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Aggregate Distribution and CO_2 Emission in the Soil of Agroforestry System

Diana Ayala-Montejo[1]*, Gerardo Sergio Benedicto-Valdés[2]*, Juan Fernando Gallardo Lancho[3], Eduardo Valdés-Velarde[1], Sergio Márquez Beber[1], and Noris Ledesma[4]

[1]*Crop Science, Universidad Autónoma Chapingo, Texcoco, Mexico*

[2]*Colegio de Posgraduados, Montecillo, Texcoco, Mexico*

[3]*CSIC-IRNASa, Salamanca, Spain*

[4]*Tropical Research & Education Center, University of Florida, IFAS, Homestead, FL*

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Coffee agroforestry systems in Mexico are characterized by their high species diversity and their potential to mitigate CO_2 emissions. Currently, these systems are being modified with the introduction of avocado as a way to address sanitation and price problems. This modification could alter organic matter concentrations, change soil aggregation, as well as influence soil biological activity and CO_2 emissions. The objective of the research was to evaluate the variation of aggregate size and CO_2 emissions produced by soil respiration with the changes generated by the introduction of avocado into a coffee agroforestry system, to demonstrate its potential to reduce CO_2 emissions and maintain carbon stores in the soil. Five agroforestry systems were selected: 1) traditional coffee polyculture with renovation; 2) traditional coffee polyculture with severe pruning and cleaning; 3) traditional coffee polyculture abandoned; 4) coffee and avocado agroforestry system (ACS); and 5) avocado monoculture. In each system, soil samples were collected at three depths: 0–10, 10–20, and 20–30 cm, for triplicate, during the 2019–20 production cycle, to determine bulk density, aggregate distribution, minimum weight diameter (MWD), chemical characteristics, soil respiration, soil organic carbon (SOC) and degradation rate constant (k_t). In the ACS a lower range (0.6–0.8 mm) of MWD at three depths, lower soil respiration (150 kg CO_2-C $ha^{-1}\cdot h^{-1}$), positive SOC balance and negative k_t were found. Therefore, the introduction of avocado contributes to the reduction of CO_2 emissions from soil respiration and to the conservation of carbon stores.

Agroforestry systems are recognized for their ability to mitigate carbon dioxide (CO_2) emissions from soil biological activity (Yago et al., 2019). In Veracruz, Mexico, coffee agroforestry systems dominate and are characterized by a high diversity of species that fulfill the functions of providing shade for coffee production, food, and raw materials for self-consumption. Currently, coffee agroforestry systems are being displaced by avocado monoculture, due to price variations in the coffee market (Jaffe et al., 2008) and low production caused by sanitary damage attributed to climatic variations (Villers et al., 2009).

Coffee agroforestry systems modified with avocado plantings generate variation in floristic composition and this could have a negative impact on biodiversity and environmental services (Escamilla, 2016). This change in floristic composition could influence the variation of CO_2 emissions generated by soil respiration (SR) because the quantity and quality of organic residues entering the soil could be altered. These alterations could change the microenvironments where microorganisms release CO_2 to the atmosphere, affecting concentration as well as the potential to store carbon (C) in the soil (Iqbal et al., 2010). Variation in the quantity and quality of organic residues could alter soil organic matter concentrations and change the soil aggregation state. This aggregation can influence the development of soil biological activity and CO_2 emissions (Chatterjee et al., 2020).

The objective of this research was to evaluate the variation of aggregate size and CO_2 emissions produced by soil respiration with the changes generated by the introduction of avocado plants in the coffee agroforestry system in the region of Huatusco, Veracruz, Mexico, to demonstrate the potential of modified agroforestry systems to reduce CO_2 emissions and carbon storage in the soil.

Materials and Methods

The experiment was conducted in the community of Tlaxopa, Municipality of Huatusco de Chicuellar, Veracruz (19°10'25" N Lat.; 96°57'30" W Long., México) at an average altitude of 1300 m. In study area, the climate is semi-warm and humid with an average annual temperature and precipitation of 16.4°C and 2018 mm/year, respectively. The soils are Andosols with a dark color, fine texture, strong acidity, and high organic matter content.

Five agroforestry systems were selected: 1) traditional coffee polyculture with renovation (CPR); 2) traditional coffee polyculture with severe pruning and cleaning (CPC); 3) traditional coffee polyculture–abandoned (CPA) (systems 1–3 are 21 years old); 4) coffee and avocado agroforestry system (ACS); and 5) avocado monoculture (MCA) (systems 4-5 are eight years old). Soil sampling points were randomly located in each systems.

*Corresponding authors. Email: diayalamontejo@gmail.com; bsergio@colpos.mx

For the 2019–20 production cycle, soil samples were collected at three depths: 0–10,10–20, and 20–30 cm, in triplicate, to determine bulk density, aggregate distribution, minimum weight diameter (MWD), chemical characteristics, soil respiration, soil organic carbon (SOC) and the degradation rate constant (k_t). The determination of aggregates in the soil was carried out with the methodology of Le Bissonnais (1996), using the following sieve sizes: 6.35, 4.76, 3.36, 2.0, 1.0, 0.5, 0.25, and < 0.25 mm. The resulting information was used to determine the minimum weight diameter (MWD) and bulk density with the cylinder method ($Mg \cdot m^{-3}$). Soil CO_2 emissions were assessed using soil respiration (SR). EGM-4 equipment was used to measure the CO_2 emissions flux generated by SR. It is based on the dynamic chamber method proposed by Parkinson (1981). SOC and inorganic carbon of soil (ICS) were determined before and after incubation. All determinations were performed in a TOC-V CPN Shimadzu C analyzer. These determinations were used to perform C balance using the methodology proposed by Rahman (2013). The SOC degradation rate constant (k_t) was calculated according to the kinetic model proposed by Tanvea et al. (2008). Statistical analysis consisted of analysis of variance (ANOVA, $P < 0.05$) and Tukey's HSD mean comparison to analyze CO_2 emissions generated by soil respiration. The minimum weight diameter was compared with a dual-axis plot to analyze interactions.

Result and Discussion

Soil pH ranged from 3.6 to 4.8 in all systems and at all depths, a range that corresponds to highly acidic soils (Table 1). The low bulk density values correspond to typical Andosols soils; the values ranged from 0.48 to 0.70 $Mg \cdot m^{-3}$ and increased with depth. These results are in agreement with those reported by Rosas et al. (2008) for coffee plantations. The CPA had the highest bulk density at the 0–10 and 20–30 cm depths, however at the intermediate depth (10–20 cm), the CPR and CPA had values similar to ACS. Bulk density results showed that traditional coffee systems have lower soil porosity (73.2 to 75.4%) for the development of biological activity than systems associated with avocado (73.9 to 82.3%) at the three depths (a real density of 2.65 $g \cdot cm^{-3}$ was used). This confirms that the agronomic management in systems associated with avocado produce soil conditions similar to intensively managed ones (Siavosh et al., 2010).

The CPA had an average of 72.8% aggregates with diameters > 1mm, at the 0–10 cm depth (Fig. 1A); 69.9% at 10–20 cm (Fig. 1B) and 62.7% at 20–30 cm (Fig.1C). For systems associated with avocado, an average of 74.2% aggregates with diameters < 1 mm was reported for the 0–10 cm depth, 69.4% at 10–20 cm and 62.5% at 20–30cm. These distributions showed that the aggregates are 250% higher in the traditional coffee systems compared to the agroforestry system modified with avocado. The distribution of aggregates < 1 mm in ACS is attributed to the low bulk density values generated by the introduction of avocados into the system. Bulk density values are lower than the average (0.82 $Mg \cdot m^{-3}$) reported by Siavoch et al. (2010) for traditional coffee systems with minimum weight diameters varying between 0.6 to 0.8 mm, a range that confirms the high potential to store carbon in the long term but deficient to generate soil activity, i.e., generate lower CO_2 emissions (Chattterjee et al., 2020).

Cumulative respiration ($kg \cdot ha^{-1} \cdot h^{-1}$ CO_2-C) ranged from 46.7 to 62.6 in all systems and at all depths (Table 2). CPC system with pruning and severe cleaning had the highest CO_2 emissions by microbial respiration in the swallowest depth (0–10cm); the same was seen at the lowest depth (20-30 cm) while at intermediate depth (10–20 cm) no significant differences were found between systems. ACS had 18.8% less emissions than CPC but emitted 9.9% more CO_2 than the traditional coffee–abandoned (CPA) at the 0–10 cm depth (Fig. 1E). At 10–20 cm there were no statistically significant differences and at 20–30cm depth (Fig. 1F) it resembles the system with lower soil respiration (CPR). This system corresponds to coffee renewed, i.e., with a high density of young coffee which has not yet created conditions which promote soil microbial activity at deeper soil layers (Handa et al., 2014).

The MCA with intensively managed had MDW 50% higher than ACS and so exceeds the 50% soil respiration values (Fig 2A). Similarly, CPC reported higher SR than traditional coffee. This may be attributed to the presence of aggregates that exceeded the CPR by 44.8% and CPS by 28.2%. However intensive pruning management contributes to a MWD 3.7 times higher than that for MCA. This relationship is also observed at the other depths (Figs. 2B and 2C). All systems not associated with avocado had an increase in SOC >100% (Fig. 2D), CPR (132%), and CPC (207%) had the highest values of minimum weight diameter and SOC. Since CPA had a higher MWD than the CPR (132%), it generated a smaller increase in SOC. At depths of 10–20 and 20–30cm (Fig. 2E) the variation in SOC had the same tendency as at the shallowest depth for systems associated with avocado, CPC had a lower SOC increase; CPR and CPA were the ones with the larges increases in SOC by soil respiration, both systems having a greater than 400% increase. The modification of the systems generated less soil activity which can be attributed to the fact that ACS and MCA systems are less diversified than traditional coffee systems (Xi et al., 2012). Cumulative emissions,

Table 1. General characteristics of the soils of each studied system.

	pH			BD ($Mg \cdot m^{-3}$)		
System	0–10 cm	10–20 cm	20–30 cm	0– 10 cm	10–20 cm	20–30 cm
ACS	4.8 ± 0.31 a	4.7 ± 0.24 a	4.6 ± 0.27 a	0.49 ± 0.03 b	0.55 ± 0.04 ab	0.55 ± 0.04 ab
MCA	4.8 ± 0.31 a	4.4 ± 0.24 a	4.4 ± 0.27 a	0.48 ± 0.03 b	0.49 ± 0.04 b	0.47 ± 0.04b
CPR	3.7 ± 0.31 a	3.7 ± 0.24 a	3.8 ± 0.27 a	0.66 ± 0.03 a	0.67 ± 0.04 ab	0.69 ± 0.04 a
CPC	4.0 ± 0.31 a	3.7 ± 0.24 a	3.7 ± 0.27 a	0.65 ± 0.03 a	0.71 ± 0.04 a	0.70 ± 0.04 a
CPA	3.7 ± 0.31 a	3.6 ± 0.24 a	3.7 ± 0.27 a	0.67 ± 0.03 a	0.67 ± 0.04 ab	0.66 ± 0.04 a
P-Value	0.0676	0.0331	0.1179	0.0012	0.0155	0.0053
HSD	1.437	1.119	1.264	0.137	0.192	0.172

ACS = Avocado-coffee system. MCA = Monoculture of avocados. CPR = Coffee traditional polyculture with renewal. CPC = Coffee traditional polyculture with pruning and severe cleaning. CPA = Coffee traditional polyculture abandoned.
Tukey test ($P \leq 0.05$); different letters indicate statistically significant differences.
P-Value: Probability value; MSD: Minimal significant difference.

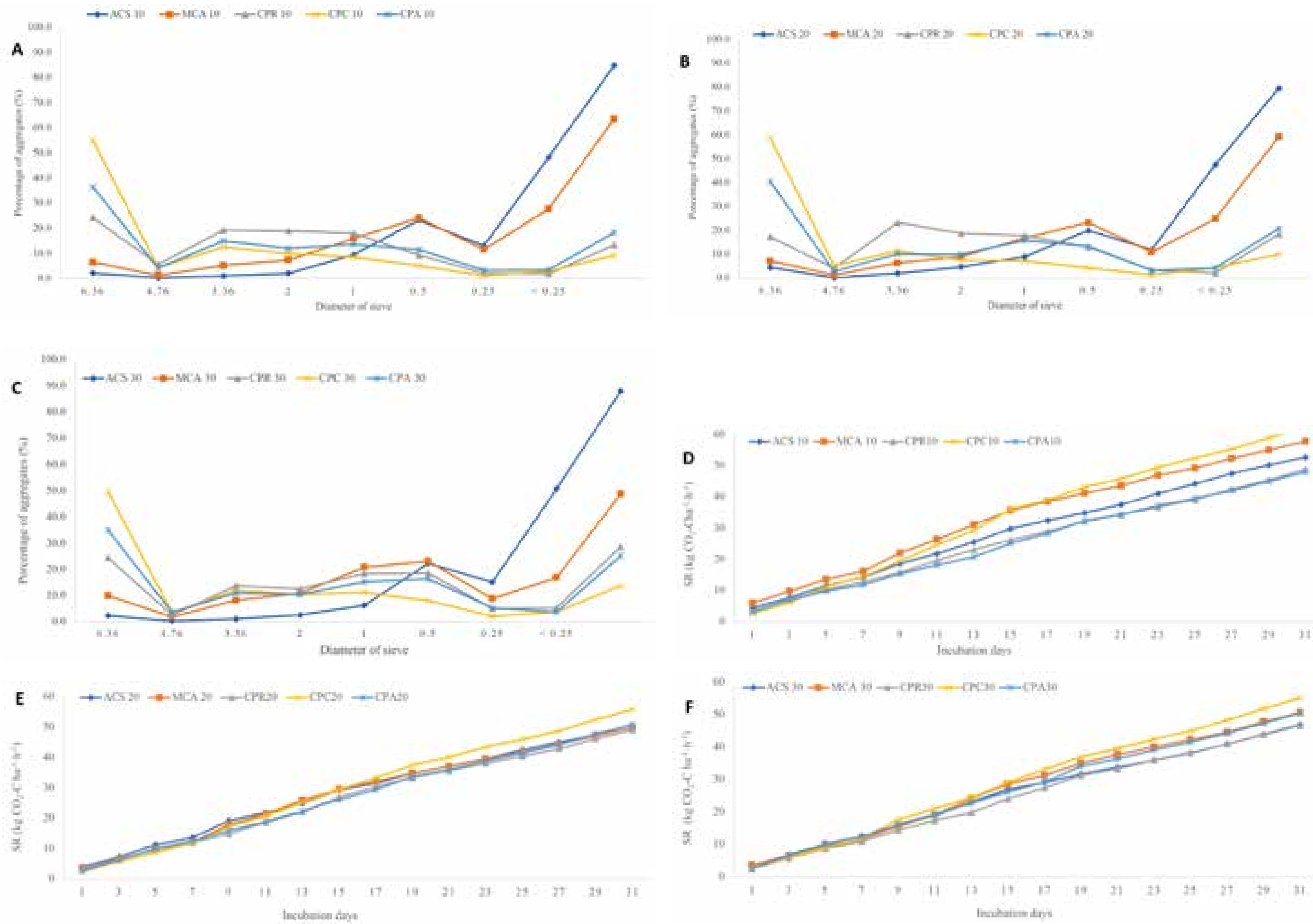

Fig. 1. Average distribution of soil aggregates. (**A**) Percentage of aggregates by sieve size at the depth of 0–10 cm; (**B**) Percentage of aggregates by sieve size at the depth of 10–20 cm; (**C**) Percentage of aggregates by sieve size at the depth of 20–30 cm; (**D**) Accumulated SR at the depth of 0–10 cm; (**E**) Accumulated SR at the depth of 10–20 cm; (**F**) Accumulated SR at the depth of 20–30 cm.

however, are similar the average (147 kg·ha^{-1}·h^{-1} CO_2-C) reported by Hergoualc'h et al. (2008) in coffee system with Andosols soils. For traditional coffee systems, the greater diversity of composition species contributes to soil biological activity and thus there is an increase in CO_2 emissions (Chen & Chen, 2019). Sheng et al. (2010) found that the availability of diversified substrates promotes soil respiration and Siavosh et al. (2010) showed that

Table 2. Carbon doixide (CO_2) emission generated from soil respiration.

	CO_2 emission (kg·ha^{-1}·h^{-1} CO_2 -C)		
System	0–10 cm	10–20 cm	20–30 cm
ACS	53 ± 1.95 bc	50 ± 2.32 a	47 ± 1.25 b
MCA	58 ± 1.95 ab	50 ± 2.32 a	51 ± 1.25 ab
CPR	49 ± 1.95 bc	49 ± 2.32 a	47 ± 1.25 b
CPC	63 ± 1.95 a	56 ± 2.32 a	55 ± 1.25 a
CPA	48 ± 1.95 c	51 ± 2.32 a	51 ± 1.25 ab
P-Value	< 0.05	0.31	< 0.05
HSD	9.09	10.79	5.82

ACS = Avocado-coffee system. MCA = monoculture avocado. CPR = Coffee traditional polyculture with renewal. CPC = Coffee traditional polyculture with pruning and severe cleaning. CPA = Coffee traditional polyculture abandoned. DMS = Minimal significant difference
P-Value: Probability value; Tukey test ($P \leq 0.05$).

soil respiration in traditional coffee systems is higher than in systems with intensive management.

The soil organic carbon balance was positive for ACS and reported the highest average range (9–26 Mg·ha^{-1} C) at all depths. MCA showed a positive balance in the shallowest depth (0–10 cm) (Table 3) while the other systems had a negative balance. Measurements at the three depths had statistical similarities with ACS. In traditional coffee systems, a negative balance was generated to store SOC at all depths.

The SOC degradation rate constant (K_t) was negative for the ACS system at all depths and positive for all other systems. CPA had the highest cumulative K_t at all depths, allowing for the following order: CPA = CPR > CPC > MCA > SAC. The positive SOC balance in coffee agroforestry systems modified with avocado indicates the ability of the systems to generate conditions that inhibit soil biological activity and, therefore have lower CO_2 emissions. The output of ACS was the lowest showing that the modification of traditional coffee systems influences the mineralization processes of labile SOM (Le Noë et al., 2019). In traditional coffee systems, a negative balance was generated producing higher residual C concentrations due to soil biological activity.

The ability of the systems to promote C pools and decreases emissions generated by soil activity is related to their ability to

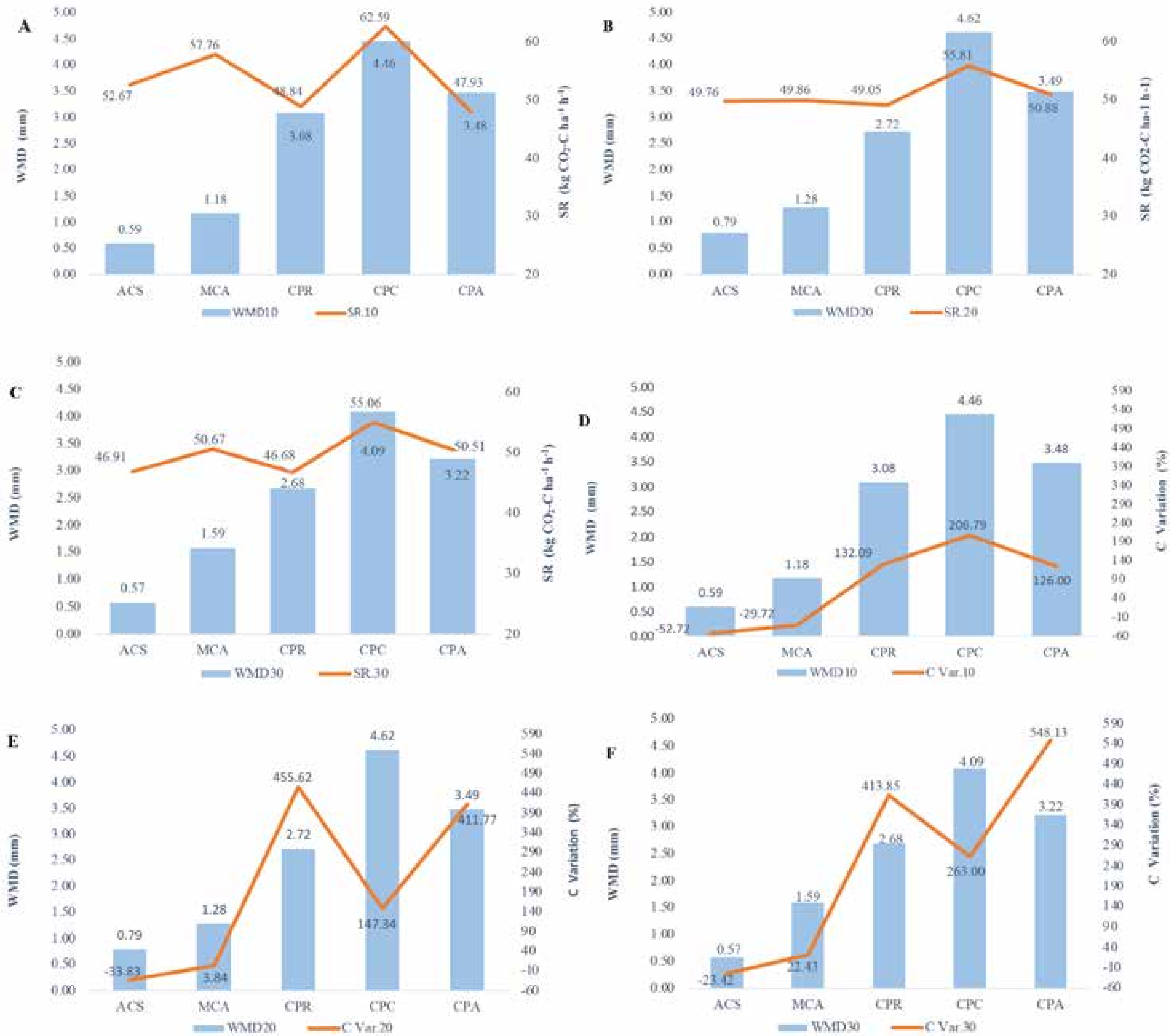

Fig. 2. Relationship between the weighted minimum diameter (WMD) and the variation of C (Var.). (**A**) WMD and accumulated soil respiration at depth of 0–10 cm. (**B**) WMD and accumulated soil respiration at depth of 10–20 cm. (**C**) WMD and accumulated soil respiration at depth of 20–30 cm. (**D**) WMD and Var. in depth of 0–10 cm. (**E**) WMD and Var. in depth of 10–20 cm. (**F**) WMD and Var. in depth of 20–30 cm.

Table 3. Soil organic carbon (SOC) balance and degradation rate constant (K_t).

	SOC balance (Mg·ha^{-1} C)			Degradation rate constant (K_t)/day		
System	0–10 cm	10–20 cm	20–30 cm	0–10 cm	10–20 cm	20–30 cm
ACS	26 ± 4.6 a	15 ± 5.1 a	9 ± 3.1 a	–2.3 ± 0.3 b	–1.24 ± 0.39 c	–0.77 ± 0.29 d
MCA	9 ± 4.6 a	–1 ± 5.1 a	–5 ± 3.1 a	–1.03 ± 0.3 b	0.15 ± 0.39 c	0.76 ± 0. 29 c
CPR	–38 ± 4.6 b	–78 ± 5.1 b	–63 ± 3.1 c	2.8 ± 0.3 a	5.56 ± 0.39 a	5.32 ± 0. 29 ab
CPC	–61 ± 4.6 c	–37 ± 5.1 c	–44 ± 3.1 b	3.6 ± 0.3 a	2.91 ± 0.39 b	4.19 ± 0. 29 b
CPA	–37 ± 4.6 b	–87 ± 5.1 c	–81 ± 3.1 d	2.7 ± 0.3 a	5.31 ± 0.39 a	6.08 ± 0. 29 a
P-Value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
HSD	21.193	23.641	14.202	1.38	1.8	1.36

ACS = Avocado-coffee system. MCA = Monoculture avocado. CPR = Coffee traditional polyculture with renewal. CPC = Coffee traditional polyculture with pruning and severe cleaning. CPA = Coffee traditional polyculture abandoned.

Tukey test ($P \leq 0.05$), different letters indicate statistically significant differences.

P-Value = Probability value, DMS = Minimal significant difference.

degrade SOM which was negative for ACS according to K_t results, suggesting that the modified systems have low soil activity. The low values of accumulated CO_2 emissions during incubation contributed to maintaining the soil C pool. This response show that the low degradation capacity of ACS contributes to decreased soil respiration (Zimmermann et al., 2009).

Conclusion

In conclusion, the lowest minimum weight diameter was generated in the two systems associated with avocados. These systems had lower microbial activity with a positive SOC balance and negative SOC aggregation constant. The ACS system generated the lowest concentration of cumulative CO_2 emissions from soil respiration. The introduction of avocado in the traditional coffee systems contributes to the reduction of CO_2 emissions and SOC storage.

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