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Evaluating Ecosystem Carbon Pools in Coffee-Based Agroforestry under the Framework of the King's Philosophy for Landscape Restoration

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ABSTRACT

Agroforestry systems are increasingly recognized as multifunctional land-use strategies that contribute to climate change mitigation, ecosystem restoration, and rural livelihoods. This study evaluated ecosystem carbon stocks across three land-use systems at the Phu Phayak Highland Agricultural Development Station, northern Thailand, under the framework of the King's Philosophy for landscape restoration. The systems comprised: (i) coffee intercropped with *Pinus kesiya*, (ii) coffee intercropped with *Morus alba* and associated species, and (iii) monoculture coffee without shade trees. Carbon stocks were quantified in aboveground biomass, belowground biomass, and soil organic carbon using plot-based measurements, allometric equations, and standard soil analyses. Results showed significant differences in carbon sequestration among systems ($p < 0.05$). The *P. kesiya*–coffee agroforestry system exhibited the highest aboveground and belowground carbon stocks, reflecting the contribution of fast-growing, deep-rooted shade trees. Although monoculture coffee maintained relatively high soil organic carbon due to intensive soil management practices, its total ecosystem carbon stock remained lower because of limited biomass accumulation. Overall, total ecosystem carbon was greater in tree-based agroforestry systems than in monoculture coffee, highlighting the importance of structural complexity, perennial biomass, and root dynamics in long-term carbon storage. These findings underline that the King's Philosophy encourages sustainable land use that optimizes ecological restoration potential while enhancing adaptive capacity to climate change in Northern Thailand. By integrating perennial tree cover with agricultural production, coffee-based agroforestry emerges as a climate-resilient land-use model that simultaneously strengthens carbon sequestration, ecosystem stability, and long-term landscape sustainability in upland regions.

1. Introduction

Forests undoubtedly have a lot to offer in the intricate game of climate change mitigation, since they exhibit the remarkable capacity to serve as powerful CO_2-manicured sinks, storing large amounts of carbon in their rich biomass and underlying soils. The recent international programmes and projects on forest ecosystem conservation/rehabilitation have been widely recognised, largely due to popular mobilisations and campaigns against forest deforestation, especially in tropical areas, which have become major hotspots of greenhouse gas emissions (Sarira et al. 2022; Sasaki et al. 2021). In biologically diverse Southeast Asia, including its highlands, forest degradation has become a horrific phenomenon occurring on a long-term, multifaceted, and serious scale due to unsustainable land use. These cover a wide spectrum of activities, including large-scale commercial logging, monoculture plantation establishment and the long-practiced method of shifting cultivation, with extremely negative impacts on the integrity of these crucial ecosystems (Chen et al. 2023; Zeng et al. 2018).

A positive example of this challenge is found at the Phu Phayak Highland Agricultural Development Station in Nan Province, Northern Thailand. The project represented the King's Philosophy and integrated approach to development, which values environmental conservation equally with social and economic progress by establishing agroforestry systems comprising *C. arabica* with *Pinus kesiya* or *Morus alba*. These systems not only promote carbon storage but also expand forest areas while providing livelihood benefits and contributing to household income for local communities (Caramori et al. 2020; Roslinda et al. 2023).

Agroforestry is internationally well-regarded as an effective and sustainable land-use system, combining a wide range of different environmental functions with substantial socio-economic benefits, especially in the tropical zones where it most clearly manifests its effects (Beenhouwer et al. 2016; Kumar et al. 2018). In the more general context of global climate action initiatives, including but not limited to the historic, above mentioned Paris Agreement, such innovative land management is known to provide very significant contributions toward sequestering carbon from CO_2 in the atmosphere, preserving biodiversity and enhancing some additional rehabilitation and recovery of degraded low-lying or barren lands which have been conventionally mismanaged or neglected (Niguse et al. 2022). Agroforestry, by combining trees with crops, enhances above- and belowground carbon stocks through increased tree biomass and vegetation structure (Hartoyo et al. 2025). In Bangladesh, a species-rich home garden with high tree density sequesters much more soil organic carbon than a species-poor system, and biodiversity is therefore considered an important factor for carbon storage (Islam et al. 2015). Restoration of croplands to coffee-based agroforestry in India has increased soil C stocks to levels similar to those in natural forests (Hombegowda et al. 2016). Similarly, carbon management in tropical forest systems can enhance soil fertility and facilitate ecological restoration (Rahman et al. 2023).

Additional studies in Ethiopia, Indonesia, and India show that mixed tree-based systems can store 50−200 Mg.C/ha, sequestering up to 2 Mg.C/ha/year (Betemariyam et al. 2020; Panwar et al. 2022), depending on species composition and stand age. The use of carbon balance indicators in these complex systems has further highlighted their key role as an essential tool for surveillance and monitoring the effectiveness of ecological restoration projects, as well as a basis for evidence-based climate-mitigation strategies (Adekiya et al. 2023). The success story of Phu Phayak is a shining example of the King's Philosophy in practice and demonstrates that complex processes such as ecosystem rehabilitation and carbon sequestration can be interwoven with the demand for socio-economic development. By carefully interspersing shade trees indigenous to these intensively managed coffee plantations, the project notably increases not only biomass generation capacity but also fundamental soil carbon sequestration, while contributing to the resilience of area ecosystems. The latter, in turn, serves the dual goals of ecological restoration and rural community development, and also creates a mutually enhancing relationship that benefits both the environment and human life (Royal Project Foundation 2020).

2. Materials and Methods

2.1. Study Area

The study in question had been conducted with the best care possible at the Phu Phayak Highland Agricultural Development Station, located in the well located Chalerm Phra Kiat District of Nan Province centrally surrounded by multiple mountain ranges as part of a national park, scenic Northern Thailand on latitude 19°30′ N and longitude 101°13′ E (**Fig. 1**).

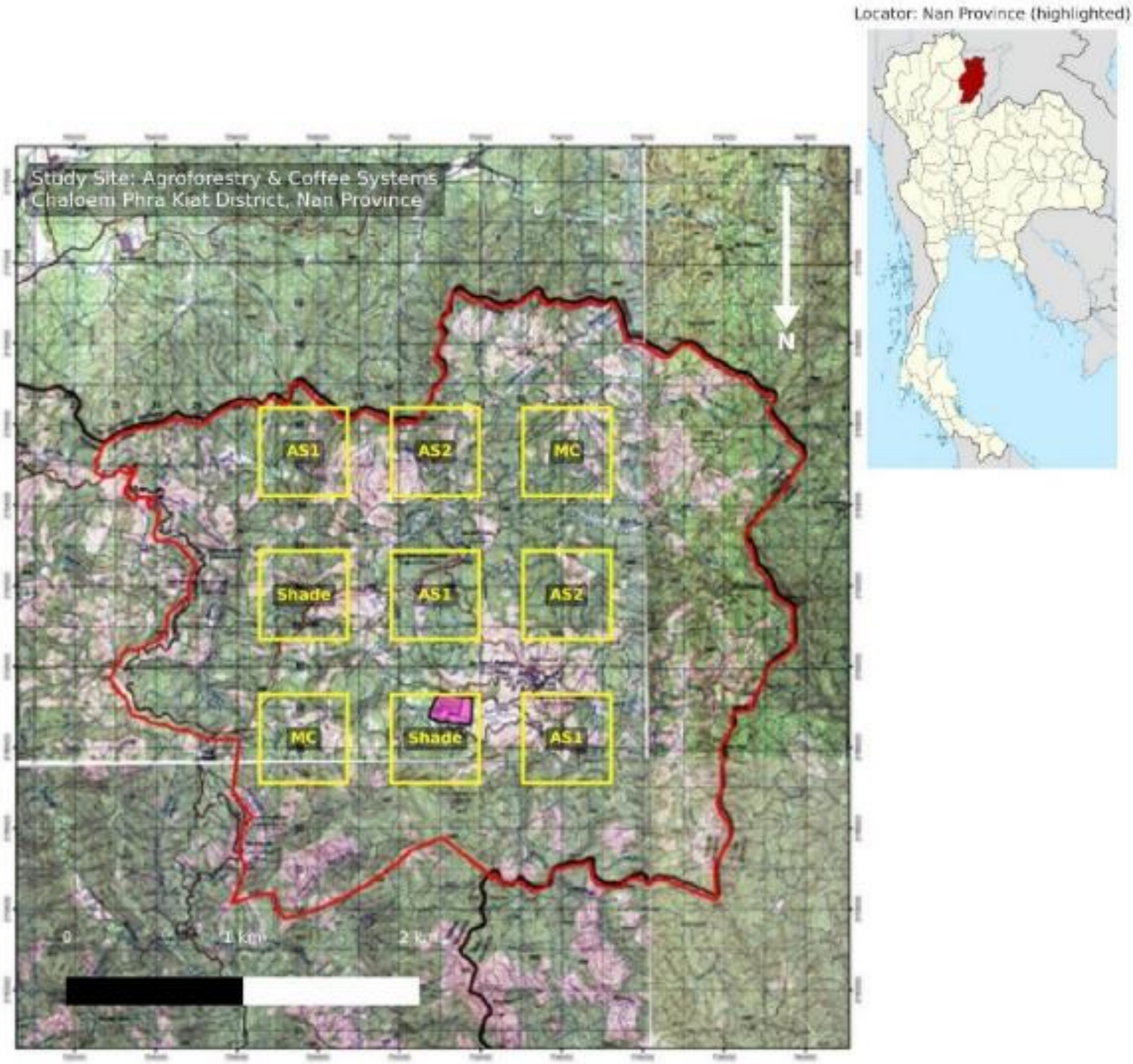

Fig. 1. Study area in the Phu Phayak Highland Agricultural Development Station.

The station is located between 700 and 1200 meters above sea level (masl), and has a typical tropical monsoon climate. This type of climate is characterized by an annual rainfall regime of 1,200–1,500 mm and a mean annual temperature of 15–25°C. Soil types in this region are sandy loam and loamy sand, which occur on moderate (slope < 20–30°) to steep (slope up to 20–30°) slopes, characteristic of hill agroforestry landscapes in upland areas of north and northeastern Thailand. The local vegetation is mostly a combination of pines, specifically *Pinus kesiya* and broad-leaved species. In this natural setting, the experiment agroforestry plots have been carefully established to incorporate these native trees into the production of arabica coffee (*Coffea arabica*), facilitating a synergy between agriculture and forestry. Three representative agroforestry coffee plantations were selected for a detailed study. The first location, aptly named the Pinus site, features very stylish coffee plants shaded by the lofty, majestic *P. kesiya* trees. Another site, the Morus site, shows coffee plants flourishing in the nurturing shade of several *Morus* (mulberry) species. The third site, however, the Sun Coffee site (so named because of the lack of shade from a canopy and sparse ground cover), is a bare monoculture coffee plantation with no overhanging trees to protect it. All these sites had a history of severe deforestation, but they are managed under intensive, long-term agroforestry, involving establishment and maintenance, to stimulate the rehabilitation of the surrounding fragmented woodland. Notable is the Sun Coffee site, which features *C. arabica* between scattered forest trees, with just enough shade to offer the most sunlight while also remaining ecologically diverse.

It is organized into sub-compartments at the Phu Payak Agricultural Development Station, with an elaborate plantation system for which a variety of canopy integration levels are clearly visible (**Table 1**). Amidst this deliberate setting, the Pinus stand site is an example of a very well-managed shaded coffee system in which it flourishes under the canopy of *P. kesiya*, a species with proven shade potential. The Morus site, however, offers a healthy combination of several species, including *Morus alba*, *Musa* spp., and *Mangifera* spp., which, in particular, provide significant shade, maintaining the ecological status quo of this region. Additionally, the Sun Coffee site can be considered a vital open-grown reference system for gaining better insight into the effects of different shade management practices on coffee yield. The relief of all these plots is mountainous, having an average slope between 20° and 30°, adding to the complexity of the agricultural activity practiced in this region.

Table 1. Profiles of sampled plantations, including geographic location, elevation, dominant tree species and age of stands

Plantation	Site	N	E	Altitude (masl)	Dominant tree species	Stand age (year)
Pinus site	*Pinus kesiya*	19.30.805	101.13.141	1,028	*Pinus kesiya*	8
Morus site	*Morus alba*	19.30.839	101.13.162	985	*Morus alba*	15
Sun site	Sun coffee	19.30.349	101.12.824	1,019	*Coffea arabica*	15

2.2. Experimental Design

The focus was to compare carbon sequestration potential across three land-use systems: Agroforestry System 1 (AS1), coffee intercropped with *Pinus kesiya*; Agroforestry System 2 (AS2), coffee and *Morus alba* (mulberry) forwarded as coffee crop; and Monoculture Coffee (MC), coffee without shade trees (control). Each system consisted of nine plots (40 m × 40 m) in a randomized block design, with of three replicates per system (**Fig. 2**). This design will control for most of the variation in spatial heterogeneity between sampling units such as slope, soil type and microclimate, leaving differences in carbon sequestration due to land management rather than and extraneous environmental variation.

2.3. Data Collection

2.3.1. Aboveground biomass (AGB)

The aboveground biomass was estimated to determine C sequestration in coffee trees and shade trees. Biomass of *P. kesiya* and *M. alba* was determined using species-specific allometric equations derived from tree diameter at breast height (DBH) and total height for trees with DBH

≥ 10 cm. Equation 1 was applied to estimate tree biomass (Andrade et al. 2021; Daba and Soromessa 2019; Djomo and Chimi 2017).

$$AGB = 0.0673 \times (DBH)^{2.5735} \quad (1)$$

where *AGB* is the aboveground biomass (kg), and *DBH* is the tree diameter (cm).

For coffee trees, this study used a species-specific equation (Andrade et al. 2021). Biomass was converted to its carbon content by multiplying by 0.50, assuming that about half of the dry biomass is carbon (IPCC 2019).

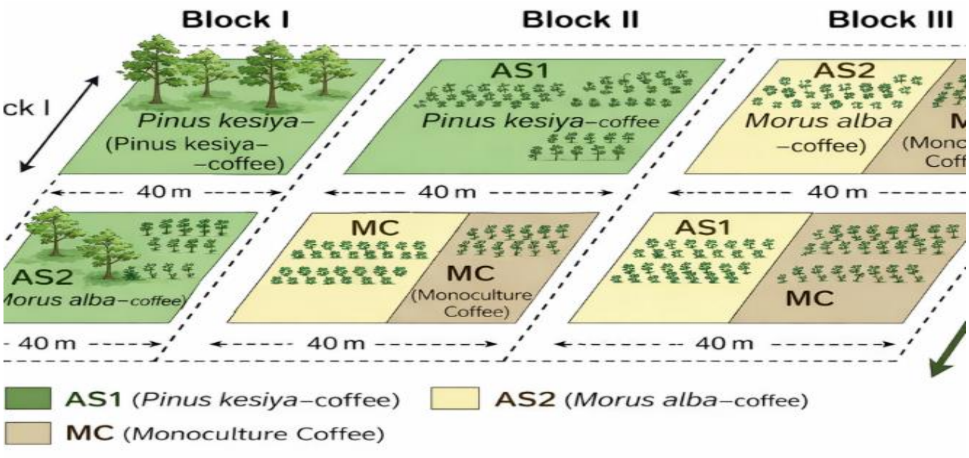

Fig 2. Schematic representation of the design plot experiment.

2.3.2. *Belowground biomass (BGB)*

Root biomass was calculated by core sampling with five replicates (3 cm diameter) at random locations in each plot from two soil depths (0–30 and 30–60 cm). To estimate root biomass, the dry weight of cleaned root samples was extrapolated using the root-to-shoot ratio method (Andrade et al. 2021; Defrenet et al. 2016; Gautam et al. 2021). Carbon content in roots was calculated as 50% of the dry weight of roots, according to the IPCC guidelines for carbon fraction in plant biomass (IPCC 2006; IPCC 2019).

2.3.3. *Soil organic carbon (SOC)*

Soil samples were collected from 3 random sampling locations in each plot using a soil auger at 2 depths (0–15 cm and 15–30 cm) for a total of 6 soil samples per plot. All soil samples were air-dried, ground gently, sieved through a 2 mm mesh, and analysed for organic carbon using the Walkley–Black wet oxidation method, which is well known for its applicability to tropical soils (Bhattacharyya et al. 2015; Enang et al. 2018). Bulk density of soil (on a dry basis) was measured from undisturbed core samples, and total SOC content was estimated using Equation 2 (Nelson and Sommers 1996).

$$SOC\ (Mg.C/ha) = SOC\ concentration\ (\%)\ x\ bulk\ density\ (g\ cm^{-3})\ x\ depth\ (cm) \quad (2)$$

where the total SOC per plot was obtained by summing carbon stocks from both soil layers.

2.4. *Carbon Sequestration Calculations*

The amount from three of these pools: aboveground carbon (AGC), belowground carbon (BGC) and soil organic carbon was added together to give the total ecosystem C stock (C_{total}). Biomass carbon was estimated using Equation 3 (IPCC 2006; IPCC 2019).

$$Carbon\ content\ (Mg.C/ha) = Biomass\ (Mg/ha) \times 0.50 \quad (3)$$

The typical method involves measuring SOC concentration, BD, and sampling depth to estimate SOC sequestration. Total ecosystem carbon storage was converted to CO_2 equivalents using a factor of 3.67 (IPCC 2019) and presented in Mg.C/ha.

2.5. Environmental Data Collection

Soil moisture, pH, and macronutrients (N, P, and K) were also determined as environmental factors affecting C stock to investigate their relationships with C accumulation. Soil moisture was measured with a field moisture probe, pH was measured with a calibrated pH meter, and nutrient content in each plot was analysed in the laboratory from soil samples retrieved. They were used to investigate potential associations between ecological and environmental factors and carbon storage.

2.6. Statistical Analysis

For all plot-level data, a one-factor analysis of variance (ANOVA) was used to test for differences in C storage among the three land-use systems (AS1, AS2, MC). Differences were post-hoc tested (whenever $p < 0.05$) using Tukey's Honestly Significant Difference (HSD) test (Tukey 1977; Zar 2010), if the overall F-test was significant. A Pearson correlation analysis was conducted to examine the relationship between C sequestration and environmental factors (soil moisture and soil pH). P-values < 0.05 were considered to be statistically significant.

3. Results and Discussion

3.1. Carbon Sequestration in Aboveground Biomass

Regarding aboveground biomass, carbon sequestration varied significantly across the three land-use systems (**Table 2**). *Pinus kesiya*–coffee agroforestry system (AS1) had the highest AGB carbon stock, indicative of high-biomass conifers, while coffee was grown in association with them. AGB carbon in the *Morus*–*Mangifera*–coffee system (AS2) was much lower than that of MCS.

Table 2. Summary of aboveground biomass for each system, including tree and coffee plant

Land-use system	Tree species	Aboveground biomass (AGB) (Mg.C/ha)	AGB carbon (Mg.C/ha)
Agroforestry system 1	*Pinus kesiya* *Coffea arabica*	92.524	46.262
Agroforestry system 2	*Morus alba* *Mangifera indica* *Coffea arabica*	14.996	7.498
Monoculture coffee system	*Coffea arabica*	3.292	1.646

These results underscore the need to incorporate bamboo or shade trees into coffee to help provide aboveground carbon compared with monoculture systems. Such trends have also been observed in tropical agroforestry, e.g., where tree-crop systems contribute to higher biomass and canopy complexity indices and greater litter inputs, thereby increasing carbon stocks (Betemariyam et al. 2020; Hombegowda et al. 2016; Islam et al. 2015; Niguse et al. 2022). In this regard, *P. kesiya* stands out as a key structural species, consistent with previous evidence indicating that species choice and stand architecture play major roles in C sequestration in tree-based systems (Chheng et al. 2016; Nath et al. 2022; Pragasan 2020).

3.2. Carbon Sequestration in Belowground Biomass (BGB)

Patterns in belowground biomass were similar to those observed for aboveground biomass stocks (**Table 3**). *Eucalyptus*–coffee and a *P. kesiya*–coffee system showed the highest belowground C, suggesting extensive root systems and high root/shoot ratios. In comparison, AS2 had intermediate values, and the MCS stored less belowground biomass.

Table 3. Belowground biomass (root carbon) for each system

Land-use system	Tree species	Belowground biomass (BGB) (Mg.C/ha)	BGB carbon (Mg.C/ha)
Agroforestry system 1	*Pinus kesiya*	17.560	8.780
	Coffea arabica		
Agroforestry system 2	*Morus alba*	6.481	3.240
	Mangifera indica		
	Coffea arabica		
Monoculture coffee system	*Coffea arabica*	2.149	1.075

Tree-based systems with deep and extensive root systems contribute to subsoil carbon input, soil aggregate stabilization, and increased carbon residence time in the system (Andrade et al. 2021; Defrenet et al. 2016; Gautam et al. 2021). These findings highlight that agroforestry not only enhances the aboveground carbon pool but also provides a vital contribution to belowground carbon, which may help maintain ecosystem functioning compared to monoculture coffee.

3.3. Soil Organic Carbon (SOC) Sequestration

Similarly, SOC stocks showed an opposite trend to biomass (**Fig. 3**). MCS had the highest SOC in the 0–30 cm profile, followed by AS1 and AS2, which had relatively lower SOC.

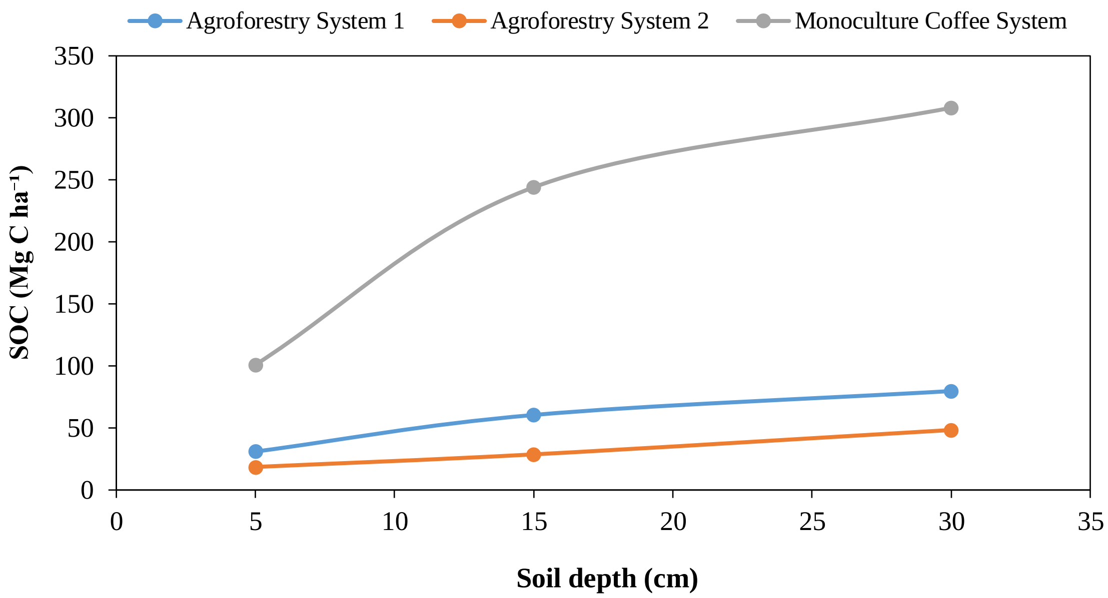

Fig. 3. Levels of SOC at different depths and land-use systems.

The high SOC content in the MCS may be due to intensive soil management practices, such as continuous mulching, incorporation of organic residues, and minimum tillage, which promote carbon accumulation and protection in the topsoil (Adekiya et al. 2023; Magar et al. 2020; Paudel and Kafle 2023). Despite agroforestry often being associated with higher SOC stocks resulting from litterfall and root turnover (Rahman et al. 2023), this result suggests that management may override structural predictability at certain spatial scales. It also indicates that shaded systems in Phu Phayak may not yet have reached an intermediate level of soil recovery compared to long-managed monoculture plots.

3.4. Total Carbon Sequestration

When integrating AGB, BGB, and SOC pools, clear differences in total ecosystem carbon emerged (**Table 4**). The *P. kesiya*–coffee system (AS1) accumulated the highest mean total carbon, followed by AS2; while MCS, despite its higher SOC, stored the lowest sum of all (including biomass pools). Results of Tukey's HSD test showed significant differences among systems ($p < 0.05$).

Table 4. Total carbon sequestration in each system, including biomass and soil contributions

Land-use system	Component	Carbon sequestration (Mg.C/ha)
Agroforestry System 1	Aboveground biomass (AGB)	46.262
	Belowground biomass (BGB)	8.780
	Soil organic carbon (SOC)	171.27
	Total carbon sequestration	226.312
Agroforestry System 2	Aboveground biomass (AGB)	7.498
	Belowground biomass (BGB)	3.240
	Soil organic carbon (SOC)	65.67
	Total carbon sequestration	76.408
Monoculture Coffee System	Aboveground biomass (AGB)	1.646
	Belowground biomass (BGB)	1.075
	Soil organic carbon (SOC)	653.18
	Total carbon sequestration	655.901

These results highlight a more effective contribution of tree-based agroforestry systems to overall carbon pools than coffee monocultures, as diversified perennial systems can significantly raise landscape-level carbon stocks (Ehrenbergerová et al. 2015; Garedew 2019; Niguse et al. 2022; Walsh et al. 2025).

3.5. Environmental Data and Soil Properties

The properties of soil showed a similar relationship to the distribution of carbon (**Fig. 4**). The MCS was also accompanied by higher soil fertility (pH, N, P, and K contents were slightly higher, and soil moisture content tended to be higher), along with higher SOC. On the other hand, agroforestry had lower nutrient levels and, by contrast, higher gross C inputs derived from biomass. Correlation Analysis (pH r = 0.595; N r = 0.542; P r = 0.532; K r = 0.519) revealed that balanced soil chemical conditions favour carbon sequestration where microbial processes and root productivity are supported (Borah and Parmar 2024; Parihar et al. 2019). However, in the absence of significant woody biomass, these favorable soil conditions do not lead to maximized total ecosystem carbon as indicated by MCS.

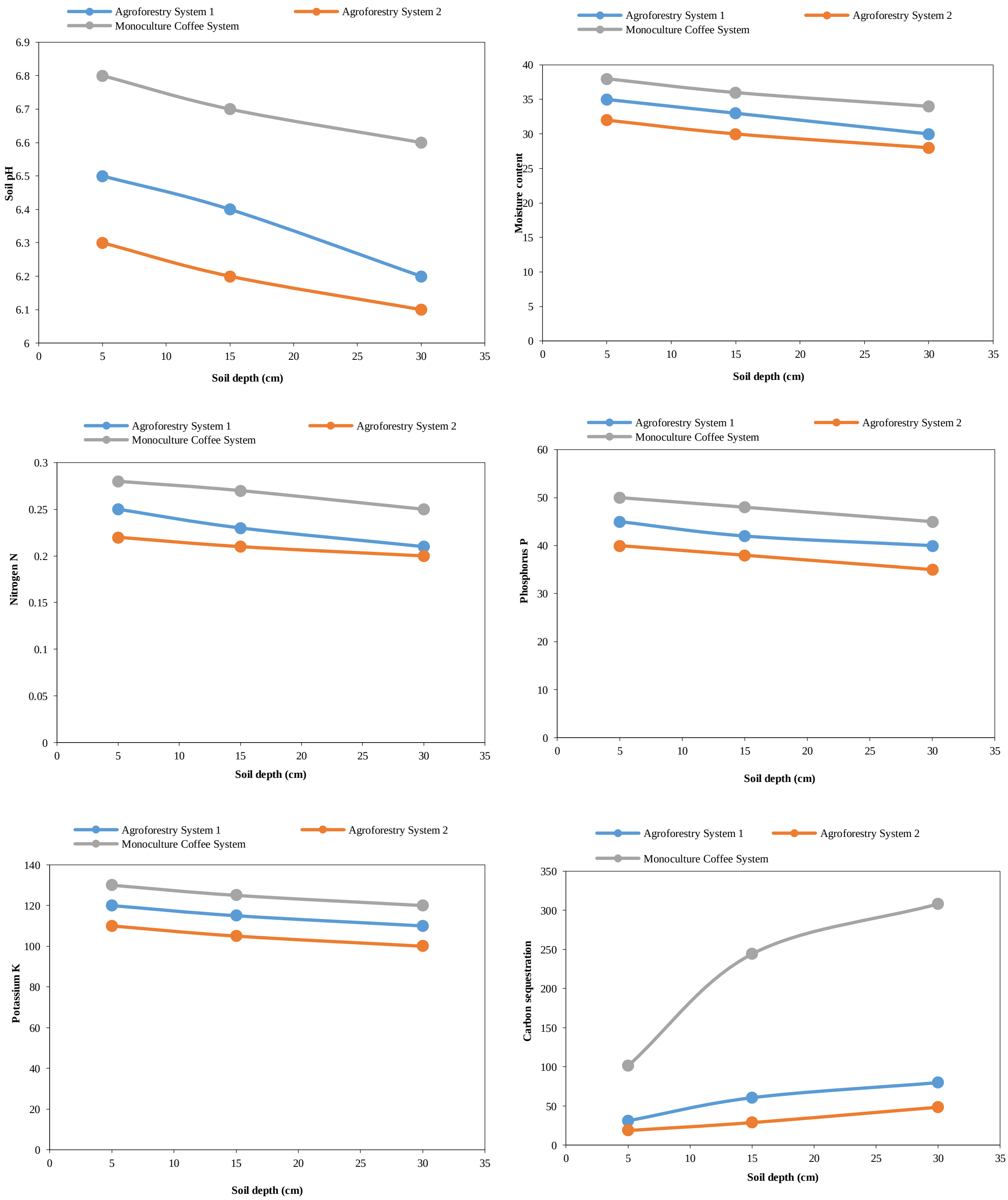

Fig. 4. Soil properties and C sequestration by depth in combined different land-use systems.

3.6. Comparative Carbon Sequestration Dynamics and Implications

Assessing the interrelationships among biomass, soil organic carbon (SOC), and soil properties indicates that both tree-based agroforestry systems are likely to sequester more total carbon than other land uses, especially the *P. kesiya*–coffee system. This result also highlighted the benefits of a diverse, perennial-based system vs. monoculture coffee. Although SOC in MCS can be high due to intensive management, it does not have the large, persistent biomass stocks found in agroforestry.

These results are consistent with the observation that agroforestry systems can store much more carbon than monocultures by combining vertical stratification, perennial biomass, and continuity of organic inputs (Ehrenbergerová et al. 2015; Garedew 2019; Niguse et al. 2022; Walsh et al. 2025). When combined with deep-rooted and/or nitrogen-fixing trees, mixed-species systems are even better at soil structure, nutrient cycling, and stabilization of SO (Koutika et al. 2021; Melinda and Takalapeta 2021; Tonucci et al. 2023). Roba (2017) and VijayKumar et al. (2024) also concluded that deep-rooting and N_2-fixing tree species promote soil organic carbon accumulation, findings similar to those of Haider et al. (2024) and Sivakumar and Manimaran (2025).

From a management perspective, the results highlight two complementary principles: 1) Structural enhancement via tree integration (as in Agroforestry System 1) maximizes total carbon stocks and ecosystem resilience; 2) Long-term soil management (such as mulching, minimal disturbance, and organic inputs) is paramount to maintain SOC in all systems (Adekiya et al. 2023; Matsumoto et al. 2020; Singh et al. 2024).

This is very much in line with King's philosophy, which emphasizes balanced development, ecological regeneration, and long-term contributions to local communities. The Phu Phayak example shows that agroforestry underpinned by this philosophy can serve as a pragmatic model for mitigating climate change, rehabilitating soils, and improving livelihoods in highland landscapes. Combined with innovative incentives such as payments for ecosystem services (PES) and carbon credits initiatives, those systems provide a scalable path to integrate carbon sequestration, biodiversity protection, and sustainable production into regional and national climate policies (Houghton 2020; IPCC 2019; Sharma and Shah 2025; Tasfiah 2024).

4. Conclusions

This study demonstrates that trees in coffee agroecosystems contribute significantly to total C sequestration, especially deep-rooted, fast-growing species such as *Pinus kesiya*. The total C stock attained the highest value under the *P. kesiya*–coffee system (226.312 Mg.C/ha), followed by the *Morus*–*Mangifera*–coffee system (76.408 Mg.C/ha), and the lowest under monoculture coffee (655.901 Mg.C/ha). These findings reinforce the idea that AF not only provides multiple ecological benefits by integrating above- and belowground carbon pools with the SOC pool, but also increases the magnitude and stability of potential C sinks in tropical highland areas. The SOC content was higher in the monoculture coffee system, primarily due to intensive mulching and minimal soil disturbance, but the total ecosystem carbon pool was low due to poor biomass accumulation. This disparity highlights that structural complexity, root penetration depth, and litterfall inputs in systems are key long-term controls on carbon sequestration. A further demonstration of the interplay between vegetation structure and soil fertility parameters (pH, N, P, and K) shows that the relative contributions of ecological and edaphic factors depend on sequestration efficiency. On a regional level, the Phu Phayak Highland Agricultural Development Station is an example of how His Majesty the King's approach to development based on sufficiency economy through reforestation and watershed management, enhanced agriculture and sustainable communities, can work well. Once established, these agroforestry systems are a win-win because they are multifunctional, increasing carbon sequestration, oil health and smallholder mountain farmers' livelihoods. At the policy level, this research has demonstrated that too much is at stake to leave agroforestry outside national climate change mitigation matrices and payment schemes, including temperate zone (T-VER) and PES. Scaling up the tree-based approach in the highlands of Thailand would help substantially knock down targets, both those from the Paris Agreement and those set by national development plans to build a low-carbon society. We conclude that by combining ecological design and local wisdom in agroforestry management, the restoration of degraded land can not only be achieved, but also ensure carbon balance and socio-economic resilience over the longer term. Future research needs to focus on monitoring long-term soil C fluxes, species-specific sequestration efficiencies, and socio-economic co-benefits to maximise agroforestry as a flagship of climate-smart landscapes.

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Author Contributions

C.P.: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft Preparation; K.K.: Investigation, Resources, Data Curation; S.N.: Software, Validation, Visualization, Writing – Review and Editing; S.M.: Supervision, Project Administration, Funding Acquisition.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve language clarity, refine the academic tone, and check the consistency of references. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

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