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Impacts of oil palm cultivation on soil organic carbon stocks in Mexico: evidence from plantations in Tabasco State

Alfredo Isaac Brindis-Santos[1], David Jesús Palma-López[2,*], Ena Edith Mata-Zayas[3] and David Julián Palma-Cancino[4]

[1] Facultad de Ciencias Agrícolas, Campus IV, Universidad Autónoma de Chiapas, Entronque Carretera Costera y Huehuetán Pueblo, C.P. 30660 Huehuetán, Chiapas, Mexico
[2] Colegio de Postgraduados, Campus Tabasco, Periférico Carlos A. Molina S/N, C.P. 86500 Cárdenas, Tabasco, Mexico
[3] Universidad Juárez Autónoma de Tabasco-División Académica de Ciencias Biológicas, Carretera Villahermosa-Cárdenas km. 0.5 S/N, Entronque a, Bosques de Saloya, C.P. 86150 Villahermosa, Tabasco, Mexico
[4] Centro Universitario de la Costa-Universidad de Guadalajara, Av. Universidad, 203, Delegación Ixtapa, C.P. 48280 Puerto Vallarta, Jalisco, México

Abstract – There is a need for more studies on the effects of oil palm plantations on soil organic carbon storage and on the environmental services provided by these agrosystems in Mexico. This study focused on estimating the soil organic carbon stocks in three areas within oil palm plantations (palm circle, under the frond and between palm rows), at three soil depths (20, 40 and 60 cm) and comparing the carbon storage between different land-uses: a 20-year-old pasture (GS20), a 20-year-old oil palm plantation (OP20), and a secondary forest (SF20). Our results suggest that oil palm plantations store soil organic carbon mainly under frond areas when sown in lixisols and luvisols, with lower carbon sequestration in the palm circle. Regarding the soil depth, the estimated carbon storage was 87 Mg C ha^{-1} and 67 Mg C ha^{-1} at depths of 20 and 60 cm, respectively. Regarding land-use comparison, results indicate an increase (not statistically significant) in carbon storage to 27% at 20 cm depth and 18% at 60 cm between pasture and palm plantation. The second-growth forest presented higher carbon storage compared to both other land uses.

Keywords: tropical soils / organic matter / carbon storage / land-use change / agrosystems

Résumé – Impacts de la culture du palmier à huile sur les stocks de carbone organique du sol au Mexique : exemple de plantations de l'État de Tabasco. Au Mexique, l'effet des plantations de palmiers à huile sur le stockage du carbone organique du sol (COS) et sur les services environnementaux fournis par ces agrosystèmes est particulièrement méconnu et nécessite des études de terrain. L'objectif de cette étude était d'estimer les stocks de carbone organique du sol dans différentes zones de la plantation (dans la zone d'égouttement, sous les frondes et entre les rangées de palmiers) et à différentes profondeurs du sol (20, 40 et 60 cm), et de comparer le stockage de carbone entre différents usages du sol : une prairie de 20 ans (GS20), une plantation de palmiers à huile de 20 ans (OP20) et une forêt secondaire (SF20). Les résultats suggèrent que la plantation de palmiers à huile échantillonnée stocke le carbone principalement dans les zones sous les frondes lorsqu'elle est plantée sur des lixisols et des luvisols, avec une séquestration de carbone plus faible dans la zone d'égouttement. En termes de profondeur du sol, le stockage de carbone estimé était de 87 Mg C ha^{-1} et 67 Mg C ha^{-1}, à des profondeurs respectives de 20 et 60 cm. Concernant la comparaison des diffèrents usages des terres, les résultats montrent une augmentation (non-significative en termes statistiques) du stockage de carbone de 27 % à 20 cm et de 18 % à 60 cm, entre la prairie et la plantation, ce qui suggèrerait que les plantations de palmiers à huile pourraient avoir à long terme un impact négatif sur l'environnement plus faible que l'élevage du bétail. Cependant, la forêt secondaire présente toujours le stockage de carbone le plus élevé dans le sol.

Mots clés : sols tropicaux / matière organique / stockage de carbone / changement d'utilisation des terres / agrosystèmes

*Corresponding author: dapalma@colpos.mx

1 Introduction

Palm oil from *Elaeis guineensis* Jacq. is the most consumed source of vegetable fat worldwide (Brad *et al.*, 2015); from 2007 to 2019, the harvested areas of this crop have increased by 94% (FAOSTAT, 2020). *E. guineensis* is a perennial plant introduced to Mexico from Africa in the second half of the 19th century. The first plantations were established in the southern state of Chiapas (Arias *et al.*, 2014). Later on, new plantations were established in other South Mexican states with favourable climate conditions. The country remains a small producer compared to Malaysia or Indonesia. In 2019, the total harvested surface area of oil palm plantations in Mexico was 108 690.17 ha (SIAP, 2020). The state of Tabasco is the third major producer of oil palm in Mexico, representing 25% of the harvested area of this crop in the country, with a surface area of 26 718.74 ha in 2019 (SIAP, 2020).

There is still an intense debate about the effect of oil palm plantations on the emissions of greenhouse gases into the atmosphere and the contribution from these plantations to the global carbon cycle (Germer and Sauerborn, 2008; Carlson *et al.*, 2013; Kho and Jepsen, 2015). Some studies focused on explaining what occurs with the soil organic carbon (SOC) cycle after the conversion of primary forests to oil palm plantations (Frazão *et al.*, 2014; Rahman *et al.*, 2018); others, such as Goodrick *et al.* (2015), focused on explaining the SOC dynamics after the conversion of pastures to oil palm plantations. In Mexico, such studies are still lacking, mainly because the palm industry is still in development. Besides, palm plantations are very heterogeneous (Nelson *et al.*, 2013; Carron *et al.*, 2015), and impacts on soil may vary at both macro and micro levels. Therefore, it is necessary to evaluate oil palm plantations with samples from the different areas within the plantation (palm circle, under the frond, and between rows) to determine if the management in these areas may affect the soil carbon sequestration potential.

The objective of this study was to estimate the SOC storage in oil palms in different areas of a plantation and to compare the C storage in palm plantation with grasslands, using secondary forest, the closest landscape at time zero, as a control. Finally, the data obtained were compared to determine which area of the oil palm plantation has the largest impact on carbon storage and to evaluate whether plantation management in the different areas affects soil carbon storage potential.

2 Materials and methods

2.1 Study area

The research was carried out in the Sierra region of Tabasco (Mexico), in Jalapa and Tacotalpa in the southern region of the state, located in the physiographic province of the southern Gulf Coastal Plain. The sampling sites were set within a 7080 ha area between the coordinates 17° 31' 57" and 17° 47' 44" N and 92° 42' 55" and 92° 54' 22" W. The climate is warm-humid with abundant rainfall in summer in Jalapa and warm-humid with rainfall all year round in Tacotalpa, according to Köppen's classification, as modified by García (2004). The average temperature is 26 °C (without frost), and the average rainfall is 2000 to 4000 mm yr^{-1} (Zavala-Cruz *et al.*, 2016).

The dominant natural vegetation in the area corresponds to secondary forests (SF) after plantations of bananas (*Musa paradisiaca* L.) and cocoa (*Theobroma cacao* L.) were abandoned. There are also areas of Bahiagrass (*Paspalum notatum* F.), African star grass (*Cynodon sp.* P.), and giant grass (*Pennisetum purpureum* S.) devoted to extensive cattle raising, and annual crops such as maize (*Zea mays* L.) and beans (*Phaseolus vulgaris* L.). Moreover, there have also been land-use changes from medium and high evergreen forests to forest plantations of cedar (*Cedrela odorata* L.), Spanish elm (*Cordia alliodora*), mahogany (*Swietenia macrophylla* K.), teak (*Tectona grandis* L.), beechwood (*Gmelina arborea* L.), and oil palm (*Elaeis guineensis* Jacq.) (Salazar-Conde *et al.*, 2004; Sánchez-Munguía, 2005).

2.2 Study sites

Oil palm (*Elaeis guineensis* Jacq.) systems in the Sierra region are mainly cultivated on slightly hilly terrain. According to previous literature, the area used for oil palm plantations in that region is dominated by soils from the luvisol and lixisol groups (Zavala-Cruz *et al.*, 2016; Brindis-Santos *et al.*, 2020). For a better understanding of the behaviours in the evaluated systems, the geomorphological landscapes were zoned, and the soils associated with the study sites were determined. They are characterised by developing higher clay content in the subsurface horizon, by the process of argilization, and by different degrees of acidity, which depend on the low to moderate saturation of bases in the two soil groups (Brindis-Santos *et al.*, 2020). Soil classification followed the World Soil Reference (IUSS Working Group WRB, 2014), and the physical and chemical properties of soils studied were previously characterised in a study by Brindis-Santos *et al.* (2020; Tab. 1).

Information about present and past land uses was gathered from one hundred local farmer interviews. Once the data were analysed, the sample sites in the three systems were selected: 20-year-old oil palm plantation (OP20), 20-year-old pastures (GS20), and a 20-year-old second-growth forest (SF20; a medium evergreen tropical secondary forest). OP20 plantations were planted in sites previously used to cultivate grasses. In the study area, 90% of the oil palm plantations are established in communal agricultural land (owned by a civil association of local farmers) with small production. The agronomic practices include inorganic fertilisation, using 4 kg of nitrogen per plant per year (N 46%) directly applied to the soil in June and December. The GS20 system is used to feed cattle in extensive grazing, and the system receives organic residues mainly from roots and cattle manure, which is partially converted into soil carbon.

2.3 Sampling strategy

Within each OP20 site, six oil palms were randomly selected, and six soil profiles were taken at a depth up to 70 cm in the three management zones of the plantation (total: 4 sites × 6 profiles × 3 management zones). These zones were: the palm circle dripping area (DA), within a radius or horizontal distance of 0.6 m from the plant stipe; under the frond (UF) that remains after harvesting the bunches 2.0 m away from the plant stipe; and between rows of palm trees (BR) 2.5 m away from the plant stipe. The latter was based on Carron *et al.* (2015) according to the

Table 1. Physical and chemical characteristics of the soils inside the oil palm plantation (means ± SD).
Tableau 1. *Caractéristiques physico-chimiques des sols dans les plantations de palmier étudiées (moyenne ± écart-type).*

Soil Group	Depth (cm)	Bulk density (g cm^{-3}) [a]	Carbon (%) [a]	Mg C ha^{-1} [a]	pH H_2O [b]	Munsell Color	Texture of soil (%) [b]		
							Cl	Si	Sa
LV	0–20	1.3 ± 0.12	1.8 ± 0.3	69 643	6.5 ± 0.2	7.5YR 4/3	34 ± 4.5	37 ± 8.5	29 ± 4.9
	20–60	1.6 ± 0.15	0.6 ± 0.1	57 143	6.0 ± 0.1	2.5YR 4/4	46 ± 4.9	20 ± 6.0	34 ± 12.5
LX	0–20	1.2 ± 0.17	1.6 ± 0.3	60 174	5.7 ± 0.2	7.5YR 4/3	16 ± 1.2	36 ± 3.2	48 ± 2.5
	20–60	1.5 ± 0.24	0.4 ± 0.1	37 608	5.1 ± 0.2	10YR 4/6	45 ± 4.9	25 ± 1.5	30 ± 2.1
LX	0–20	1.3 ± 0.13	1.7 ± 0.2	68 812	5.4 ± 0.1	7.5YR 4/3	31 ± 4.1	16 ± 1.5	53 ± 8.2
	20–60	1.7 ± 0.30	0.4 ± 0.1	42 346	5.2 ± 0.2	10YR 4/6	60 ± 8.7	14 ± 2.6	26 ± 6.5

[a] Bulk density and C values are the mean of four samples collected in four soil profiles in each of the four sites selected in the oil palm plantation (n = 16).
[b] pH and texture of soil data are based upon the mean of the samples collected in three soil profiles (at depth 0–60 cm) with four replicates each (n = 12). Cl = Clay; Si = Silt; Sa = Sand. LV = Luvisols; LX = Lixisols.

definition of zones that receive organic waste inputs in OP plantations. According to Hernández-Rojas *et al.* (2018), regarding the total cultivated area of one hectare of oil palm in Tabasco, 13.4% corresponds to DA, 44.4% corresponds to UF and 42.2% corresponds to BR. Therefore, we distributed the random sampling to be proportional to the spatial distribution in the plantation. In each zone of the plantation, the sampling stratification consisted of three different depths: 0–20, 20–40, and 40–60 cm. At the GS20 and SF20 sites, six soil profiles in each site (total: 4 sites × 2 land uses × 6 profiles = 48) were taken at depth up to 70 cm.

For SOC comparison between OP20, GS20 and SF20, four sites were selected for each land use, and this variable was evaluated under similar environmental conditions. The four SF20 and GS20 plots were around the OP20 plantations. In each of the twelve sampled sites, a rectangular sampling area of 20 × 60 m^2 was established (Etchevers *et al.*, 2005). According to farmers, the oil palm plantations were planted with a three bold planting design and at a distance of 9 m between plants, forming an equilateral triangle with a planting density of 143 oil palm plants per ha.

2.4 Soil sample processing and SOC estimation

Two series of soil samples were taken at each sample site and depth. The first series of samples were dried in the shade, then crushed and sifted through a 2 mm-sieve to determine the soil texture using the Bouyoucos method (Brindis-Santos *et al.*, 2020). One part of this series was used to analyse the organic carbon (C). The stones and root fragments were removed according to the methodology proposed by Etchevers *et al.* (2005). The analyses were determined using Perkin-Elmer 2410 series II elemental carbon equipment with an oven at 950 °C.

The second series of samples were taken with a cylinder with a known volume to calculate the bulk density (Blake and Hartge, 1986). The soil contained in the cylinder was dried in a drying stove at 105 °C until it reached a constant weight. To determine the bulk density, the sample dry weight was divided by the volume of the cylinder. Finally, the bulk density values were used to transform the C results obtained in percentages to absolute SOC values (Mg C ha^{-1}).

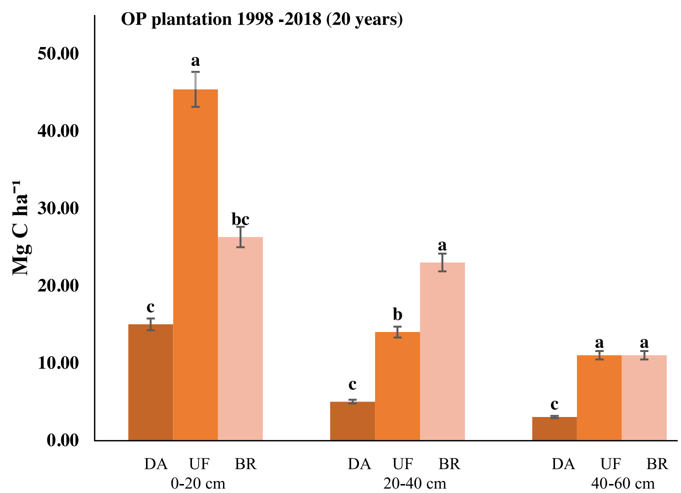

Fig. 1. Soil organic carbon (SOC) storage in different crop areas in an oil palm plantation at different soil depths.
Fig. 1. *Stockage de Carbone organique du sol (COS) dans différentes zones d'une plantation de palmier à huile.*

2.5 Statistical analysis

The Kolmogorov–Smirnov test was performed to determine if the data met the assumption of normality and variance homoscedasticity. Samples were analysed for statistically significant differences with an analysis of variance and a mean comparison using Tukey's rank test ($p \leq 0.05$) utilising the SAS statistical software for Windows 6.12 (SAS Institute, Cary, North Carolina, USA).

3 Results

3.1 SOC storage in different areas of the oil palm plantation

The variance analysis showed statistically significant differences ($p \leq 0.05$) between the SOC contents in the different areas (UF, BR and DA) of the OP20 plantation.

Table 2. Soil organic carbon (SOC) stocks in the different management zones registered in different areas of the world.
Tableau 2. *Stocks de Carbone organique du sol (COS) dans les différentes zones d'une plantation de palmier à huile enregistrés dans différentes parties du monde.*

Country	Age of Agrosystems	Depth	DA	UF	BR	Oil palm management indications	Author
				Mg C ha^{-1}			
Mexico	20	0–60	23	70	60	The agronomic practices include inorganic fertilization, using 4 kg plant year^{-1} of N 46% directly applied to the soil, in June and December.	Brindis-Santos *et al.* (2020)
Malaysia	29 39 49	0–70	49 58 65	56 70 75	38 56 60	In the first few years after planting, leguminous cover crops were grown to protect from erosion and maintain soil fertility.	Rahman *et al.* (2018)
Brazil	4 8 25	0–30	N/R N/R N/R	36 27 29	33.4 27 25	The authors do not indicate the agronomic management in the crop, however, they mention that it was previously cultivated with grass.	Frazão *et al.* (2013)
Indonesia	25	0–30	52	54	52	This study represents what is considered to be, by the plantations, "good practice" management of oil palm plantation related to management of soil organic input.	Khasanah *et al.* (2015)

N/R = The authors did not state. DA = Palm circle; UF = Under the frond area; BR = Between the palm trees row area. for different depths and age classes for oil palm.

Carbon storage under the frond was statistically higher ($p \leq 0.05$) than in the dripping area at all sampled depths. At a 0–20 cm depth, the average SOC content under the frond is 13% higher than between rows and 67% higher than in the dripping area . At the middle depth (20–40 cm), the BR area showed statistically higher SOC storage ($p \leq 0.05$) than UF (by 43%) and DA (by 78%). In all management areas, SOC storage decreased as the depth increased (Fig. 1 and Tab. 2).

3.2 SOC storage in various land uses

The secondary forests (SF20) presented the highest SOC storage (214 Mg C ha^{-1} at 0–60 cm depth) compared to pastures (GS20) and palm plantations (OP20). Carbon storage appeared to increase between GS20 and OP20 at 0–20 cm depth (Fig. 2); however, this increase was not statistically significant ($p > 0.05$). The soil organic carbon storage at depths of 0–20 cm and 20–60 cm in palm plantations (OP20) was significantly lower ($p \leq 0.05$) than in secondary forests (SF20), by 27% and 28%, respectively. 20-year-old pastures (GS20) showed significantly lower ($p \leq 0.05$) SOC storage compared to SF20 by 44% at a depth of 0–20 cm and by 40% at a depth of 20–60 cm.

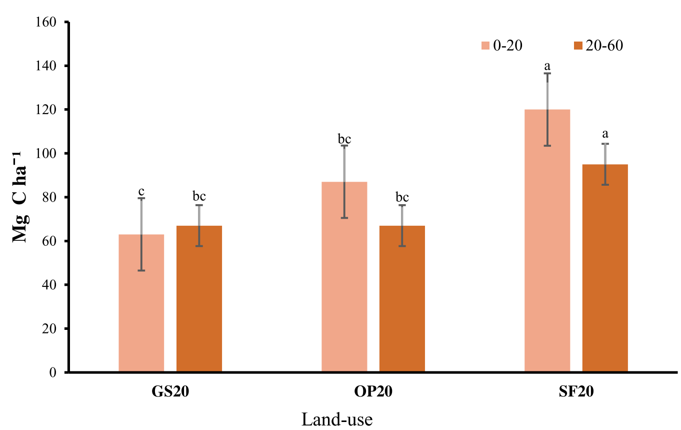

Fig. 2. Total soil organic carbon (SOC) storage in a 20-year-old oil palm plantation (OP20), a 20-year-old pasture (GS20), and a 20-year-old secondary-growth forest (SF20).
Fig. 2. *Stockage de Carbone organique du sol (COS) dans une plantation de palmiers à huile de 20 ans, un pâturage de 20 ans et une forêt secondaire de 20 ans.*

4 Discussion

The soil organic carbon storage in oil palm plantations in Tabasco showed differences in each management zone. Under frond areas (UF) showed the highest SOC storage potential. Similar findings were reported in various studies (Compte *et al.*, 2012; Frazão *et al.*, 2013; Khasanah *et al.*, 2015), where the SOC storage sequence found by crop area in oil palm plantations is UF > DA > BR. For instance, in Rahman *et al.* (2018), in Sarawak, Malaysia, where their results regarding SOC storage in oil palm plantations in UF were 25% higher than those in the palm circle (DA) and 16% higher than in the between rows area (BR). Another study in Malaysia mentioned that frond cut off wastes in oil palm plantations, generating approximately 9.8 to 14.9 Mg C ha-plantation^{-1} year^{-1}, represented an increase of 16% to 26% in SOC storage

Table 3. Soil organic carbon (SOC) stocks in different agrosystems, countries and types of soils.
Tableau 3. *Stocks de Carbone organique du sol (COS) dans différents agrosystèmes, pays et types de sols.*

Country	Agrosystems	Age of agrosystems	C Soil (Mg C ha^{-1})		Soil	Author
Mexico	Young teak	20	40		Cambisols	Ruíz-Blandon *et al.* (2019)
	Old rubber	50	87.3			
Indonesian	Young rubber	10	85.2		Acrisols	Borchard *et al.* (2019)
	Cacao agroforestry	2	68.5			
	Coffee and rubber tree		117.51			
Brazil	Open grown coffee	17	117.86		N/R	Zaro *et al.* (2020)
		6	15.7	20.4		
New Guinea	Conversion of grassland to oil palm	9	4.5	8.8	Andisols	
		12	10.3	11.2		Goodrick *et al.* (2015)
		25	10.7	14.0		

N/R = The authors did not state.

potential during a 4-year period (Aljuboori, 2013). Our results suggest a similar situation for the oil palm plantations studied in the study site. Our UF results were also similar to those of Rüegg *et al.* (2019) for oil palm plantations in the eastern Colombian plain, where UF areas contained 20% more SOC than in "harvesting pathway areas" and 22% more SOC than in "transition areas".

In this study, the dripping area (DA) presented the lowest SOC storage potential at the hectare level; however, this is because it only represented 13.3% of the total area in the plantations studied. Recently, Rüegg *et al.* (2019) mentioned that DA received the largest amounts of fasciculate superficial roots due to the root growth pattern and nitrogen fertilisation, whereby SOC storage in this management zone may be attributed to organic waste from roots (Haron *et al.*, 1998; De Carvalho *et al.*, 2014). These results may suggest the importance of the reintegration of organic residues into the soil of oil palm plantations since there is a positive effect on the properties of the soil related to the sustainable yield of the crop. Research in recent years indicates a significant role of the roots (belowground C biomass) in increasing carbon stocks input on many agrosystems (Katterer *et al.*, 2011; Fan *et al.*, 2017; Basile-Doelsch *et al.*, 2017).

Regarding organic carbon storage according to soil depth, palm plantation (OP20) at a depth of 0–20 cm showed a greater SOC storage (87 Mg C ha^{-1}) than that at subsequent depths. SOC storage gradually decreased as the depth of the soil layer increased to 20–40 cm (42 Mg C ha^{-1}) until it reached the last layer at a depth of 40–60 cm (25 Mg C ha^{-1}). In the soil layer at a depth of 0–20 cm, our results were higher than the results reported by Rahman *et al.* (2018), who performed a chronosequence of OP plantations from ages 29, 39 and 49 and obtained 45, 60 and 65 Mg C ha^{-1} of SOC storage, respectively, at depths of 0–20 cm. Frazão *et al.* (2014) reported SOC storage of 39 and 67 Mg C ha^{-1} in 23- and 34-year-old OP plantations, respectively, and these quantities were 55% and 22% lower than our results. The SOC storage at a soil depth of 0–20 cm in our research is similar to the findings by Ramos *et al.* (2017) in an agroforestry system of oil palm and cocoa (*Theobroma cacao)* in Brazil, reporting a SOC content of 66 Mg C ha^{-1} at a depth 0–30 cm. Our results differ from those presented by Leblanc and Russo (2008), who reported 96 Mg C ha^{-1} of stored SOC at a depth 0–30 cm in Costa Rica; however, that research also included the carbon sequestered from aboveground biomass representing approximately 20% of the total SOC sequestration. In our study, we did not consider aboveground carbon storage.

In this research, the SOC contents of oil palm plantations were seemingly higher than the SOC contents of pastures, ranging from 16–27% in SOC storage after conversion from grassland to oil palm in a 20-year period; however, these results were not statistically different ($p > 0.05$). These findings agree with Goodrick *et al.* (2015)'s results after conversion from grassland to oil palm in 6-, 9-, 12- and 25-year plantations in Indonesia (Tab. 3). The secondary forest presented the largest carbon storage capacity (214 Mg C ha^{-1}). The secondary forest total SOC storage performance was superior to the 138 Mg C ha^{-1} reported by Borchard *et al.* (2019) over the 0–100 cm soil depth.

When compared with other agrosystems, the SOC storage in oil palm plantations (OP20) showed mixed performances. Compared to a commercial plantation of 20-year-old teak (*Tectona grandis* L.) at a 0–30 cm depth, oil palm almost doubles the SOC storage (Ruíz-Blandon *et al.*, 2019). Compared to a 50-year-old rubber tree (*Hevea brasiliensis*) plantation, a young rubber tree plantation, and a cacao agroforestry system, all in Kalimantan, Indonesia (Borchard *et al.*, 2019), oil palm plantation increased the soil carbon by 43, 45 and 56%, respectively. The age of the plantation can explain the superior SOC storage capacity.

Our results regarding the total SOC storage in OP were similar to the carbon storage reported by Zaro *et al.* (2020) in a coffee with rubber tree agroforestry system in Brazil; this author obtained 20% less SOC storage at a depth of 0–70 cm. Such comparisons only are illustrative of potential discrepancies among various alternative land uses. However, further field measurements would be necessary to adequately compare oil palm with such alternatives, while considering site-specific influences like soil type, depth, agrosystem age, management, etc.

Soil organic carbon is not the only variable to account for when dealing with the carbon balance of agricultural production. Above and belowground vegetation is important to properly compare SOC between pastures and OPP

(Khasanah *et al.*, 2015). In our research, there are no statistical differences in SOC between oil palm plantations and pastures; however, if aboveground C biomass were considered, oil palm carbon stock could probably be higher than 41.4 Mg C ha^{-1} during the first 12 years of planting (Frazão *et al.*, 2013). That means it compensates for the losses of SOC in the soil during the first years after conversion from a pasture (Fargione *et al.*, 2008).

In future research in our study area, a life cycle assessment (LCA) approach could be recommended when analysing the overall carbon balance and further impacts in oil palm plantations. Indeed, LCA may help to assess i) greenhouse-gas fluxes and impacts in a more comprehensive way, including other non-carbon-based ones (*e.g.*, N_2O from fertilisers), and ii) other environmental impacts (*e.g.*, acidification). Such a comprehensive view is paramount to avoid problem shifting and provide tracks to optimise practices at the system level for palm oil, which is considered one of the agricultural activities with the greatest potential for development in the coming years in Mexico (Stichnothe and Bessou, 2017; Hernández-Rojas *et al.*, 2018).

5 Conclusion

Carbon storage in the secondary forest soil was much higher than in the two agrosystems, oil palm plantations and pastures. When comparing the various management zones within the oil palm plantations, the results showed greater soil organic carbon storage under the fronds, and the highest amount of SOC stock in the first soil layer. The incorporation of biomass from oil palm plants provides favourable conditions for the soil, which was evidenced by the increased amount of SOC in the management areas receiving the largest amount of organic residues under the frond.

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