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Soil Organic Carbon Stocks Across Different Agroforestry Systems in Coffee-Based Land Use: A Case Study in Malang, Indonesia

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Abstract

Agroforestry systems have garnered significant attention for their potential in enhancing soil organic carbon (SOC) stocks, particularly in coffee plantations. The different shading conditions not only diversifies production but also plays a crucial role in soil health and carbon sequestration. The study aimed to investigate the SOC stocks under various coffee-based agroforestry systems. Four different shading conditions have been examined, namely: A (unshaded), B (*Leucaena leucocephala* shade), C (*Pinus* sp. shade), and D (complex agroforestry). The results were analyzed descriptively by comparing the influence of varying shading conditions in enhancing SOC stocks. The results indicated that complex agroforestry had the highest SOC (1.33%), followed by *L. leucocephala* shade (1.20%), unshaded (1.02%), and *Pinus* sp. shade (0.96%). In the complex agroforestry system, the diversification of plant species increases soil organic matter (SOM) and root biomass, thus improve SOC. Meanwhile, the *Pinus* sp. shade exhibited the lowest SOC due to the lower quality of its resistant litter. The complex agroforestry also recorded the highest SOC stocks (42.7 t C ha^{-1}), followed by unshaded (39.9 t C ha^{-1}), *L. leucocephala* shade (38.3 t C ha^{-1}), and *Pinus* sp. shade (30.5 t C ha^{-1}). The SOC stocks in the unshaded system exceeded those under *L. leucocephala* shade due to higher bulk density resulting from the absence of complex root systems. Moreover, the complex agroforestry exhibited elevated levels of soil N, P, K, and CEC. These findings implied that complex agroforestry system represents a multifaceted approach to enhance SOC stocks and soil health in coffee plantation.

Keywords: Agroforestry, soil organic carbon, coffee

INTRODUCTION

Indonesia is renowned for its coffee production, yet the intensification of agricultural practices has contributed to soil degradation, threatening ecosystem integrity and coffee yield stability. In response, the integration of trees into coffee cultivation—commonly through agroforestry systems—has emerged as a sustainable alternative to conventional approaches. Integrating trees into coffee farming practices not only improves soil fertility but also increase carbon storage potential, contributing to both agricultural resilience and climate change mitigation.

Malang, Indonesia, is recognized for its robust production of Arabica and Robusta coffee, often cultivated under shade trees that support ecological balance and improve coffee quality (Rowe *et al*., 2022; Sudharta *et al*., 2022). Coffee-based agroforestry systems in this region also enhance carbon sequestration, offering a sustainable strategy to address environmental challenges.

Agroforestry systems represent a multifaceted intervention that significantly impacts SOC stocks, particularly in coffee plantations. Research has demonstrated that agroforestry systems improve soil health through the addition of organic matter derived from tree litter, which increases SOC stocks compared to monoculture approaches (Notaro *et al*., 2014; Ramadhani *et al*., 2024). Ramadhani *et al*. highlighted that coffee agroforestry contributes substantial nutrient inputs to the soil, including nitrogen and potassium, enhancing overall soil chemical status (Ramadhani *et al*., 2024). Moreover, Notaro *et al*. found that such systems can improve microbial activity and soil structure, both vital for promoting plant health and increasing soil carbon levels (Notaro *et al*., 2014). This is particularly important in regions like Malang, where climatic conditions favor coffee cultivation.

The capacity of agroforestry systems to sequester carbon depends on the diverse interactions between various plant species, which contribute to higher carbon stocks (Yasin *et al*., 2019). Research on coffee under tree shade suggests that these agroecological systems maintain higher SOC stocks, reinforcing the idea that agroforestry facilitates a synergistic relationship between aboveground biodiversity and belowground carbon storage in coffee systems (Broeckhoven *et al*., 2025; Chatterjee *et al*., 2019). By allowing for the reintroduction of perennial vegetation into agricultural settings, agroforestry promotes nutrient cycling and reduces soil erosion, further supporting increased SOC levels (Garedew *et al*., 2019; Wienhold & Goulão, 2023). These findings suggest that agroforestry is not merely a way to produce coffee but also a strategy for combating climate change through intensified carbon storage in soils.

The role of agroforestry in maintaining SOC stocks in coffee plantations is increasingly recognized as critical for overall agricultural sustainability and climate resilience in Indonesia. By combining agronomic benefits with ecological advantages, agroforestry systems could serve as a cornerstone for future coffee production strategies, particularly in regions vulnerable to climate fluctuations. The present study aims to assess the SOC stocks in coffee plantations under varying agroforestry practices in Malang, Indonesia, thereby providing evidence for the implementation of agroforestry as a viable and effective intervention in enhancing soil health and carbon sequestration.

MATERIALS AND METHODS

Research Location and Time Description

This study was conducted in a coffee-growing region in Malang, East Java, Indonesia, situated at elevations ranging from 508 to 627 meters above sea level. The area is characterized by a moderately wet (type C) climate based on the classification of Schmidt-Ferguson, with annual rainfall exceeding 2.000 mm per year and 4 dry months. An average annual temperature of 22–28 °C in the study site.

Field sampling was carried out during the dry season in July 2024 to minimize temporal variability in soil moisture and facilitate access to sampling plots. The research commenced with a site survey, followed by soil sampling, biomass collection, and subsequent laboratory analyses.

Experimental Design and Statistical Analysis

The study employed a completely randomized design (CRD) with four distinct agroforestry system treatments, each representing different canopy cover conditions: (A) Unshaded coffee monoculture, (B) Coffee shaded with *Leucaena leucocephala*, (C) Coffee shaded with *Pinus* sp., and (D) Complex agroforestry system. Complex agroforesty system consist of coffee shaded with *L. leucocephala, Cocos nucifera, Musa* spp., *Persea americana, and Durio zibethinus.*

Each treatment was replicated three times, with sampling plots sized 2 m × 2 m per replicate. The effect of shading system on SOC stock was analyzed descriptively by comparing the SOC values across different condition.

Materials and Tools

Materials and instruments were used for field sampling and laboratory analysis consist of soil core sampler (stainless steel, 5 cm diameter), hammer and (additional tool for undisturbed soil sampling), GPS device (Garmin GPSmap 76CSx) for georeferencing plots, machete and pruning shears (for clearing surface litter), aluminum sample containers, analytical balance (±0.001 g accuracy), oven (for drying at 105 ^{O}C), muffle furnace (for combustion at 550 °C), sieve set (2 mm and 0.5 mm mesh), measuring tape and ruler (for core height verification).

Soil Sampling Procedure for Carbon Stock Analysis

Soil samples for carbon stock analysis were collected using a stratified random sampling design across representative land-use. Sampling locations were georeferenced using a handheld GPS device with sub-meter accuracy. Each sampling point's latitude, longitude, and elevation were recorded simultaneously for spatial reference and potential temporal monitoring.

At each sampling point, undisturbed soil cores were taken using a stainless-steel cylindrical core sampler (100 cm^3 volume) to determine bulk density, while adjacent disturbed samples were collected for SOC analysis. Sampling was conducted at three depth intervals: 0–10 cm, 10–20 cm and 20–30 cm, to capture vertical variation in carbon distribution. Each depth layer was sampled separately, with three replicates per plot composited to represent each layer and condition.

All samples were labeled, transported, and stored in cool and dry conditions to preserve integrity before analysis. Quality control included duplicate analysis of 10% of the samples and the use of standard reference soil material

Soil Analysis

Soil samples were air-dried, ground, and passed through a 2-mm sieve prior to analysis. Total nitrogen (N) was measured using the Kjeldahl digestion method, involving acid digestion with concentrated H_2SO_4 and a catalyst, followed by distillation and titration. Available phosphorus (P) was determined using the Bray I method, with P concentrations measured colorimetrically via the molybdenum blue method at 882 nm. Exchangeable potassium (K) was extracted using 1 N ammonium acetate (NH_4OAc) at pH 7.0 and quantified by flame photometry. Cation exchange capacity (CEC) was assessed by saturating the soil with 1 N NH_4OAc at pH 7.0, followed by displacement with 1 N NaCl, and the released NH_4 was measured to calculate CEC in cmol(+) kg^{-1}.

Bulk density (BD) was measured using the core method, where undisturbed soil samples were collected using a stainless-steel core sampler of known volume, oven-dried at 105 °C for 24 hours, and bulk density was calculated as the oven-dry mass divided by the volume of the core.

SOC content was analyzed using the Walkley–Black method, where a known weight of air-dried, sieved (0.5 mm) soil was digested with potassium dichromate ($K_2 Cr_2O_7$) and sulfuric acid, and the organic carbon content was determined via titration to estimate oxidizable organic carbon. The SOC stock (t C ha^{-1}) per depth (0–10 cm, 10–20 cm and 20–30 cm) was calculated using the formula:

$$\text{SOC stock} = \text{SOC}(\%) \times \text{bulk density } (\text{g cm}^{-3}) \times \text{soil depth (cm)} \times 10$$

The factor of 10 is used to convert the units from g cm^{-2} to t C ha^{-1}. The SOC stocks (t C ha^{-1}) of 30 cm depth soils were calculated by accumulating values across soil depths up to 30 cm per hectare.

RESULTS AND DISCUSSION

1. Soil Chemical Properties Across Distinct Agroforestry System

Table 1 demonstrate the comparison of soil chemical properties, namely soil nitrogen, phosporus, potassium, and cation exchange capacity (CEC) content of different agroforestry system.

The agroforestry systems demonstrated distinct effects on soil nutrient concentrations (N, P, and K) and cation exchange capacity (CEC), indicating their role in improving soil fertility. Compared to the unshaded system, all shaded systems enhanced total nitrogen (N), available phosphorus (P), exchangeable potassium (K), and CEC values. Soils under complex agroforestry exhibited the highest value for total N (1.4 g kg^{-1}), available P (13.4 mg kg^{-1}), exchangeable K (0.98 cmol(+) kg^{-1}), and CEC (18.79 cmol(+) kg^{-1}), suggesting a synergistic effect of diverse plant species on nutrient cycling and cation retention.

Complex agroforestry systems have shown the most beneficial effects on soil nutrient dynamics. These systems often exhibit improved soil fertility indicators, including elevated levels of N, P, K, and CEC, owing to the additive effects of diverse plant litter and the interaction between various tree root systems (Bertalot *et al.*, 2013). Ilany *et al.* (2010) also highlighted that intercropping with diverse species can lead to improved soil N, P, and K content due to a combination of enhanced organic matter inputs and reduced competition for nutrients among plants. By integrating different tree species, these agroforestry systems are capable of enhancing nutrient cycling and expanding the availability of both macro and micronutrients in the soil (Islam *et al.*, 2024; Sudharta *et al.*, 2022; Sumit *et al.*, 2024).

The system shaded with *L. leucocephala* also demonstated notable improvements in soil fertility parameters, particularly in N (1.4 g kg^{-1}) and CEC (18.73 cmol(+) kg^{-1}), likely due to its nitrogen-fixing ability and high-quality litter contribution. Agroforestry involving *L. leucocephala* can elevate soil N concentrations effectively compared to monoculture coffee systems. The nitrogen-fixing ability of *L. leucocephala* contributes to increased soil N levels, making it an essential component for improving soil fertility in coffee cultivation systems (Tully *et al*., 2013a; Tully *et al*., 2013b). Moreover, Hossain *et al*. (2022) highlight how the inclusion of *L. leucocephala* aids in nitrogen dynamics within agroecosystems, enhancing soil productivity by reducing reliance on synthetic fertilizers.

Table 1. Comparison of chemical properties of different agroforestry system

Agroforestry system	N (g kg-1)	P (mg kg-1)	K (cmol(+) kg-1)	CEC (cmol(+) kg-1)
Unshaded	0.7	1.80	0.36	16.88
Shaded with *L. leucocephala*	1.4	2.40	0.62	18.73
Shaded with *Pinus*	1.2	8.50	0.71	15.64
Complex agroforestry	1.4	13.4	0.98	18.79

In contrast, although the system shaded with *Pinus* sp. showed an elevated P concentration (8.50 mg kg^{-1}), it resulted in relatively lower CEC (15.64 cmol(+) kg^{-1}) and N (1.2 g kg^{-1}), potentially due to the more recalcitrant nature of pine litter and its acidic influence on soil properties. The litter from *Pinus* sp. may initially slow the decomposition process due to its high lignin content (Chae *et al.*, 2019). This type of litter can also lead to reduced soil pH and lower nutrient availability over time due to allelopathic effects and the low nutrient profile of the needles (Chae *et al.*, 2019; Haraguchi & Sakaki, 2020; Metlen *et al.*, 2012).

In unshaded coffee systems, soil fertility is often compromised due to increased nutrient leaching and erosion, resulting in lower levels of N, P, K, and CEC compared to shaded systems (Aji *et al.*, 2021; Nurcholis *et al.*, 2024). The absence of shade can lead to higher surface temperatures and evaporation rates, which reduce overall soil moisture and nutrient retention. Studies indicate that nitrogen levels can be significantly lower in unshaded monocultures due to the lack of organic matter input from litter and reduced microbial activity, which is critical for nutrient cycling (Notaro *et al.*, 2014; Nurcholis *et al.*, 2024).

Overall, the presence of tree cover, especially with leguminous or diverse species, appears to enhance soil nutrient availability (N, P, and K) and CEC. These findings underscore the potential of complex-based agroforestry systems in sustaining soil health and fertility, particularly in tropical or nutrient-depleted environments.

2. Soil Organic Matter (SOM) Under Various Coffee-Based Agroforestry System

The litter dry matter content and soil organic matter (SOM) varied across the different coffee-based agroforestry systems (Table 2), reflecting the influence of shade type and complexity on litter quality.

The highest litter dry matter content was observed under the complex agroforestry system (90.9%), followed by shading with *Pinus* sp. (88.2%), *L. leucocephala* (63.3%), and the lowest in the unshaded system (59.7%). In terms of SOM content, the complex agroforestry system also recorded the highest value (2.29%). The trend indicates that greater canopy cover and structural complexity enhance litter diversity and moisture loss, thereby increasing dry matter and SOM accumulation. Further research on coffee agroforestry systems indicates that the complexity of shade tree arrangements affects biodiversity and litter dynamics, with more diverse systems generally leading to improved ecological outcomes, such as enhanced litter quality and greater SOM content (Aerts *et al.*, 2011). Mixed shade systems can help sustain a balanced microclimate that reduces temperature fluctuations detrimental to coffee ecology (Ehrenbergerová *et al.*, 2018).

Interestingly, although the *Pinus*-shaded system had a high dry matter content, its SOM content (1.65%) was relatively low, potentially due to the lower degradability of pine needles and the associated slower microbial activity. Pine litter typically has a high lignin content, which can lead to slower decomposition

Table 2. Litter dry matter content (%) and soil organic matter (SOM) under various coffee-based agroforestry system

Agroforestry system	Litter dry matter content (%)	Soil organic matter (%)
Unshaded	59.7	1.75
Shaded with *L. leucocephala*	63.3	2.06
Shaded with *Pinus*	88.2	1.65
Complex agroforestry	90.9	2.29

rates compared to leguminous species like *L. leucocephala* (Chae *et al*., 2019). Moreover, the composition of *Pinus* sp. litter is usually more challenging in fostering biological activity due to its nutrient-poor profile compared to leguminous litter, which can curtail microbial growth and function in the soil (Haraguchi & Sakaki, 2020).

In contrast, shading with *L. leucocephala*, a nitrogen-fixing legume, yielded higher SOM (2.06%) than both *Pinus* sp. and the unshaded system (1.75%), highlighting the positive contribution of leguminous litter to soil quality. The litter from *L. leucocephala* is rich in nitrogen and generally decomposes relatively quickly, thus contributing to the rapid replenishment of SOM (Ssenku *et al*., 2014). High nitrogen levels within its litter not only enrich the soil but also enhance microbial activity, which is critical for nutrient cycling and overall soil fertility (Hossain *et al*., 2022).

These findings underscore the role of agroforestry design in regulating litter quality parameters, which are closely linked to nutrient cycling, soil organic carbon buildup, and overall soil fertility. The greater diversity of litter sources in multistrata systems may also enhance microbial activity and nutrient cycling, contributing to long-term soil fertility and carbon sequestration potential. Therefore, the complex agroforestry system appears to offer the most favorable conditions for both litter stability and SOM enrichment, supporting its potential as a sustainable strategy for enhancing soil health in coffee-growing regions.

3. The Influence of Agroforestry System on SOC Stocks

Table 3 illustrates the influence of different shading conditions on soil organic carbon (SOC) content (%), bulk density (g cm^{-3}), and SOC stocks (t C ha^{-1}) within coffee-based agroforestry system.

The complex agroforestry system recorded the highest SOC content (1.33%) and SOC stocks (42.7 t C ha^{-1}), despite sharing a similar bulk density (1.07 g cm^{-3}) with systems shaded by *L. leucocephala*. This result suggests that the greater plant diversity and litter inputs (Table 2) in complex systems contribute to enhanced carbon accumulation in the soil. Adekiya *et al*. (2021) demonstrate that agroforestry practices involving various vegetation types lead to higher soil nutrient levels, including N, P, and K, especially in the topsoil where litter accumulation is more pronounced. This result also aligns with previous findings indicating that multi-species systems enhance litter diversity, root biomass, and microbial activity, all of which contribute to carbon accumulation in soils (Cardinael *et al*., 2015).

In contrast, the shaded with *Pinus* sp. system showed the lowest SOC concentration (0.96%) and SOC stock (30.5 t C ha^{-1}), likely due to the lower-quality, recalcitrant litter and acidic microenvironment commonly associated with coniferous species. Research indicates that the litter from *Pinus* sp. is often characterized by high lignin content and low nutrient availability, which contributes to slower decomposition rates compared to other (Notaro *et al*., 2014). Studies show

Table 3. The influence of shaded condition on SOC (%), bulk density (g cm^{-3}), and SOC stocks (t C ha^{-1}) in coffee-based agroforestry systems

Agroforestry system	SOC (%)	Bulk density (g cm^{-3})	SOC stock (t C ha^{-1})
Unshaded	1.02	1.30	39.9
Shaded with *L. leucocephala*	1.20	1.07	38.3
Shaded with *Pinus*	0.96	1.06	30.5
Complex agroforestry	1.33	1.07	42.7

Figure 1. Unshaded (A), *L. leucocephala* (B), *Pinus* sp. (C), and Complex agroforestry (D)

that the composition of litter is critical for promoting microbial activity, which in turn affects organic carbon formation. The dense, resinous nature of *Pinus* sp. litter can inhibit microbial processes necessary for transforming litter into stable organic matter, thereby resulting in lower SOC levels (Notaro *et al*., 2014).

Interestingly, while the shaded with *L. leucocephala* system slightly improved SOC concentration (1.20%) compared to the unshaded control (1.02%), its SOC stock (38.3 t C ha^{-1}) was marginally lower than that of the unshaded system (39.9 t C ha^{-1}). This may be attributed to higher bulk density (1.30 g cm^{-3}), which, despite lower SOC percentage, contributes to higher calculated carbon stock. A lack of vegetation in unshaded condition or complex root networks directly contributes to poor soil aggregation (Vergani & Graf, 2015). An aggregation deficiency results in a compact arrangement of soil particles, culminating in elevated bulk density levels.

These findings underscore the importance of vegetation structure and litter characteristics in shaping soil carbon dynamics. Consistent with previous studies (Hairiah *et al*., 2011), complex agroforestry systems appear to offer superior benefits for soil carbon sequestration, making them a promising strategy for enhancing both soil health and climate change mitigation in coffee-growing regions.

CONCLUSION

The findings demonstrate that complex agroforestry systems markedly enhance soil quality and confer greater ecosystem benefits relative to other coffee-based agroforestry systems. This system exhibited the highest values of SOC (1.33%), SOC stock (42.7 t C ha^{-1}), and superior soil chemical properties, including increased concentrations of N (1.4 g kg^{-1}), P (13.4 mg kg^{-1}), K (0.98 cmol(+) kg^{-1}), and CEC (18.79 cmol(+) kg^{-1}), reflecting a substantial capacity for carbon sequestration, improved nutrient availability and retention. In contrast, the unshaded system consistently exhibited the lowest values across these parameters. Collectively, these results highlight the ecological and agronomic advantages of structurally complex and species diverse agroforestry systems in promoting soil health and supporting sustainable coffee production.

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