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Soil Carbon Sequestration in Ultramafic Soils: A Comparative Study of Ultramafic Forests and Early-Stage Agroforestry Systems in Pahu Agromining Trial Farm, Ranau, Sabah, Malaysia

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ABSTRACT

Ultramafic landscapes are ecologically unique yet remain underrepresented in tropical soil carbon research, particularly under transitioning land-use systems. This study assessed soil organic carbon (SOC) sequestration in Pahu Agromining Trial Farm, Kg. Pahu Pinawantai, Ranau, Sabah, a living laboratory cultivated with Phyllanthus rufuschaneyi, by comparing two types of land use; an early-stage agroforestry system with an adjacent ultramafic forest. Three inventory plots, 10m × 10m were established in each land-use system, and soil composite samples were collected to evaluate SOC stocks and associated physicochemical properties. For the determination of total organic carbon (TOC), total nitrogen (TN), and total phosphorus (TP), samples were outsourced to the Chemistry Section of the Forest Research Centre, Sandakan. Meanwhile, soil organic matter (SOM), bulk density, and soil pH were analysed at the Kompleks Sains dan Teknologi (KomSAT) Laboratory, Universiti Teknologi MARA Sabah Branch. Results showed that mean SOC stocks were higher in the early-stage agroforestry system (42.20 ± 15.25) than in the ultramafic forest (30.94 ± 9.44). Nonetheless, the difference was not statistically significant ($p > 0.05$), indicate that SOC stocks in the early-stage agroforestry system are comparable to those of the adjacent ultramafic forest, thus suggesting that soil carbon levels have not changed substantially at this early transitional stage. Correlation analyses indicated moderate to strong positive relationship ($r = 0.300 – 0.900$) between SOC and selected soil physicochemical properties. Overall, the findings suggest that early-stage agroforestry systems have the potential to function as complementary soil carbon sinks in ultramafic environments. This study highlights the potential of agroforestry as a nature-based solution that not only supports climate change mitigation in tropical ultramafic landscapes but also presents promising opportunities for participation in emerging nature-based carbon credit markets in Sabah through enhanced carbon sequestration and sustainable land management practices.

***Key words**: Agroforestry, hyperaccumulators, land-use, soil organic carbon, Ultramafic soils*

INTRODUCTION

Soil carbon sequestration is increasingly recognised as a critical nature-based solution for climate change mitigation, directly supporting Sustainable Development Goal (SDG) 13: Climate Action, particularly within tropical landscapes where soil organic carbon (SOC) stocks are among the largest and most dynamic globally (Kaushal *et al.*, 2023; Joseph, 2024). Despite being commonly perceived as edaphically constrained ecosystems, ultramafic land use systems possess significant potential to contribute to Sabah's aspiration to maintain its officially recognised carbon-negative status. Through the integration of agroforestry practices and sustainable land management, ultramafic soils may enhance long-term carbon sequestration,

ecosystem resilience, and landscape restoration, thereby supporting Sabah's capacity to absorb more carbon than it emits. While significant attention has been given to forest ecosystems and conventional agricultural soils, ultramafic soils remain underexplored despite their unique geochemical properties and ecological significance (Vithanage *et al*. 2019). Characterised by high concentrations of magnesium and heavy metals, low calcium-to-magnesium ratios, and inherent nutrient limitations, ultramafic soils are often perceived as marginal for plant growth (van der Ent *et al.* 2018). However, these same constraints may slow organic matter decomposition, indicating a potentially important yet poorly understood role in long-term carbon stabilization and the enhancement of soil carbon sequestration potential.

Ultramafic land uses represent stable ecosystems that have adapted to these edaphic conditions, over long evolutionary timescales resulting in distinctive vegetation structure, slow nutrient cycling, and persistent carbon pools. These ecosystems contribute not only to climate regulation but also to biodiversity conservation, aligning with SDG 15: Life on Land, as they support highly specialised and often endemic flora (van der Ent *et al*. 2014; De-Castro *et al.* 2025). In contrast, early-stage agroforestry systems established on ultramafic soils are emerging as a sustainable land-use strategy, integrating perennial crops with woody species to enhance productivity while maintaining ecological functions. Such systems are increasingly promoted as climate-smart agriculture approaches that also support rural livelihoods and food security, contributing to SDG 2: Zero Hunger. In addition, land use is a key factor controlling soil carbon stocks through its influence on vegetation inputs and soil biological processes (Zhou *et al.*, 2019). Interestingly, early-stage agroforestry represents a transitional land use that may enhance SOC compared with ultramafic forest, where carbon storage is constrained by low fertility and strong geochemical controls.

It is known that agroforestry has been widely recognised for its capacity to enhance SOC through increased litter inputs, root biomass, and improved microclimatic conditions (Besar *et al*., 2020; Podong *et al*., 2024). Nonetheless, the effectiveness of agroforestry in restoring or enhancing soil carbon stocks on ultramafic soils remains largely unquantified, particularly during the early stages of system establishment when soil carbon dynamics are most sensitive to management interventions. Existing studies on carbon sequestration in agroforestry systems have predominantly focused on fertile tropical soils (Vijayanathan *et al*., 2022), volcanic soils (Sukartono *et al*., 2023), or degraded agricultural lands (Siarudin *et al*., 2021), leaving a critical research gap regarding carbon dynamics in ultramafic landscapes. Furthermore, comparative empirical evidence between the two land-use types; managed agroforestry systems and ultramafic forests on the same soil substrate remains scarce, limiting the ability to inform land-use planning, restoration strategies, and national carbon accounting frameworks. Hence, comparing SOC between these land uses therefore provides insight into carbon soil responses to land-use change in ultramafic landscapes.

In this study, the research questions focus on determining whether early-stage agroforestry systems can rapidly restore soil organic carbon (SOC) to levels comparable to those of natural ultramafic forests, or whether intrinsic soil constraints limit carbon accumulation regardless of land-use intervention. Therefore, this study aims to evaluate the variations in SOC stocks between early-stage ultramafic agroforestry systems and adjacent ultramafic forests, while elucidating the underlying physicochemical drivers that govern SOC dynamics in these unique edaphic environments.

MATERIALS AND METHODS

This study was conducted at the Pahu Agromining Trial Farm, located near Pahu Village, North Borneo, Sabah, Malaysia (335 m asl, 6°07′49″ N, 116°46′22″ E) (Nkrumah *et al*., 2019; Tisserand et al., 2021) (**Fig. 1**). The site is developed on ultramafic soil classified as a Eutric Chromic Cambisol, which has been comprehensively characterised in previous studies

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(Tisserand *et al.,* 2021). The farm is dominated by *Phyllanthus rufuschaneyi,* a nickel (Ni) hyperaccumulator species well adapted to ultramafic substrates and widely recognised for its suitability for agromining applications. Established as the world's first dedicated agromining experimental facility, the Pahu Agromining Trial Farm serves as a primary experimental field for agricultural and scientific research, jointly implemented through a collaboration between Botanickel Sabah Sdn. Bhd. and TANiLAB, Universiti Teknologi MARA (UiTM) Sabah Branch, Kota Kinabalu Campus. In line with long-term land management objectives, Botanickel Sabah Sdn. Bhd. advocates for crop integration and intercropping systems at the site, thereby reinforcing its role as a transitional platform linking agromining with diversified agroforestry systems.

Pahu Agromining Trial Farm was classified as an early-stage agroforestry system due to the deliberate integration of non-crop woody species within the cultivated area. In addition to the primary crop, *Phyllanthus rufuschaneyi*, *Rinorea bengalensis* has been established as a shelter belt, while naturally occurring and planted tree species such as *Callicarpa* sp. are also present, indicating strong potential for transition towards a more integrated agroforestry configuration (**Fig. 2a**). The presence of serpentine rocks at the study site represents an important feature of ultramafic ecosystems (**Fig 2c**).

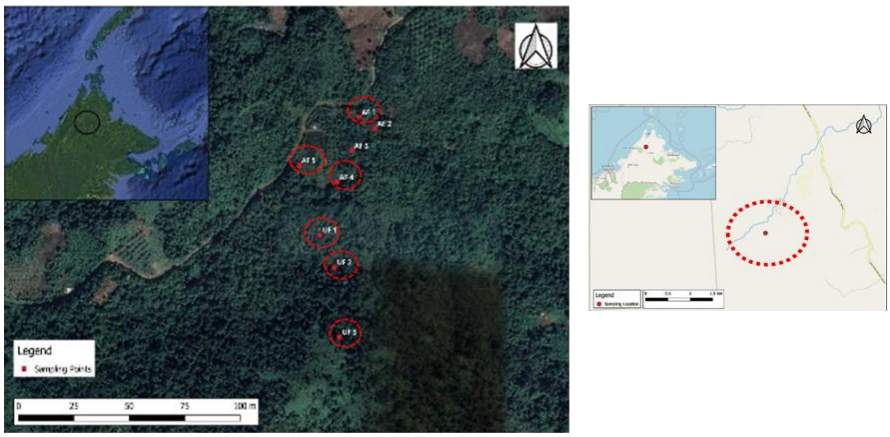


Figure 1: Map of Study Area and Sampling Locations

Soil Sampling and Processing

As the Pahu Agromining Trial Farm is a newly established 'living laboratory' and the first research site in Sabah, this study focused on creating an initial baseline using six sampling points. To ensure these results were accurate despite the small sample size, we used composite sampling, mixing multiple soil replicates from each plot to reduce the impact of natural soil variations and provide a reliable representation of carbon levels for both land-use types.

Soil samplings were carried out on 27th and 30th August 2025 in the study area. Soil sampling was conducted both at the Pahu Farm (**Fig. 2a**) and in an adjacent ultramafic forest located approximately 200 m from the farm (**Fig. 2b**), enabling direct comparison between early-stage agroforestry and forest soils. Three sampling points were established for each vegetation type, each with a 10 m temporary plot (**Fig. 3a**). Within each plot, a soil sample with five replicates is collected as vertical depth increment undisturbed cores at 20 cm depth extracted with a soil auger (**Fig. 3b**). Then, the samples were thoroughly mixed and bulked into one composite sample of about 1 kg. Simultaneously, individual samples from each sampling point were preserved for physicochemical analyses. After each sampling, the auger was rinsed with distilled water obtained from a car battery to remove any adhering soil particles. This step was critical to prevent cross-contamination between samples and to ensure

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that the high concentrations of metals inherent to ultramafic soils did not carry over to subsequent samples. The geographical position and elevation of each sampling point were recorded using the Global Positioning System (GPS), Garmin GPSMAP® 64s. We took photographs of the surroundings of the sampling locations for references. We also collected the soil for bulk density from undisturbed soil within each sampling location, using a stainless-steel core (4 cm in diameter and 7.7 cm in length) (Fig 3b). Next, the soil samples were air dried, placed in a labelled heavy-duty clear plastic bag and transferred to Soil Laboratory at Kompleks Sains & Teknologi (KOMSAT) in UiTM Sabah Branch (**Fig. 3d**).

Soil analyses

To determine the total organic carbon (TOC), total element nitrogen (TN) and total phosphorus (TP) of each collected soil sample,10 g of sub samples were taken from the labeled sample and outsourced to Chemistry Section in Forest Research Centre (FRC), Sandakan for chemical analysis. However, total potassium (K) analysis could not be conducted at the FRC as the analytical instrument was not operational at the time of analysis. Percentage moisture content (% MC) was determined by oven drying a subsample to constant weight to correct measurements to oven-dry basis. The soil samples were oven-dried at 40°C overnight and lightly ground using mortar and pestle to pass through a 100-mesh sieve (0.45 mm opening) to



Figure 2: (a) Early-stage agroforestry vegetation, (b) Ultramafic Forest, (c) Ultramafic rocks in Pahu Farm

obtain a fine subsample for microscale analyses. TN were measured simultaneously on LECO CN928 Series Combustion Analyzer (Leco, MI, USA). Meanwhile, TOC was determined titrimetrically using the rapid dichromate oxidation method adapted from the Walkey-Black procedure. A detailed description of the analysis can be found in Nelson & Sommers (1982). We use soil bulk densities to calculate soil C stock. Soil C stock is the product of soil organic C concentration, soil depth, and bulk density.

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Figure 3: (**a**) 10m x 10m plot establishments, (**b**) Collection of undisturbed soil cores for bulk density Determination, (**c**) Soil sampling using Auger, (**d**) Soil sample analysis in the laboratory

Statistical analyses

Descriptive statistics, especially means are given ± standard error of the mean (SEM) was used to describe the dataset. We performed Shapiro-Wilk Test to verify the data normality. The data normality condition met for the values of the parameters ($p > 0.05$) across the vegetation types. The significance difference of BD, SOC, TN, OM and pH across different vegetations was tested using ANOVA at 5% level of significance. The correlation test was applied to determine the relationship between the variables. SPSS software (IBM SPSS Statistics, IBM Corporation, Version 26 was used for statistical analysis for the data.

RESULTS AND DISCUSSION

Soil organic carbon across land-use systems

As summarized in **Table 1**, the early-stage agroforestry system exhibited a numerically higher mean SOC concentration (M = 42.40, SD = 15.25) compared to the ultramafic forest system (M = 30.94, SD = 9.44). However, this difference was not statistically significant, $t(4) = 1.11$, $p = 0.33$. The coefficient of variation (CV) for both the agroforestry (35.94%) and forest (30.42%) sites suggests a high degree of spatial heterogeneity, which is characteristic of the complex mineralogical profiles and specialized microbial communities found in tropical ultramafic edaphic environments.The correlation analysis revealed contrasting controls of SOC in early-stage agroforestry and natural ultramafic forest systems. Although several relationships were not statistically significant ($p > 0.05$), the magnitude and direction of the correlation coefficients provide important ecological insights into the mechanisms governing SOC dynamics in these systems, particularly given the limited sample size. The mean SOC was higher in the agroforestry ecosystem (42.20 ± 15.25) than in the forest ecosystem (30.94 ± 9.44) (Fig. 4). The coefficient of variance (CV) for early-stage agroforestry indicates high variability of SOC stocks (35.94%) within the area and ultramafic forest (30.42%) indicating moderate variability of SOC stocks (**Table 1**). The variability may be linked to differences in

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trees species composition, litter quality, root biomass distribution, and management practices typical of agroforestry systems.

Table 1: Summary of Descriptive Statistics SOC between Early-Stage Agroforestry and Ultramafic Forest

Early-Stage Ultramafic Agroforestry			Ultramafic Forest					
M	**SD**	**CV**	**M**	**SD**	**CV**	**t**	**df**	***p***
42.40	15.25	35.94	30.94	9.44	30.42	1.11	4	.33

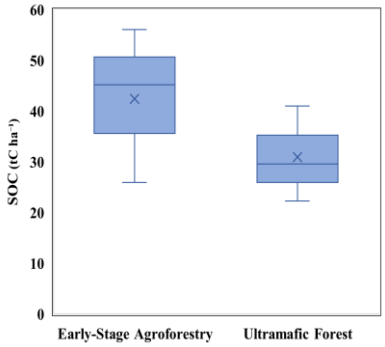


Figure 4: SOC Variability Between Two Land Uses; Early-Stage Agroforestry and Ultramafic Forest

The findings indicate that the conversion of ultramafic landscapes into agromining-based agroforestry systems does not lead to an immediate depletion of soil organic carbon. While the agroforestry system yielded a numerically higher SOC mean, the lack of statistical significance ($p > .05$) suggests that the site is likely in a successional transition where carbon stocks have not yet diverged significantly from the forest baseline (Pu *et al.,* 2025). This observation is critical, as it supports the potential of "nature-based solutions" in agromining to maintain ecosystem services even during early-stage implementation (Gatew & Zerihun, 2025). The high variability in SOC across both sites may be driven by specific soil physicochemical properties inherent to ultramafic regions. In these ecosystems, SOC stabilization is frequently governed by mineral-associated organic matter formed through interactions with iron (Fe) and magnesium (Mg) oxides rather than biomass input alone (van de Ent *et al.,* 2018).

SOC relationships with soil physicochemical properties

Correlation analyses showed generally weak to moderate relationships between soil organic carbon (SOC) stocks and most soil physicochemical properties in both the early-stage agroforestry system and the adjacent ultramafic forest, with most correlations being non-significant ($p > 0.05$). This likely reflects high spatial heterogeneity and limited sample size typical of ultramafic environments rather than the absence of SOC–soil property interactions.

In the early-stage agroforestry system, SOC exhibited positive but non-significant correlations with bulk density ($r = .159$, $p = .898$), nitrogen ($r = .896$, $p = .292$), organic matter ($r = .666$, $p = .535$), and phosphorus ($r = -.793$, $p = .416$). These positive trends in nitrogen and organic matter indicated that SOC accumulation is beginning to co-vary with nutrient-related soil properties, reflecting increasing organic inputs from litterfall and root turnover following agroforestry establishment. However, the absence of statistically significant relationships suggests that soil carbon–nutrient coupling remains weak at this early developmental stage, where biogeochemical processes have not yet stabilised.

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As shown in **Fig. 5d**, the early-stage agroforestry also exhibited a strong and statistically significant negative relationship between SOC and soil pH (r = −.999, p = 0.015), indicating higher SOC stocks under more acidic conditions. The negative direction of the correlation suggests that as soil pH increases which means the soils become less acidic, SOC stocks tend to decrease. This relationship highlights soil acidity as an important regulator of SOC stabilisation in ultramafic soils. Lower pH likely reduces microbial decomposition rates and promotes the formation of stable organo-metal complexes with Fe, Al, and Ni, thereby enhancing SOC persistence.

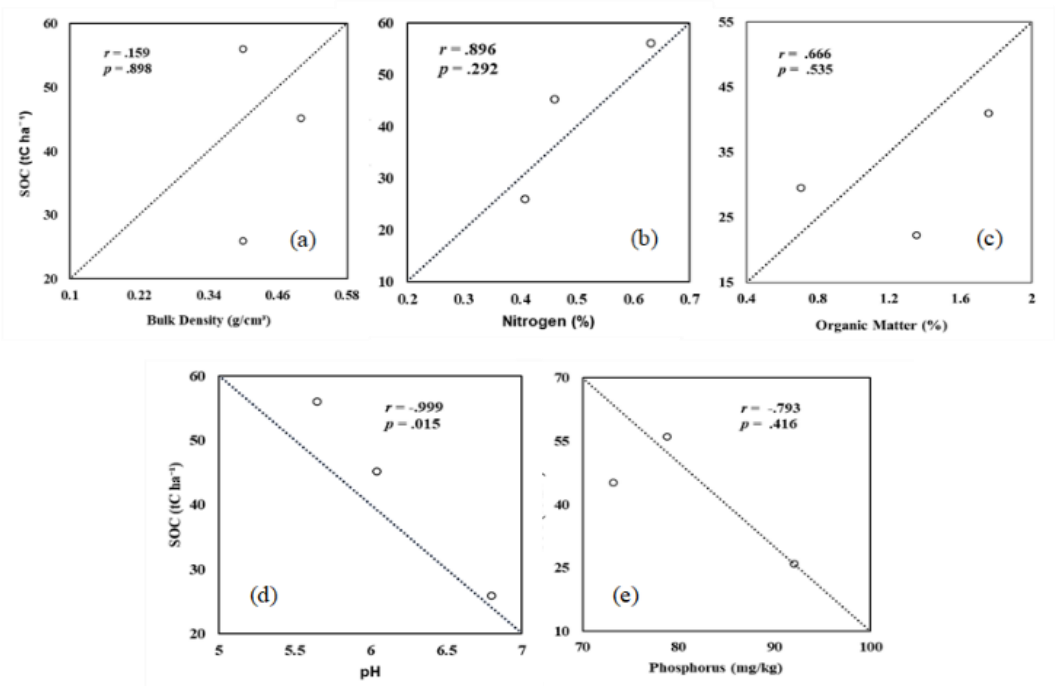


Figure 5: Correlation between soil organic carbon (SOC) and soil chemical properties (**a**) bulk density, (**b**) nitrogen, (**c**) organic matter, (**d**) pH, (**e**) phosphorus in early-stage agroforestry

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In Fig. 5e, SOC also showed a negative but non-significant association with phosphorus (r = .448, p = .704), suggesting potential phosphorus limitation in carbon-rich soils due to strong P fixation by metal oxides (Sanchez, 1976; Reed *et al.,* 2011). These results corroborate the findings of van der Ent *et al*. (2015), who observed no significant variation in total phosphorus, supporting the idea that phosphorus may be strongly immobilized in carbon-rich soils, likely due to fixation by metal oxides thus promoting carbon retention in soils. As observed in ultramafic forest, phosphorus exhibited a positive correlation with SOC (**Fig. 6e**), which can be attributed to secondary successional processes, during which increasing organic matter inputs enhance P retention and availability (Sullivan *et al*., 2019).

In agroforestry, SOC was more strongly associated with nutrient-related variables, particularly total nitrogen, reflecting the early influence of vegetation establishment, litter inputs, and management-driven organic matter accumulation. The positive correlation observed between SOC and TN across both land-use types (**Fig. 5b** & **6b**) is likely attributable to enhanced nitrogen mineralization in naturally vegetated soils, driven by the continuous input and decomposition of organic matter (Hossain and Salam, 2019). Furthermore, these findings may suggest that nitrogen availability may accelerate soil carbon sequestration in tropical forests, supporting previous findings that nitrogen enhances organic matter stabilization (Tang *et al.,* 2026). The abundance of ultramafic rocks may further enhance carbon sequestration in the early-stage agroforestry system by promoting mineral weathering and carbon mineralization processes that facilitate the formation of stable mineral-associated carbon pools (Kelemen *et al.*, 2020).

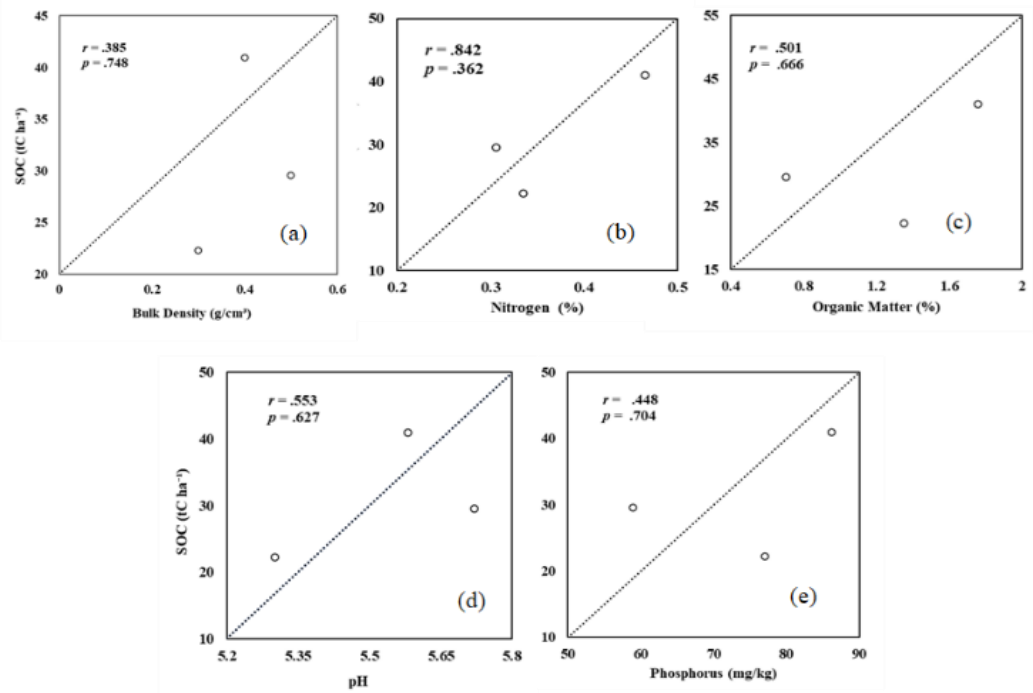


Figure 6: Correlation between soil organic carbon (SOC) and soil chemical properties (a) bulk density, (b) nitrogen, (c) organic matter, (d) pH, (e) phosphorus in ultramafic forests

Contrary to the widely reported inverse relationship between SOC and bulk density as reported by Ghimire *et al*. (2018); Joseph (2024), this study observed a positive correlation (r = .185, p = .385) between these variables in both early-stage agroforestry and ultramafic forest (**Fig. 5a** & **6a**). This discrepancy suggests that SOC accumulation in these soils may be driven

more by mineral-associated organic carbon than by aggregate formation. In ultramafic soils, strong organo-mineral interactions and high bulk mineral density may lead to increased bulk density even as SOC increases, highlighting the importance of parent material and pedogenic processes in regulating SOC–bulk density relationships. Furthermore, the relationship between SOC and bulk density in these soils is heavily mediated by the high bulk mineral density of the parent material. Ultramafic rocks possess naturally high specific gravities, which can lead to higher soil bulk density values that do not follow the typical inverse linear relationship with organic matter increases seen in more silicic soils (Dong *et al.,* 2022). This highlights that pedogenic processes specifically the weathering of mafic silicates into reactive secondary minerals are the dominant regulators of carbon sequestration patterns in these unique landscapes (Almaraz *et al., 2022*; van der Ent *et al.,* 2018).

Overall, these findings demonstrate that while early-stage agroforestry shows promising potential for enhancing SOC stocks, natural ultramafic forests currently function as more stable carbon reservoirs. Carbon sequestration in young agroforestry systems is still in a developmental phase, where biological inputs and nutrient cycling processes dominate SOC formation. Restoring SOC in agroforestry systems relies on practices that increase carbon inputs and slow its loss. Conservation-oriented measures such as reduced tillage, mulching, and cover cropping minimize nutrient and water losses, enhance biomass production, and stabilize SOC through biological, chemical, and physical mechanisms (Lal and Follett, 2009). Minimising cultivation intensity further promotes SOC accumulation by reducing soil disturbance (Nair *et al.,* 2010). Additionally, integrating organic amendments like compost, crop residues, and biofertilizers, along with supplemental irrigation where needed, can enhance carbon inputs and improve soil structure. Collectively, these approaches not only restore SOC but also strengthen soil fertility, water retention, and overall ecosystem resilience in agroforestry landscapes.

CONCLUSION

This study provides the first empirical assessment of SOC sequestration at the Pahu Agromining Trial Farm, establishing a critical baseline for the sustainable agromining practices in Sabah. The results demonstrate that early-stage agroforestry systems established on ultramafic soils can maintain SOC stocks at levels comparable to adjacent natural ultramafic forests. Although SOC concentrations were higher in systems cultivated with *Phyllanthus rufuschaneyi*, the absence of significant differences suggests that soil carbon dynamics remain relatively stable during the early phase of land-use transition. These findings indicate that intrinsic ultramafic soil constraints, including high metal concentrations and unique mineralogy, may moderate short-term carbon accumulation while limiting rapid SOC depletion Importantly, this research confirms that agromining-based agroforestry does not compromise soil carbon storage, positioning it as a viable, carbon-neutral, and ecologically compatible land-use strategy for sensitive ultramafic landscapes. However, to strengthen the robustness and spatial representativeness of these findings, future research should incorporate greater sampling intensity and a wider distribution of sampling points, alongside a broader suite of environmental parameters, including soil moisture dynamics and rainfall intensity, to better elucidate the drivers of carbon mineralization in these unique tropical ecosystems.

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