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Soil Organic Carbon Storage in Coffee Agroforestry Systems: A review
Almacén de Carbono Orgánico del Suelo en Sistemas Agroforestales de *Café*: Una revisión

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SUMMARY

Agroforestry systems (AFS) are sustainable production alternatives that efficiently store more carbon than crop monoculture. However, the simplification of AFS, in terms of canopy structure and species diversity, affects their carbon sequestration capacity. This work aimed to assess the soil organic carbon (SOC) stocks of coffee agroforestry systems with distinctive shade gradients at 0-30 and 30-100 cm depths in different regions of the world. A literature review on SOC storage in coffee agroforestry systems at the global level was carried out. The coffee production systems were classified into three groups according to the shade gradient: traditional system (TS) with dense shade, specialized system (SS) with medium shade, and full-sun system (FSS) with no shade trees. TS stored 95 Mg SOC ha^{-1} at 0-30 cm depth, followed by SS with 83 Mg ha^{-1}, and FSS with 69 Mg ha^{-1}. At 30-100 cm, TS stored 224 Mg ha^{-1}, SS 186 Mg ha^{-1}, and in FSS 126 Mg ha^{-1}. The coffee AFS in the tropical region has an average of 76 Mg SOC ha^{-1} at 0-30 cm depth and 170 Mg ha^{-1} at 30-100 cm. The AFS in the temperate region stored an average of 74 Mg ha^{-1} at 0-30 cm and 115 Mg ha^{-1} at 30-100 cm. The global median SOC stock of coffee AFS was 253 Mg SOC ha^{-1} to one-meter depth. Our study highlighted that the density of shade trees in coffee AFS significantly affects SOC storage, especially in the subsoil. Reinforcing the importance of coffee AFS for storing SOC and mitigating climate change, this review highlights the need to study SOC at deeper soil profiles to fully understand the variation in soil carbon sequestration capacity of the diverse coffee agroforestry systems around the world.

Index words: *agroecosystem, climate change mitigation, global meta-analysis, organic matter, tree cover.*

RESUMEN

Los sistemas agroforestales (SAF) son alternativas de producción sostenibles que almacenan eficazmente más carbono que los monocultivos. Sin embargo, la simplificación de los SAF, en términos de estructura del dosel y diversidad de especies, afecta su capacidad de secuestro de carbono. Este trabajo tuvo como objetivo evaluar las reservas de carbono orgánico del suelo (COS) de los sistemas agroforestales de café con gradientes de sombra distintivos a 0-30 y 30-100 cm de profundidad en diferentes regiones del mundo. Se realizó una revisión bibliográfica sobre el almacenamiento de COS en sistemas agroforestales de café a nivel mundial.

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Los sistemas de producción de café se clasificaron en tres grupos según el gradiente de sombra: sistema tradicional (ST) con sombra densa, sistema especializado (SE) con sombra media, y sistema a pleno sol (SP) sin árboles de sombra. El ST almacenó 95 Mg COS ha^{-1} a 0-30 cm de profundidad, seguido del SE con 83 Mg ha^{-1}, y el SP con 69 Mg ha^{-1}. A 30-100 cm de profundidad, el ST almacenó 224 Mg COS ha^{-1}, SE 186 Mg ha^{-1}, y SP 126 Mg ha^{-1}. El AFS de café en la región tropical tiene un promedio de 76 Mg COS ha^{-1} a 0-30 cm de profundidad y 170 Mg ha^{-1} a 30-100 cm. El AFS de la región templada almacenó una media de 74 Mg ha^{-1} a 0-30 cm y 115 Mg ha^{-1} a 30-100 cm. La media global de almacenamiento de COS de los AFS de café fue de 253 Mg COS ha^{-1} a un metro de profundidad. Nuestro estudio resaltó que la densidad de árboles de sombra en AFS de café afecta significativamente el almacenamiento de COS, especialmente en el subsuelo. Reforzando la importancia de los SFA de café para almacenar COS y mitigar el cambio climático, esta revisión destaca la necesidad de estudiar el COS en perfiles de suelo más profundos para comprender plenamente la variación en la capacidad de secuestro de carbono del suelo de los diversos sistemas agroforestales de café en todo el mundo.

Palabras clave*: agroecosistema, mitigación del cambio climático, metaanálisis global, materia orgánica, cobertura arbórea.*

INTRODUCTION

Atmospheric CO_2 concentration has increased rapidly in recent decades, with a global average of 422 mg L^{-1} (in volume) in December 2024, negatively affecting the environment and food production systems (IPCC, 2022; NOAA, 2024). There is a need to find agricultural solutions that mitigate CO_2 emissions, are resilient to climate change, and conserve or restore biological diversity (Pörtner *et al*., 2023). Agroforestry systems (AFS) are one of the environmentally friendly food production alternatives that grow trees or shrubs and crops or grasses in the same place to optimize resources, agricultural production, and natural benefits. Due to the presence of woody perennials, such as AFS, they are reported to sequester more carbon in aboveground biomass and soil than crop monoculture and serve as a natural solution to climate change (De Stefano and Jacobson, 2018; Terasaki *et al*., 2023).

One of the important AFS in the world is the coffee agroforestry system, which effectively maintains biodiversity and provides multiple ecosystem services, including carbon sequestration (Notaro, Gary, Le Coq, Metay, and Rapidel, 2022). Due to the presence of trees with different heights, these systems store carbon in the biomass of shade trees and coffee plants (Sala, Faroli, and Zamagni, 2013; Negash, Starr, Kanninen, and Berhe, 2013; Tumwebase and Byacagaba, 2016). The coffee AFS not only stores carbon in tree biomass but also releases organic matter and nutrients into the soil through aboveground litterfall, fine root turnover, and production of root exudates, all contributing to increased soil organic carbon (SOC) storage (Valdés-Velarde *et al*., 2022). Many shade trees in coffee AFS are of the Leguminosae family, which symbiotically fix atmospheric nitrogen and contribute to improving soil biological activities (Kim and Isaac, 2022). The integration of purposefully selected shade trees can enhance soil phosphorus availability and improve other biochemical properties of the soil (Getachew *et al*., 2023).

The production of quality litter due to the combination of tree species of different traits and the increase in soil macro-fauna, as well as microbial activities, helps to decompose aboveground litter and incorporate it into the soil as organic carbon (Dos Santos Bastos, Barreto, de Carvalho, Monroe, and de Carvalho, 2023; Nascimento *et al*., 2024). Coffee AFS has also been reported to improve soil physical properties, enzymatic activities, and overall soil health compared to crop monoculture, favoring soil C sequestration (Matos *et al*., 2023). Coffee AFS are found to increase the storage of labile and recalcitrant carbon in the soil, improving the balance between stocks of readily mineralizable and recalcitrant carbon (Suárez, Segura, and Andrade, 2024). Furthermore, trees with different rooting depths improve the distribution of soil organic carbon at deeper soil profiles in these AFS (De Oliveira *et al*., 2025).

Globally, coffee production covers about 12.2 million hectares of land distributed on different continents (Table 1). American content holds 42% of the global land surface under coffee production, mostly distributed in South and Central America. While the demand for coffee consumption is increasing globally, the production systems of this highly traded commodity are changing in their canopy structural attributes, shade tree species composition, and management practices due to diverse local, regional, or global drivers (Sporchia *et al*., 2023).

Table 1: Land area and production of green coffee by continent (FAOSTAT, 2025).

Continent	Land surface area	Annual production
	hectares	tons
America	5 111 232	5 662 264.74
Africa	4 299 819	1 913 991.66
Asia	2 731 691	3 442 499.07
Oceania	43 152	45 450.01
World total	12 185 894	11 064 205.48

In many regions, coffee AFS are threatened by climate change, pests, and diseases (Bosselmann, 2012; Ruelas-Monjardín, Nava, Cervantes, and Barradas, 2014). It is reported that tree species identity and the level of shade can be related to the incidence and severity of pests and diseases in coffee plantations (Ayalew *et al*., 2022). The level of shade and micro-climate within the canopy are reported to have significant impacts on the occurrence and damage by leaf rust (*Hemileia vastatrix*) in coffee plantations (López-Bravo, Virginio, and Avelino, 2012; Gagliardi, Avelino, Virginio Filho, and Isaac 2021). Many coffee AFS in the tropical region have suffered from leaf rust disease, and farmers have, therefore, simplified the conventional high-shade systems to low-shade or full-sun systems due to the shift in coffee varieties (Márquez-de la Cruz, Rodríguez, García, Sánchez, and Tinoco, 2022).

This shift from traditional rustic or polyculture AFS with high density and coverage of shade trees to specialized reduced-shade commercial plantations or no-shade monoculture coffee plantations has decreased the biological diversity and structural complexity of coffee production systems (Moguel and Toledo, 1999; Escamilla-Prado *et al*., 2021). Such changes in shade management directly affect the biomass carbon sequestration of coffee AFS because of the reduction in the woody components (Begum *et al*., 2022), yet the effect of the simplification of AFS on soil organic carbon storage has not been understood properly. Therefore, the objective of this review was to know the soil organic carbon storage at two different depths (0-30 and 30-100 cm) of coffee agroforestry systems at the global level, differentiating the shade gradients.

MATERIALS AND METHODS

Search for Information

An exhaustive search was carried out of reported works on organic carbon storage in soils of coffee agroforestry systems worldwide between 2000 and 2024. Keywords and phrases were used in both English and Spanish, which include "carbon capture, storage, content, assessment, quantification, estimation, and sequestration in coffee plantations, coffee agroforestry systems". This search was carried out in the digital platforms of Scopus, Google Scholar, and journals indexed in the National Consortium of Scientific and Technological Information Resources (CONRICyT), Mexico. Likewise, we used the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) principles to present the review and synthesis clearly and transparently (Page *et al*., 2021). The download and bibliometric analysis were done from August to November 2024.

Information Selection Methods

The first filter consisted of the identification of sources to make sure that the articles belonged to peer-reviewed journals. Non-refereed papers were discarded from the review. The second filter consisted of a bibliometric analysis by reading the articles to corroborate that the research includes SOC data in coffee agroforestry systems. The selection of the papers was based on the definition of the following criteria: 1) that the authors reported soil organic carbon in coffee agroforestry systems, 2) that it was within the range of dates, and 3) that it reports SOC stock in more than one depth category. Research papers that did not report soil carbon in coffee AFS or reported carbon in a single depth only were discarded (Figure 1). After the bibliometric analysis, a total of 77 papers were selected, of which 34 were chosen for this review as they fulfill the mentioned criteria.

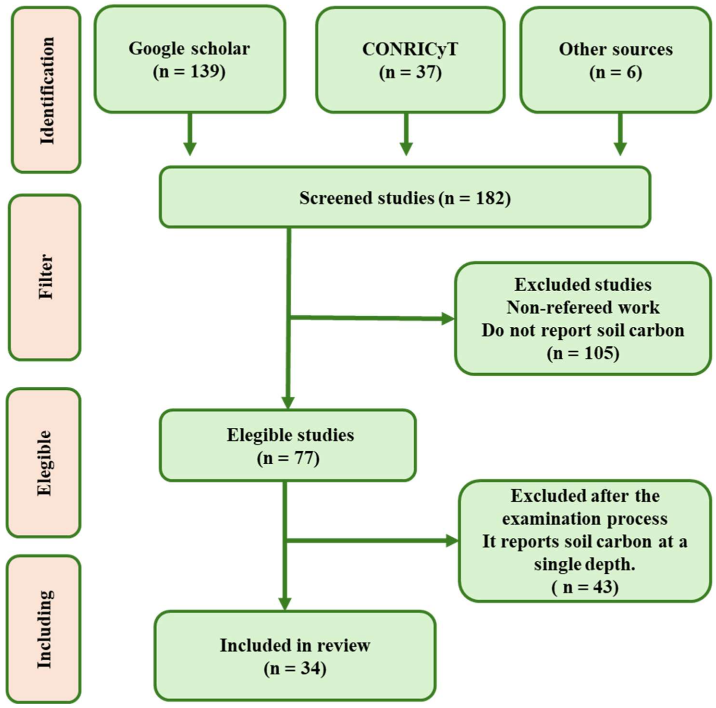

Figure 1. Diagram of the process of collecting and selecting the publications used in this review.

A database was created where key information was entered, including country of study, type of system regarding shade gradient, carbon stock in biomass, the organic carbon in the soil, soil depth, unit of measurement, climate, and geographic coordinates. This information was needed for further processing and data analysis related to SOC storage.

Data Synthesis and Analysis

We compiled the SOC stock data (Mg C ha^{-1}) at 0-30 and 30-100 cm from the selected articles. Where data to the corresponding depth was unavailable, we used regression models to estimate it. For that, we used the data from the same study and interpolated using the corresponding regression models. The SOC data had to be in continuous depth sequence (0-10 cm, 10-20 cm, 20-30 cm) to develop the slope of the model. Where available, respective standard deviation data were also included in the regression to reduce the bias from limited data variability. Finally, the SOC stock for 0-30 and 30-100 cm depth was obtained by using the corresponding regression parameters. This approach of vertical interpolation to predict SOC stock at different depths is commonly used in this field (Mishra *et al*., 2009; Mulder, Lacoste, Martin, Richer, and Arrouays, 2015).

Likewise, the type of shade for each system was standardized based on the description of each coffee production system. The type of system was organized into three groups: TS = traditional system, with a high shade of multiple tree species, SS = specialized system, with medium shade of a few selected tree species, and FSS = full sun system, the monoculture of coffee plantation without shade trees. This categorization represents the gradient from structurally complex ecosystems to intermediate and simplified agroecosystems, where the diversity of tree species is also found in decreasing order. Similarly, the climatic regions were grouped according to Köppen's classification (García, 2004), leaving the data in two regions (A = Tropical and T = Temperate). For this, study locations and their climatic characteristics were considered from each study included in the review.

The harmonized data (with the same unit and depth interval) was analyzed to determine the variations across the period, shade gradient, and region. The evolution of the number of studies on SOC in coffee AFS from 2000 to 2024 was counted at 5-year intervals up to 2020 and four years from 2021 to 2024. Since this is a meta-analysis where the assumptions of randomization are not met, parametric and non-parametric techniques were used to analyze the data. For this meta-analysis, different statistical tests were carried out on the soil carbon data of the coffee agroforestry systems to determine if there are significant differences between variables, taking into account *two variables, from 0 - 30 cm and 30 - 100 cm. The analysis of the soil carbon data was based on a general linear model analysis for the variable type of shade (system), depth, and continent to obtain the analysis of variance, and interactions, and determine if there are significant differences in SOC. It is worth mentioning that this analysis was performed separately for each variable. Similarly, the Mood median test and the Kruskal-Wallis test were used to determine the descriptive statistical values and their significance level for the variable type of shade (system) and depth. Subsequently, a separate analysis was carried out for each of the depths of 0 - 30 cm and 30 - 100 cm, to determine if there are significant differences between the shade variable (system) and depth. This was done through an analysis of variance using a general linear model and by using Tukey's mean comparison test at a 95% confidence level. We analyzed the data using the Minitab 19 statistical package.*

RESULTS AND DISCUSSION

Studies on SOC Storage in Coffee Agroforestry Systems

More studies on SOC storage in coffee AFS were reported from 2016 to 2020 (Figure 2A). Regarding the studies on shade gradient, the medium-shade specialized system was found to have a greater number of studies on SOC storage (Figure 2B). America was the continent where SOC stock in coffee AFS has been studied the most, followed by Africa, and finally Asia (Figure 2C).

Soil organic carbon stock under coffee agroforestry systems by climatic region

The coffee agroforestry systems in the tropical regions stored an average of 76 Mg SOC ha^{-1} SOC at 0-30 cm depth, while at 30-100 cm, they stored an average of 170 Mg SOC ha^{-1}. The coffee agroforestry systems located in the temperate regions stored an average of 74 Mg SOC ha^{-1} at 0-30 cm and 115 Mg SOC ha^{-1} at 30-100 cm soil depth (Figure 3).

Soil organic carbon stock of coffee agroforestry systems by continent

There were no significant differences (F = 0.93, *P* = 0.397) in SOC storage between continents (Figure 4). Significant differences were observed only between the two depth classes (F = 29.56, *P* = 0.000), with a higher stock in subsoil (30 – 100 cm). Furthermore, there was no significant interaction between continent and soil depth (F = 0.04, *P* = 0.962).

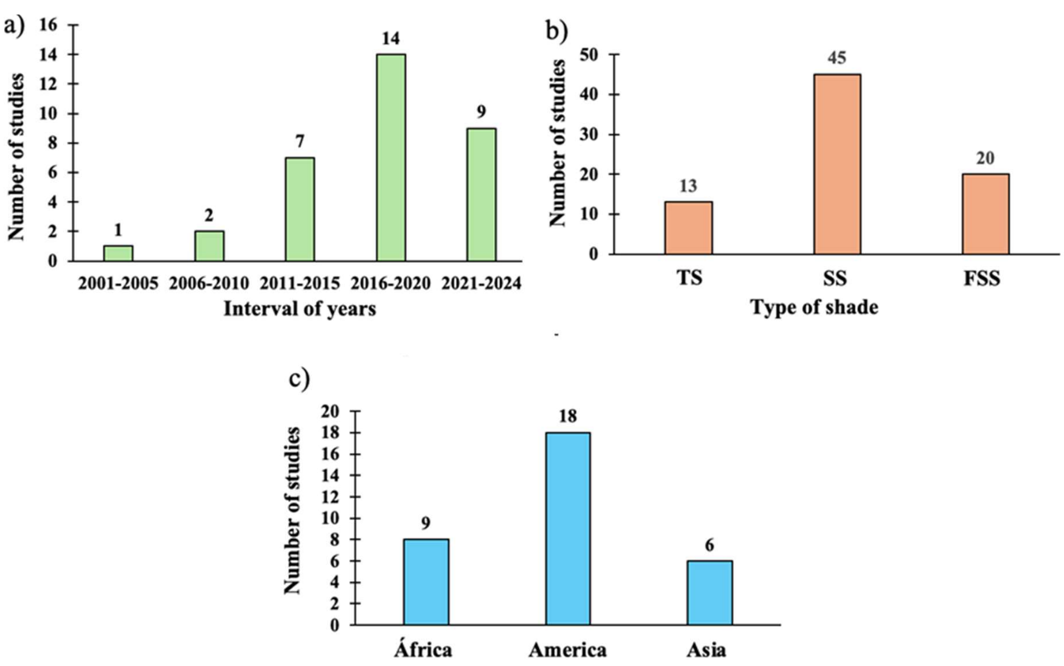

Figure 2. Number of studies on SOC storage in coffee agroforestry systems from 2000 to 2024 (a), by the type of shade (b), and by continent (c). TS = traditional system; SS = specialized system; FSS = full-sun system.

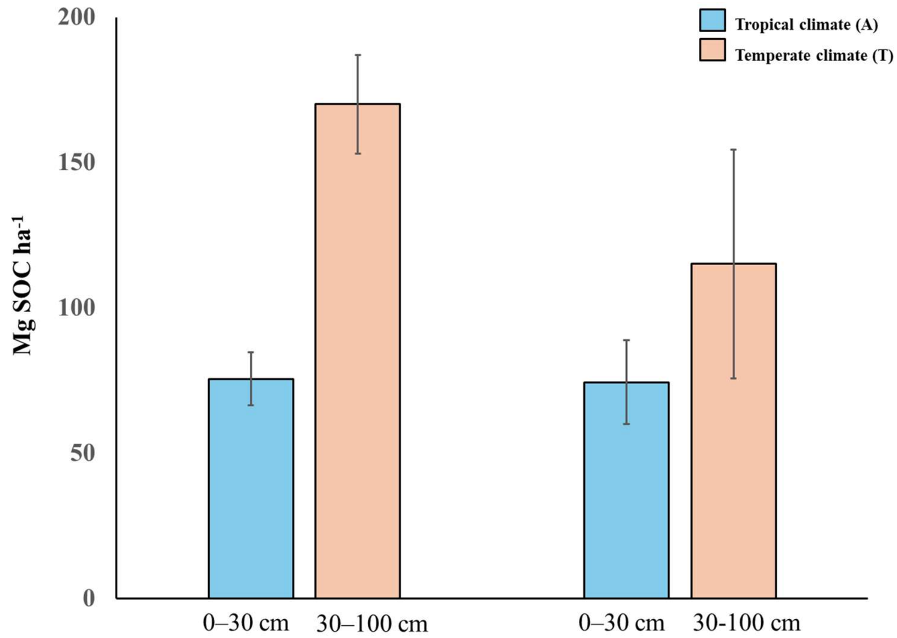

Figure 3. Effect of Tropical (A) and Temperate (T) climate on carbon sequestration in soils of coffee agroforestry systems at two depths of 0-30 cm and 30-100 centimeters.

SOC Storage in Coffee Agroforestry Systems by Shade Gradient

We found that the type of shade (system) and soil depth showed significant effects on SOC stocks (Table 2). However, the interaction between shade and depth was not significant (*P* = 0.273). In the same way, the Kruskal-Wallis non-parametric test also showed a significant difference between shade gradients (*P* = 0.038).

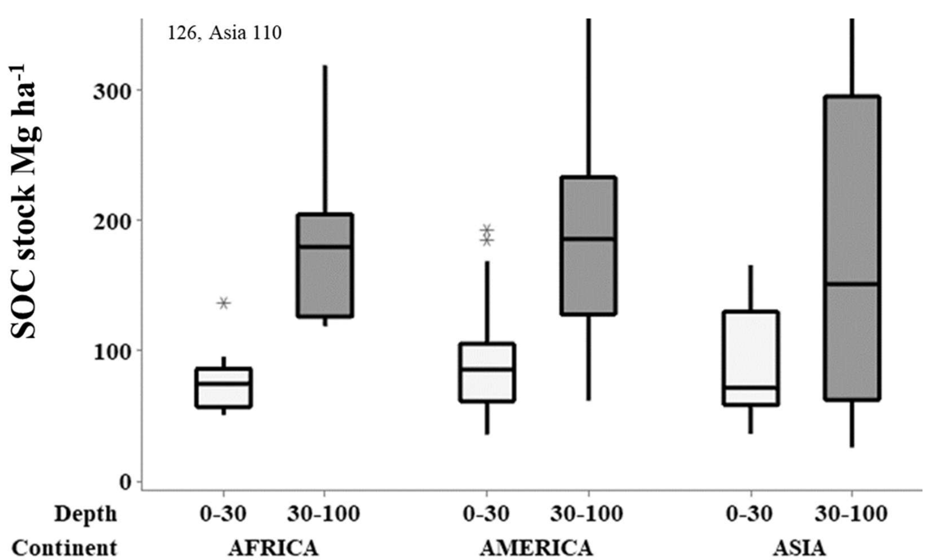

Figure 4. Soil organic carbon (SOC) stocks in coffee agroforestry systems by continent at two depth classes (topsoil: 0 – 30 cm and subsoil: 30 – 100 cm). The middle lines within the boxes represent the respective median values. DF = degrees of freedom; IQR = interquartile range.

Table 2. Analysis of variance testing the effect of shade gradient and soil depth on soil organic carbon stock in coffee agroforestry systems.

Sources of variance	Degrees of freedom	Sum of squares	Mean sum of the squares	F-value	P-value
Shade (system)	2	67 947	33 974	4.95	0.008
Soil depth	1	333 476	333 d476	48.59	0.000
Shade*Depth	2	17 952	8976	1.31	0.273
Error	150	1 029 496	6863		
Total	155	1 522 604			

At 0-30 cm, the full-sun systems stored 69 Mg ha^{-1}, the specialized system 83 Mg ha^{-1}, and the traditional high-shade system 95 Mg ha^{-1} of SOC (Figure 5). Although the median values were different and SOC stock was numerically higher in the high-shade traditional system, they were statistically non-significant ($F = 1.83$, $p = 0.167$). At 30 - 100 cm, the full-sun system stored 126 Mg ha^{-1}, the specialized system 186 Mg ha^{-1}, and the traditional system 224 Mg ha^{-1} of SOC. It is important to note that there was a significant difference in SOC storage ($F = 8.94$, $P = 0.000$) among shade gradients at subsoil (30 - 100 cm) in both parametric and non-parametric analysis.

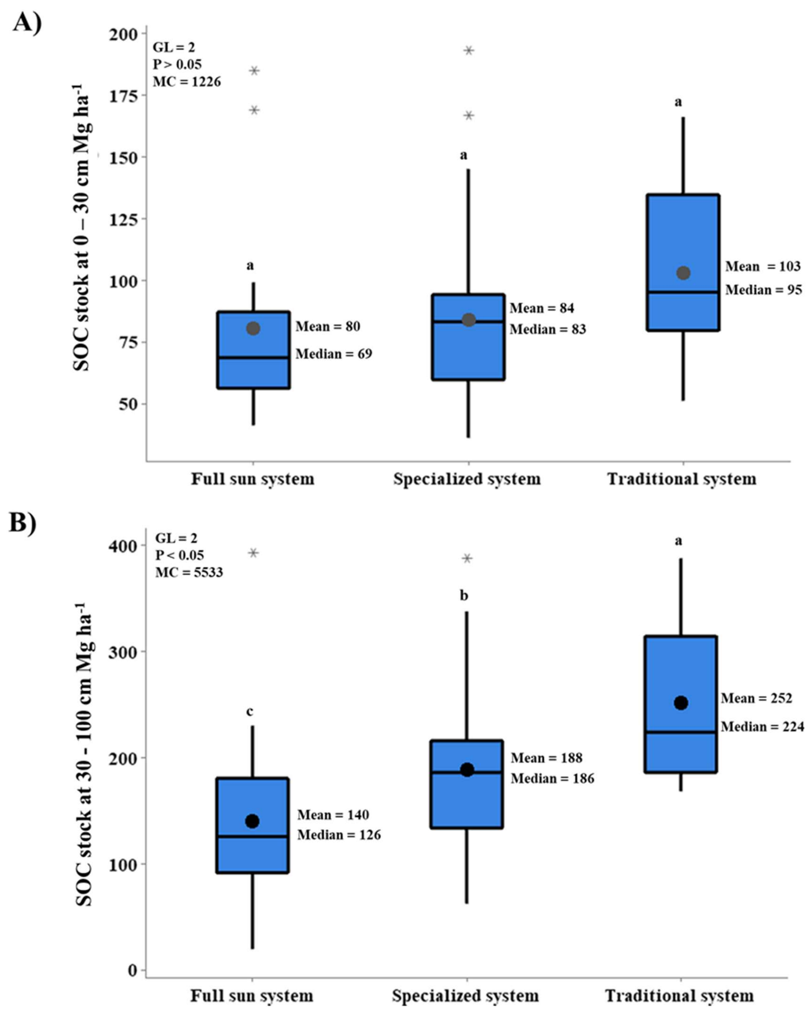

Figure 5. Soil organic carbon (SOC) storage in coffee agroforestry systems: A) at 0 - 30 cm depth by shade type and B) at 30 - 100 cm depth by shade type. DF = degrees of freedom; MSE = mean square error. Different lowercase letters above the boxes indicate the significant differences between shade gradients.

Carbon Storage in Global Coffee Agroforestry Systems

Averaged across all sites irrespective of shade gradients, we estimate the global median SOC stock of 83 Mg ha^{-1} at 0 - 30 cm and 170 Mg ha^{-1} at 30 - 100 cm depth in coffee agroforestry systems (Figure 6). In total, they store 253 Mg ha^{-1} of SOC at the one-meter depth, highlighting the capacity of these agroforestry systems to accumulate carbon in deeper soils.

Shade Gradient and SOC Storage in Coffee Agroforestry Systems

Globally, shade-grown coffee agroforestry systems are acknowledged for their capacity to sequester atmospheric carbon and store it in tree biomass and soil and for being a cropping system that preserves biodiversity (Arellano and Hernández, 2023; Ruiz-García, Conde, Gómez, and Monterroso, 2021; Xiao *et al*., 2020; Häger, 2012; Noponen, Healey, Soto, and Haggar, 2013). However, the presence of coffee leaf rust disease that affected coffee plantations in many parts of the world has been one of the main drivers leading to the reduction in the number of shade trees in these systems (Parada, Cerdán, Ortiz, Barradas, and Cervantes 2020; Libert-Amico and Paz-Pellat, 2018; Yirga, 2020). Many high-shade traditional coffee production systems were converted to medium-shade specialized systems or no-shade coffee monoculture (Manson, Nekaris, Nijman, and Campera 2024; Pohlan, Soto, and Barrera, 2006; Soto-Pinto and Jiménez, 2018). This change in shade gradient has significant implications for the carbon sequestration potential of coffee production systems (Zaro *et al*., 2020; Xiao *et al*., 2018).

Regarding research on SOC storage, this review showed that traditional systems are less studied than specialized systems despite their capacity to store more carbon. Our synthesis showed that at 0 - 30 cm depth, the traditional coffee AFS of high-shade stored 15% more SOC compared to the specialized system and 38% more compared to monoculture coffee. Meanwhile, from 30 - 100 cm depth, the traditional shaded can coffee AFS stored 20% more SOC compared to the specialized system and 78% more compared to the full sun coffee monoculture. Consistent with our findings, a study conducted in India reported that traditional coffee AFS combined with native shade trees stored 228 Mg C ha^{-1} compared to a specialized system that stored only 158 Mg C ha^{-1} (Guillemota, Maire, Munishamappa, Charbonnier, and Vaast, 2018). On the other hand, no clear effect of shade gradients was reported in a study in Costa Rica, where SOC content was poorly correlated with above-ground biomass, indicating the need for studying other factors that influence SOC sequestration (Noponen *et al*., 2013). However, another study of Puerto Rican coffee AFS demonstrated that shade trees accounted for most of the variance in total C stocks (Lugo-Pérez, Hajian, Perfecto, and Vandermeer, 2023). Though not as much as traditional high-shade systems, specialized systems also contribute to store SOC compared to full-sun monoculture coffee plantations due to the number of trees that can be found in such systems, which range from 176 to 360 trees per hectare, dominated by a few selected shade trees such as *Inga spp.* in Latin America (Soto-Pinto and Jiménez, 2018).

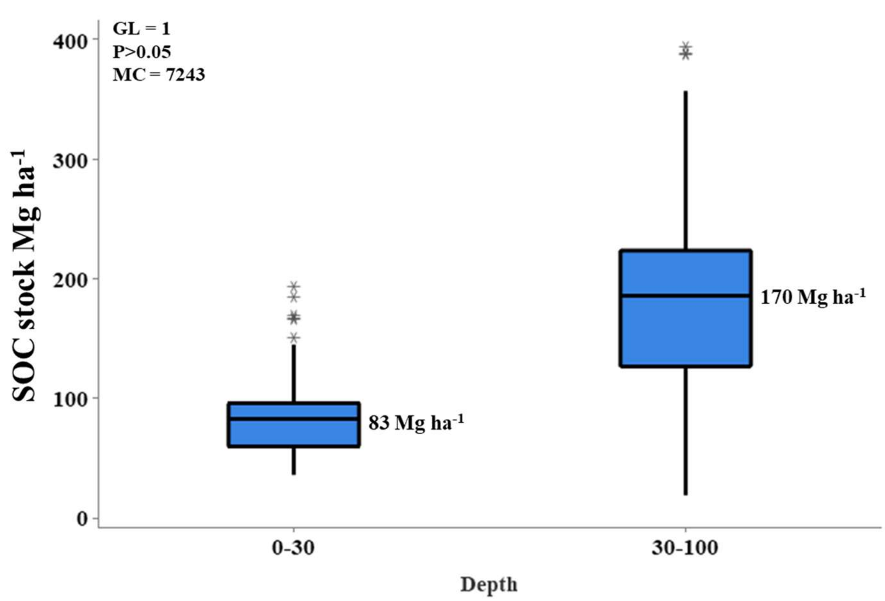

Figure 6. SOC storage in global coffee agroforestry systems at two depths. DF = degrees of freedom; MSE = mean square error.

The SOC storage of the coffee agroforestry systems to the depth of 0-30 cm is within the range of 69 to 95 Mg C ha^{-1} in this synthesis. This result is related to those reported by Valdés-Velarde *et al*. (2022), who reported the SOC stock of 63 - 76 Mg C ha^{-1} Mg ha^{-1} C in SS in coffee AFS. Meanwhile, in another study, Masuhara *et al*. (2015) reported a SOC stock of 72 Mg C ha^{-1} for SS and 92 Mg C ha^{-1} for TS in Veracruz, Mexico. What is reported in this review to a depth of 30-100 cm resembles the results reported by Masuhara *et al*. (2015), where they mention that C stored at a depth of 0-60 cm was 117 Mg ha^{-1} in SS and 154 Mg ha^{-1} in TS coffee systems with greater species diversity. We noted that the studies reporting SOC stocks to 100 cm depth are very limited.

Due to the need to understand the dynamics of SOC at greater depths (0-100 cm), studies are currently underway to generate information on the mechanisms of soil C sequestration in these coffee systems with and without shade, as well as the relationship of carbon with other elements (Chatterjee *et al*., 2019; Sarkis *et al*., 2023). A study in Costa Rica and Guatemala calculated the net C balance (sequestration minus emissions) and related it to the level of shade, where authors found that coffee AFS with shade cover over 60% were C positive, AFS with 50% cover were close to C neutral, while AFS with 40% or less shade were C negative (Walsh, Haggar, Cerretelli, Van Oijen, and Cerda, 2025). The carbon footprint is found to be lower in agroforestry systems than in monoculture, and this gives value to the integration of shade trees and their potential to sequester carbon ranging from 9 Mg ha^{-1} in full-sun systems to 53 Mg ha^{-1} in agroforestry systems (Arellano and Hernández, 2023; Sarkis *et al*., 2023).

However, it is essential to consider the trade-offs and complementarity between the C sequestration resulting from increased shade trees and the economic benefits from coffee production (Broeckhoven *et al*., 2025). Taking into account the land surface dedicated to coffee production and the global average of SOC stock from this synthesis, we estimate that soil under coffee agroforestry systems stores 1.08 (0.76 – 1.41) Pg of SOC at 0–30 cm and 3.24 (2.60- 3.89) Pg at 0 - 100 cm depth globally. Proper management of shade and soil could optimize the production, biodiversity, and carbon sequestration benefits in these agroecosystems.

Climate and SOC storage in Coffee AFS

Climatic conditions can determine C accumulation and storage in different regions (Ghimire *et al*., 2024), as observed in this review, where greater SOC was appreciated in tropical areas. Feliciano, Ledo, Hillier y Nayak (2018) also mention that carbon sequestration in the soil is higher in agroforestry systems found in a tropical climate. The differences in the diversity of the species and the rate of organic matter turnover can explain the variation in SOC storage between climatic regions (Hergoualc'h, Blanchart, Skiba, Hénault, and Harmand, 2012; Morales-Ruiz *et al*., 2025). Plant biomass production, litterfall, fine root turnover, and decomposition of aboveground litter due to the presence of diverse soil organisms have significant contributions to C cycling and storage in the soil, all of them may vary with climate (Xiao *et al*., 2020; Valdés-Velarde *et al*., 2022; Sánchez-Silva *et al*., 2022).

Since it has been shown that under climate change scenarios, SOC at topsoil (0 - 30 cm) is more susceptible to loss compared to deeper SOC that does not degrade easily (Powlson *et al*., 2011; Lozano-García, Muñoz, and Parras, 2017). Like all others, coffee AFS are also under climate change scenarios, and it is congruent to continue studying the SOC stored at deeper profiles in coffee agroforestry systems and full-sun coffee plantations to better understand the ecological response of these systems (Betemariyam, Negash, and Worku, 2020; Hergoualc'h *et al*., 2012; Jansson and Hofmockel, 2020; Nadège *et al*., 2019; Ruiz-García, Monterroso, Valdés, Escamilla, and Gómez, 2022; Salgado-Mora, Ruíz, Moreno, Irena, and Aguirre, 2018; Xiao *et al*., 2020).

In addition to organic carbon in the soil, coffee AFS stores a high amount of carbon in tree biomass, furthering the benefit of climate change mitigation. For example, a study in southwestern Ethiopia reported the SOC stock of 91.5 Mg ha^{-1} to 60 cm depth and biomass + litter stock of 195.5 Mg ha^{-1}, where coffee plants accounted for 12.8% of the biomass carbon (Niguse, Iticha, Kebede, and Chimdi, 2022). It is important to take into account the age of the system, the age of the trees, characteristics, and management because they determine the amount of carbon that can be stored in the system (Gómez-Cardozo *et al*., 2018). Native shade trees in coffee AFS, in addition to C sequestration, have multiple other uses for the livelihood of the farmers and contribute to the regulatory and supporting ecosystem services such as nutrient cycling, soil fertility, water regulation, micro-climate modulation, erosion control, germplasm conservation, habitat for wild fauna, among others (Barrios-Calderón, Gordillo, and Brindis, 2023; Delgado-Vargas and Franco, 2024; Flores-Ortiz *et al*., 2025).

Research Gaps on C Dynamics in Coffee Agroforestry Systems

The present study shows that there are still insufficient studies to present the global data on SOC storage in coffee AFS. Globally, most studies have been conducted at shallow depths that are on slopes subject to the effects of global warming, affecting the loss of C from the surface layer (Tesfay, Moges, and Asfaw, 2022). Because of this, there is a need to continue studying the carbon stored at greater depths, as mentioned by Guevara and Vargas (2021) in a study where they predict the SOC at 1 m depth. They also mention that there is uncertainty and discrepancy in the generation of data, which could be addressed by increasing the number of studies in different regions and harmonizing measurement methods. Similarly, studies are required to focus on the carbon footprint in the coffee value chain (Alhajj Ali, Tedone, Verdini, and De Mastro, 2017; Van Rikxoort, Schroth, Läderach, and Rodríguez, 2014) and the interaction of organic carbon with other soil elements and soil organisms (Sarkis *et al*., 2023). The studies on the trade-offs and synergy between yield, biodiversity, and ecosystem services from diverse management practices would provide deeper insights and guide the farmers and policymakers for the sustainability of coffee agroforestry systems (Mokondoko, Avila, and Galeana, 2022). Management practices such as soil fertility, disease, and pest control vary among producers, which might, to a certain extent, affect C sequestration. Further studies on the effect of specific management practices on biomass and soil carbon sequestration would add knowledge of the C dynamics of these important agroforestry systems.

CONCLUSIONS

There has been an increase in studies on soil organic carbon sequestration in coffee agroforestry systems since 2011 in different parts of the world. We found a greater number of studies on specialized systems with intermediate shade or monoculture systems with full solar exposure than on traditional high-shade systems in terms of soil carbon storage. Coffee AFS in tropical regions stored more C than in the temperate areas in this review, but there was no difference between continents. Traditional systems with high-density shade trees stored more C than medium-shade specialized systems and full-sun coffee monoculture systems. We found a clear difference in soil organic carbon storage in subsoils (30-100 cm depth) among the coffee systems with shade gradients. Deeper soils are important carbon reservoirs; however, most studies did not take this depth into account. Coffee agroforestry systems can store more carbon than full-sun coffee plantations in the soil, making them a good alternative that contributes to mitigating atmospheric CO_2 and consequently climate change. However, it is imperative to study the soil organic carbon that is stored at a soil profile deeper than 30 cm and thus to have more data that allows us to understand the soil C sequestration dynamics of coffee agroforestry systems.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

The data used in the study are available upon reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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Research, writing-preparation of the original draft, Analysis: D.M.A., and D.R.A.; writing-revision and methodology: F.G.H., and F.C.L.; software and supervision: M.A.L.A., and A.M.P.T, Visualization, supervision and editing: G.V.L, Conceptualization and supervision: R.P.R., and J.A.V.V.

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