Review Article

Enhancing carbon sequestration through tropical forest management: A review

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Abstract

Soil absorbs a lot of carbon dioxide (CO_2). Soil organic carbon (SOC) is understudied in tropical regions despite its importance. This study examines how forest management might increase SOC sequestration and restore degraded tropical ecosystems. Sequestering soil organic carbon could enhance soil fertility and reduce land degradation and greenhouse gas (GHG) emissions. Soil structure, aggregation, infiltration, faunal motion, and nutrient (C, N, P and S) cycling are improved. Forest ecosystem management improves C sequestration, climate change mitigation, and degraded land rehabilitation. When combined with organic residue managing and nitrogen-fixing plants, afforesting or reforesting marginal or degraded lands enhances C storing in biomass and soil and supports soil condition, food productivity, land refurbishment, and greenhouse gas reduction. Sequestered C increases biological, physical, and chemical fertility, improving soil health.

Keywords: Tropical forest; Soil carbon; Forest management; Climate change; Soil fertility

1. Introduction

From 1990 to 2015, forestry spanned 3999 million hectares, down 33% from 4128 million. The tropics account for 45 percent, or 728 million hectares, of the globe's forests, followed by the boreal, temperate, and subtropical domains. (FAO, 2020). Yet, research reveals that tropical deforestation is caused by farming and industry (Raihan, 2023a), particularly in South America and Africa (FAO, 2020). Between 2010 and 2020, Africa lost 3.9 million hectares of forests. South America followed with 1 million hectares (FAO, 2020). Pan et al. (2011) found that the forest sink is comparable to the terrestrial sink from fossil fuel emissions. Forests store 80% of aboveground C and 70% of soil organic C (Raihan et al., 2021a). Forest management is essential for carbon sequestration, soil rejuvenation, and GHG emission reduction (Ontl et al., 2020; Raihan et al., 2022a). Forest ecosystem C management involves dynamics, pool size, and chemical forms. Silviculture (tree species selection and rotation times), gaps (number of trees planted at once), turbulence (pest influxes, wind pitch, and wildfires), air contamination, and water management all affect forest management and carbon sequestration (Raihan et al., 2019). Modeling predicted forest expansion over ten European landscapes over the next century showed how European forest management affects ecosystem services including carbon sequestration, biodiversity, and sustainable timber output (Biber et al., 2020).

The study found that climate change-related storms and droughts should be considered. In the eastern US, Community Land Model 4.5 prioritizes forest area for preservation by considering drought and fire vulnerability and relativizing the C priority to biodiversity, unlike in the west (Buotte et al., 2020)Preserved temperate forests (with medium to high C storage capability) in the western US appear to be equivalent to 27-32 percent of the worldwide

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worldwide mitigation capacity previously found for boreal and temperate forests, enough to absorb fossil fuel emissions for around 8 years (Buotte et al., 2020). The US forest inventory lists 1.4 trillion plants from over 130,000 federal forestlands, demonstrating that tree planting can enhance C sequestration capacity and reduce CO_2 emissions (Domke et al., 2020).

Tropical forests store carbon underground and above (Raihan and Tuspekova, 2023). They store the most carbon (91 tha^{-1}) and produce the most wood (121 m^3ha^{-1}) of any ecosystem. Carbon-rich boreal forest soils lack them (Pan et al., 2011). Tropical woods can gather and store the most C because they have the greatest C concentration (Raihan et al., 2018; Raihan, 2023b). Figure 1 simplifies the global C cycle in tropical forest ecosystems. Their potential to sequester atmospheric C has increased the greatest during the past two eras, making them decisive to climate change mitigation (Fernández-Martnez et al., 2019). MACC-II and Jena CarboScope atmospheric inversion models and 10 dynamic universal plants models assessed this capacity. The findings suggest that ecosystems' carbon dioxide absorption may fight against global warming and climate change (Raihan et al., 2022b). Therefore, forest management is vital for C sequestration, land restoration (destroyed woodlands and additional domains), climate change mitigation, natural forest preservation, and biodiversity (Raihan and Tuspekova, 2022a).

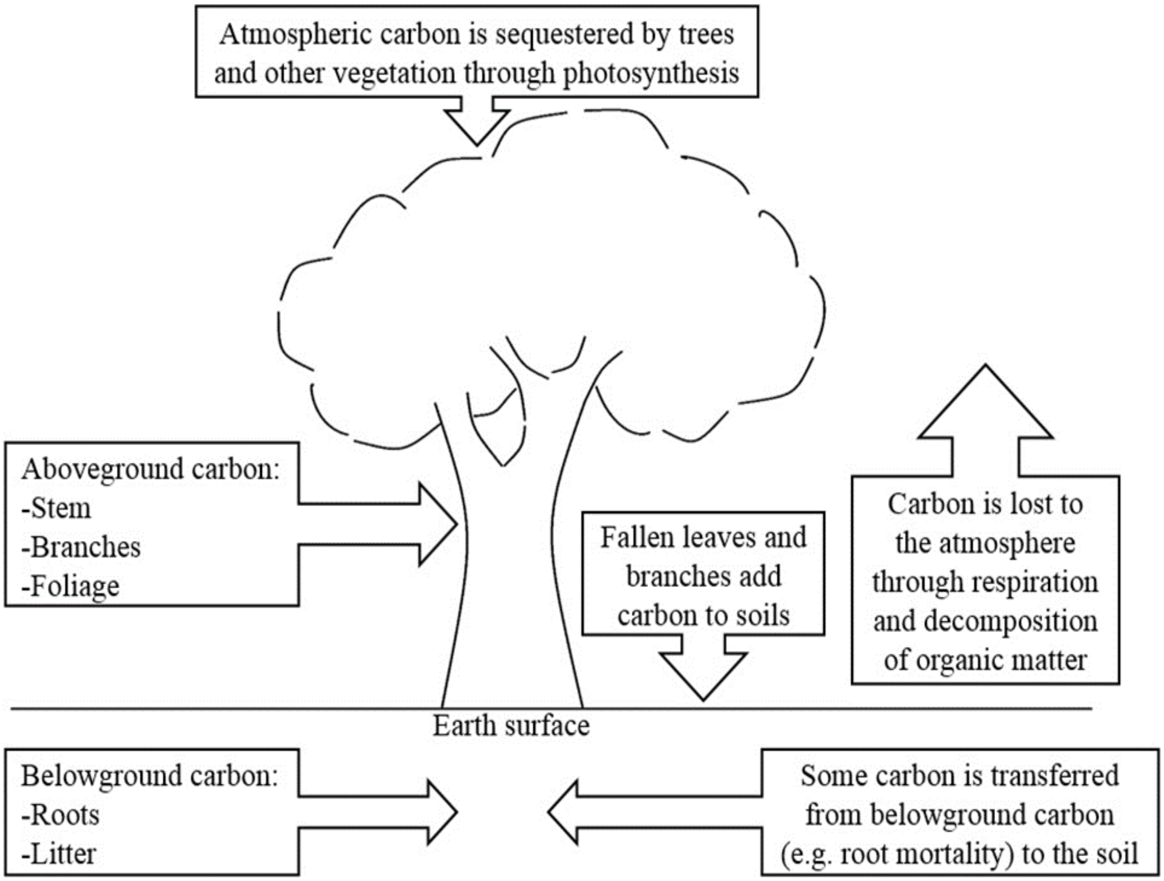

Figure 1. Carbon sequestration in forests.

By 2020, global forest C was predicted to reach 662 Gt (or 163 tha^{-1}) (FAO, 2020). Forest soils contain 50% of terrestrial ecosystems' organic carbon (Mayer et al., 2020; Raihan and Said, 2022). Tropical forest soils contain three times more carbon (C) than air or plants. Forest biogeochemical cycles of carbon (C), water, and other factors affect global climate (Malhi et al., 2020). Forest ecosystems need adaptability and resilience to survive climate change (Begum et al., 2020; Raihan and Tuspekova, 2022b; Raihan et al., 2023a). Tropical forests fear climate change may dry them off. Yet, during the past two decades, they have gotten even better at sequestering atmospheric C, improving their ability to mitigate climate change (Fernández-Martnez et al., 2019; Raihan et al., 2022c). Malhi et al. (2020) discovered that land-use alteration, including habitation loss and overexploitation, affects ecosystems more than climate change. Rising population, soil fertility decline, and food shortages cause land degradation, which worsens the consequences of climate change on forest ecosystems in tropics (Jaafar et al., 2020; Raihan and Tuspekova, 2022c; Raihan et al., 2023b). The UN and other international initiatives (such as the "Bonn Challenge" and the "UN-Decade on Ecosystem Restoration" [2021-2030]) have been calling for land dilapidation detachment and the UN-Sustainable Development Goals for years. Natural or human-caused soil deterioration has four main types: chemical (salinization, acidification, leaching, pollution, nutrient depletion, etc.); biological (drop in soil organic material, damage of soil biodiversity, demise of soil C sink bulk, etc.); physical (compaction, runoff and erosion, desertification, etc.); ecological (nutrient cycling disruption, hydrological cycle perturbations, input use efficiency decline, etc.). Forest management and tree planting on degraded land increase soil and ecosystem C pools (Raihan and Tuspekova, 2022d).

Studies on SOC have increased during the previous two decades (Mayer et al., 2020; Ali et al., 2022). Most publications and articles discuss SOC and its function in nutrient cycling, soil fertility, crop production, climate change, and land restoration (Lal, 2013). The "4 per 10000 Initiative," also known as Soils for Food Security and Climate Change, was proposed at the 21st Conference of the Parties (COP) of the UNFCCC, drawing worldwide attention to soil (Soussana et al., 2019). Climate change and land degradation threaten agriculture, forestry, food production, and sustainability (Raihan and Tuspekova, 2022e). Therefore, the 22nd COP focused on fertilizer usage and manure management for sustainable and resilient agriculture.

However, SOM serves as a reservoir for nutrients and is commonly utilized as an indicator for assessing soil fertility, as well as soil health in terms of its chemical, physical, and biological properties. SOC comprises 50-99% of the total amount of SOM. The pool of SOM is relatively stable and has a mean residence time of several decades. Therefore, it may take more than 2 years to accurately evaluate changes in SOC. Nevertheless, alterations in the biodegradability of SOM or the biomass of microorganisms can be easily observed within a shorter timeframe. Soils are a crucial reservoir of carbon, serving as both a source and sink of carbon (Raihan et al., 2022d). The factors influencing this include climate, soil texture, soil acidity, vegetation cover, biomass inputs, management practices, as well as soil depth, initial carbon levels, and soil type (Marin-Spiotta and Sharma, 2013; Akpa et al., 2016). The quality of SOM is improved through the process of SOC accretion, particularly when it is safeguarded by fine soil fractions (Eclesia et al., 2012; Sang, 2013). The decline in SOM quality is attributed to increased carbon mineralization resulting from climate, management practices, or edaphic factors (Bonfatti et al., 2015; Cook et al., 2016). Soil carbon sequestration has the potential to enhance soil fertility, increase crop production, and mitigate climate change by reducing greenhouse gas emissions (Paustian et al., 2016; Raihan, 2024a). The storage of SOC plays a crucial role in controlling, mitigating, and halting land degradation (Raihan, 2023c). Shimamoto et al. (2018) conducted a global meta-analysis on the restoration of ecosystem services in tropical forests. They found that restoration efforts were particularly effective in enhancing biodiversity protection in degraded former pasture land, as well as in increasing carbon storage in degraded former agricultural plots. The authors posited that the appropriate approach expands the restoration of ecosystem services in degraded tropical forests.

Research on SOC should prioritize monitoring and assessment in areas with accelerated decomposition, such as tropical forest ecosystems experiencing land degradation exacerbated by large stocks and climate change (FAO, 2020; Raihan and Tuspekova, 2022f). Sustainable soil management, specifically through carbon sequestration, is a crucial component for restoring and sustaining soil health, as well as mitigating climate change and restoring land (FAO, 2020; Raihan et al., 2023c). Therefore, the present study will primarily focus on SOC management in tropical forest ecosystems, which are currently the most threatened forest ecosystems. This research aims to address both climate change mitigation and land degradation prevention/restoration. Afforestation on agricultural, grassland, or city-edge property may affect the ecology and economics. Introducing nitrogen-fixing species and managing organic wastes promote SOC sequestration and nutrient cycling, which help forest ecosystems thrive. Tropical soil organic carbon (SOC) amounts and quality have been understudied, despite their potential to promote C sequestration and avoid land degradation through their links to nitrogen (N) and phosphorus (P). This study explores the influence of SOC quantity and quality (i.e., SOC connected with N or P cycles, C stocks, stable versus labile C forms) on land rehabilitation in tropical forest ecosystems. Reforestation and afforestation of marginal and degraded tropical forest ecosystems may improve soil healthiness, climate change, and land degradation.

2. Methodology

2.1. Systematic literature review

An extensive literature review was performed to delve into the relationships between land restoration, SOC, and other elements in tropical forest ecosystems, and soil carbon management and storage. This helped to reveal how crucial forest management is to the quality and quantity of carbon sequestered and land recovered in tropical ecosystems. As can be seen in Figure 2, the review adhered to the tenets of the systematic review methodology. By deconstructing the research questions into their component concepts, it is possible to develop a set of search terms that would allow to conduct a thorough and representative search of the literature on the topic of handling soil C and its relation to climate change plus land refurbishment in tropical forest ecosystems. Database classification terms have also been taken into account, along with synonyms, single and plural models, broader terms, alternative spellings, and more specific terms

2.2. Criteria for inclusion and exclusion

This study conducted a systematic literature review to address the potential relationships between adaptation to climate change and resiliency in tropical forest ecosystems, the interplay between SOC and other nutrient pedaling, and the associations to land refurbishment. All of the retrieved publications and papers were evaluated based on a set of encoded measures for insertion and elimination of primary research paper. This investigation included primary examinations that assess SOC managing in the context of mitigating climate change or rehabilitating degraded land in tropics. The qualitative and quantitative secondary literature on forests in tropics is also discussed After conducting a comprehensive search of the relevant literature, 86 articles published between 1990 and 2022 were chosen for further analysis. The papers came from the academic aggregators Google Scholar, Scopus, and Web of Science (WOS). To build a paradigm for future forest research and management that takes into account both carbon sequestration and land degradation restoration , this paper provides an overview of the links between these two processes in forests in tropics over the extended period.

Figure 2. The procedure of systematic review conducted by the study.

This study solely used research articles published in peer-reviewed journals to assure the quality of the results, which provide a foundation for future tropical forest research and management taking into account carbon sequestration and land degradation restoration. These papers were then reviewed to determine if their primary topic was similar to that of the current investigation.

2.3. Extraction of data and evaluation of quality

Even though no precise instrument for quality valuation was utilized, the review safeguarded that evidence mined from the research papers (meeting the insertion conditions) was applicable (useful), and legal (close to the actuality) by evaluating the research etiquette and queries, foundations of information, and the choice of the appraisal.

3. Results and Discussion

3.1. Enhancing soil carbon through tropical forest management

Owing to their vital function in the universal C sequence and various ecosystem provisions, incorporating C sequestration (in biomass and soil), forests require careful management to increase sequestration of C and approve soil vigor (Raihan, 2023d). According to Fernandez-Martinez et al. (2019), tropical forest ecosystems have improved in this regard during the past two decades due to their increasing capability to sequester carbon. Depending on how the forest is managed, sequestration of C may occur in tropical forests. Table 1 presents a glance of sequestration of C in some tropical forests. The rate of SOC sequestration is controlled by the tree species, type of soil and environment, climate and geographic factors, and has been examined extensively (Mayer et al., 2020). C sequestration in biomass and soil is a common result of managing forest ecosystems through afforestation and reforestation, but the efficacy of these practices is highly dependent on edaphic parameters in addition to those listed above (Dou et al., 2016; Raihan, 2023e).

Table 1. Sequestration of carbon in some tropical forests.

Location	Forest type	Sequestrated C	Sources
Panama	Teak plantation	3-41 Mg C ha^{-1}	Derwisch et al. (2009)
Colombia	Mixed forest	122-141 Mg C ha^{-1}	Saatchi et al. (2011)

Venezuela	Mixed forest	118-139 Mg C ha^{-1}	Saatchi et al. (2011)
Bolivia	Mixed forest	84-94 Mg C ha^{-1}	Saatchi et al. (2011)
Myanmar	Mixed forest	146-157 Mg C ha^{-1}	Saatchi et al. (2011)
Papua New Guinea	Mixed forest	147-153 Mg C ha^{-1}	Saatchi et al. (2011)
Vietnam	A. mangium and Eucalypt plantation	11.5 t C ha^{-1}yr^{-1}	Sang et al. (2013)
Indonesia	Production forest	46.32 t C ha^{-1}	Situmorang et al. (2016)
Cameroon	Mixed forest	318 t C ha^{-1}	Zapfack et al. (2016)
India	All types of forests	3979 million tons	Indian State of Forest (2017)
Brazil	Eucalypt and A. mangium plantation	C accretion	Pereira et al. (2018)
Ghana	Plantation forests	56-70 Mg Cha^{-1}	Brown et al. (2020)
Nepal	Community forests	301 tha^{-1}	Joshi et al. (2020)
Peru	Agroforestry	106 Mg C ha^{-1}	Aragón et al. (2021)
Thailand	Teak plantation	45-82 Mg C ha^{-1}	Chayaporn et al. (2021)
Costa Rica	Natural forest	18210 tons	Paniagua-Ramirez et al. (2021)
Malaysia	All types of forests	157.5 t C ha^{-1}	Raihan et al. (2021b)
Congo	Peatland	634 Mg C ha^{-1}	Crezee et al. (2022)

Soil C storage has been improved, especially in macroaggregates (>2000 m), as a result of afforestation of large uncultivated regions in central China with woodland, shrubland, and agricultural plants (Dou et al., 2016). In compared to pure acacia and eucalypt stands, which contained 16.7 and 15.9 tha^{-1}, respectively, the soil carbon stocks in the top 25 cm of the mixed-species stands, which contained 50% acacia and 50% eucalypt, increased to 17.8 ± 0.7 tha^{-1}, after afforestation of native tropical savannas. Carbon stock under A. mangium plantations in Malaysia increased from year 1 (74.9 tha^{-1}) to years 3 (89.9 tha^{-1}) and 5 (138.9 tha^{-1}) by 15 tha^{-1} and 64 tha^{-1}, respectively, despite the soil type being loamy siliceous with low fertility (Lee et al., 2015). A framework for long-term sequestration of C in the Makiling forest reserve and the Philippines was given by Camacho et al. (2009). The authors recommended reforestation, especially of fast-growing and high-timber species, to increase C sequestration. Strategies for reforestation and afforestation, such as the introduction of fast-growing Natural fertilizer substitutes (NFS) or bacteria that fix nitrogen, or the leaving of organic residues on the field after harvesting wood, can enhance SOC stocks additionally in coarse-textured soils that have a high rate of SOC decomposition (Dubliez et al., 2018; Mayer et al., 2020). This is because the introduction of fresh organic residues or N-rich organic matter alters microbial activity and/or bacterial makeup (Bini et al., 2018; Pereira et al., 2018). Carbon and nitrogen accumulation in soil microbes demonstrate that after 27 months, combined plantation of acacia and eucalyptus had exceeded those of pure or treated stands. Plants that fix N can promote soil fertility and carbon sequestration in tropical forest plantations by interacting with biota and nutrient availability (Bini et al., 2018; Raihan and Bijoy, 2023).

There was a significant difference between the climate mitigation capability of secondary spontaneously regenerated forest and managed forest plantations of 42 to 47 years old *Aucoumea klaineana*, *Tarrietia utilis*, *Cedrela odorata*, and *Terminalia ivorensis* in Ghana's moist and wet zones (Brown et al., 2020). For C sequestration and storage purposes, natural forests continue to excel (Raihan, 2023f). An analysis published in support of developing forest management techniques to improve C sequestration in forest soils found a total of 23.48 million metric tons of carbon with a C sequestration capability of 4 tC ha^{-1}yr^{-1} (Chinade et al., 2015). Soil carbon (C), which accounts for 36-46% of the Malaysian forest ecosystem, was not factored in (Chinade et al., 2015). The SOC has been considered in different settings (Forest Survey of India, 2017; Joshi et al., 2020). The total amount of SOC, the largest pool, rose from 3,968 million tons in 2015 to 3,979 million tons in 2017; the total amount of aboveground C stock rose from 2,220 million tons in 2015 to 2,238 million tons in 2017; and the total amount of belowground C stock fell from 695 million tons in 2015 to 699 million tons in 2017. Joshi et al. (2020) also evaluated SOC sequestration in damaged and undisturbed community forests in Nepal's Terai region close to the city of Kanchanpur. The non-degraded community forests sequestered 54.21 ± 3.59 tha^{-1} of SOC and had a total carbon stock of 301.08 ± 27.07 tha^{-1}, while the degraded community forests sequestered only 42.55 ± 3.10 tha^{-1} of SOC and had a total carbon stock of 152.68 ± 22.95 tha^{-1}. A study of forest management in a 35-year-old teak plantation in western Thailand emphasized the plantation's ability to absorb C in aboveground biomass and help to reducing the impacts of climate change (Chayaporn et al., 2021). The annual CO_2 sequestration ranking was found to be between 28 and 43 tons CO_2 ha^{-1}yr^{-1}, with an average of 36.7 tons CO_2 ha^{-1}yr^{-1} when the net ecosystem exchange in a Thai rubber tree plantation (*Hevea brasiliensis* Müll.Arg.) was measured using the eddy covariance method (Satakhun et al., 2019). Over 24.9 kilograms of carbon dioxide were stored in the soil for every kilogram of natural-rubber latex harvested from these plants, according to the study.

Yet, SOC sequestration is not necessarily the result of managing forest ecosystems. One factor that may limit the amount of SOC that can be sequestered in forest ecosystems is their advanced age. The San Luis Campus (Monteverde) in Costa Rica found that secondary woods are more able to absorb carbon (C) through tree growth than primary forests (Paniagua-Ramirez et al., 2021). Three short eucalypt plantation rotations (only 6-8 years) after decades of agricultural output and pasture in Brazil depleted soil carbon stocks along a large geographical gradient (Cook et al., 2016). The ability of forest ecosystems to restore damaged lands and mitigate climate change may be compromised by conditions that either boost or inhibit C sequestration (Malhi et al., 2020; Raihan, 2023g). The soil, weather, and plants are all elements that have a role. Sayer et al. (2019) found that 15 years of litter stores in a mature lowland tropical forest in Panama did not raise C stocks. In humid tropics, SOC storage depends on soil mineral stability. After three rotations, 21 years after planting, a sand-based eucalypt plantation in the Congolese coastal plains lost C accretion (Epron et al., 2015). Carbon accretion was observed at the completion of the first phase of eucalyptus and acacia plantings after 7 years in one length of the Congolese coastline, but the percentage of C in POM decreased at 5 relatives to two years into the second rotation. Due to the plantation's fresh organic waste's high N content and sandy soils' low C saturation capacity, SOM turnover is predicted to increase (Epron et al., 2015).

High decomposition rates slow C sequestration. Environment (drought, extended dry season), management (leaving organic leftovers on the field after wood collection), and reforestation cause this (Epron et al., 2015; Akpa et al., 2016; Raihan, 2023h). Marin-Spiotta and Sharma (2013) analyzed soil carbon data from 510 tropical afforestation and reforestation sites in 32 nations and territories. The study found that climate change, not land use or forest age, drives soil C variability in successional and forest plantation environments. This study demonstrated that soil C reserves in tropical forest plantations were not correlated with forest age. Campo et al. (2016) conducted a study comparing the soils of Mexico's tropical forests under different precipitation patterns, and they hypothesized that soils exposed to longer drought periods might have a higher content of resistant biopolymers, resulting in an accumulation of organic matter due to selective preservation. It may take decades for forest ecosystems to recover from the potential loss of SOC if this resource has been diverted. It took more than two decades, according to research by Cook et al. (2014) in Southeast Brazil, for soil SOC stores of native forests to return to pre-conversion levels after they were converted from mature forests to forest plantations and grasslands. In their study of primary and secondary seasonally dry tropical forests in central Mexico, Saynes et al. (2005) found that complete reinstatement of soil C and N dynamics did not occur until 60 years into secondary succession. Thirty years after establishing a plantation or pasture at 27 locations in South America (Brazil, Argentina, and Uruguay), researchers noticed a shift in SOC levels (Eclesia et al., 2012).

There are a variety of obstacles that make it difficult, if not impossible, for tropical forest ecosystems to absorb C, uphold land refurbishment, and moderate climate change (Raihan, 2023i). Possible causes include the knowledge gap and measurement error in some areas, as well as socioeconomic influences (correlated to social, economic, environmental, and political contexts). Kalimantan's degraded forests, which are threatened by palm oil plantations and peatland fires, have a storing prospective of between 0.8 and 1.1 PgC, according to emission aspects assessed using lidar or a random forest map (Ferraz et al., 2018). Kalimantan's damaged forests, the authors reasoned, had a much greater storage potential than South America's second-growth forests (35.33 Mg Cha^{-1}).

3.2. SOC and land degradation restoration in tropical forests

Nutrients like nitrogen and phosphorus can affect the total amount and longevity of SOC that is sequestered. Nitrogen availability is linked to carbon dioxide storage (Liu et al., 2018). Several studies on soil C dynamics suggest that N deposition can enhance soil C sequestration through various mechanisms. These mechanisms include reducing the decomposition of plant litter and soil organic matter, inhibiting soil respiration, and altering microbial enzymatic activity (Lu et al., 2021). N-fixation enables C to accumulate in mixed-species plantations, which has been linked to high rates of C sequestration (Bauters et al., 2015; Dubliez et al., 2018). By increasing plant development below and above ground, raised soil N levels can increase SOC accumulation (Fornara et al., 2013). N-fixing plants may potentially enhance SOM permanency by inducing biotic alterations facilitated by the incorporation of N-rich litter (Bini et al., 2018; Pereira et al., 2018). In two tropical forest soils, Cusack et al. (2010) found that N additions increased SOC stores in Puerto Rico. Although nitrogen deposition and climate change are mentioned as global change agents affecting the stability of sequestered SOC in forest ecosystems in the tropics, the authors conclude that much is yet understood.

Sequestration of SOC is simultaneous to phosphorus (P), a key ingredient for vegetation growth, lumber expansion, and agricultural output. Access to phosphorus is linked to SOC mineralization in tropical forests, despite the fact that phosphorus is a limiting element in many of these ecosystems (Bachegaet al., 2016). Decomposer starvation/inhibition and low microbial biomass/activity resulted from the stoichiometric (N:P) imbalance brought by low P concentrations in the litter of *A. mangium*, a natural fertilizer substitutes (Santos et al., 2017). Compared to the soil and the material they break down, microbial communities have low C:N:P ratios and hence require high amounts of N and P. As a result, bacteria can only store so much nitrogen and phosphorus before they begin to release it (Schleuss et al., 2020). Soil nitrogen (N) availability is low, whereas phosphorus (P) demand is considerable (Schleuss et al., 2020). Synergistic effects between P and C accumulation are typically observed in diversified species stands with Sensitive types, as compared to monoculture plantation.

The superiority of sequestered SOC is also affected by the presence of animals and microorganisms in the soil (Bini et al., 2018; Pereira et al., 2018; Santos et al., 2017). Litter decomposition in monocultures was regulated by water-soluble components and lignin concentration, but in tropical forests, decomposer activity was limited by energy or P availability. A change in the makeup of soil microorganisms and bacteria is associated with increased microbial endeavor in litter and soil, indicating more effective nutrient cycling (Bini et al., 2018). In two N-rich tropical forest soils, C cycling was affected by microbial community composition, enzyme capabilities, and soil C chemistry in Puerto Rico (Cusack et al., 2010). It shows how microorganisms improve SOC sequestration and relate SOM to nutrients like nitrogen and phosphorus. Tropical forest soil processes produce stable, less mineralized C, which helps mitigate climate change and restore land (Baccini et al., 2017; Raihan, 2023j). Figure 3 shows how established sequestered SOC connected to additional nutrients besides good soil elements can uphold SOC sequestration and related co-benefits.

Stable segregated SOC and its subsidies on land restitution are augmented by the dynamics of additional nutrients including N, P, and S. The connection between C and N, P, and S for improved physical (cluster) and chemical (N, P, and S disposal) properties, as well as to turn volatile C from agricultural and animal leftovers into stable SOM (Lal, 2013). The accessibility of inorganic nutrients like N, P, and S is decisive to the sequestration of C hooked on the further settled agreed segment of the SOM consortium, and this is true regardless of soil type or C responses. McDonald et al. (2018) shown robust interactions between decomposition proportions, photosynthesis, and soil's capacity to hold carbon, nitrogen, and phosphorus. This partially addresses the second question given by the review by showing that there is a relationship between the quality of the SOC that has been sequestered (its linkage to other N, P nutrients), land retrieval, and the long-term assistances in forest tropical ecosystems.

Degraded Brazilian woods have been turned into carbon-sequestering restored areas with the help of legume vegetation, nitrogen-fixing microbes, and arbuscular mycorrhizal fungus (Macedo et al., 2008). Assuming the deforested area had identical C stocks to the restored area, the authors discovered a 23 Mg ha^{-1} increase in soil C stock and a 1.7 Mg ha^{-1} rise in N stock after 13 years of legume tree planting (Macedo et al., 2008). Natural fertilizer substitutes (NFS) are often utilized to restore agriculturally unsuitable or marginal soils by increasing chemical fertility (Raihan, 2024b). Increasing nitrogen (N) contents and carbon (C) status both contribute to this goal (Wang et al., 2010; Chen et al., 2011). Restoration of southern Chinese soils with *Acacia mangium* and *A. auriculiformis* enhanced carbon and nitrogen cycling (Wang et al., 2010). Chen et al. (2011) observed that in Guangdong Province, Southern China, *Acacia crassicarpa* stands demonstrated bigger carbon sinks and greater SOC stocks *than Eucalyptus urophylla* stands (330±76 C m^{-2} yr^{-1} vs 1960±178 g C m^{-2} yr^{-1}). Comparing *A. mangium* and *E. urophylla* plantings, resultant woods, and meadows across Vietnam's edaphic and climatic gradients reveals a favorable correlation between aboveground biomass output and soil C, N, and P levels (Sang et al., 2013; Raihan, 2023k). Ahmed et al. (2010) in Malaysia found that total C and P concentrations rose from ages 0 to 6, 12, and 17. Carbon and phosphorus can be absorbed by forests that have been restored with native trees, according to studies.

Unexpected events have the potential to prevent the utilization of NFS plantations for C sequestration and land restoration. The soil's clay content, annual precipitation, and average temperature all have an effect on soil C stocks in Brazilian eucalypt plantations; this may be true for other species as well (Cook et al., 2014). From a depth of 0-30 cm beneath 18-26 years old eucalypt planting, Cook et al. (2014) observed that SOC stock diminishes with planting age in tropical and subtropical contexts, reporting a fall from an average of 29 Mg ha^{-1} (0.87 Mg ha^{-1}yr^{-1}). The present study's findings show that SOC sequestration occurs as a result of the managing of organic deposits or the introduction of NFS in the restoration or refurbishment developments of tarnished lands or forests

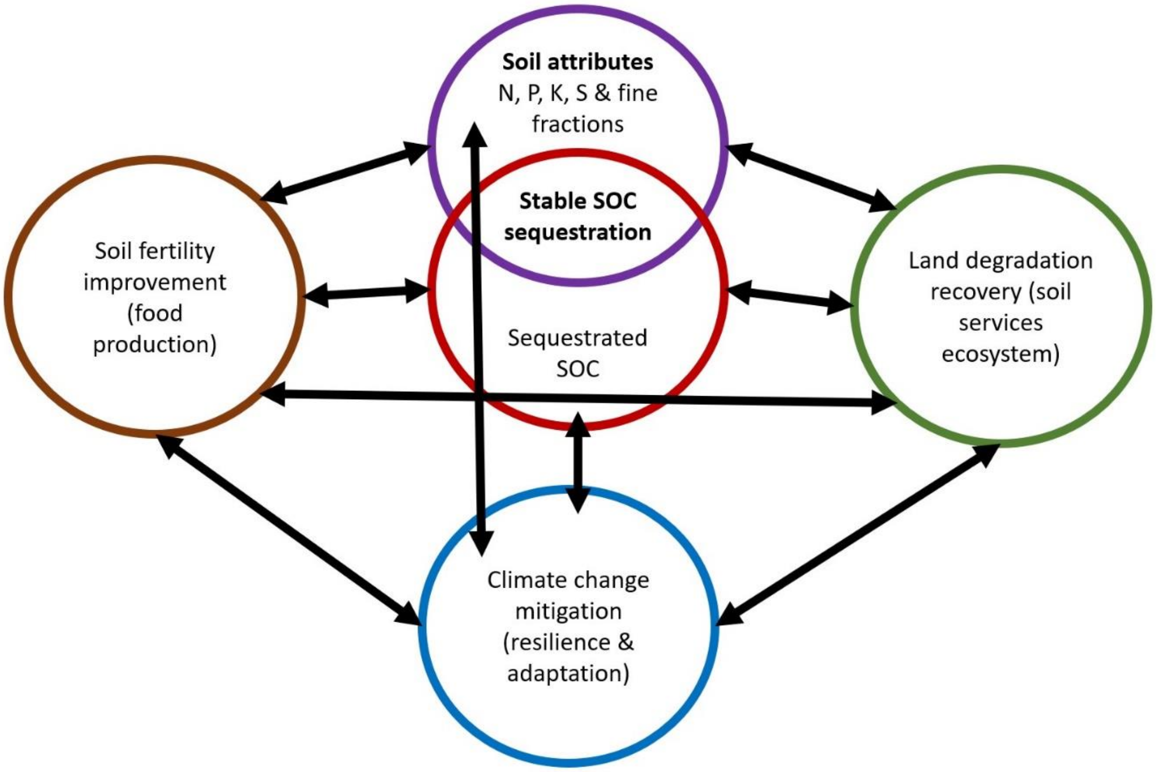

Figure 3. Conceptual framework of stable SOC sequestration and its co-benefits.

4. Conclusions

This review focused on forest management, specifically methods that boost sequestration of SOC and restoration of land, in order to improve the condition of SOC sequestered in tropical forest ecosystems (interactions to other nutrients driven by soil biota). However, due to the fact that it is dependent on edaphic and additional influences like land-use record, climate, ecosystem, and even intrinsic features, SOC sequestration may not always occur. This is because of the fact that it is possible for SOC to be sequestered in a system. C sequestration management is essential if one wishes to restore degraded lands in tropical ecosystems, mitigate the effects of climate change, and preserve the health of the soil. In the process of sequestering carbon, soil biota plays an essential part and have significant connections to other soil fractions and nutrients (including nitrogen, phosphorus, and sulfur). The management of forest ecosystems (planting or natural) associated with specific methods (initiating NFS, overseeing organic deposits, etc.) that generally increase sequestration of SOC and its superiority can result in long-term benefits for the mitigation of climate change and the restoration of land. These benefits can be achieved through the management of forest ecosystems (balanced C, connection to N, P, and soil segments).

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