Comparison of selected soil properties and soil organic carbon accumulation under different agroforestry models in Muong E and Nam Lau communes, Son La province

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So sánh một số tính chất đất và khả năng tích lũy carbon hữu cơ trong đất giữa các mô hình nông lâm kết hợp khác nhau tại xã Mường É và Nậm Lầu, tỉnh Sơn La

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ABSTRACT

This study evaluated the effects of six agroforestry (AF) models on soil physico-chemical properties and soil organic carbon (SOC) accumulation in Muong E and Nam Lau communes, Son La province, Northern Vietnam. The AF systems included Michelia mediocris + tea*,* Zanthoxylum rhetsa + coffee*,* Zanthoxylum rhetsa + tea*,* Canarium tramdenum + coffee*,* Macadamia integrifolia + tea*, and* Camellia sinensis *or* Coffea arabica *monocultures as controls. Field indicators such as crop growth, canopy cover, litter biomass, soil pH, moisture, available nutrients, bulk density, organic matter, and SOC stock were analyzed at two depths (0-20 cm and >20-40 cm). Results showed that AF models significantly improved soil quality compared with monocultures, with soil pH ranging 5.1-5.5, soil moisture generally 2–3 times higher than in monocultures, organic matter 2.81-4.68%, bulk density 1.21-1.35 g cm^{-3}, and SOC stock 8.07–14.11 t ha^{-1}-approximately 2-3 times greater than monocultures. The* M. mediocris + tea*,* Z. rhetsa + coffee*, and* C. tramdenum + coffee *models performed best, reflecting higher litter input, better moisture retention, and enhanced nutrient cycling. These findings confirm that AF systems not only enhance soil fertility but also contribute to carbon sequestration and erosion control on sloping Ferralsols. The study provides scientific evidence for promoting agroforestry as a sustainable land-use strategy to restore soil productivity and strengthen climate resilience in upland regions of orthern Vietnam.*

Từ khóa:
Đất feralit đỏ vàng, carbon hữu cơ, chất hữu cơ, nông lâm kết hợp, Sơn La, tích lũy carbon.

TÓM TẮT

Nghiên cứu này đánh giá ảnh hưởng của sáu mô hình nông lâm kết hợp (NLKH) đến các tính chất lý - hóa của đất và khả năng tích lũy carbon hữu cơ (SOC) tại hai xã Mường É và Nậm Lầu, tỉnh Sơn La. Các mô hình gồm: Giổi xanh + Chè, Mắc khén + Cà phê, Mắc khén + Chè, Trám đen + Cà phê, Mắc ca + Chè và hai mô hình đơn canh đối chứng (Chè - Camellia sinensis, Cà phê - Coffea arabica). Các chỉ tiêu nghiên cứu bao gồm sinh trưởng cây trồng, độ che phủ tán, sinh khối vật rụng, pH đất, độ ẩm, dinh dưỡng dễ tiêu, khối lượng riêng, hàm lượng chất hữu cơ và trữ lượng SOC ở hai tầng đất (0-20 cm và > 20-40 cm). Kết quả cho thấy các mô hình NLKH cải thiện rõ rệt chất lượng đất so với đơn canh, với pH dao động 5,1-5,5; độ ẩm cao gấp 2-3 lần so với đơn canh; hàm lượng hữu cơ 2,81–4,68%; khối lượng riêng 1,21-1,35 g/cm^3; và trữ lượng SOC 8,07-14,11 tấn/ha - cao hơn khoảng 2-3 lần so với mô hình đơn canh. Ba mô hình Giổi xanh + Chè, Mắc khén + Cà phê và Trám đen + Cà phê cho kết quả vượt trội nhờ tán che hợp lý, lượng vật rụng lớn và khả năng giữ ẩm tốt. Kết quả khẳng định hệ thống NLKH góp phần cải thiện độ phì đất, tăng khả năng tích lũy carbon, kiểm soát xói mòn và phục hồi đất dốc feralit đỏ vàng, hướng tới phát triển nông nghiệp bền vững và thích ứng biến đổi khí hậu tại vùng núi phía Bắc Việt Nam.

1. INTRODUCTION

Agroforestry (AF) systems have demonstrated greater carbon sequestration potential than monocultures while improving soil structure and nutrient status through increased canopy cover, litter input, and reduced erosion [1, 2]. In the mountainous regions of northern Vietnam, where Ferralsols are steep, nutrient-poor, and prone to degradation [3], AF models are increasingly adopted to enhance soil fertility and ecosystem stability. However, most previous studies have mainly quantified total carbon stocks, with limited attention to how different AF combinations influence soil physico-chemical properties and soil organic carbon (SOC) distribution [4]. Clarifying these interactions is essential for evaluating the ecological benefits of AF systems and their role in sustainable land-use planning.

Vietnam has diverse agroforestry practices integrating trees with tea, coffee, fruit crops, and timber species, especially in the Northwestern provinces such as Son La, Dien Bien, Yen Bai [5]. These regions experience high rainfall, steep slopes, and frequent soil erosion, making AF a key strategy to prevent land degradation and restore soil productivity [6]. Nevertheless, systematic assessments of soil properties and SOC dynamics under different AF models remain limited.

This study therefore aimed to compare selected soil properties and SOC accumulation under six representative AF models in Muong E and Nam Lau communes, Son La province. The findings are expected to provide scientific evidence for selecting suitable AF models that improve soil quality and support sustainable agricultural and environmental management in Northern Vietnam.

2. RESEARCH METHODS

2.1. Research subjects and study sites

The study was conducted in Muong E and Nam Lau communes, Son La province, where Ferralsols (red-yellow soils) developed on acidic magmatic and metamorphic rocks are predominant (sources). A total of five AF models were evaluated together with two monoculture controls:

+ Muong E commune: (i) *Michelia mediocris* + *tea*, (ii) *Zanthoxylum rhetsa* + *Arabica coffee,* (iii) *Macadamia* + *tea*, (iv) *Zanthoxylum rhetsa* + *tea,* and (v) *tea monoculture* (control).

+ Nam Lau commune: (i) *Canarium tramdenum* + *Arabica coffee* and (ii) *coffee* monoculture (control).

The agroforestry (AF) models covered areas ranging from 0.6 to 1.5 ha, established on slopes of 15–20°, and were directly managed by local farm households. For each plot, GPS coordinates (WGS84), elevation, and slope were recorded in the field. Baseline soil properties, including pH, texture, organic matter, and soil organic carbon (SOC), prior to model establishment, were obtained from initial soil surveys. The year of establishment and the age of tree species were documented to provide site history and ensure comparability among the studied models.

Management practices differed among crops. Coffee and tea were fertilized with NPK (5:10:3) (0.2 kg plant^{-1} yr^{-1}, once annually) during the first three years after planting, while woody and fruit trees were not fertilized. No pesticides were applied during the observation period.

Soil and litter sampling were carried out in April 2025, corresponding to the end of the dry season under stable weather conditions. Composite soil samples were taken from five points (four corners and one center) in each plot at two depths (0–20 cm and >20–40 cm). Samples were collected beneath the tree canopy after removing roots (>2 mm), gravels, and rock fragments to ensure consistency.

The climate across the study sites is relatively uniform, with no significant differences observed between Muong E and Nam Lau communes.

2.2. Experimental design and field data collection

In each AF model, three standard plots (500 m^2; 20 × 25 m) were randomly established to survey upper-canopy tree species. For all trees within these plots, diameter at breast height (DBH) was measured at 1.3 m above the ground using a diameter tape, and total height was determined with a laser hypsometer. In parallel, three subplots (100 m^2 each) were set up to measure the growth of intercropped coffee and tea. For coffee and tea plants, stem diameter was measured at 5 cm above the ground using a vernier caliper, and plant height was measured from the base to the top of the canopy. Topographic parameters (elevation and slope) were determined using a GPS receiver and a handheld compass. Canopy cover of the upper tree layer was assessed at ten evenly distributed points within each plot using the Gap Light Analysis Mobile App, and the mean value was used to represent each plot [5].

Litter biomass (leaves, twigs, and fallen fruits) was collected using 10 evenly distributed 1 m^2 litter traps installed within each plot. Traps were placed approximately two weeks prior to soil sampling (April 2025, end of the dry season) and all litter accumulated during this period was collected for analysis. The samples were oven-dried at 65°C until a constant weight was achieved, and the results were expressed as Mg ha^{-1}. This procedure followed CIAT (2001) guidelines and standard agroforestry research practices in Vietnam [6].

2.3. Soil sampling and analysis

In each standard plot, one composite soil sample was obtained from five evenly distributed points: one at the center and four at the corners of the plot, approximately 20 m from the center (Figure 1a). Soil samples were collected at two depths (0-20 cm and >20-40 cm). Samples were placed in 1-kg polyethylene bags, labeled, and transported to the laboratory. Roots >2 mm, gravels, and stones were removed prior to analysis.

All soil analyses were performed at the Soil and Environment Laboratory of the Vietnam National University of Forestry (VNUF). All procedures followed Vietnamese national standards (TCVN).

+ Bulk density (g/cm^3): 100 cm^3 volumetric cylinder, oven-dried and weighed.

+ Organic matter (OM, %): TCVN 8726:2012.

+ Soil pH (H_2O, 1:2.5): TCVN 7377:2004.

+ Available nitrogen (NH_4^+): TCVN 6640:2000.

+ Available phosphorus (P_2O_5): TCVN 8941:2011.

+ Available potassium (K_2O): TCVN 6648:2000.

+ Soil texture: pipette method, TCVN 5294:2008.

SOC stock was estimated based on the IPCC (2006) methodology:

$$SOC = h \times D \times OM \times 0.58 \times 100$$

Where,

SOC: soil organic carbon stock (t/ha);

h: soil depth (cm);

D: soil bulk density (g/cm^3);

OM: organic matter content (%);

and 0.58 is the conversion factor from OM to C [7].

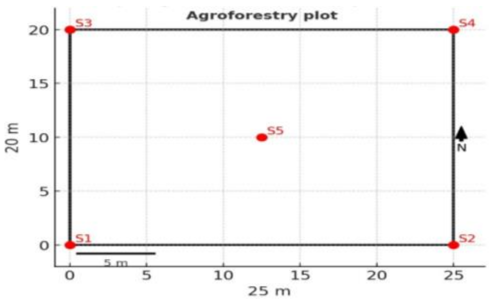

Figure 1a. Soil sampling layout in the 500 m² AF standard plot, 20 × 25 m)

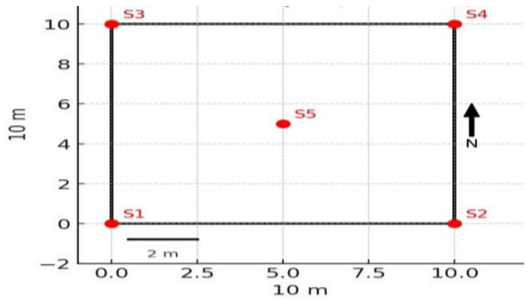

Figure 1b. Soil sampling layout in the 100 m² monoculture subplot, 10 × 10 m, tea/coffee)

2.4. Data analysis

Data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test. When the assumptions were met, differences among models at each soil depth were analyzed using one-way ANOVA, followed by post hoc comparisons with the least significant difference (LSD) test at $\alpha = 0.05$. All statistical analyses were performed using SPSS version 26.

For the integrated evaluation, six representative soil indicators (pH, gravimetric soil moisture, available NH_4^+, available P_2O_5, available K_2O, and soil organic carbon) were normalized to a 1–3 scale (1 = low, 2 = medium, 3 = high) using percentile thresholds (≤25% =

score 1; 26–75% = score 2; ≥76% = score 3). The composite score for each model was calculated as the arithmetic mean of these indicators, where higher values indicated a greater overall impact. This percentile-based normalization method has been applied in Vietnam for integrated soil fertility assessment [5] and is consistent with land quality indicator frameworks for sustainable land management developed by the International Center for Tropical Agriculture [6]. Results were visualized using heatmaps to illustrate differences among models.

3. RESULTS

3.1. Selected characteristics of AF models

The AF models studied were established at the household scale in a largely spontaneous manner. Such characteristics may indirectly influence soil properties and SOC accumulation. The key features of the models established and applied locally are summarized in Table 1.

Table 1. Selected characteristics of AF models in the study

Model	Species	Mean height (m)	Diameter $D_{1.3}/D_{0.5}$ (cm)	Density (trees/ha)	Canopy cover (%)	Litter biomass (t/ha)
Michelia mediocris + tea	*Michelia mediocris*	9.39	13.49	100	0.22	8.0
	Tea	0.43	2.85	15,000		
Zanthoxylum rhetsa + coffee	*Zanthoxylum rhetsa*	6.78	8.20	100	0.22	11.5
	Arabica coffee	1.20	2.31	4,500		
Macadamia + tea	Macadamia	4.25	3.85	120	0.20	7.0
	Tea	0.45	3.43	15,000		
Zanthoxylum rhetsa + tea	*Zanthoxylum rhetsa*	9.50	15.29	100	0.20	7.0
	Tea	0.35	5.41	15,000		
Canarium tramdenum + coffee	*Canarium tramdenum*	7.00	13.38	120	0.25	12.0
	Arabica coffee	2.25	3.80	4,500		
Coffee monoculture		*Arabica coffee*	1.75	4.22	5,000	3.0
Tea monoculture		*Tea*	0.46	3.35	15,000	2.8

Source: Data collected in 2025

The results indicate that the AF models in Muong E and Nam Lau were established on sloping terrain (15–20°) at the household scale, with areas ranging from 0.6 to 1.5 ha. Tree-crop composition and planting density varied considerably among models, influencing canopy structure, plant growth, and the capacity to supply organic biomass.

As shown in Table 1, survey results showed that the highest litter biomass was recorded in the *Canarium tramdenum* + *coffee* model (12.0 t/ha) and the *Zanthoxylum rhetsa* + *coffee* model (11.5 t/ha), while the lowest values were observed in tea monoculture (2.8 t/ha) and *coffee* monoculture (3.0 t/ha). High litter production reflects the substantial contribution of perennial woody species to litterfall inputs, thereby enriching the soil organic nutrient pool [8].

Canopy cover ranged from 20% to 25% depending on the model, with the highest value in *Canarium tramdenum* + *coffee* (25%) and the lowest in *Macadamia + tea* (20%). Canopy cover helps reduce erosion and regulate the soil microclimate; however, excessive shade can limit light availability for heliophilous crops such as *tea* and *coffee* [1]. The *Zanthoxylum rhetsa* + *tea* model exhibited moderate canopy cover (20%) but relatively low litter biomass (7.0 t/ha), suggesting potential competition for light or nutrients between woody and intercrop species.

In terms of growth performance, *Zanthoxylum rhetsa* (height 9.5 m, DBH = 15.29 cm) and *Michelia mediocris* (height 9.39 m, DBH = 13.49 cm) demonstrated high biomass accumulation potential. Planting densities among models ranged from 110 to 200 woody trees/ha, 4.500 - 5.000 coffee plants/ha, and 15.000 tea plants/ha. Such differences directly influence canopy cover and the extent of competition for soil resources.

Figure 2. ***Macadamia*** **+ tea model (a);** ***Michelia mediocris*** **+ tea model (b);**
Zanthoxylum rhetsa **+ tea model (c);** ***Canarium tramdenum*** **+ coffee model (d)**

3.2. Selected soil properties

The research results are summarized in Table 2.

Table 2. Selected soil properties in the study area (mean values of three plots per model)

Model	Soil depth (cm)	pH H_2O	Gravimetric moisture (%)	Available nutrients (mg/100 g soil)			Soil particle-size distribution (%)		
				NH_4^+	P_2O_5	K_2O	<0.002 mm	0.02-0.002 mm	2.0 - 0.02 mm
Michelia mediocris +	0–20	5.4	2.83	3.12	0.91	4.15	28.91	47.51	23.58
	>20–40	5.2	2.94	2.76	0.77	3.86	29.15	47.65	23.20
Zanthoxylum rhetsa + Coffee	0–20	5.4	8.23	2.55	1.62	4.52	33.37	52.45	14.18
	>20-40	5.2	8.64	2.05	1.23	3.86	33.89	52.19	13.92
Macadamia + Tea	0–20	5.4	4.67	3.12	0.92	4.13	32.51	46.32	21.17
	>20–40	5.1	5.14	2.17	0.68	3.85	33.27	46.45	20.28
Zanthoxylum rhetsa + Tea	0–20	5.5	4.54	2.37	0.91	5.53	32.85	53.91	13.24
	>20–40	5.1	4.98	1.95	0.78	4.85	33.18	53.78	13.04
Canarium tramdenum + Coffee	0–20	5.3	7.18	2.35	1.31	4.82	32.45	54.36	13.19
	>20-40	5.1	7.95	2.17	1.15	3.89	32.85	54.24	12.91
Coffee (monoculture)	0-20	5.3	1.97	2.13	1.04	3.34	35.28	44.36	20.36
	>20-40	5.1	2.91	1.57	0.71	3.17	34.28	45.19	20.53
Tea (monoculture)	0-20	4.7	1.48	1.98	1.01	2.86	32.28	45.76	21.96
	>20-40	4.3	1.87	1.62	0.69	2.43	31.66	44.38	23.96

Source: Data collected in 2025

The results presented in Table 2 reflect the physico-chemical properties of surface soil (0-20 cm) and subsoil (>20-40 cm) in both AF and monoculture systems. These factors directly influence soil moisture retention, nutrient supply, and soil fertility, thereby determining production efficiency and ecological sustainability.

Soil pH ranged from 4.3 to 5.5, classifying the soils as strongly to moderately acidic [6]. The highest value was recorded in the *Zanthoxylum rhetsa + tea* model (5.5 in the surface layer), while the lowest was observed in tea monoculture (4.3 in the subsoil layer). Maintaining pH > 5 in most AF models indicates the positive effects of litter inputs and woody root systems in reducing soil acidity, consistent with findings by Gijsman et al. (2007) and Nair et al. (2009) [2, 8].

Soil moisture showed considerable variation, from very low in tea monoculture (1.48–1.87%) to very high in the *Zanthoxylum rhetsa + coffee* model (8.23–8.64%). The *Michelia mediocris + tea* and *Canarium tramdenum + coffee* models also maintained moisture levels >7%, far exceeding those in monocultures. This reflects the role of canopy cover and litter in reducing evaporation and enhancing moisture retention-a phenomenon well-documented in AF systems on sloping lands [9, 10].

Available nutrient content:

NH_4^+ content was highest in the *Macadamia* + tea model (3.12 mg/100 g soil), followed by *Michelia mediocris + tea* and *Zanthoxylum rhetsa + coffee*. These models are characterized by thick litter layers, deep-rooted woody species, and active Organic Matter (OM) cycling.

P_2O_5 content was highest in *Michelia mediocris + tea* and *Macadamia* + tea (3.12 mg/100 g soil), and lowest in tea monoculture (1.62 mg/100 g soil) and coffee monoculture (2.13 mg/100 g soil). This pattern is consistent with the tendency of acidic soils to fix phosphorus, which can be mitigated by microbial activity that mobilizes P from litter inputs [5].

K_2O content was highest in *Zanthoxylum rhetsa + coffee* (1.62 mg/100 g soil) and *Canarium tramdenum + coffee* (1.31 mg/100 g soil), reflecting enhanced potassium supply in models intercropping perennial woody species with coffee.

Soil texture: Most soils fell within the medium to heavy loam category; clay content (<0.002 mm) ranged from 28.91% to 35.28%, with the highest values in *Zanthoxylum rhetsa + tea* and *Zanthoxylum rhetsa + coffee* (>35%). The silt fraction (0.02-0.002 mm) was dominant (44.36-54.36%), with the highest proportions in *Canarium tramdenum + coffee* and *Zanthoxylum rhetsa + tea*. This texture is typical of Ferralsols developed on shale and metamorphic rocks in the northern mountainous region [11], offering good moisture and nutrient retention but potentially poor drainage if not properly managed.

Overall, the AF models-particularly *Zanthoxymum rhetsa + coffee*, *Michelia mediocris + tea*, and *Macadamia + tea*-exhibited higher pH, better moisture retention, richer available nutrient content, and more balanced texture compared with monocultures. In contrast, tea and coffee monocultures tended to acidify soils, deplete nutrients, and pose a risk of land degradation.

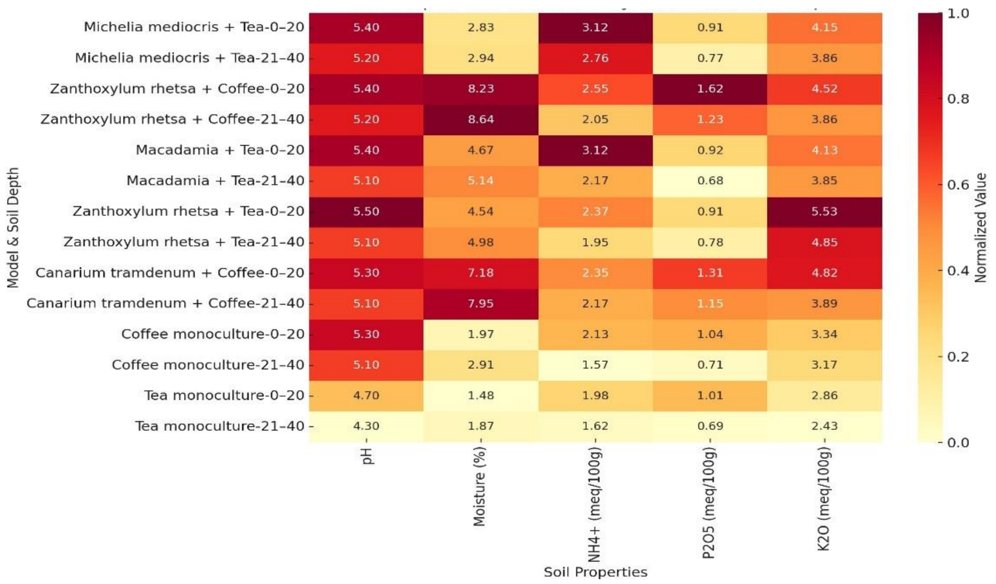

Figure 3. Heatmap of soil indicators across the studied models

The heatmap reveals a clear differentiation among the models. The group with the highest overall soil quality comprised *Zanthoxylum rhetsa* + *coffee*, *Michelia mediocris* + *tea,* and *Macadamia* + *tea*, all of which exhibited outstanding values for moisture content, NH_4^+, P_2O_5, K_2O, and fine particle fraction. Monoculture models (*tea, coffee*) were in the low-quality group, particularly for pH, moisture, and NH_4^+.

In most models, nutrient indicators and moisture content in the 0-20 cm soil layer were markedly higher than in the 21-40 cm layer, confirming the role of litter and shallow root systems in nutrient accumulation. These results allow classification of models by composite soil quality, identification of soil layers in need of improvement, and prioritization of models for wider adoption-such as *Zanthoxylum rhetsa + coffee* or *Michelia mediocris + tea*.

3.3. Organic matter (OM) content, bulk density (g/cm^3), and soil organic carbon (SOC) accumulation

The research results are summarized in the Table 3.

Table 3. Organic matter (OM) content, bulk density (g/cm^3) and soil organic carbon (SOC) accumulation in the study area (mean values of three plots per model)

Model	Soil depth (cm)	Bulk density (g/cm^3)	Organic matter (%)	SOC stock (t/ha)	Total SOC stock (t/ha)
Michelia mediocris + tea	0-20	1.34	4.67	7.26	14.11
	>20-40	1.40	4.22	6.85	
Zanthoxylum rhetsa + coffee	0-20	1.22	4.68	6.62	12.79
	>20-40	1.35	3.94	6.17	
Macadamia + tea	0-20	1.30	4.18	6.30	11.64
	>20-40	1.34	3.43	5.33	
Zanthoxylum rhetsa + tea	0-20	1.32	2.81	4.30	8.07
	>20-40	1.40	2.32	3.77	
Canarium tramdenum + coffee	0-20	1.21	4.58	6.43	12.45
	>20-40	1.32	3.93	6.02	
Coffee monoculture	0-20	1.4	1.58	2.57	4.16
	>20-40	1.45	0.95	1.59	
Tea monoculture	0-20	1.45	1.47	2.39	3.89
	>20-40	1.52	0.91	1.50	

Source: Data collected in 2025

The results indicate that AF models have a pronounced impact on factors related to SOC accumulation:

Bulk density (g/cm³): Bulk density (g/cm³) in AF models ranged from 1.21 to 1.35 g/cm³, lower than in monoculture systems (1.40-1.52 g/cm³). Lower bulk density (g/cm³) reflects looser soil structure, which is favorable for humus retention and microbial activity. These findings are consistent with Nair et al. (2009) and Montagnini & Nair (2004), who reported that AF systems improve soil structure [2, 12].

Organic matter (OM): OM content in AF models ranged from 2.81% to 4.68%, 2-3 times higher than in tea and coffee monocultures (1.47-1.58%). Intercropping with native woody species contributes organic biomass, increases canopy cover and moisture retention, and creates conditions for long-term OM maintenance. These results are in line with previous studies both in Vietnam and internationally [1, 13].

SOC stock (t/ha): SOC stock (t/ha) in AF models ranged from 8.07 to 14.11 t/ha, 2-3 times higher than in monocultures (3.89-4.16 t/ha). The highest value was recorded in *Michelia mediocris + tea* (14.11 t/ha), followed by *Zanthoxylum rhetsa + coffee* and *Canarium tramdenum + coffee* (>12 t/ha). The increase in SOC in these models is closely linked to high litter production, thick litter layers, appropriate canopy cover, and high soil moisture retention, all of which favor Organic Matter (OM) decomposition–mineralization and accumulation. These findings are consistent with Jose (2009), Nair et al. (2009), and Tran Ngoc Ngoan (2018) regarding the role of AF in enhancing carbon stocks through biomass inputs and improved soil microbial conditions [1, 2, 13].

Based on the indicators presented in the data tables and heatmaps (Figure 3), the variables were standardized and composite scores were calculated to rank the impact level of each model. The results are presented in Table 4.

Table 4. Ranking of the overall impact of AF models on soil quality and SOC accumulation

Model	pH	Moisture	NH_4^+	P_2O_5	K_2O	SOC score (1-3)
Michelia mediocris + tea	3	3	2	3	2	3
Zanthoxylum rhetsa + coffee	3	3	2	2	3	3
Canarium tramdenum + coffee	2	3	2	2	3	3
Macadamia + tea	3	2	3	3	2	2
Zanthoxylum rhetsa + tea	3	2	2	2	2	2
Coffee monoculture	2	1	1	1	2	1
Tea monoculture	1	1	1	1	1	1

Note: Scores were normalized on a 1–3 scale; higher values indicate better soil quality.

Based on the composite mean scores in Table 4, tree-crop based systems-particularly *Michelia mediocris + tea*, *Zanthoxylum rhetsa + coffee*, and *Canarium tramdenum + coffee*-achieved the highest overall performance, reflecting the strongest impact on soil quality and SOC accumulation. These systems maintained higher soil pH, greater moisture retention, and higher levels of available nutrients (NH_4^+, P_2O_5, K_2O) and organic matter than monocultures. The combination of deep-rooted native woody species with perennial crops enhanced litter input, improved soil structure, and created a stable microclimate conducive to nutrient cycling and carbon sequestration.

Moderate performance was observed in the *Macadamia + tea* and *Zanthoxylum rhetsa + tea* models, which also improved soil fertility but to a lesser extent, likely due to lower litter production and slower nutrient turnover rates.

In contrast, monoculture systems (*tea* and *coffee*) recorded the lowest scores (2.25-2.35), characterized by stronger soil acidity, lower moisture content, and reduced SOC accumulation. This pattern underscores the ecological limitations of monocropping on sloping Ferralsols and reinforces that diversified agroforestry systems provide more sustainable pathways for soil restoration and long-term productivity.

4. DISCUSSION

Sampling was conducted at the end of the dry season (April 2025), which may influence soluble nutrient levels. Multi-season monitoring with repeated litterfall and SOC fractionation (particulate vs. mineral-associated) would better clarify carbon stabilization and nutrient cycling trajectories across AF configurations. Because soluble N, P, and K are seasonally sensitive, they were interpreted alongside more stable metrics (OM, SOC, and bulk density) to avoid short-term moisture or phenological bias and strengthen inference about long-term soil improvement under AF.

Vertical stratification was evident: the 0-20 cm layer stored more SOC and nutrients than the >20–40 cm layer, consistent with surface litter decomposition and fine-root activity. This supports residue retention (mulching) and minimal soil disturbance in the topsoil. Management context also helps explain model differences: tea and coffee received NPK only during the first three years (0.2 kg $plant^{-1}$ yr^{-1}, once annually), whereas woody and fruit trees were not fertilized. Hence, higher SOC in AF systems primarily results from perennial biomass inputs and physical soil protection rather than fertilizer effects.

Key drivers of SOC accumulation in AF models include (i) abundant litterfall from native timber species (*Michelia mediocris*, *Canarium tramdenum*), (ii) deeper and more extensive root systems enhancing rhizodeposition and aggregate formation, and (iii) moderated microclimate under 20–25% canopy cover that reduces evaporation and erosion. These mechanisms collectively improve soil structure, moisture, and nutrient cycling efficiency.

Agroforestry systems significantly enhanced soil quality indicators, particularly OM and SOC, compared with monocultures. Differences in pH, moisture, NH_4^+, P_2O_5, K_2O, and bulk density emphasize the role of litter biomass and canopy cover in maintaining soil ecological balance. Models such as *Michelia mediocris* + tea and *Zanthoxylum rhetsa* + coffee showed the strongest carbon storage potential, aligning with previous findings [8, 10] that AF enhances SOC through biomass input, canopy diversification, and improved soil microclimate.

Lower bulk density and higher soil moisture under AF also foster microbial activity, accelerating OM mineralization and sustaining long-term carbon retention. These improvements are particularly valuable for sloping Ferralsols, where water retention and erosion control are essential for stable productivity. Moreover, *Zanthoxylum rhetsa*-based systems, with higher fine-particle content, showed greater water-holding capacity and reduced nutrient leaching-key to maintaining soil fertility on steep terrain.

Although SOC accumulation varied among systems due to stand age, species composition, and site conditions, overall results demonstrate AF's strong potential for soil restoration in degraded uplands. Composite scoring ranked *Michelia mediocris + tea*, *Zanthoxylum rhetsa + coffee*, and *Canarium tramdenum + coffee* as top-performing models, with 2.5-3.6 times higher SOC than monocultures. These findings reinforce that AF not only enhances carbon storage but also improves overall soil quality in red-yellow Ferralsols of northern Vietnam.

5. CONCLUSION

This study demonstrated that agroforestry systems substantially improved soil quality and soil organic carbon (SOC) accumulation compared with monocultures on sloping Ferralsols of Northern Vietnam.

Tree-crop based models, particularly *Michelia mediocris + tea* and *Zanthoxylum rhetsa + coffee*, showed the highest performance, with SOC stocks *2.5-3.6 times greater* than monocultures. Timber-based combinations such as *Canarium tramdenum + coffee* and *Macadamia + tea* also enhanced soil fertility, though at a slower rate due to the gradual decomposition of woody litter.

The main mechanisms driving these improvements include greater litter biomass input, diversified and deeper root systems, and moderated microclimatic conditions that collectively enhance nutrient retention, soil aggregation, and moisture stability. Strong correlations between SOC, soil moisture, and nutrient availability confirm the crucial role of agroforestry in maintaining long-term soil health and ecological resilience.

Overall, agroforestry represents a sustainable land-use strategy that increases carbon sequestration, improves soil fertility, and mitigates erosion and degradation on sloping lands. Future studies should focus on multi-season monitoring, SOC fractionation, and economic assessment to clarify carbon stabilization pathways and evaluate the scalability of these agroforestry models across diverse agro-ecological zones in northern Vietnam.

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