

**SOIL ORGANIC CARBON SEQUESTRATION DURING
THE RESTORATION OF UPLAND EVERGREEN
FOREST IN NORTHERN THAILAND**

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**BACHELOR OF SCIENCE
(ENVIRONMENTAL SCIENCE)**

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MARCH 2026

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Dedication

To my beloved parents, my dear sister and my great teachers,

I would like to thank them for their unconditional love, endless support, encouragement, and sacrifices throughout my academic journey. This achievement would not have been possible without their constant belief in me.

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First of all, I deeply thank my advisor, Assoc. Prof. Dr. Steve Elliott, for his invaluable guidance, constructive feedback, and continuous support throughout the completion of my bachelor's thesis. His expertise and encouragement greatly contributed to the development and quality of this research. My sincere appreciation is extended to the [Forest Restoration Research Unit \(FORRU-CMU\)](#) and [The Next Forest](#) for funding and supporting this project. I am especially grateful to my friends, Htet Aung Khant, Nay Tun Lin, and Pyae Shan Tun, for their technical assistance, field equipment support, and help during fieldwork throughout this [BKIND project](#). Finally, I thank the professors and staff of the Environmental Science Research Center, Chiang Mai University, for their guidance and support throughout my academic journey.

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Abstract

This study evaluated sequestration of soil organic carbon (SOC) during restoration of upland evergreen forest by the framework species method (FSM) in northern Thailand. Soil samples were collected from four plots: 12-year restoration forest, 24-year restoration forest, reference forest (natural forest), and control (abandoned agricultural field). By using a customized split-core sampler at three different depths (0-5 cm, 5-10 cm, and 10-15 cm), soil samples were collected from eight sampling points per plot. SOC was analyzed at each depth, along with nitrogen (N), phosphorus (P), potassium (K) and pH. Natural forest had the highest SOC at 56.94 tC/ha, followed by the 12-year-old restoration (R12) plot, at 48.74 tC/ha. The control plot had a lower SOC stock at 38.20 tC/ha, while the 24-year-old restoration (R24) plot showed the lowest SOC stock among the studied sites with 33.10 tC/ha. The restored plots showed higher N and K and slightly lower pH than the control plot, indicating enhanced nutrient accumulation and organic matter cycling during forest recovery. Phosphorus levels were elevated in the control plot (probably due to fertilizer application) and lower in both the restored and reference plots. The results demonstrated that the FSM can increase SOC levels and soil fertility in the first decade, but land-use legacy can influence such variables long after restoration has been initiated. The study raises the possibility of generating carbon-credit income to pay restoration costs and incentivize stakeholders through enhanced soil-carbon sequestration in restored upland evergreen forests.

Keywords: Soil organic matter, Soil organic carbon, Climate change, Forest restoration, FORRU, Framework species method

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LIST OF ABBREVIATIONS

Term	Definition
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
FSM	Framework Species Method
FORRU-CMU	Forest Restoration Research Unit, Chiang Mai University
CMU	Chiang Mai University
ANOVA	A statistical method used to compare differences among group means
RES	Restoration Site
R12	12-year-old Restoration Forest (planted in 2012)
R24	24-year-old Restoration Forest (planted in 2000)
REF	Reference Forest
RFF	Remnant Forest Fragment
CONTROL	Abandoned Agricultural Control Plot
Gt	Gigatonne
Mt	Megatonne

Pg	Petagram
SU	Sampling Unit
N	Nitrogen
P	Phosphorus
K	Potassium
IPCC	Intergovernmental Panel on Climate Change
FAO	Food and Agriculture Organization
T-VER	Thailand Voluntary Emission Reduction Program
MEMS	Microbial Efficiency–Matrix Stabilization
NPP	Net Primary Productivity

GLOSSARY

Term	Definition
Abandoned Agricultural Land	Former farmland that is no longer cultivated and is often used as a control site in restoration studies
Aboveground Biomass	The total mass of living plant material above the soil surface, including stems, branches, and leaves
Biodiversity Recovery	The process by which species richness, abundance, and ecological interactions return following ecosystem restoration
Carbon Sequestration	The process of capturing and storing atmospheric carbon dioxide in vegetation, soils, and other carbon pools
Ecosystem Restoration	The process of assisting the recovery of a degraded, damaged, or destroyed ecosystem
Framework Species Method (FSM)	A forest restoration approach that uses selected native tree species to accelerate natural regeneration and attract wildlife
Net Primary Productivity (NPP)	The rate at which plants accumulate biomass after accounting for respiration losses
Reference Forest	A mature or relatively undisturbed forest used as a benchmark to evaluate restoration success

Restoration Site	An area where ecological restoration activities have been implemented to recover ecosystem structure and function
Soil Organic Carbon (SOC)	The carbon component of soil organic matter derived from decomposed plant and animal residues
Soil Organic Matter (SOM)	Organic components of soil, including plant and animal residues at various stages of decomposition
Species Richness	The number of different species present in a given area

CHAPTER 1

Introduction

1.1 Background

Climate change is one of the most pressing environmental issues of the 21st century (IPCC, 2021). It is caused by a rise in greenhouse gases in the atmosphere, particularly carbon dioxide, driven primarily by the burning of fossil fuels and land-use change. Human activities release approximately 40 Gt of CO₂ annually, of which 70% comes from the burning of fossil fuels. The remaining 30% is emitted by land-use change (Friedlingstein et al., 2020). Deforestation, alone, accounts for nearly 10% of global carbon dioxide emissions each year (Baccini et al., 2017). When forests are cleared or degraded, large amounts of carbon stored in vegetation are released as carbon dioxide, while soil organic carbon (SOC) is rapidly depleted by erosion and reduced organic inputs (Don et al., 2011). Therefore, strong forest restoration and conservation efforts are needed to reduce carbon emissions and thus help to mitigate climate change.

Soil organic carbon (SOC) is one of the largest carbon stores in the terrestrial biosphere. It plays an important role in global climate regulation (FAO, 2017). Globally, soils store more carbon than the atmosphere and vegetation combined, which makes them a critical component of climate-mitigation strategies (FAO, 2017). The accumulation of SOC results from the balance between carbon inputs from leaf litter fall, dried root and losses due to decomposition, disturbance and wildfires (Cotrufo et al., 2015). In forest ecosystems, SOC contributes to nutrient cycling, soil fertility and long-term ecosystem stability. It is estimated that forest soils contain a carbon stock that is at least three times larger than the carbon within the living biomass of forest ecosystems (Carvalhais et al., 2014).

Tropical forests are among the world's largest carbon sinks. This is due to their high net primary productivity (NPP), which is sustained by warm temperatures, abundant moisture and continuous year-round ideal growing conditions (IPCC, 2019). However, human population growth, resulting in deforestation and expansion of agricultural and urban landscapes, has reduced forest cover and decreased carbon storage across Southeast Asia (Murdiyarso et al., 2008). In 2020, Thailand retained 17 Mha of natural forest, representing 33% of its land area. In 2024, the country lost

63,000 hectares of natural forest, resulting in an estimated 29 Mt of CO₂ emissions (Global Forest Watch, 2024). Upland evergreen forests are particularly important because they support high biodiversity, regulate watershed hydrology and store large amounts of SOC (Giambelluca and Gerold, 2011). In these montane systems, soil carbon is sensitive to land-use history, disturbance and restoration practices.

Forest restoration results in rapid accumulation of biomass (of which just under half is carbon), which ends up in the soil when trees shed leaves, branches and eventually die. Active restoration, involving the planting of native forest tree species and managing competing vegetation, accelerates forest recovery much faster than passive natural regeneration (Elliott et al., 2013). The Forest Restoration Research Unit (FORRU-CMU) in Chiang Mai has implemented restoration projects for over 30 years, creating chronosequences of restored evergreen forest plots that provide valuable opportunities to evaluate long-term soil biomass recovery (Elliott et al., 2019). In evergreen forests, the dynamic interactions between vegetation, soil microorganisms, and soil organic matter (SOM) influence SOC sequestration. Forest restoration has great potential to enhance carbon storage and soil health significantly, particularly when the framework species method (FSM) is employed (Jantawong et al. 2017).

Another important development is the emergence of various carbon-credit schemes in Thailand as financial mechanisms to fund forest conservation and restoration. Under the Mae Fah Luang Foundation's Carbon Credit from Community Forests for Sustainability project, local communities receive payments when their forests are verified under the national T-VER (Thailand Voluntary Emission Reduction Program) voluntary carbon-credit system, and the generated credits are sold to companies seeking to offset their emissions (Mae Fah Luang Foundation, 2023)). These payments directly support essential forest-management activities, including fire prevention, patrolling, and enrichment planting, while also contributing to community development funds and livelihood diversification (Mae Fah Luang Foundation, 2023). Such actions provide communities with a more stable long-term income rather than traditional agriculture, which is vulnerable to climate and market price fluctuations. As emphasized by the Thailand Development Research Institute, integrating carbon markets into local economies helps to shift incentives toward forest protection and strengthens local economic resilience (Tangkitvanich, 2023). In this way, Thailand's growing forest-based carbon-credit sector offers a pathway to deliver mutually

reinforcing benefits: climate-change mitigation, ecological recovery and improved community well-being. However, such mechanisms rely on accurate assessment of forest carbon (including soil carbon) and an understanding of the factors that might affect SOC accumulation.

1.1.1 Research Objectives

This study tested the hypothesis that forest restoration age under the Framework Species Method (FSM) increases soil organic carbon (SOC) stocks progressively towards levels typical of remnant upland evergreen forests. It evaluated SOC accumulation in upland evergreen forest restoration plots in the Upper Mae Sa Valley, Chiang Mai Province, northern Thailand, where forest restoration plots were established annually since 1996. By comparing SOC levels in control plots (no restoration), restoration plots of different ages and the reference forest, this study provides insights into the long-term recovery of below-ground carbon and the effectiveness of FSM in restoring soil conditions toward those of natural forests. In addition to SOC, key soil variables: nitrogen (N), phosphorus (P), potassium (K), soil pH and soil moisture were also assessed, to better understand nutrient status and soil health across sites. The results are expected to contribute towards improving forest-restoration strategies and strengthening the role of restored forests in climate-change mitigation.

1. To evaluate soil organic carbon (SOC) accumulation across four sites:
 - i. control plots (abandoned agricultural land),
 - ii. 12-year-old restoration forest,
 - iii. 24-year-old restoration forest, and
 - iv. reference forest (Pha Dong Seang natural upland evergreen forest).

2. To assess the effects of the framework species method (FSM) on a range of other soil variables compared with remnant evergreen forests.

1.2 Literature Review

1.2.1 Soil organic carbon in tropical forests

Soil organic carbon (SOC) is a fundamental component of tropical forest ecosystems because it underpins nutrient cycling, soil fertility, microbial activity and long-term carbon sequestration. Although tropical forests store a greater proportion of their total carbon in biomass (56%) than in soils (32%), this distribution contrasts sharply with boreal forests, where approximately 60% of carbon is stored in soils and only 20% in biomass (Pan et al., 2011). At the global scale, total soil carbon in the upper 100 cm of the world's terrestrial surface is estimated at 2157–2293 petagrams of carbon (Pg C). This roughly 1462–1548 Pg C is held as soil organic carbon, while an additional 695–748 Pg C occurs as soil carbonate carbon (Batjes, 1996). Soil organic carbon (SOC) dynamics are driven by inputs from litterfall, fine root turnover and rhizodeposition, while carbon losses occur through microbial decomposition, leaching and physical erosion (Six et al., 2002). Furthermore, fire acts as both a loss and transformation pathway for SOC, causing immediate carbon losses through combustion and erosion, while simultaneously producing pyrogenic carbon forms that may contribute to longer-term soil carbon persistence, as well as destroying the plants that would have added carbon to soils subsequently (Santín & Doerr, 2016).

Among forest types, tropical forests contribute disproportionately to SOC sequestration, due to their year-round primary productivity and rapid organic matter inputs (IPCC, 2019). When soils remain undisturbed, tropical forests function as strong carbon sinks; however, soil organic carbon (SOC) in these regions declines rapidly when forests are cleared, degraded or repeatedly cultivated (Don et al., 2011). In the lowland humid tropics, land-use intensification and forest conversion result in substantial losses of total ecosystem carbon, with natural forests maintaining the highest above and below-ground carbon stocks. In contrast, grasslands retain only a small fraction of their original carbon (Murdiyarso et al., 2002). In subtropical montane forests, SOC increases at higher elevations, primarily because lower temperatures slow down microbial decomposition, while forest-type differences in litter quality, species richness and stand attributes further modulate SOC accumulation (Fan et al., 2025).

1.2.2 Soil recovery during restoration

Many studies show that restoring forest structure and function can substantially increase SOC, compared with degraded or agricultural land, although recovery rates vary widely, depending on climate, soil type, restoration method and the degree of disturbance (Silver et al., 2000; Lang et al., 2019). Restoration is crucial for re-establishing and stabilizing long-term soil-carbon storage, because tropical soils often lose substantial proportions of SOC, immediately following deforestation and even more when converted to agricultural land (Don et al., 2011).

Active restoration approaches, such as the framework species method (FSM), substantially accelerate ecological recovery, compared with passive natural regeneration (Elliott et al., 2022). The method involves planting fast-growing, canopy-forming native tree species that rapidly shade out weeds, attract seed-dispersing animals, and create microhabitats conducive to natural forest succession (Elliott & Blakesley, 2013). By promoting rapid biomass accumulation, increased litterfall and extensive root development, the FSM enhances both organic matter inputs and soil biological activity, which are key drivers of SOC formation. Kavinchan et al. (2015) showed that in restored forests, established by the FSM, soil carbon increased over the first 14 years of recovery, although legacy effects of past land use confounded direct comparisons with abandoned agricultural or naturally regenerating sites. However, comparisons between active restoration and natural regeneration remain debated. Reid et al. (2018) showed that studies favoring natural regeneration may be influenced by site selection bias. Natural regeneration is often studied in areas where forest recovery has already begun, while active restoration is typically implemented in more severely degraded sites. Therefore, active restoration and natural regeneration should be viewed as complementary strategies, and their effectiveness depends largely on site conditions and the level of initial degradation.

Forest restoration also improves soil physico-chemical properties, which indirectly support SOC stabilization. Forest restoration gradually improves soil conditions by creating a cooler, more shaded environment, thus promoting soil moisture retention and reducing erosion. Such changes improve soil structure and help to stabilize soil organic carbon (Ghazoul & Chazdon, 2017). Vegetation recovery increases litterfall and root turnover, which enhance decomposition and return nitrogen (N) and potassium (K) to the soil, while phosphorus (P) often becomes depleted, because

plant uptake exceeds replenishment in subtropical restored forests (Xu et al., 2018). Improved nutrient inputs and vegetation recovery often enhance microbial activity. According to the microbial efficiency-matrix stabilization (MEMS) framework, these microbial processes are responsible for transforming plant litter into microbial products that become stabilized as mineral organic carbon, through binding with soil minerals (Cotrufo et al., 2013). These improvements underline how restoration accelerates the transition from labile to more stable carbon stores, increasing the long-term persistence of SOC.

Despite these positive movements, global syntheses show that restored forests rarely recover soil organic carbon (SOC) stocks to the levels of intact natural forests within the first several decades of regrowth (Silver et al., 2000; Guo & Gifford, 2002). Furthermore, Poeplau et al. (2011) reported that SOC recovery, after land-use change, can be slow in previously managed or disturbed soils, with initial losses influenced by site preparation, cessation of carbon inputs and reduced soil-biota activity. Nevertheless, restoration remains one of the most effective natural solutions to climate change, in terms of recovery of SOC in tropical ecosystems. In short, forest restoration re-establishes critical pathways for accelerating ecosystem recovery, improving soil fertility and enhancing resilience to climate change (Kavinchan et al., 2015). In Northern Thailand, long-term restoration initiatives, such as the FSM projects of FORRU-CMU, demonstrate that actively restored forests can accumulate substantial SOC and bring out substantial ecological recovery, when protected and well-managed over time (Elliott, 2019). Overall, evidence strongly supports the role of forest restoration, as a key strategy for enhancing SOC, especially when restoration techniques incorporate ecological principles, long-term management and species diversity.

1.2.3 Vegetation effects on soil-carbon dynamics

Plant functional traits, such as life span, biomass allocation patterns, productivity, and tissue chemical composition, play a crucial role in regulating soil organic carbon (SOC) accumulation and soil nutrient cycling (Matson, 1990). For instance, in tropical plantations, soil carbon storage varies among tree species: vegetation with a high proportion of nitrogen-fixing tree species sequesters 2.3 tC ha⁻¹ more than pure *Eucalyptus* stands after 17 years of afforestation in Hawaii (Kaye et al., 2000). Accordingly, the potential for soil-carbon sequestration cannot be accurately assessed without considering vegetation characteristics and species functional traits (Garcia-Oliva

& Masera, 2004). The introduction of native and non-native planted species further modifies ecosystem carbon dynamics by influencing plant growth rates, carbon allocation strategies and organic matter quality, which together affect both the quantity and residence time of carbon within ecosystems (Lugo, 1992).

Therefore, understanding the long-term impacts of reforestation on plant-community structure and ecosystem functioning is essential for the enhancement of both carbon sequestration and biodiversity conservation (Silver et al., 2000). Soil-carbon storage can be further increased by enhancing organic matter inputs, promoting deeper carbon accumulation, increasing soil-carbon density and reducing carbon turnover rates within soil systems (Post & Kwon, 2000). According to Rasse et al. (2005), root biomass and other below-ground carbon inputs are often more important for long-term soil-carbon stabilization than aboveground litter alone, particularly in forest ecosystems. Moreover, microbial activity and root–microbe interactions play key roles in controlling soil-carbon persistence by regulating decomposition rates and carbon protection within soil aggregates (Six et al., 2002).

1.2.4 Forest restoration

Forest restoration on degraded tropical lands encompasses a spectrum of methodologies, broadly categorized into passive restoration (or natural regeneration) and active restoration (interventions involving planting or structural manipulation) (Chazdon, 2017). The choice of method is primarily dictated by the degree of degradation, the presence of resilient soil seed banks, proximity of restoration sites to intact seed sources and the availability of resources (Holl & Aide, 2011). Natural regeneration is widely recognized as the most cost-effective restoration pathway, where densities of remnant tree seedlings, saplings and live tree stumps remain high and where seed-disperser communities remain intact and a nearby remnant of mature forest remnants are nearby. A study showed that naturally regenerating Neotropical secondary forests can recover up to approximately 90% of old-growth above-ground biomass over several decades, although the rate of recovery strongly depends on water availability, soil fertility and prior land-use intensity (Poorter et al., 2016). Moreover, on highly degraded lands, dominated by herbaceous vegetation, the successional trajectory is often arrested, resulting in low biodiversity and high fire risk. Where tree-seed dispersal across the landscape is limited and/or where fires are frequent, the “grassland”

stage persists for decades, with minimal ecological recovery and biomass accumulation (Elliott, 2019).

The Forest Restoration Research Unit (FORRU) at Chiang Mai University has been developing the framework species method (FSM) of restoration since 1994. It is an approach to forest-ecosystem restoration, originally conceived in Australia (Goosem & Tucker, 1995), designed to accelerate natural forest regeneration by planting 20 to 30 native tree species that are representative of the pre-disturbance (reference) forest ecosystem and which also perform well on exposed deforested sites, suppress weed growth and attract seed-dispersing wildlife (Elliott et al., 2022). Jantawong et al. (2017) reported that in forest restored by the FSM, above-ground tree carbon accumulation amounted to 105.8 tC/ha over 14 years after tree planting—a level that is already approaching that of mature natural forest in the vicinity (181.5 tC/ha). In a recent assessment of forest restoration using the FSM in northern Thailand, restored plots accumulated 87.46 tC/ha (49% of reference forest levels) in aboveground tree carbon after 12 years and 149.84 tC/ha (84%) after 24 years (Tun, 2025).

CHAPTER 2 Methodology

2.1 Study site

The study was conducted in the upper Mae Sa Valley, Mae Rim District, Chiang Mai Province, northern Thailand, above the Hmong hill tribe communities of Ban Mae Sa Mai and Ban Mae Sa Noi ($18^{\circ}52'07.24''$ N, $98^{\circ}51'08.47''$ E) at an elevation of approximately 1,018 m above sea level (Figures 1 and 2). This area lies within Doi Suthep Pui National Park and has long served as a demonstration site for forest-ecosystem restoration research by the Forest Restoration Research Unit of Chiang Mai University (FORRU-CMU).

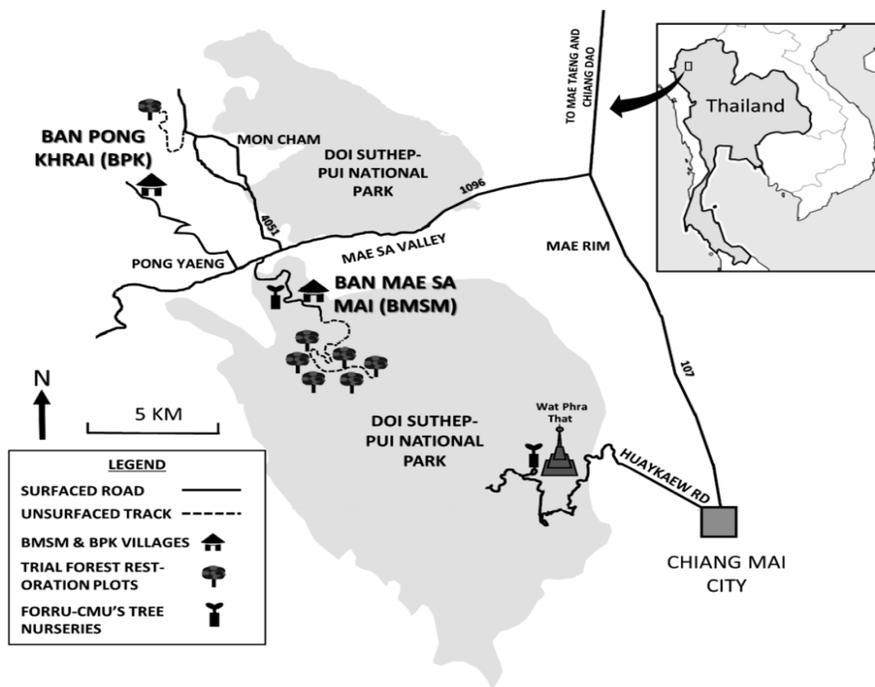


Figure 1. Location of the study area in relation to Chiang Mai,

Table 1 shows pre-restoration soil physical and chemical properties measured in 1997 at the restoration site and in the primary evergreen forest at the same altitude (at Tum Reusi). Soil pH was significantly lower at the restoration site than at the evergreen forest (mean \pm SD: 5.4 ± 0.42 vs. 6.2 ± 0.54 , $p < 0.001$). Soil organic matter and total nitrogen were also significantly lower at the restoration site, whereas total phosphorus was significantly higher. No significant differences were observed for exchangeable potassium or soil moisture at field capacity. Soil texture at both sites was classified as sandy loam, although the restoration site had a higher sand content and lower silt and clay fractions compared with the evergreen forest (Elliott et al., 2000).

2.2 Community

Ban Mae Sa Hmong hill-tribe communities (Ban Mae Sa Mai and Ban Mae Sa Noi) are located in the upper Mae Sa Valley, Chiang Mai Province, within Doi Suthep–Pui National Park. Originally, the area was covered by primary evergreen seasonal forests (Maxwell & Elliott, 2001). The village was established in 1922 and was relocated in the early 1960s. Following its inclusion in the national park in 1981, the community experienced land tenure insecurity due to legal restrictions on settlement and land use (Elliott et al., 2019). In response, local leaders formed the Ban Mae Sa Mai Natural Resources Conservation Group in the early 1990s and they designated the Pah Dong Saeng area as a community forest to control forest use and wildlife exploitation and protect water sources, by locally enforced rules (Elliott et al., 2019).

As a result of prolonged land-use pressure, the site is considered to be stage-3 degradation (Elliott et al., 2013). Initial restoration efforts, with plantation species supplied by the Royal Thai Forest Department, were unsuccessful, but subsequently, the community began a long-term collaboration with Chiang Mai University’s Forest Restoration Research Unit (FORRU-CMU), using the framework-species method (mixed native forest tree species). This partnership, involving villagers, researchers, and national park officials, led to successful forest restoration and improved watershed services (Elliott et al., 2019). Following the administrative division of the village in 2004, the communities now comprise a combined population of around 1300 people, with livelihoods based on agriculture, handicrafts and employment at nearby institutions such as the Queen Sirikit Botanical Garden (Elliott et al., 2019). Between 1997 and 2013, a total of 33 hectares of upland evergreen tropical forest were restored in the study area. Restoration plots were

established between 1996 and 2013 through a long-term collaboration between the local community. Plots were planted annually, using the framework-species method. Restoration activities were implemented on previously abandoned agricultural land, characterized by low densities of natural regenerants and dominance of herbaceous weeds (Elliott et al., 2013). This restoration effort was successful, leading to the recovery of biodiversity and the re-establishment of key ecosystem services within the restored landscape (Elliott et al., 2019).

The target ecosystem for restoration was the upland evergreen forest that historically dominated the upper Mae Sa Valley before agricultural expansion during the mid-20th century (Maxwell & Elliott, 2001). This forest type is characterized by a closed canopy, high tree species diversity and year-round carbon inputs from litterfall. Control plots in this study were abandoned agricultural fields (pre-restoration conditions) that had been left to regenerate naturally, while nearby remnant old-growth evergreen forest was used as a benchmark target for long-term recovery of soil organic carbon (Elliott et al., 2019).

2.3 Soil samples collection procedure

Soil organic carbon (SOC) levels were examined across four distinct plot types, representing different stages of ecosystem recovery: (1) control plot (CON) abandoned agricultural fields (starting conditions before restoration), (2) 12-year restoration forest (R12), (3) 24-year restoration forest (R24) and (4) remnant mature reference forest (RFF). Across each of the 4 sites, 8 circular subplots (radius 5 m) were positioned randomly (to reduce spatial bias and capture within-plot variability) for a parallel survey of the woody vegetation (Figure 3).

Soil samples were collected in each of the 8 survey circles, 1 meter north of each center pole (i.e. rules-based sampling to prevent bias) (Figure 3). The samples were collected using a 7.5 cm diameter split-core soil sampler (Figure 4), which allowed standardized extraction across all plots. Since such samplers were not commercially or locally available, it was co-designed by myself and a local mechanic to ensure appropriate dimensions, durability, and suitability for field conditions. The sampler was a cylindrical tube and constructed from stainless steel, with an internal diameter of 7.5 cm and a length of 30 cm, designed to extract intact soil cores to the target sampling depth. The lower end of the sampler was sharpened to facilitate penetration into the soil, while the upper end was reinforced to withstand manual hammering during insertion. A labeled schematic diagram

of the sampler, including dimensions and materials (Figure 4). Each extracted soil core was carefully sectioned into three depth intervals (0–5 cm, 5–10 cm, and 10–15 cm) to allow depth-specific analysis. Samples were immediately placed in labeled zip-lock bags after collection to minimize moisture loss and preserve sample integrity. Wet and dry soil masses were recorded, and visible stones and roots were removed to maintain sample integrity (Figure 5).



Figure 3. Example of baseline photo-monitoring around the 2nd circular sample plot center in restored forests.



Figure 4. Split-core soil sampler used for soil profile collection, with samples separated into three different depth intervals.

2.4 Measurements

In the laboratory, the soil samples were first dried (Figure 6) to remove surface moisture and then dried at 105°C for 24 hours in the oven. The samples were then sieved through a 2-mm mesh to eliminate debris. The dried samples were weighed using an electronic balance. The Soil samples from the two adjacent sampling units (SUs) were combined for analysis of soil organic matter (SOM). As a result, four composite samples per site were obtained for each of the three soil depths. These samples were analyzed at the CMU Agricultural Soil Laboratory for SOM content, using the Walkley–Black method, which estimates SOM based on the loss of sample weight following oxidation with potassium dichromate and sulfuric acid (Walkley & Black, 1934). Soil organic matter (SOM) values were converted to soil organic carbon (SOC), using a conversion factor of 0.58 (Nelson & Sommers, 1996).

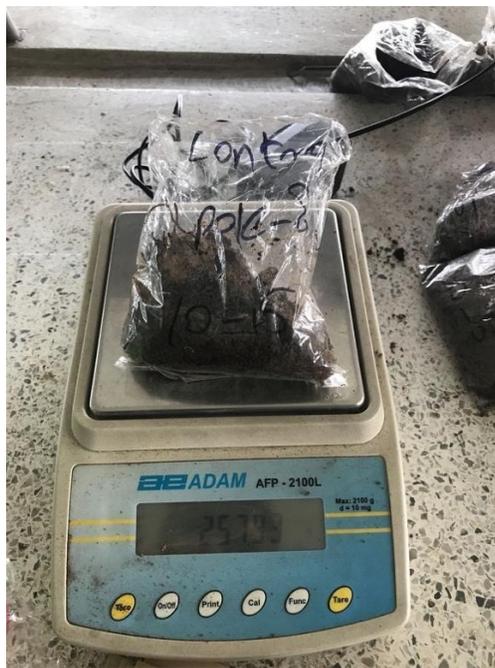


Figure 5. Measurement of fresh soil sample weight prior to laboratory analysis.

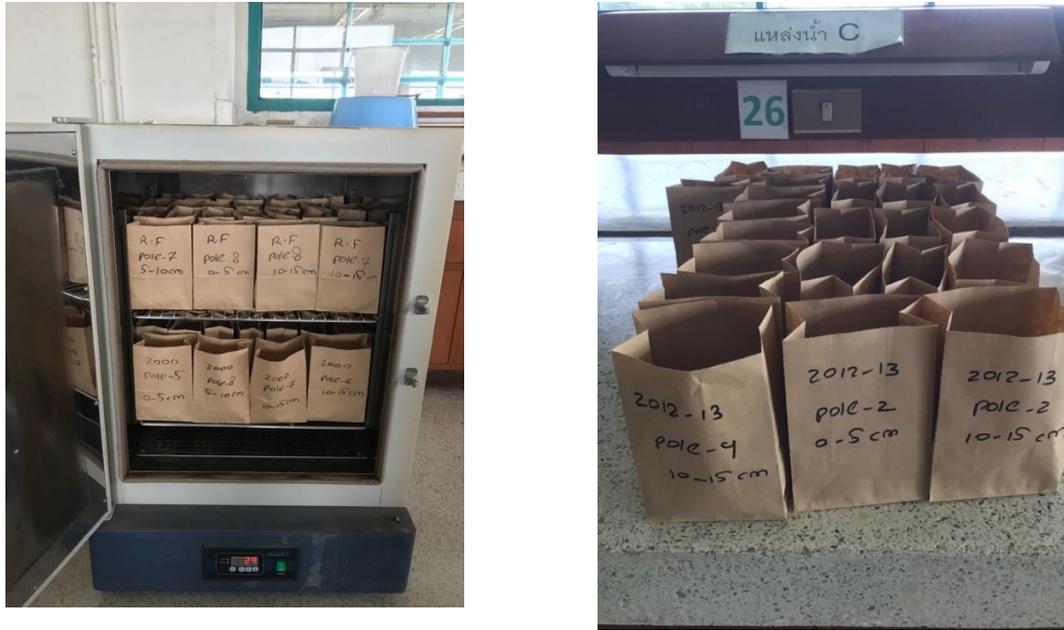


Figure 6 . Measurement of fresh soil sample weight prior to laboratory analysis.

To ensure analytical accuracy and minimize potential laboratory errors, three standard samples with known carbon concentrations (5%, 10% and 15%) were prepared. These standards were produced by homogeneously mixing activated charcoal (85% carbon) with pure sand (containing 0% carbon). A mass-balance equation was applied to determine the precise quantity of charcoal required to achieve each target carbon concentration. The prepared standards were included alongside forest soil samples during laboratory analysis. Deviations between measured and known carbon values were subsequently used to calculate correction multipliers to increase the accuracy of the absolute soil-carbon concentration.

The deviation between laboratory-measured values and known standard carbon concentrations varied with carbon content. Therefore, an empirical correction equation was derived using curve fitting based on a scatter plot of the difference between the laboratory-reported values and the known carbon contents of the standards plotted against the reported laboratory results. This equation was then used to calculate correction factors, which were applied to all soil samples according to their reported carbon values.

The critical data thus obtained were: i) total mass (g) of dry soil of each of 8 cores (15 x 7.5 cm) and 24 sub-cores, per site and ii) four determinations of SOM at 3 depths per site from the lab

analysis. Carbon in each sub-core (in gm) was determined by multiplying each sub-core dry mass (gm) by the lab-derived per cent carbon content at each respective SU-pair, divided by 100. The carbon mass per sub-core (gm), thus derived, was then divided by the cross-sectional area of the core (44.2 cm), to calculate a value for SOC in gm/cm for each sub-core. The result was multiplied by 100,000,000 to get a value “per ha” and divided by 1,000,000 to convert grams to metric tonnes, thus resulting in the following equation:

$$\text{Soil C (t ha}^{-1}\text{)} = \frac{\text{Core dry mass (g)} \times (\% \text{ C}/100) \times 100,000,000}{(3.14159 \times (\text{core radius (cm)})^2) \times 1,000,000}$$

Carbon values from all three sub-cores within each of the eight sampling units per site were summed to estimate total soil carbon stocks per hectare to a depth of 15 cm.

Additional lab analyses quantified soil fertility parameters: total nitrogen (N), available phosphorus (P), exchangeable potassium (K), soil pH and soil moisture. Total nitrogen was determined using the Kjeldahl digestion method, while available phosphorus was measured using the Bray II extraction method. Exchangeable potassium was analyzed by ammonium acetate extraction followed by flame photometry. Soil pH was measured in a soil water suspension using a pH meter, and soil moisture content was determined gravimetrically by oven-drying the samples. These parameters were selected because they are widely used indicators of soil fertility, nutrient availability and biogeochemical cycling in forest ecosystems. Nitrogen, phosphorus and potassium are essential macronutrients that regulate plant growth and microbial activity, while soil pH influences nutrient solubility and microbial processes. Soil moisture was measured to account for its strong control on microbial activity, organic matter decomposition and nutrient mobility.

Subsamples from each depth layer (0–5 cm, 5–10 cm, and 10–15 cm) were homogenized, prior to analysis, to ensure representativeness. Total nitrogen was determined to evaluate the recovery of organic matter-associated nutrients during forest restoration. Available phosphorus and exchangeable potassium were measured to assess nutrient replenishment following land-use change and to examine differences in nutrient retention among forest age classes. Soil pH was measured to characterize soil chemical conditions that regulate nutrient availability and to identify

potential legacy effects of past land use. Soil moisture was determined by oven-drying subsamples at 105°C for 24 hours to constant weight. Samples were reweighed after drying to ensure no further weight loss before calculating moisture content. The resulting dry mass was used to correct nutrient concentrations and to support the interpretation of SOC and nutrient dynamics across plots.

CHAPTER 3

Results and Discussion

3.1 Results

3.1.1 Soil organic carbon

Table 2. Soil organic matter (SOM), soil organic carbon (SOC) and bulk density in control (CON), restoration sites (R24 and R12) and reference forest (REF), compared with pre-restoration levels and Tum Reusi reference forest REF(TR) (1997). Mean values not sharing the same superscripts are significantly different among sites ($P < 0.05$). nd=no data.

Soil property	SITES					
	Pre-restoration 1997 (n=16)	CON (n=4)	R12 (n=4)	R24 (n=4)	REF (PSD) (n=4)	REF(TR) 1997 (n=20)
SOM (%)	5.35 ^c	5.73 ^{bc}	9.83 ^a	6.59 ^b	9.96 ^a	7.3 ^{ab}
/100g	±0.1	±1.53	±2.29	±1.35	±3.43	±2.48
SOC (%)	3.10 ^c	3.32 ^{bc}	5.70 ^a	3.82 ^b	5.78 ^a	4.24 ^{ab}
/100g	±0.57	±0.89	±1.33	±0.78	±1.92	±1.44
Bulk density (g/cm ³)	nd	1.54 ^a ±0.05	1.15 ^b ±0.13	1.16 ^b ±0.03	1.35 ^b ±0.14	nd

Mean SOM and SOC differed significantly among forest types (t-test, $p < 0.05$; Table 2). R12 and REF values were significantly higher than both the CON and R24 values. The reference forest REF(TR), representing the undisturbed Tum Reusi primary evergreen forest measured in 1997, showed values that did not differ significantly from either the restored forests or the modern reference forest. SOM and SOC values in REF(PDS) were statistically indistinguishable from those observed in REF(TR), suggesting comparable soil carbon status between the two reference forest plots. In addition, SOM and SOC values between the CON and the R24 were also

statistically indistinguishable. Soil carbon appeared to have increased since 1997, moderately in the control plot and substantially in the forest plots.

Mean bulk density also differed significantly among sites (t-test, $p < 0.05$; Table 2). It was significantly higher in the control plot than in all forested plots.

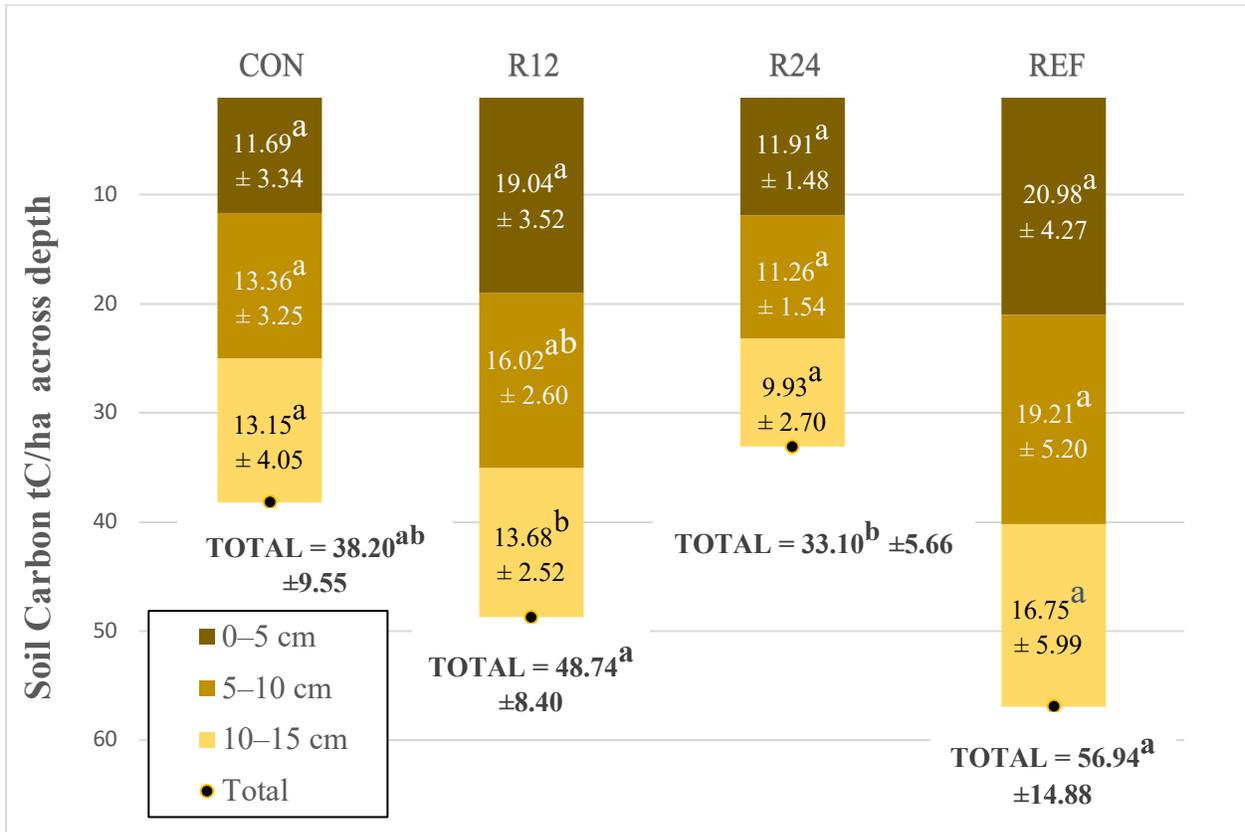


Figure 7. Soil organic carbon stocks (tons carbon per hectare) across soil depths at four study sites

Mean (\pm SD) soil organic carbon stocks (tons carbon per hectare) across soil depths at four study sites. Within sites, differences in depth-level means, not sharing the same superscripts, are significant ($p < 0.05$). Differences between total means, not sharing the same superscripts, are significant among sites ($p < 0.05$).

Comparing among sites, the total mean carbon stock in the R12 was statistically indistinguishable from that of the REF. However, CON was also statistically indistinguishable from both R12 and

REF, according to the superscript groupings. In contrast, R24 had significantly lower total SOC stocks than the reference forest.

Mean SOC stocks declined with increasing soil depth, consistently in all the forest plots, but not in the abandoned control plot, which had the lowest mean SOC in the uppermost layer. However, differences among the means were only statistically significant in the R12 plot ($p < 0.05$; Figure 7). The REF and R12 consistently showed higher SOC in the upper soil layer, compared with the control and the R24, indicating greater carbon accumulation in the surface soil. Overall, SOC stocks were concentrated in the topsoil layer across most forest types, suggesting that surface litter inputs and organic matter accumulation play an important role in soil carbon storage.

3.1.2 Soil chemical properties

Table 3. Means (\pm SD) of four soil chemical properties (0–15 cm depth) pre-restoration (1997) ($n=16$) compared with control, restored (R24 and R12) and reference (REF) plots ($n=4$) in the current study. Mean values within rows, not sharing the same superscript are significantly different ($p<0.05$).

Parameter	Pre-restoration 1997 ($n=16$)	CON ($n=4$)	R12 ($n=4$)	R24 ($n=4$)	REF (PSD)($n=4$)	REF (TR) 1997 ($n=20$)
pH	5.4 ^{bc} ± 0.42	5.9 ^b ± 0.35	5.3 ^c ± 0.11	5.4 ^c ± 0.22	5.3 ^c ± 0.20	6.2 ^a ± 0.54
N (%)	0.26 ^c ± 0.04	0.37 ^b ± 0.05	0.48 ^a ± 0.03	0.39 ^{ab} ± 0.03	0.48 ^a ± 0.09	0.37 ^{ab} ± 0.12
P (mg kg ⁻¹)	nd	2.18 ^a ± 1.62	0.09 ^b ± 0.04	0.04 ^b ± 0.05	0.06 ^b ± 0.11	nd
K (mg kg ⁻¹)	274.84 ^a \pm 137.64	113.49 ^b ± 35.67	280.17 ^a ± 33.22	256.62 ^a ± 48.99	289.57 ^a ± 92.95	295.67 ^a \pm 72.90
Soil Moisture (%)	nd	44.04 ^a ± 4.78	50.21 ^a ± 5.48	40.28 ^b ± 4.08	46.55 ^a ± 8.66	nd

Mean pH was significantly higher in REF(TR) than in all other sites ($p < 0.05$). The control site showed slightly higher pH than the three forested sites but did not differ significantly from the pre-restoration (1997) values. Available phosphorus concentrations were significantly higher in the control site compared with all forested plots ($p < 0.05$). Nitrogen (N) and potassium (K) concentrations were significantly lower in the control site than in the forested plots. Nitrogen and potassium concentrations did not differ significantly among the forested sites (R12, R24, and REF(PDS)), REF(TR), and the pre-restoration (1997) site. Soil moisture was significantly lower in R24 than in CON, R12, and REF ($p < 0.05$), while no significant differences were observed among CON, R12, and REF.

3.2 Discussion

3.2.1 Recovery of soil organic carbon after forest restoration

The sampling regime in this study produced somewhat equivocal results, possibly due to the limited number of samples collected and the high variability of the data. Pre-restoration data from 1997 provided a baseline for evaluating soil organic carbon (SOC) recovery in the Upper Mae Sa Valley. Before restoration, SOM and SOC concentrations were relatively low (5.35% and 3.10%, respectively) (Table 2), reflecting soil degradation. In comparison, all restored and reference sites in this study exhibited higher SOM and SOC concentrations, indicating clear improvement in soil carbon recovery after forest restoration. SOC increased from the control (3.32%) to R24 (3.82%) and reached the highest values in R12 (5.70%), which was statistically comparable to the reference forest (5.78%). Historical data from the Tum Reusi primary evergreen forest site REF(TR), collected in 1997, provided a benchmark representing an undisturbed forest ecosystem. Interestingly, SOM and SOC values in REF(PDS) were statistically indistinguishable from those observed in the REF(TR) (7.3% and 4.24%, respectively), suggesting that the selected reference forest (PDS) retains soil carbon concentrations comparable to those of a primary evergreen forest, even though parts of the PDS forest have been subject to disturbance (fire and coffee growing) in recent years.

These findings demonstrate that forest restoration has substantially enhanced surface soil carbon concentrations relative to degraded pre-restoration conditions. However, soil organic carbon dynamics are strongly depth-dependent, with distinct processes regulating carbon input, turnover, and stabilization across soil layers (Balesdent et al., 2018). Recent carbon inputs are primarily concentrated in surface soils, with a global median incorporation depth of approximately 10 cm, indicating that topsoil responds more rapidly to changes in vegetation and land use. In contrast, subsoil carbon dynamics are substantially slower, with turnover rates up to seven times lower than those of surface soils (Balesdent et al., 2018). This suggests that the observed SOC recovery in this study largely reflects changes in the upper soil layers (0–15 cm), while deeper carbon pools may still be recovering more slowly.

The total SOC stock (0–15 cm) varied among restoration stages. The reference forest (REF) exhibited the highest SOC stock (56.94 tC/ha), followed by the 12-year-old restoration site (R12) with 48.74 tC/ha. The control plot (CON) contained 38.20 tC/ha, while, unexpectedly, the 24-year-old restoration site (R24) showed the lowest SOC stock among all sites, at 33.10 tC/ha (Figure 7). This pattern challenges the common assumption that soil carbon steadily accumulates as forest stands mature. The relatively high SOC in R12 indicated that restoration using the Framework Species Method (FSM) had been effective in enhancing soil carbon stocks toward levels comparable to those of a mature reference forest. Previous studies have shown that the FSM promotes rapid canopy closure, increases litterfall, and improves nutrient cycling, all of which contribute to organic matter inputs into the soil (Kavinchan et al., 2015). The insignificance of the difference between R12 and the reference forest indicated that high recovery of surface SOC can occur within approximately 12 years of restoration. These findings support the view that the FSM can accelerate soil carbon recovery in degraded tropical landscapes.

On the other hand, the unexpectedly low SOC observed in R24 indicates that restoration age alone does not determine soil carbon accumulation. One key explanation is the legacy effect, which is that historical land use exerted long-term control over soil properties. Previous intensive agricultural practices, prolonged cultivation, all-year-round crop rotation and chemical fertilizers may have altered soil structure and organic matter dynamics, creating persistent carbon deficits that remain even after two decades of restoration. Furthermore, differences in litter input rate, litter production, decomposition and erosion rates may influence the net SOC accumulation. For

example, Kavinchan's (2013) study showed that litterfall production generally increases with forest age due to greater biomass and canopy development, whereas decomposition rates are more strongly controlled by litter quality and nutrient content rather than site age. Litter decomposition constants (k) did not differ significantly among sites despite variations in forest age, indicating that carbon-loss processes remain relatively similar across restoration stages (Kavinchan, 2013). This suggests that even if older sites receive greater litter inputs, comparable decomposition rates may limit net SOC accumulation. Furthermore, decomposition was primarily influenced by litter quality (e.g., nitrogen content), which helps to explain why SOC does not always increase linearly with forest age (Kavinchan, 2013).

Moreover, bulk density (BD) values also provided further insight into this carbon distribution. High bulk density is often associated with soil compaction, which can reduce porosity, restrict root growth, and negatively affect crop productivity (Nyéki et al., 2017). The control plot exhibited the highest BD (1.54 g/cm^3), which falls into the characteristic of compacted, low porosity and degraded agricultural soil with low organic matter content and weak aggregation (Figure 8). In contrast, the two restored forests (R12 and R24) showed much lower BD values (1.15 and 1.16 g/cm^3), which fall within well-aggregated soil structure, higher porosity, and greater biological activity, reflecting significant recovery of soil physical properties following restoration (Figure 8). The lower BD in these restored plots indicates improved soil conditions that promote root growth, water infiltration, and microbial processes. The reference forest (REF), with a BD value of 1.35 g/cm^3 , falls within the typical range of mineral forest soils with sandy loam texture and generally good soil structure. Interestingly, both restored plots exhibited even lower BD values than the REF, suggesting that soil physical conditions in the restored forests may have improved beyond those of the reference site. Although REF represents natural forest conditions, its BD is higher than that of both restored plots, indicating that the restored forests may have developed better soil physical structure in terms of porosity and aggregation.

These differences are important because SOC stock (tC/ha) is calculated by using the core dry soil mass for each sampling point. The elevated BD in the control plot increased soil mass per hectare, which resulted in relatively high SOC stock values, despite having the lowest SOC concentration (% per 100 g soil). Therefore, the higher carbon stock in the control compared with R24 did not necessarily indicate better carbon sequestration, but rather reflected soil compaction and higher

soil mass. When the SOC concentration per 100g is considered, the control clearly contains lower carbon enrichment as shown in Table 2. Therefore, SOC concentration and bulk density are important factors to consider when evaluating the effectiveness of forest restoration, as they reflect both biochemical recovery and physical improvement of soil structure.

Sites		BULK DENSITY (G CM ⁻³)	
CONTROL		BULK DENSITY < 1.0 (G CM ⁻³)	Very Loose: High organic, peat soil, undisturbed forest.
1.5445 G CM ⁻³		BULK DENSITY 1.0 – 1.2 (G CM ⁻³)	Loose: Well-aggregated forest, high biological activity.
R12		BULK DENSITY 1.2 – 1.4 (G CM ⁻³)	Moderately Dense: Mineral forest soil, sandy loam, good structure.
1.153 G CM ⁻³		BULK DENSITY 1.4 – 1.6 (G CM ⁻³)	Dense: Compacted soil, degraded agricultural, low organic matter.
R24		BULK DENSITY > 1.6 (G CM ⁻³)	Dense: Compacted soil, degraded agricultural, low organic matter.
1.161 G CM ⁻³		BULK DENSITY > 1.6 (G CM ⁻³)	Very Dense: Highly compacted clay, heavy machinery impact, poor aeration.
REF			
1.35625 G CM ⁻³			

Figure 8. Bulk density classification across study sites and associated soil properties (Nyéki et al., 2017).

3.2.2 Comparison with other studies

Tun Pyae Shan (2025), who evaluated tree-carbon at the same sites and time, reported that aboveground tree-carbon stocks were substantially higher in R24 (149.84 t/ha) than in R12 (87.46 t/ha), with R24 reaching approximately 84% of the reference-forest value. These findings indicated substantial recovery of aboveground biomass in R24. Therefore, the low SOC in R24 cannot be attributed to insufficient vegetation growth or reduced carbon input from biomass production. Instead, this suggests that belowground carbon dynamics may respond more slowly and remain constrained by legacy effects, previous land use, historical soil degradation, decomposition and surface runoff due to the slope difference. This suggests a potential difference between

aboveground biomass recovery and soil organic carbon accumulation, although further investigation of belowground processes would be required to support the underlying mechanisms.

A similar pattern was observed by Kavinchan et al. (2015), who studied SOC along a restoration chronosequence in the same Upper Mae Sa Valley. In their study, the 11-year-old restoration plot (R11) exhibited the lowest total SOC stock (161.8 tC/ha to 2 m depth) among the restoration sites, whereas the younger restoration plots (R2 and R7) had substantially higher SOC stocks (251–254 tC/ha). The natural forest also showed relatively high SOC stocks (244.96 tC/ha). This pattern is consistent with the present study, where SOC stocks in restored forests remain lower than those in mature or reference forests. They attributed this anomaly to persistent land-use legacy effects, particularly carbon depletion in deeper soil layers that had not yet recovered. Their findings reinforce the interpretation that historical land use can override restoration age effects on SOC stocks. The similarity between their results and the present study strengthens the argument that SOC recovery trajectories are characteristic of restored forests in this region.

Results from another of FORRU's restoration-plot systems at Mon Cham (on the northern side of the Mae Sa Valley), using exactly the same methods, showed clear differences in the magnitude of SOC recovery following restoration (Table 4) compared with the present study (Forest Restoration Research Unit, 2022). In that study, the Framework Species Method (FSM) was applied to restore the evergreen forest at a similar altitude. Soil samples were collected to a depth of 15 cm using the same core sampling protocol. At Mon Cham, SOC values ranged from 23.43–17.86 tC/ha in the control (CON), 26.61–26.00 tC/ha in the youngest restoration plots (MC22; 6 months–1.5 years), 22.22–19.29 tC/ha in the older restoration plots (MC12; 10.5–11.5 years), and 25.63–27.50 tC/ha in the nearby reference forest (REF). The results indicate that SOC recovery in Ban Mae Sa Mai was higher than that observed at Mon Cham. These differences suggest that SOC recovery following restoration may depend on initial site conditions, degree of degradation, and levels of anthropogenic disturbance, and may also be influenced by microclimatic factors such as soil temperature, moisture availability, and canopy cover, which were not explicitly assessed in this study.

Table 4. Comparison of soil organic carbon stocks (0–15 cm depth) between Mae Sa Mai (present study) and Mon Cham.

Location	Forest/Site type	Soil organic carbon (tC/ha) at 0–15 cm
Mae Sa Mai (in this study)	Control (CON)	37.82
	R12	48.48
	RES200	32.81
	REF	56.64
Mon Cham (1st Survey)	Control (CON)	17.86
	Restored forest (MC12 ≈ R12)	19.29
	REF	27.5

3.2.3 Carbon credit potential as a financial incentive for forest restoration

The carbon sequestration results from this study, when integrated with the aboveground biomass findings of Tun Pyae Shan (2025), at the same study sites, provide a strong economic rationale for forest restoration in the Upper Mae Sa Valley. Tun Pyae Shan (2025) reported that approximately 150 (tC/ha) of aboveground tree carbon accumulated over 24 years in R24, equivalent to about 550 tCO₂/ha. At a carbon price of 67.64 USD/tCO₂, this corresponds to a potential gross value of 37,064 USD/ha. After accounting for restoration establishment costs, carbon sequestration profits over 24 years were estimated at 2,195 USD/ha for 100% tree planting, 3,889 USD/ha for mixed tree planting and assisted natural regeneration (50:50), and 5,687 USD /ha for 100% assisted natural regeneration, with sequestration costs ranging from 3.99 to 10.34 USD/tCO₂ (Jantawong et al., 2022; Tun Pyae Shan, 2025). Importantly, Jantawong et al. (2022) further demonstrated that the financial viability of restoration is strongly enhanced when carbon is monetized through carbon credit markets. Their analysis showed that forest restoration could generate net present values (NPV) of approximately 22,215–25,157 USD/ha over 14 years, with break-even occurring within 4 to 7 years depending on initial site conditions. In contrast, conventional maize cultivation, a dominant land use in northern Thailand, yielded only about 96 USD/ha/year, or approximately

1,347 USD/ha over the same 14-year period. Their findings indicated that carbon-based forest restoration can produce returns more than 16 times higher than maize farming, clearly demonstrating that restoration can generate net financial returns that exceed conventional agricultural income.

Importantly, those calculations were based solely on aboveground tree carbon. The present study shows that substantial carbon has also accumulated belowground, particularly in R12 and the reference forest, where SOC stocks approached or matched natural forest conditions. In this study, soil organic carbon stocks were converted to carbon dioxide equivalents using the same technique of analysis applied by Tun Pyae Shan (2025). The measured SOC stocks were first converted to CO₂ equivalents using the standard factor of 3.67, and the resulting CO₂ values were then multiplied by the same carbon price of 67.64 USD/tCO₂ used in the aboveground carbon assessment. Based on this approach, soil carbon stored within the upper 15 cm of soil corresponded to approximately 208.76 tCO₂/ha in the reference forest, 178.70 tCO₂/ha in R12, 121.39 tCO₂/ha in R24, and 140.18 tCO₂/ha in the control site, which represents potential gross carbon credit values of about 16,557 USD/ha, 14,173 USD/ha, 9,628 USD/ha, and 11,118 USD/ha, respectively. Because carbon markets quantify sequestration in CO₂ equivalents at the ecosystem level, inclusion of soil organic carbon would increase the total mitigation value per hectare beyond the estimates derived from tree biomass alone. However, the realization of this financial potential depends on stable carbon prices, transparent monitoring and verification systems, manageable transaction costs, and clear land tenure arrangements (Jantawong et al., 2022). Without these enabling conditions, the projected economic benefits may remain theoretical rather than practically accessible to local communities. Nonetheless, the combined recovery of aboveground and belowground carbon provides robust support for positioning carbon credit income as a major justification for forest restoration initiatives in northern Thailand.

3.2.5 Soil chemical properties

Soil chemical properties varied significantly among plots, reflecting differences in disturbance history, vegetation development, and nutrient cycling processes (Table 3). Soil pH differed significantly among sites. The highest pH was recorded in the primary evergreen forest at Tum Reusi Primary Evergreen Forest REF(TR), which was significantly higher than in all other plots.

In contrast, the control plot showed a moderately high pH, while the restored and reference plots in the current study (R12, R24, and REF) had lower and statistically similar values. The pre-restoration soil measured in 1997 showed an intermediate value that overlapped statistically with both the control and restored plots. These results suggest that forest restoration has led to slightly more acidic soil conditions compared with the control site. Slightly acidic soil conditions are generally more favorable for forest ecosystems, as they enhance nutrient availability and support microbial processes that regulate decomposition and nutrient cycling (Msimbira & Smith, 2020). Such decreases in soil pH during forest succession are commonly associated with increasing organic matter inputs and litter decomposition, which produce organic acids such as humic and fulvic compounds (Brady & Weil, 2016). The similar pH values observed among R12, R24, and REF indicate that restored plots have already developed soil acidity comparable to the secondary reference forest. However, the higher pH in REF(TR) suggests that soil chemical conditions in the primary forest differ somewhat from those in the study plots. These differences in soil pH may reflect variations in soil-forming factors, including differences in soil mineral composition, vegetation history, and site conditions such as hydrology, which are known to strongly influence soil properties (Weil & Brady, 2016).

Total nitrogen showed clear differences among restoration stages. The lowest nitrogen concentration occurred in the pre-restoration soil, indicating substantial nutrient depletion before forest restoration. Nitrogen levels increased in the control plot and were highest in the restored and reference plots, particularly R12 and REF, which were statistically indistinguishable. R24 showed intermediate values, overlapping with both higher and lower groups, while REF(TR) had a similar intermediate level. The substantial increase in nitrogen compared with the pre-restoration condition suggests that forest recovery has enhanced soil nitrogen accumulation. As vegetation structure develops, greater litterfall and improved nutrient retention promote the buildup of soil organic nitrogen. The similarity between restored plots and the reference forest indicates that nitrogen cycling processes recover relatively quickly once vegetation cover and litter inputs are re-established.

Available phosphorus showed a different pattern, with the control plot exhibiting significantly higher concentrations than the restored and reference plots. This elevated phosphorus level likely reflects reduced plant uptake and lower biological demand due to limited vegetation cover, and

may also be influenced by the accumulation of residual phosphorus from past fertilizer inputs. In contrast, the lower phosphorus levels in the restored and reference plots can be attributed to greater plant uptake and immobilization within microbial biomass. In tropical forest ecosystems, phosphorus is rapidly incorporated into biomass and soil organic matter, often resulting in low concentrations of extractable phosphorus despite active nutrient cycling (Vitousek et al., 2010).

Moreover, unlike carbon (C) or nitrogen (N), phosphorus (P) cannot be lost to the atmosphere as a gas and is relatively stable and sticks to the soil. It strongly binds to soil particles and accumulates over time, forming a “legacy phosphorus” pool driven by long-term inputs and inefficient nutrient use (Sharpley et al., 2013). This accumulation is often exacerbated by repeated fertilizer application, where phosphorus inputs exceed plant uptake, resulting in long-term phosphorus buildup in the soil. So, this legacy phosphorus exists in various forms, including labile, organic, and mineral-bound fractions, which can be slowly released over extended periods. Moreover, phosphorus readily reacts with soil minerals such as aluminum (Al), iron (Fe), and calcium (Ca), forming relatively insoluble phosphate compounds that reduce its mobility and bioavailability. As a result, phosphorus tends to persist in soils and is difficult to remove. Its losses occur primarily through physical processes such as surface runoff and soil erosion, rather than gaseous pathways, allowing legacy phosphorus to remain a long-term source of nutrient release to surrounding ecosystems (Sharpley et al., 2013).

Exchangeable potassium was significantly lower in the control plot, while all other plots showed substantially higher values. Potassium concentrations were highest in the reference forests, including REF and REF(TR), and were similarly high in the restored plots R12 and R24. The pre-restoration soil also showed relatively high potassium levels, although large variability suggests considerable spatial heterogeneity. The lower potassium concentration in the control plot likely reflects reduced nutrient recycling caused by limited litter inputs. In contrast, the higher potassium levels in restored and reference plots indicate improved nutrient retention and more active internal nutrient cycling associated with forest recovery (Brady & Weil, 2016).

Soil moisture varied among the study sites, with the highest value observed in R12, followed by REF and CON, while the lowest value occurred in R24. The relatively high soil moisture in R12 suggests that forest restoration has improved soil water retention compared with degraded

conditions. Increased litter inputs and the accumulation of soil organic matter can enhance soil aggregation and porosity, promoting greater water infiltration and storage. Similarly, the relatively high moisture in REF, a natural evergreen forest, reflects the stable microclimate and continuous litter layer typical of mature forests, which help reduce evaporation and maintain soil moisture. In contrast, the lower soil moisture in R24 may reflect site-specific factors such as soil properties, slope position, or legacy effects from past land use that influence water-holding capacity. These variations in soil moisture may also influence microbial activity, organic matter decomposition, and nutrient cycling across the study sites.

CHAPTER 4

Conclusions

Forest restoration using the Framework Species Method (FSM) demonstrates substantial recovery of soil organic carbon (SOC) but also the potential for lasting influence of previous land use. Across the four study sites, restored forests accumulated considerable belowground carbon, although SOC did not increase linearly with restoration age. The 12-year-old restoration site reached SOC levels comparable to the reference forest, whereas the 24-year-old restoration site showed lower soil carbon stocks, indicating that belowground recovery is strongly influenced by historical land use and site-specific ecological constraints. These findings highlight the complex relationship between aboveground and belowground carbon dynamics, where biomass accumulation does not necessarily result in proportional increases in soil carbon.

Importantly, the recognition of ecosystem carbon gains also highlights the potential economic value of carbon credits as a financial incentive for restoration. The economic valuation of carbon sequestration suggests that restoration could generate meaningful long-term returns. However, as with biomass-based carbon markets, practical implementation depends on stable carbon prices, accessible market mechanisms, transparent monitoring systems, and clear land tenure arrangements. Without addressing these structural and governance challenges, the financial benefits of carbon credits may remain difficult to realize for smallholders.

Finally, this study emphasizes that effective forest restoration should be evaluated through an integrated assessment of belowground carbon pools. Such an approach improves the scientific basis for carbon accounting, informs restoration planning, supports sustainable development and climate mitigation initiatives in northern Thailand.

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APPENDIX

Appendix A - Data Analysis

Table 5. F-Test Two-Sample for Variances between CONTROL and R12

	<i>CONTROL</i>	<i>R12</i>
Mean	38.22618704	48.7307462
Variance	91.21814831	70.6434799
Observations	4	4
df	3	3
F	1.291246531	
P(F<=f) one-tail	0.419295993	EQUAL
F Critical one-tail	9.276628153	

Table 6. t-Test: Two-Sample Assuming Unequal Variances between CONTROL and R12

	<i>CONTROL</i>	<i>R12</i>
Mean	38.22618704	48.7307462
Variance	91.21814831	70.6434799
Observations	4	4
Hypothesized Mean Difference	0	
df	6	
t Stat	-1.651337611	
P(T<=t) one-tail	0.074879809	
t Critical one-tail	1.943180281	NOT significant
P(T<=t) two-tail	0.149759619	
t Critical two-tail	2.446911851	

Table 7. F-Test Two-Sample for Variances between R12 and R24

	<i>R12</i>	<i>R24</i>
Mean	48.73074615	33.10421098
Variance	70.64347987	32.0020742
Observations	4	4
df	3	3
F	2.207465661	
P(F<=f) one-tail	0.266129009	EQUAL
F Critical one-tail	9.276628153	

Table 8. t-Test: Two-Sample Assuming Equal Variances between R12 and R24

	<i>R12</i>	<i>R24</i>
Mean	48.73074615	33.10421098
Variance	70.64347987	32.0020742
Observations	4	4
Hypothesized Mean Difference	0	
df	5	
t Stat	3.084768786	
P(T<=t) one-tail	0.013660609	
t Critical one-tail	2.015048373	Significantly more carbon in R12
P(T<=t) two-tail	0.027321218	
t Critical two-tail	2.570581836	

Table 9. F-Test Two-Sample for Variances between R24 and REF

	<i>R24</i>	<i>REF</i>
Mean	33.10421098	56.9281467
Variance	32.0020742	221.2668765
Observations	4	4
df	3	3
F	0.144631111	
P(F<=f) one-tail	0.07329151	EQUAL
F Critical one-tail	0.107797789	

Table 10. t-Test: Two-Sample Assuming Equal Variances between R24 and REF

	<i>R24</i>	<i>REF</i>
Mean	33.10421098	56.9281467
Variance	32.0020742	221.2668765
Observations	4	4
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.994005051	
P(T<=t) one-tail	0.020089455	Significantly more carbon in REF
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.04017891	
t Critical two-tail	2.776445105	

Table 11. F-Test Two-Sample for Variances between R12 and REF

	<i>R12</i>	<i>REF</i>
Mean	48.73074615	56.9281467
Variance	70.64347987	221.2668765
Observations	4	4
df	3	3
F	0.319268211	
P(F<=f) one-tail	0.186731953	EQUAL
F Critical one-tail	0.107797789	

Table 12. t-test Two-Sample Assuming Equal Variances between R12 and REF

	<i>R12</i>	<i>REF</i>
Mean	48.7307462	56.9281467
Variance	70.6434799	221.266877
Observations	4	4
Pooled Variance	145.955178	
Hypothesized Mean Difference	0	
df	6	
t Stat	-0.9595805	
P(T<=t) one-tail	0.18716108	NOT significant
t Critical one-tail	1.94318028	
P(T<=t) two-tail	0.37432216	
t Critical two-tail	2.44691185	

Table 13. F-Test Two-Sample for Variances between CONTROL and R24

	<i>CON</i>	<i>R24</i>
Mean	38.22618704	33.10421098
Variance	91.21814831	32.0020742
Observations	4	4
df	3	3
F	2.850382377	
P(F<=f) one-tail	0.206281026	EQUAL
F Critical one-tail	9.276628153	

Table 14. t-Test: Two-Sample Assuming Equal Variances between CONTROL and R24

	<i>CON</i>	<i>R24</i>
Mean	38.22618704	33.10421098
Variance	91.21814831	32.0020742
Observations	4	4
Pooled Variance	61.61011126	
Hypothesized Mean Difference	0	
df	6	
t Stat	0.922840287	
P(T<=t) one-tail	0.195844943	
t Critical one-tail	1.943180281	
P(T<=t) two-tail	0.391689885	NOT significant
t Critical two-tail	2.446911851	

Table 15. F-Test Two-Sample for Variances between CONTROL and REF

	<i>Con</i>	<i>REF</i>
Mean	38.226187	56.9281467
Variance	91.2181483	221.266877
Observations	4	4
df	3	3
F	0.41225397	
P(F<=f) one-tail	0.24291456	Equal
F Critical one-tail	0.10779779	

Table 16. t-Test: Two-Sample Assuming Equal Variances between CONTROL and REF

	<i>Con</i>	<i>REF</i>
Mean	38.22618704	56.9281467
Variance	91.21814831	221.2668765
Observations	4	4
Pooled Variance	156.2425124	
Hypothesized Mean Difference	0	
df	6	
t Stat	-2.115935899	
P(T<=t) one-tail	0.039362156	
t Critical one-tail	1.943180281	
P(T<=t) two-tail	0.078724312	NOT significant
t Critical two-tail	2.446911851	

Appendix B - Soil chemical properties

Table 17. Soil chemical properties of control, restored (R24 and R12), and reference (REF) sites at different soil depths

Depth(cm)	(pH)	(OM, %)/100g	(OC, %)/100g	(N, %)/100g	P (mg/kg)	K (mg/kg)
CONTROL						
0-5	6.0025	7.46	3.461227864	0.373	2.6875	134.2375
5-10	5.8925	7.4775	3.481298872	0.373875	2.31	111.0025
10-15	5.81	7.02	3.043246008	0.351	1.5475	95.2225
R12						
0-5	5.2725	10.8	7.016725436	0.54	0.14	316.325
5-10	5.2775	9.63	5.698295004	0.4815	0.08	274.875
10-15	5.2825	8.405	4.391110495	0.42025	0.04	249.3
R24						
0-5	5.3625	8.3	4.281210062	0.415	0.0525	254.6
5-10	5.3575	7.9575	3.934016005	0.397875	0.0425	258.95
10-15	5.3575	7.255	3.264399671	0.36275	0.0175	256.3
REF						
0-5	5.315	10.7	6.936067487	0.535	0.1225	306.775
5-10	5.41	9.6675	5.785845586	0.483375	0.0225	312.625
10-15	5.2825	8.405	4.391110495	0.42025	0.04	249.3