherry coffee}}$ corresponded to a theoretical value of the carbon footprint for Arabica coffee plantations in the region.

2.1 Carbon footprint of the Arabica coffee plantations

The lowest values of carbon footprint were found in traditional polycultures (0.52 kgCO_{2eq}/kg $_{\text{cherry coffee}}$), followed by shaded monocultures (0.56 kgCO_{2eq}/kg $_{\text{cherry coffee}}$), commercial polycultures (0.60 kgCO_{2eq}/kg $_{\text{cherry coffee}}$) and the highest values on unshaded monocultures (0.64 kgCO_{2eq}/kg $_{\text{cherry coffee}}$), it was found that carbon footprint increases with the level of technification in plantations and planting density (Figures 1). CO_2 emission categories presented the following behavior: the application of pesticides/herbicides contributed only in 0.002 kgCO_{2eq}/kg $_{\text{coffee cherry}}$ to the total carbon footprint in traditional polycultures (Killian et al., 2013). This was explained by the type of plantation where low or no investment inputs by the coffee producer were needed. On the other hand, since shaded monoculture require a higher amount of management activities with greater associated inputs, CO_{2eq} emissions due to the application of pesticides/herbicides increased to 0.02 kgCO_{2eq}/kg $_{\text{cherry coffee}}$ (Noponen et al., 2012; Ratchawat et al., 2020). Although this component was not reported for unshaded plantations, it is likely that its value is similar or higher to the one reported for commercial shaded plantations.

The other minor component of the total carbon footprint are the CO_2 emissions of fossil fuels consumption. These fuels are used to operate minor machinery like pruners, chain saws, and so forth. Also, to transport the cherry coffee to the mill. Emissions from this component were similar for all management systems: 0.021 kgCO_{2eq}/kg $_{\text{cherry coffee}}$ in traditional polycultures and 0.023 kgCO_{2eq}/kg $_{\text{cherry coffee}}$ in unshaded monocultures (Killian et al. 2013; van Rickxoort et al. 2014).

The third component, fertilization, represented more than 90% of the total carbon footprint in all management systems (Figure 1). Its emissions were directly related to the amount of nitrogen fertilizer applied to the plantations, thus the lowest emissions were found in traditional polycultures (0.49 kgCO_{2eq}/kg $_{\text{cherry coffee}}$), while the highest values were observed in unshaded monocultures (0.62 kgCO_{2eq}/kg $_{\text{cherry coffee}}$) (Killian et al., 2013; Van Rickxoort et al., 2014). Shaded monocultures (0.52 kgCO_{2eq}/kg $_{\text{cherry coffee}}$) and commercial polycultures (0.55 kgCO_{2eq}/kg $_{\text{cherry coffee}}$) had similar emission values (Noponen et al., 2012; Van Rickxoort et al., 2014).

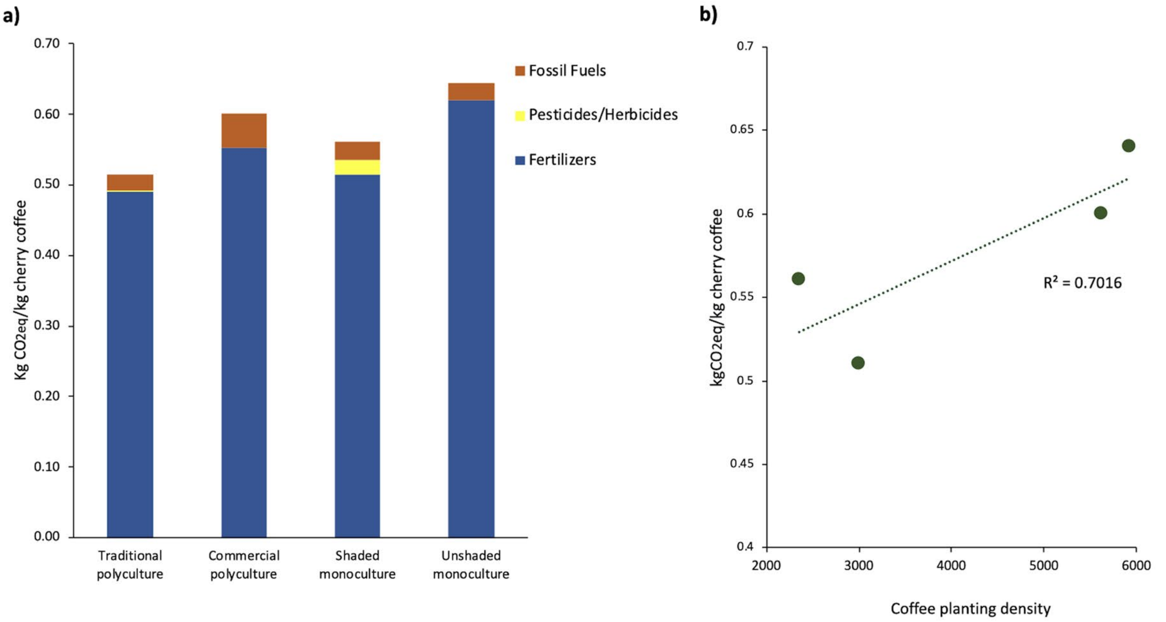

Figure 1: a) Composition of the carbon footprint by type of Arabica coffee plantations management in Mexico and Central America. b) Correlation analysis among coffee planting density and carbon footprint. Data were obtained from: Killian et al. (2013); Bunn et al. (2019); van Rickxoort et al. (2014); Ratchawat et al. (2020); Noponen et al. (2012); Soto-Pinto and Aguirre Dávila (2015); Rahn et al. (2014); Ortiz-Ceballos et al. (2020); Schmitt-Harsh et al. (2012); Pinoargote et al. (2016); Richards and Méndez (2013) and Goodall et al. (2014).

According to these data, the "hot spot" of CO_{2eq} emissions at the farm level was fertilization with nitrogen sources. The applied fertilizer promotes an enhancement of the natural nitrification of the soil, which consequently increases the N_2O emissions (Hergoualc'h et al., 2007). This gas has a warming potential 298-fold the CO_2, for this reason, its impact is greater on the carbon footprint than the other components.

Tropical ecosystems cycle nitrogen faster than temperate forest at higher latitudes, this could mean that adding N-fertilizers to tropical soils will have a stronger effect on N_2O emissions than in temperate regions (Hall; Matson, 1991). However, it has been reported that the N_2O emissions can be diminished without sacrificing the coffee farmer income by optimizing the N-fertilization and increasing the P availability in tropical soils (Capa; Pérez-Esteban; Masaguer, 2015). It is important to point, that N fertilizers have different nitrification/denitrification potentials (Velthof et al., 1997). Even when there is no consensus of which kind of N fertilizer has the lowest N_2O emissions, there is enough evidence to group fertilizers into low N_2O and high N_2O emitter (Table 2). Then, the type of N compound added as fertilizer is another important factor that could affect the rate of emissions of N_2O. As a result, the correct selection of the type of fertilizer applied to coffee plantations is another important factor that can contribute to reduce its CO_{2eq} emissions.

Table 2: Classification of different N type fertilizers according to their N2O emission potential

Low emission fertilizers	High emission fertilizers
Calcium ammonium nitrate Ammonium Nitrate based fertilizers Ammonium bicarbonate Ammonium phosphate	Urea Anhydrous ammonia Urea ammonium nitrate

Classification according to (Velthof et al., 1997; Bouwman; Boumans, 2002; Millar et al., 2010).

Strategies to reduce nitrous oxide emissions should consider the N-fixing trees usually established as shade trees (*e.g. Inga* spp. Fabaceae) avoiding using N fertilizers when soil has reached a N-saturated state (Hergoualc'h et al., 2008). The average green mulch produced by trees of the *Inga* genus can contain 2.9% N (Leblanc; McGraw, 2004), of which 57% comes from atmospheric N fixation through bacterial symbiosis (Leblanc; Mcgraw; Nygren, 2007). This incorporation of N to the soil should be used in the fertilization calculations of the coffee plantation; however, more field studies are required for adequate recommendations.

Another strategy to optimize fertilization in coffee plantations may be the use of mycorrhizae and biofertilizers. Some studies in coffee indicate that the use of mycorrhizae can improve the use of fertilizer applied (Vaast; Zasoski, 1992; Vieira et al., 2020). In the same way, the combination of mycorrhizal fungi and nitrogen fixation bacteria, allows to decrease 25-30% the fertilizer applied maintaining the crops yield (e.g. *Discorea alata*, *Capsicum annuum*) (Kumar et al., 2022; Sharma et al., 2022). This effect has not been proved in commercial coffee plantations, and its relationship with the carbon footprint, but it is an area of opportunity for further research studies.

Compared to other coffee-producing regions in America, the carbon footprint of the Central American region is 50% less than that reported for monocultures in Brazil (1.4 $kgCO_{2eq}/kg_{cherry\ coffee}$, Martins et al., 2018), and 30% higher than the arabica coffee produced in Tolima area, Colombia (0.24 $kgCO_{2eq}/kg_{cherry\ coffee}$, Andrade et al., 2014). This difference may be due to the degree of technification and coffee intensity cultivation in the different coffee-growing regions. For example, monoculture production in Brazil incorporates the use of agricultural machinery for harvesting and irrigation (Santos; Ribeiro; Rodriguez, 2023), these components directly impact the carbon footprint. In the case of the Tolima region in Colombia, coffee is produced mainly by small-holders, in different production systems where monoculture predominates (Rodriguez; Mora-Delgado, 2019). The lower carbon footprint of Tolima comparing to Central America may be due to a higher yield per hectare with a similar use of nitrogenous fertilizers, due to the use of improved varieties and plantations renewal of the last years (Gobernación de Tolima, 2021).

2.2 The carbon stock capacity of different coffee production systems

When managed from an agroforestry perspective, Arabica coffee plantations are recognized as productive systems that can maintain several ecosystem services, as soil protection, habitat for native biodiversity and water infiltration (Soto-Pinto et al., 2010; Richards; Mendez, 2013). One of these valuable services is the carbon sequestration in living biomass and soil, which is a key factor to reduce or mitigate the carbon footprint (Soto-Pinto; Aguirre-Dávila, 2015).

In Central America, Arabica coffee is produced on the humid regions of the mountains, mainly by small farmers (<10 ha) (ICO, 2018). In those regions, the traditional coffee plantation incorporates different species of shade trees, many of them native species (e.g. *Quercus* spp, *Liquidambar* spp, *Fraxinus* spp.), N-fixers (*Inga* spp, *Acacia* spp.), and other fruit trees (*Musa* spp, *Persea* spp, *Pimienta* spp.) (Soto-Pinto et al., 2010). However, the technification strategies adopted by large producers (>10 ha) involves the homogenization of the plantation, using only one shade species or none (Perfecto et al., 2005). These differences affect not only the biodiversity but also the amount of carbon that the plantation can retain, both in living biomass and soil.

The findings in this review showed that total carbon stored in trees and coffee trees biomass has similar average values among different agroforestry management systems. The average values for each of them were: traditional polyculture 45.2 C Mg/ha, commercial polyculture 45.4 C Mg/ha, and shaded monoculture 43.3 C Mg/ha. This likeness is explained by the fact that when carbon stored in shade and functional trees decreases, by their partial remotion, the carbon stored in coffee trees increases due to an increase in their plantation density (Figure 2a). However, total stored C strongly decreases when shaded and functional trees are totally removed (unshaded monoculture 9.7 C Mg/ha). Despite that there is an increase in the planting density of coffee trees in intensive production systems, the carbon stored in the biomass of the coffee trees is not enough to compensate for the carbon lost from the stem, canopy and root of the shade or functional trees (Figure 2a).

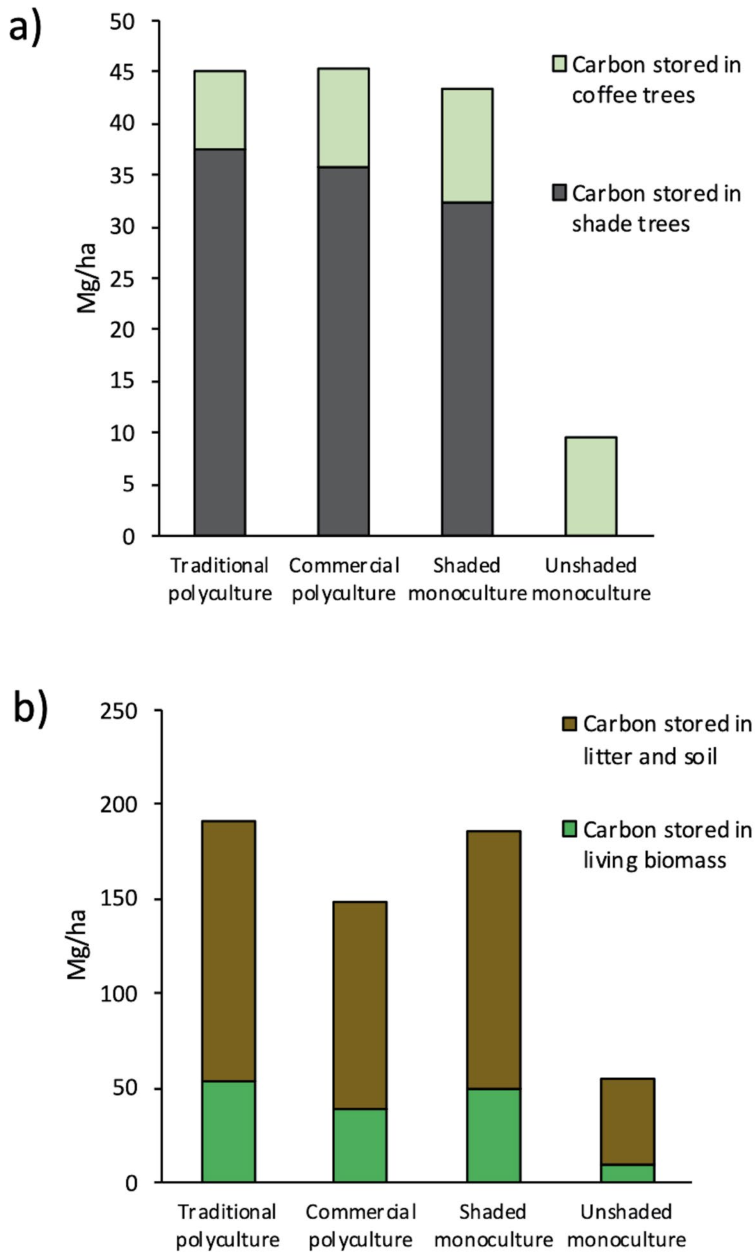

Figure 2: Carbon stored in the different stocks of a coffee plantation categorized by management system a) carbon distribution in living biomass; b) comparison of carbon stocked in living biomass and in litter and soil (0-0.3 m depth). Data were obtained from: Soto-Pinto and Aguirre Dávila (2015); Van Rickxoort et al. (2014); Rahn et al. (2014); Ortiz-Ceballos et al. (2020); Schmitt-Harsh et al. (2012); Pinoargote et al. (2016); Richards and Méndez (2013) and Goodall et al. (2014). Data for carbon stored in litter and soil for unshaded monoculture was estimated using a linear regression model.

On the other hand, the sum of all C contained in living biomass (i.e. trees, coffee trees, herbaceous, epiphytes, liana, etc.), showed a greater differentiation regarding to the type of plantation management. For instance, a traditional polyculture showed the highest average value of carbon stored (53.6 C Mg/ha), followed by the shaded monoculture (49.1 C Mg/ha), the commercial polyculture (39.6 C Mg/ha), and finally the unshaded monoculture (9.7 C Mg/ha) (Figure 2b). This could be, because when coffee cultivation intensifies, biodiversity tends to decrease both flora and fauna (Philpott et al., 2008; De Beenhouwer et al., 2013).

Compared with the C content in a tropical forest in Veracruz-Mexico (192 Mg/ha in living biomass), the commercial coffee polyculture maintains 28% of that carbon value, while the unshaded monoculture the 5%, similar to pasture cattle (Hughes; Kaufman; Jaramillo, 2000). Similar values of C in biomass of the mountain cloud forest of Chiapas Mexico (189 Mg/ha) (De Jong et al., 1999), confirm the storage potential of C of the primary ecosystems where Arabica coffee is grown.

This review also found that the carbon contained in the living biomass of shaded coffee plantations is strongly correlated ($R^2 = 0.89$) with the carbon contained in litter and soil (0-30 cm). This reservoir is 2.6-fold higher than the C content in the living biomass (Figure 2b). The relationship between the amount of carbon stored in living biomass and that stored in litter and soil has been previously reported for coffee plantations in Soto Pinto et al. (2010). However, they reported a relation of 3.7-fold C in soil than the one estimated in living biomass, a higher value than the relation found here (average 2.6 fold).

The highest values of carbon content in litter and soil (0-30 cm depth) were found in the traditional polyculture (136.9 C Mg/ha) and in the shaded monoculture (137.3 C Mg/ha), while the lowest was found in the commercial polyculture (108.6 C Mg/ha). The high correlation between the carbon contained in the living biomass and the soil made possible to estimate the carbon that the soil of an unshaded coffee plantation could contain (45.5 C Mg/ha; Figure 2b). However, field studies are required to corroborate the estimated data.

The data on C content in litter and soil (0-30 cm) of the coffee agroecosystems reviewed here are similar to those reported for tropical forests in Mexico (100 t/ha, Hughes et al., 2000). This indicates that these coffee production systems prevent carbon previously fixed in tropical soils by natural vegetation from being lost. In the case of unshaded monocultures, certain soil conservation strategies could contribute to increasing their C storage values, for example, the use of cover crops like *Arachis pintoi* (Castillo et al., 2005) and maintain soil with herbaceous vegetation on slopes (Singh; Benbi, 2018). However, the effect of these strategies must be tested and quantified for commercial unshaded coffee monocultures.

According to the presented data, using cover trees in coffee plantations is very important to conserve a portion of the carbon stocks in tropical ecosystems, both in living biomass and in the soil. Likewise, incorporating them into unshaded plantations would allow a recovery of carbon stocks, which would mitigate the carbon footprint of coffee production (Van Rikxoort et al., 2014). New trees within the plot can sequestrate 1.3 C Mg/ha per year (density of 239 trees/ha; Richard; Mendez, 2013) transforming the coffee plantation into neutral carbon emission or even a negative carbon emission system (while the shade trees grow).

3 CONCLUSIONS

This review showed that the main emission factor that contributes to the carbon footprint is the application of nitrogen fertilizers. Which increased in unshaded plantations due to the system intensification. To mitigate this factor, it is recommended i) to perform recurrent soil analyzes to apply only the necessary amount of nitrogen to the crop, ii) use fertilizers with low nitrification/denitrification potential, iii) explore the use of mycorrhizal fungi or nitrogen fixing bacteria to decrease the use of chemical fertilizers, iv) quantify the N contributed by the litter of shade trees belonging to the Fabaceae family to the soil.

It was also found that a coffee agroecosystem with shade trees, conserves a portion of ~ 28% of the C potential that a tropical forest possesses in its aboveground biomass, while an unshaded monoculture loses 95%.

4 AUTHORS CONTRIBUTION

CA wrote the manuscript and performed the experiment, CH supervised the experiment and co-work the manuscript, and CH review and approved the final version of the work, CA and CH conducted all statistical analyses.

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