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REVIEW ARTICLE

Enhancing Soil Carbon Sequestration and Land Restoration through Tropical Forest Management

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Abstract
Soil has a high capacity for absorbing carbon dioxide (CO_2). The significance of soil organic carbon (SOC) in tropical regions is often overlooked, despite its crucial role. This study investigates the potential of forest management to enhance the sequestration of SOC and rehabilitate degraded tropical ecosystems. Sequestering soil organic carbon has the potential to improve soil fertility while also mitigating land degradation and reducing greenhouse gas (GHG) emissions. The improvement of soil structure, aggregation, infiltration, faunal mobility, and nutrient cycling (specifically carbon, nitrogen, phosphorus, and sulfur) is observed. Managing forest ecosystems enhances carbon sequestration, mitigates climate change, and rehabilitates degraded land. By integrating organic residue management with nitrogen-fixing plants, afforestation or reforestation of marginal or degraded lands can effectively increase carbon storage in both biomass and soil. This approach also promotes soil health, improves food productivity, restores land quality, and contributes to the reduction of GHG emissions. The sequestration of carbon promotes the biological, physical, and chemical fertility of the soil, hence enhancing soil health.

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

Introduction

Between 1990 and 2015, the total area of land used for forestry decreased by 33%, from 4128 million hectares to 3999 million hectares. Tropical regions comprise 45 percent, or 728 million hectares, of the world's woods, with the boreal, temperate, and subtropical regions following suit (FAO, 2020). However, studies indicate that tropical deforestation is mostly attributed to agricultural and industrial activities (Raihan, 2023a), with a particular focus on South America and Africa (FAO, 2020). Africa saw a net loss of 3.9 million hectares of forests between 2010 and 2020. According to the FAO (2020), South America has a total of 1 million hectares. Pan et al. (2011) discovered that the carbon absorption capacity of forests is similar to that of the land in terms of absorbing carbon dioxide released from burning fossil fuels. Forests contain 80% of the carbon stored above the ground and 70% of the carbon stored in the soil (Raihan et al., 2021a).

Effective forest management is crucial for the processes of carbon sequestration, soil rejuvenation, and reduction of greenhouse gas emissions (Ontl et al., 2020; Raihan et al., 2022a). Managing forest ecosystems entails understanding the dynamics, size, and chemical composition of their pools. Forest management and carbon sequestration are influenced by various factors such as silviculture (the selection of tree species and rotation periods), gaps (the quantity of trees planted at once), turbulence (including pest influxes, wind pitch, and wildfires), air contamination, and water management (Raihan et al., 2019). A study conducted by Biber et al. (2020) used modeling techniques to forecast the extension of forests in 10 European landscapes over the next century. The study examined how forest management practices in Europe impact ecosystem services such as carbon sequestration, biodiversity, and sustainable timber production. The study concluded that it is important to take into account storms and droughts that are caused by climate change. Within the eastern region of the United States, the Community Land Model 4.5 places a high importance on conserving forested areas. This is achieved by taking into account factors such as susceptibility to drought and fire, and by comparing the relative importance of preserving biodiversity. This approach differs from the one used in the western region (Buotte et al., 2020). Preserved temperate forests in the western US, which have a moderate to high capacity for storing carbon, are estimated to have a mitigation capacity equivalent to 27-32 percent of the global capacity previously observed in boreal and temperate forests. This capacity is sufficient to absorb fossil fuel emissions for around 8 years, according to Buotte et al. (2020).

According to the US forest inventory, there are 1.4 trillion plants in over 130,000 federal forestlands. This shows that planting trees can increase the ability to store carbon and decrease CO_2 emissions (Domke et al., 2020). Tropical trees sequester carbon both below and above ground (Raihan and Tuspekova, 2023). The ecosystem in question has the highest carbon storage capacity, with a value of 91 tha^{-1}, and also exhibits the highest wood production, with a value of 121 m^3ha^{-1}. According to Pan et al. (2011), boreal forest soils that are rich in carbon do not have them. Tropical forests have the highest carbon concentration, allowing them to accumulate and retain the most carbon (Raihan et al., 2018; Raihan, 2023b). Figure 1 illustrates the simplified global carbon cycle in tropical forest habitats. Their capacity to capture and store atmospheric carbon has shown the most significant growth in the recent two periods, making them crucial for mitigating climate change (Fernández-Martnez et al., 2019). The capacity was examined by MACC-II and Jena CarboScope atmospheric inversion models, as well as 10 dynamic universal plants models. The findings indicate that the ability of ecosystems to absorb carbon dioxide may serve as a countermeasure against global warming and climate change (Raihan et al., 2022b). Hence, effective forest management has a crucial role in carbon sequestration, the regeneration of degraded woodlands and other areas, the mitigation of climate change, the preservation of natural forests, and the conservation of biodiversity (Raihan and Tuspekova, 2022a).

The FAO (2020) anticipated that by 2020, the world forest carbon stock would reach 662 gigatonnes (or 163 tonnes per hectare). Forest soils comprise 50% of the organic carbon found in terrestrial ecosystems (Mayer et al., 2020; Raihan and Said, 2022). Tropical forest soils possess a carbon (C) content that is three times more than that found in the atmosphere or plants. The biogeochemical cycles of carbon (C), water, and other components in forests have an impact on the Earth's climate on a global scale (Malhi et al., 2020). Forest ecosystems require adaptability and resilience in order to endure the impacts of climate change (Begum et al., 2020; Raihan and Tuspekova, 2022b; Raihan et al., 2023a). Tropical forests are concerned that climate change may lead to increased aridity. However, over the past twenty years, they have significantly enhanced their capacity to capture atmospheric carbon, hence boosting their effectiveness in addressing climate change (Fernández-Martnez et al., 2019; Raihan et al., 2022c). Malhi et al. (2020) found that land-use alteration, which encompasses the loss of habitats and excessive exploitation, has a greater impact on ecosystems compared to climate change.

The combination of increasing population, declining soil fertility, and food shortages leads to land degradation, which exacerbates the impact of climate change on forest ecosystems in tropical regions (Jaafar et al., 2020; Raihan and Tuspekova, 2022c; Raihan et al., 2023b). The United Nations and other global initiatives, such as the "Bonn Challenge" and the "UN-Decade on Ecosystem Restoration" (2021-2030), have long been advocating for the separation of land dilapidation and the achievement of the UN Sustainable Development Goals (SDGs). Soil deterioration can occur naturally or as a result of human activities. There are four main types of soil deterioration: chemical, biological, physical, and ecological. Chemical deterioration includes processes such as salinization, acidification, leaching, pollution, and nutrient depletion. Biological deterioration involves a decrease in soil organic material, damage to soil biodiversity, and a decline in the ability of soil to store carbon. Physical deterioration includes compaction, runoff and erosion, and desertification. Ecological deterioration disrupts nutrient cycling, perturbs the hydrological cycle, and leads to a decline in the efficiency of input use.

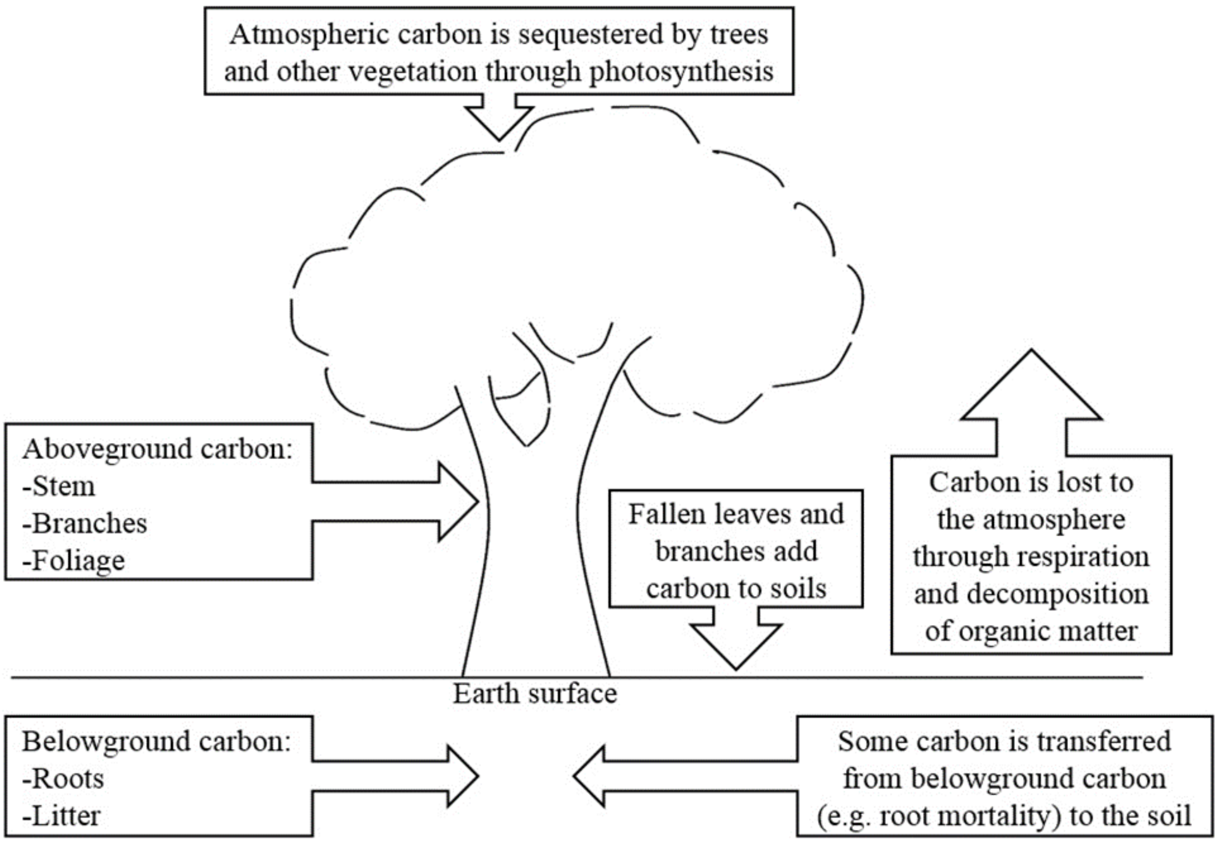

Figure 1. Carbon sequestration in forests.

Implementing forest management practices and engaging in tree planting activities on degraded land have been shown to enhance the accumulation of carbon in the soil and contribute to the preservation of ecosystem carbon pools (Raihan and Tuspekova, 2022d). Research on SOC has shown a significant growth over the past two decades (Mayer et al., 2020; Ali et al., 2022). The majority of publications and articles focus on the topic of soil organic carbon (SOC) and its role in several areas such as nutrient cycling, soil fertility, crop production, climate change, and land restoration (Lal, 2013). The "4 per 10000 Initiative," alternatively referred to as Soils for Food Security and Climate Change, was introduced during the 21st Conference of the Parties (COP) of the UNFCCC, garnering global interest in soil (Soussana et al., 2019). Climate change and land degradation pose significant threats to agriculture, forestry, food production, and sustainability (Raihan and Tuspekova, 2022e). Hence, the 22nd Conference of the Parties (COP) placed emphasis on the utilization of fertilizers and the management of manure as means to achieve sustainable and resilient agriculture.

Nevertheless, soil organic matter (SOM) functions as a storage for nutrients and is frequently employed as an indicator for evaluating soil fertility, as well as the chemical, physical, and biological characteristics of soil health. Soil organic carbon (SOC) accounts for 50-99% of the total quantity of soil organic matter (SOM). The SOM pool exhibits a notable level of stability and maintains an average residence length of several decades. Hence, it is possible that the process of appropriately assessing changes in SOC may require a duration beyond 2 years. However, changes in the ability of SOM to be broken down by natural processes or in the amount of microbes present can be readily seen over a shorter period of time. Soils have a vital role in storing carbon, acting as both a supplier and absorber of carbon (Raihan et al., 2022d). The variables that affect this phenomenon encompass climate, soil texture, soil acidity, vegetation cover, biomass inputs, management approaches, as well as soil depth, starting carbon levels, and soil type (Marin-Spiotta and Sharma, 2013; Akpa et al., 2016).

The quality of soil organic matter (SOM) is enhanced by the accumulation of soil organic carbon (SOC), especially when it is protected by small soil particles (Eclesia et al., 2012; Sang, 2013). The decrease in soil organic matter (SOM) quality is ascribed to the heightened process of carbon mineralization caused by climate changes, management methods, or soil-related factors (Bonfatti et al., 2015; Cook et al., 2016). Soil carbon sequestration can improve soil fertility, boost agricultural output, and reduce climate change by reducing greenhouse gas emissions (Paustian et al., 2016; Raihan, 2024a). The storage of soil organic carbon (SOC) is essential for effectively managing, reducing, and stopping land degradation (Raihan, 2023c). Shimamoto et al. (2018) performed a comprehensive worldwide meta-analysis on the recovery of ecosystem services in tropical forests. The researchers discovered that restoration initiatives were especially successful in improving the preservation of biodiversity in previously damaged grazing land, as well as in augmenting carbon storage in previously depleted agricultural areas. The authors proposed that the most suitable method involves enhancing the recovery of ecosystem services in deteriorated tropical forests.

Research on soil organic carbon (SOC) should give priority to monitoring and assessing places where decomposition is happening rapidly, such as tropical forest ecosystems that are suffering land degradation worsened by high amounts of organic matter and climate change (FAO, 2020; Raihan and Tuspekova, 2022f). Carbon sequestration is an essential aspect of sustainable soil management, which plays a critical role in restoring and maintaining soil health, as well as reducing climate change and rehabilitating land (FAO, 2020; Raihan et al., 2023c). Hence, the main objective of this study is to concentrate on the management of soil organic carbon (SOC) in tropical forest ecosystems, which are now facing the highest level of endangerment among all forest ecosystems. The objective of this research is to tackle both the mitigation of climate change and the prevention/restoration of land degradation.

Planting trees on agricultural, grassland, or city-edge property can have an impact on both the environment and the economy. The introduction of nitrogen-fixing species and the management of organic wastes enhance the sequestration of soil organic carbon (SOC) and the cycling of nutrients, hence promoting the growth and development of forest ecosystems. The study of tropical soil organic carbon (SOC) levels and characteristics has been insufficient, despite their capacity to enhance carbon sequestration and prevent land degradation by influencing nitrogen (N) and phosphorus (P) levels. This study investigates the impact of the quantity and quality of soil organic carbon (SOC) on land rehabilitation in tropical forest ecosystems. The study specifically examines the influence of SOC coupled with nitrogen or phosphorus cycles, carbon stocks, and stable versus labile carbon forms. Restoring and planting trees in marginal and degraded tropical forest habitats can enhance soil fertility, mitigate climate change, and combat land degradation.

Methodology

A comprehensive literature analysis was conducted to investigate the connections between land restoration, soil organic carbon (SOC), and other components in tropical forest ecosystems, as well as soil carbon management and storage. This has demonstrated the importance of forest management in relation to the amount and quality of carbon sequestered and land restored in tropical ecosystems. Figure 2 clearly demonstrates that the review followed the principles of systematic review methodology. By breaking down the research questions into their individual concepts, it is feasible to create a list of search terms that would enable a comprehensive and representative literature search on the subject of managing soil carbon and its connection to climate change and land restoration in tropical forest ecosystems. The classification of databases has been considered, including synonyms, singular and plural models, broader phrases, alternate spellings, and more specific terms.

This study conducted a systematic literature review to examine the potential connections between climate change adaptation and resilience in tropical forest ecosystems, the interaction between soil organic carbon (SOC) and other nutrient cycling processes, and the links to land restoration. The retrieved publications and papers were assessed using a set of encoded criteria for the inclusion and exclusion of primary research papers. This project involved conducting primary assessments to evaluate the management of social-ecological systems in the context of mitigating climate change or repairing degraded land in tropical regions. The secondary literature on forests in the tropics, both qualitative and quantitative, is also examined.

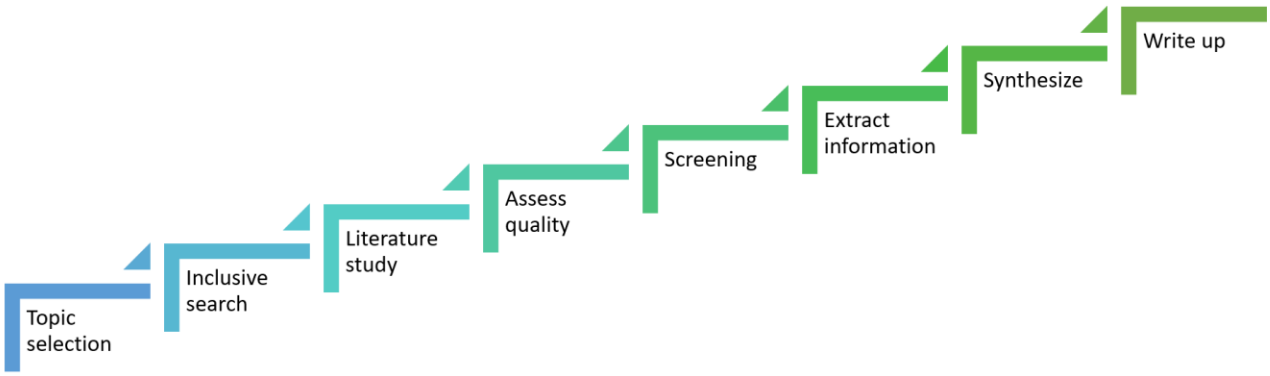

Figure 2. The procedure of systematic review conducted by the study.

Following an extensive examination of the pertinent literature, a total of 86 publications published from 1990 to 2022 were selected for further scrutiny. The papers were sourced from the academic aggregators Google Scholar, Scopus, and Web of Science (WOS). This work presents an overview of the connections between carbon sequestration and land degradation repair in tropical forests over a long period of time. The goal is to establish a model for future forest research and management that considers both of these processes. This study exclusively utilized research articles published in peer-reviewed journals to ensure the credibility and reliability of the findings. These findings serve as a basis for future research and management efforts in tropical forests, with a focus on carbon sequestration and the restoration of land degradation. Subsequently, these articles underwent evaluation to ascertain whether their main subject matter aligned with that of the present inquiry.
Although a specific instrument for quality assessment was not used, the review ensured that the evidence extracted from the research papers (that met the inclusion criteria) was relevant and accurate by evaluating the research methodology and questions, sources of information, and the selection of the evaluation criteria.

Results and Discussion

Enhancing soil carbon through tropical forest management

Due to their crucial role in the overall carbon cycle and the numerous benefits they provide to ecosystems, such as carbon sequestration in biomass and soil, forests necessitate meticulous management to enhance carbon sequestration and improve soil health (Raihan, 2023d). Fernandez-Martinez et al. (2019) state that tropical forest ecosystems have demonstrated enhanced capacity to trap carbon during the previous two decades. The sequestration of carbon (C) in tropical forests can occur depending on the management practices employed. Table 1 provides a summary of carbon sequestration in various tropical forests. The rate of soil organic carbon (SOC) sequestration is influenced by various elements such as tree species, soil type, environmental conditions, climate, and geographic considerations. This topic has been extensively studied and documented by Mayer et al. (2020). Carbon sequestration in biomass and soil is a frequent outcome of managing forest ecosystems through afforestation and reforestation. However, the effectiveness of these activities relies heavily on soil conditions, in addition to the parameters mentioned earlier (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 Cha^{-1}	Derwisch et al. (2009)
Colombia	Mixed forest	122-141 Mg Cha^{-1}	Saatchi et al. (2011)
Venezuela	Mixed forest	118-139 Mg Cha^{-1}	Saatchi et al. (2011)
Bolivia	Mixed forest	84-94 Mg Cha^{-1}	Saatchi et al. (2011)
Myanmar	Mixed forest	146-157 Mg Cha^{-1}	Saatchi et al. (2011)
Papua New Guinea	Mixed forest	147-153 Mg Cha^{-1}	Saatchi et al. (2011)
Vietnam	*A. mangium* and Eucalypt plantation	11.5 $tCha^{-1}yr^{-1}$	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 Cha^{-1}	Aragón et al. (2021)
Thailand	Teak plantation	45-82 Mg Cha^{-1}	Chayaporn et al. (2021)
Costa Rica	Natural forest	18210 tons	Paniagua-Ramirez et al. (2021)
Malaysia	All types of forests	157.5 tC ha^{-1}	Raihan et al. (2021b)
Congo	Peatland	634 Mg Cha^{-1}	Crezee et al. (2022)

The afforestation of huge uncultivated regions in central China with woodland, shrubland, and agricultural plants has led to an improvement in soil carbon storage, particularly in macroaggregates (>2000 m), as reported by Dou et al. (2016). Compared to pure acacia and eucalypt stands, which had soil carbon levels of 16.7 and 15.9 tha^{-1} respectively, the mixed-species stands consisting of 50% acacia and 50% eucalypt showed a rise in soil carbon stocks to 17.8 ± 0.7 tha^{-1} after afforestation of natural tropical savannas. The carbon stock in *A. mangium* plantations in Malaysia showed an increase 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). Camacho et al. (2009) provided a framework for the long-term storage of carbon (C) in the Makiling forest reserve and the Philippines. The authors suggested the implementation of reforestation, particularly focusing on fast-growing and high-timber species, as a means to enhance the process of carbon sequestration. Reforestation and afforestation strategies, such as using fast-growing natural fertilizer substitutes (NFS) or nitrogen-fixing bacteria, or leaving organic residues on the field after wood harvesting, can further increase soil organic carbon (SOC) stocks in coarse-textured soils that have a high rate of SOC decomposition (Dubliez et al., 2018; Mayer et al., 2020). The reason for this is that the addition of new organic residues or organic matter rich in nitrogen changes the activity of microorganisms and/or the composition of bacteria (Bini et al., 2018; Pereira et al., 2018). Soil microorganisms showed higher levels of carbon and nitrogen buildup after 27 months in the combination plantation of acacia and eucalyptus compared to pure or treated stands. Plants that engage in nitrogen fixation can enhance soil fertility and carbon sequestration in tropical forest plantations through their interactions with organisms and nutrient availability (Bini et al., 2018; Raihan and Bijoy, 2023).

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 differed significantly (Brown et al., 2020). Natural forests remain highly effective for carbon sequestration and storage (Raihan, 2023f). A study conducted to promote the development of forest management practices for enhancing carbon sequestration in forest soils discovered a total of 23.48 million metric tons of carbon, with a carbon sequestration capacity of 4 metric tons per hectare per year (Chinade et al., 2015). The Malaysian forest ecosystem does not take into consideration soil carbon (C), which makes up 36-46% of it (Chinade et al., 2015). The Soil Organic Carbon (SOC) has been examined in several contexts, including the Forest Survey of India in 2017 and a study conducted by Joshi et al. in 2020. The SOC pool, which is the largest, increased from 3,968 million tons in 2015 to 3,979 million tons in 2017. The aboveground C stock also increased from 2,220 million tons in 2015 to 2,238 million tons in 2017. However, the belowground C stock decreased from 695 million tons in 2015 to 699 million tons in 2017. Joshi et al. (2020) assessed the process of soil organic carbon (SOC) sequestration in both damaged and undisturbed community forests located in Nepal's Terai area near the city of Kanchanpur. The undisturbed community forests stored 54.21 ± 3.59 tha^{-1} of soil organic carbon (SOC) and had a total carbon stock of 301.08 ± 27.07 tha^{-1}. In contrast, the degraded community forests stored only 42.55 ± 3.10 tha^{-1} of SOC and had a total carbon stock of 152.68 ± 22.95 tha^{-1}. A recent investigation on forest management in a 35-year-old teak plantation located in western Thailand highlighted the plantation's capacity to sequester carbon in its aboveground biomass, hence mitigating the effects of climate change (Chayaporn et al., 2021). The study conducted by Satakhun et al. (2019) determined that the yearly CO_2 sequestration rate in a Thai rubber tree plantation (*Hevea brasiliensis* Müll.Arg.) ranged from 28 to 43 tons CO_2 $ha^{-1}yr^{-1}$, with an average of 36.7 tons CO_2 $ha^{-1}yr^{-1}$. These measurements were obtained using the eddy covariance method to assess the net ecosystem exchange. The study found that for every kilogram of natural-rubber latex extracted from these plants, 24.9 kilos of carbon dioxide were retained in the soil.

However, it is important to note that SOC sequestration does not exclusively occur as a consequence of forest ecosystem management. An inhibiting factor for the sequestration of SOC in forest ecosystems is their mature age. A study conducted at the San Luis Campus (Monteverde) in Costa Rica has revealed that secondary forests have a greater capacity to sequester carbon (C) through tree growth compared to primary forests (Paniagua-Ramirez et al., 2021). According to Cook et al. (2016), the soil carbon reserves in Brazil were reduced throughout a vast geographical gradient due to three short eucalypt plantation cycles lasting only 6-8 years, after decades of agricultural output and grazing. The capacity of forest ecosystems to rehabilitate degraded lands and alleviate climate change may be hindered by factors that either enhance or impede carbon sequestration (Malhi et al., 2020; Raihan, 2023g). The soil, weather, and plants are all constituent factors that have a significant effect. In their study, Sayer et al. (2019) discovered that the accumulation of litter over a period of 15 years in a fully developed lowland tropical forest in Panama did not result in an increase in carbon stocks. The storage of soil organic carbon (SOC) in humid tropics is contingent upon the stability of soil minerals. According to Epron et al. (2015), a sand-based eucalypt plantation in the Congolese coastal plains had a decrease in carbon accretion after three rotations, 21 years after it was planted. After 7 years, carbon accumulation was noticed at the end of the initial phase of eucalyptus and acacia plantings along a section of the Congolese coastline. However, the proportion of carbon in particulate organic matter reduced by 5% after two years into the second rotation. The presence of high nitrogen content in the fresh organic waste from the plantation, along with the low capacity of sandy soils to retain carbon, is expected to result in an increase in soil organic matter turnover (Epron et al., 2015).

Accelerated breakdown rates hinder the process of carbon sequestration. The occurrence of this phenomenon is attributed to environmental factors such as drought and extended dry seasons, as well as management practices such as leaving organic residues on the field after wood collection. Additionally, reforestation efforts have also been identified as a contributing factor (Epron et al., 2015; Akpa et al., 2016; Raihan, 2023h). Marin-Spiotta and Sharma (2013) examined soil carbon data from 510 sites where tropical afforestation and reforestation took place in 32 different nations and territories. The study concluded that soil carbon variability in successional and forest plantation ecosystems is primarily influenced by climatic change, rather than land use or forest age. This study revealed that there was no correlation between the age of tropical forest plantings and the amount of carbon reserves in the soil. In their study, Campo et al. (2016) examined the soils of Mexico's tropical forests and compared them under varying precipitation patterns. They proposed the hypothesis that soils experiencing prolonged drought periods may contain a greater amount of resilient biopolymers, leading to the accumulation of organic matter through selective preservation. The possible diversion of SOC could result in the destruction of forest ecosystems, which may take several decades to recover. Research conducted by Cook et al. (2014) in Southeast Brazil revealed that it took over twenty years for the soil SOC stores of native forests to recover to their original levels after being transformed from mature forests to forest plantations and grasslands. Saynes et al. (2005) discovered that the restoration of soil carbon and nitrogen processes in primary and secondary seasonally dry tropical forests in central Mexico took 60 years to fully occur during secondary succession.

Researchers observed a change in soil organic carbon (SOC) levels at 27 places in South America (Brazil, Argentina, and Uruguay) thirty years after establishing a plantation or pasture, according to Eclesia et al. (2012).
Tropical forest ecosystems have numerous barriers that hinder their ability to absorb carbon, support land restoration, and mitigate climate change (Raihan, 2023i). Possible factors contributing to this phenomenon include the disparity in knowledge and inaccuracies in measurement in certain domains, as well as the impact of socioeconomic impacts, which are interconnected with social, economic, environmental, and political contexts. The forests in Kalimantan, which have been damaged and are at risk due to palm oil plantations and peatland fires, have the potential to store between 0.8 and 1.1 PgC (petagrams of carbon), as determined by emission assessments using lidar or a random forest map (Ferraz et al., 2018). The scientists concluded that the damaged forests in Kalimantan have a significantly higher capacity for storing carbon than the second-growth forests in South America (35.33 Mg Cha^{-1}).

SOC and land degradation restoration in tropical forests

Nutrients such as nitrogen and phosphorus have the potential to influence both the overall quantity and duration of soil organic carbon (SOC) that is stored. The availability of nitrogen is connected to the storage of carbon dioxide (Liu et al., 2018). Multiple studies on the dynamics of soil carbon indicate that nitrogen deposition can increase the storage of carbon in the soil through different methods. These mechanisms encompass the reduction of plant litter and soil organic matter breakdown, the inhibition of soil respiration, and the alteration of microbial enzymatic activity (Lu et al., 2021). The process of nitrogen fixation allows for the accumulation of carbon in mixed-species plantations, which has been associated with elevated rates of carbon sequestration (Bauters et al., 2015; Dubliez et al., 2018). Raised soil nitrogen (N) levels can enhance the accumulation of soil organic carbon (SOC) by promoting plant development both below and above ground (Fornara et al., 2013). Nitrogen-fixing plants have the potential to improve the long-term stability of soil organic matter by causing changes in living organisms through the addition of nitrogen-rich plant material (Bini et al., 2018; Pereira et al., 2018). Cusack et al. (2010) discovered that the addition of nitrogen improved the storage of soil organic carbon (SOC) in two tropical forest soils in Puerto Rico. While nitrogen deposition and climate change are acknowledged as worldwide factors that impact the stability of sequestered soil organic carbon (SOC) in tropical forest ecosystems, the authors assert that there is still much to be comprehended.
The sequestration of soil organic carbon (SOC) occurs concurrently with phosphorus (P), which is a crucial element for the growth of plants, the increase of timber production, and the agricultural output. Phosphorus availability is connected to soil organic carbon (SOC) mineralization in tropical forests, even though phosphorus is a restricting factor in many of these ecosystems (Bachega et al., 2016). The lack of phosphorus in the litter of *A. mangium*, a natural substitute for fertilizer, led to a stoichiometric imbalance (N:P) which caused hunger or inhibition of decomposers, as well as reduced microbial biomass and activity (Santos et al., 2017). Microbial communities have low C:N:P ratios in comparison to the soil and the material they decompose, which means they need significant amounts of nitrogen (N) and phosphorus (P). Bacteria have a limited capacity to hold nitrogen and phosphorus, and once this capacity is reached, they start to release these elements (Schleuss et al., 2020). The availability of nitrogen (N) in the soil is limited, while there is a significant demand for phosphorus (P) (Schleuss et al., 2020). Typically, diverse species stands with Sensitive kinds show synergistic effects in the accumulation of P and C, as opposed to monoculture plantations.
The presence of animals and microbes in the soil also impacts the superiority of sequestered SOC (Bini et al., 2018; Pereira et al., 2018; Santos et al., 2017). The decomposition of litter in monocultures was controlled by water-soluble components and the concentration of lignin. However, in tropical forests, the activity of decomposers was restricted by the availability of energy or phosphorus (P). An alteration in the composition of soil microorganisms and bacteria is linked to heightened microbial activity in litter and soil, suggesting enhanced efficiency in the process of nitrogen cycling (Bini et al., 2018). The study conducted in Puerto Rico by Cusack et al. (2010) found that the cycling of carbon in two nitrogen-rich tropical forest soils was influenced by the composition of the microbial community, the capacities of enzymes, and the chemistry of soil carbon. The text demonstrates the role of microorganisms in enhancing the storage of soil organic carbon (SOC) and its

connection to essential nutrients such as nitrogen and phosphorus. The soil processes in tropical forests provide stable, less mineralized carbon, which plays a crucial role in mitigating climate change and facilitating land restoration (Baccini et al., 2017; Raihan, 2023j). Figure 3 illustrates the connection between established sequestered soil organic carbon (SOC) and extra nutrients, which contribute to the maintenance of SOC sequestration and its associated co-benefits.

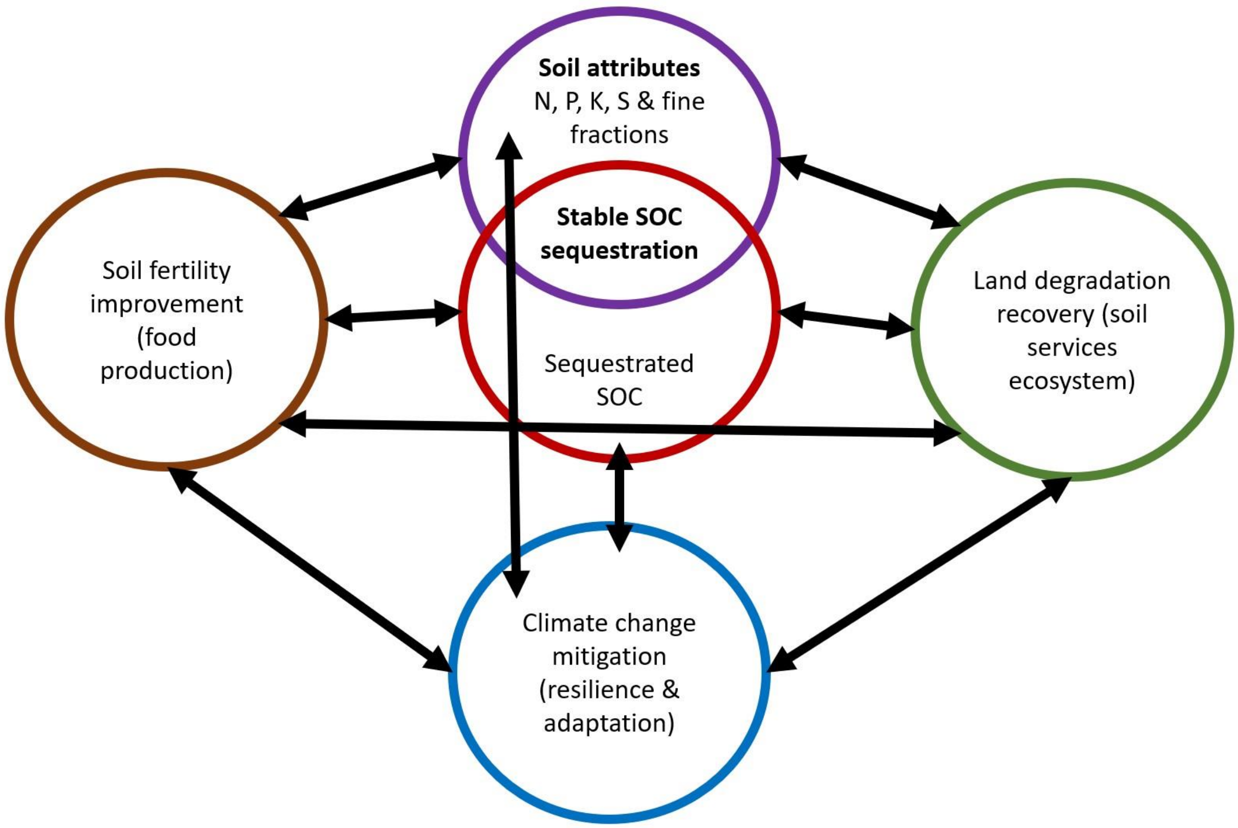

Figure 3. Conceptual framework of stable SOC sequestration and its co-benefits.

The stable segregation of SOC (soil organic carbon) and its subsidies on land restitution are enhanced by the dynamics of other nutrients such as nitrogen (N), phosphorus (P), and sulfur (S). The relationship between carbon (C) and nitrogen (N), phosphorus (P), and sulfur (S) is important for enhancing the physical properties of clusters and the chemical disposal of N, P, and S. Additionally, this relationship helps convert volatile carbon from agricultural and animal waste into stable soil organic matter (SOM) (Lal, 2013). The availability of inorganic nutrients such as nitrogen (N), phosphorus (P), and sulfur (S) is crucial for the storage of carbon (C) in the deeper layers of the soil organic matter (SOM) community. This holds true independent of the type of soil or the response of carbon. McDonald et al. (2018) demonstrated strong correlations among decomposition proportions, photosynthesis, and the soil's capacity to retain carbon, nitrogen, and phosphorus. This addresses a part of the second point raised in the review by demonstrating a connection between the quality of the sequestered SOC (its association with other N, P nutrients), land recovery, and the long-term benefits in tropical forest ecosystems.

Brazilian forests that have undergone degradation have been transformed into regions that trap carbon through the assistance of legume plants, nitrogen-fixing microorganisms, and arbuscular mycorrhizal fungus (Macedo et al., 2008). The scientists found that after 13 years of planting legume trees, there was a 23 Mg ha^{-1} increase in soil carbon stock and a 1.7 Mg ha^{-1} increase in nitrogen stock in the deforested region, assuming it had the same carbon stocks as the restored area (Macedo et al., 2008). Natural fertilizer substitutes (NFS) are commonly employed to enhance the chemical fertility of agriculturally inappropriate or marginal soils (Raihan, 2024b).

The objective can be achieved by enhancing the nitrogen (N) levels and carbon (C) status, as demonstrated by Wang et al. (2010) and Chen et al. (2011). The study conducted by Wang et al. (2010) found that the use of *Acacia mangium* and *A. auriculiformis* in the restoration of southern Chinese soils improved the processes of carbon and nitrogen cycling. In their study, Chen et al. (2011) found that *Acacia crassicarpa* stands in Guangdong Province, Southern China, had larger carbon sinks and higher stocks of soil organic carbon (SOC) compared to *Eucalyptus urophylla* stands. The carbon sink for *Acacia crassicarpa* stands was measured at 330±76 C m^{-2} yr^{-1}, while for *Eucalyptus urophylla* stands it was 1960±178 g C m^{-2} yr^{-1}. A comparison of *A. mangium* and *E. urophylla* plantations, as well as the resulting woodlands and meadows, across different soil and climate conditions in Vietnam, shows a positive relationship between aboveground biomass production and levels of soil carbon, nitrogen, and phosphorus (Sang et al., 2013; Raihan, 2023k). In Malaysia, Ahmed et al. (2010) discovered that the concentrations of total carbon (C) and phosphorus (P) increased progressively from ages 0 to 6, 12, and 17. Studies have shown that restored forests with native plants are capable of absorbing carbon and phosphorus.

Unforeseen circumstances can hinder the use of NFS plants for carbon sequestration and land restoration. The presence of clay in the soil, the amount of rainfall received annually, and the average temperature all influence the amount of carbon stored in the soil of eucalypt plantations in Brazil. This relationship may also hold true for other species, as suggested by Cook et al. (2014) who found that the soil organic carbon (SOC) stock decreases as eucalypt planting age increases in tropical and subtropical areas. They observed a decline from an average of 29 Mg ha^{-1} to 0.87 Mg $ha^{-1}yr^{-1}$ over a depth of 0-30 cm beneath eucalypt plantations aged 18-26 years. The findings of this study demonstrate that the sequestration of soil organic carbon (SOC) is a direct effect of managing organic deposits or introducing NFS in the restoration or refurbishment of degraded lands or forests.

Conclusions

This review examined forest management techniques that enhance the sequestration of soil organic carbon (SOC) and the restoration of land, with the goal of improving the state of SOC stored in tropical forest ecosystems. The study also explored the influence of soil biota on the interactions between SOC and other nutrients. However, SOC sequestration may not always occur since it is influenced by factors such as edaphic conditions, land-use history, climate, ecosystem characteristics, and intrinsic features. This is due to the possibility of SOC becoming sequestered within a system. Effective carbon sequestration management is crucial for the restoration of degraded lands in tropical ecosystems, the mitigation of climate change impacts, and the preservation of soil health. Soil biota plays a crucial role in the sequestration of carbon and has important interactions with other components of soil, such as nitrogen, phosphorus, and sulfur. Managing forest ecosystems, whether through planting or allowing natural growth, involves implementing specific methods such as initiating National Forest Systems and overseeing organic deposits. These methods generally enhance the sequestration of soil organic carbon (SOC) and can lead to long-term benefits in terms of mitigating climate change and restoring land. These benefits can be attained by effectively managing forest ecosystems, which involves maintaining a proper balance of carbon, as well as ensuring a strong connection to nitrogen, phosphorus, and soil components.

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References

Ahmed, O. H., Hasbullah, N. A., & Ab Majid, N. M. (2010). Accumulation of soil carbon and phosphorus contents of a rehabilitated forest. *The Scientific World Journal*, *10*, 1988-1995.

Akpa, S. I., Odeh, I. O., Bishop, T. F., Hartemink, A. E., & Amapu, I. Y. (2016). Total soil organic carbon and carbon sequestration potential in Nigeria. *Geoderma*, *271*, 202-215.

Ali, A., Rahman, S., & Raihan, A. (2022). Soil carbon sequestration in agroforestry systems as a mitigation strategy of climate change: a case study from Dinajpur, Bangladesh. *Advances in Environmental and Engineering Research*, *3*(4), 1-15.

Aragón, S., Salinas, N., Nina-Quispe, A., Qquellon, V. H., Paucar, G. R., Huaman, W., ... & Roman-Cuesta, R. M. (2021). Aboveground biomass in secondary montane forests in Peru: Slow carbon recovery in agroforestry legacies. *Global Ecology and Conservation*, *28*, e01696.

Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D., & Houghton, R. A. (2017). Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science*, *358*(6360), 230-234.

Bachega, L. R., Bouillet, J. P., de Cássia Piccolo, M., Saint-André, L., Bouvet, J. M., Nouvellon, Y., ... & Laclau, J. P. (2016). Decomposition of Eucalyptus grandis and Acacia mangium leaves and fine roots in tropical conditions did not meet the Home Field Advantage hypothesis. *Forest Ecology and Management*, *359*, 33-43.

Bauters, M., Ampoorter, E., Huygens, D., Kearsley, E., De Haulleville, T., Sellan, G., ... & Verheyen, K. (2015). Functional identity explains carbon sequestration in a 77-year-old experimental tropical plantation. *Ecosphere*, *6*(10), 1-11.

Begum, R. A., Raihan, A., & Said, M. N. M. (2020). Dynamic impacts of economic growth and forested area on carbon dioxide emissions in Malaysia. *Sustainability*, *12*(22), 9375.

Biber, P., Felton, A., Nieuwenhuis, M., Lindbladh, M., Black, K., Bahýl', J., ... & Tuček, J. (2020). Forest biodiversity, carbon sequestration, and wood production: modeling synergies and trade-offs for ten forest landscapes across Europe. *Frontiers in Ecology and Evolution*, *8*, 547696.

Bini, D., Santos, C. A. D., Silva, M. C. P. D., Bonfim, J. A., & Cardoso, E. J. B. N. (2018). Intercropping Acacia mangium stimulates AMF colonization and soil phosphatase activity in Eucalyptus grandis. *Scientia Agricola*, *75*, 102-110.

Bond, W. J., Stevens, N., Midgley, G. F., & Lehmann, C. E. (2019). The trouble with trees: afforestation plans for Africa. *Trends in ecology & evolution*, *34*(11), 963-965.

Bonfatti, B. R., Hartemink, A. E., Giasson, E., Tornquist, C. G., & Adhikari, K. (2016). Digital mapping of soil carbon in a viticultural region of Southern Brazil. *Geoderma*, *261*, 204-221.

Brown, H. C., Berninger, F. A., Larjavaara, M., & Appiah, M. (2020). Above-ground carbon stocks and timber value of old timber plantations, secondary and primary forests in southern Ghana. *Forest ecology and management*, *472*, 118236.

Buotte, P. C., Law, B. E., Ripple, W. J., & Berner, L. T. (2020). Carbon sequestration and biodiversity co-benefits of preserving forests in the western United States. *Ecological Applications*, *30*(2), e02039.

Camacho, L. D., Camacho, S. C., & Youn, Y. C. (2009). Carbon sequestration benefits of the Makiling forest reserve, Philippines. *Forest Science and Technology*, *5*(1), 23-30.
Campo, J., & Merino, A. (2016). Variations in soil carbon sequestration and their determinants along a precipitation gradient in seasonally dry tropical forest ecosystems. *Global Change Biology*, *22*(5), 1942-1956.
Crezee, B., Dargie, G. C., Ewango, C. E., Mitchard, E. T., Emba B, O., Kanyama T, J., ... & Lewis, S. L. (2022). Mapping peat thickness and carbon stocks of the central Congo Basin using field data. *Nature Geoscience*, *15*(8), 639-644.
Chayaporn, P., Sasaki, N., Venkatappa, M., & Abe, I. (2021). Assessment of the overall carbon storage in a teak plantation in Kanchanaburi province, Thailand–Implications for carbon-based incentives. *Cleaner Environmental Systems*, *2*, 100023.
Chen, D., Zhang, C., Wu, J., Zhou, L., Lin, Y., & Fu, S. (2011). Subtropical plantations are large carbon sinks: evidence from two monoculture plantations in South China. *Agricultural and Forest Meteorology*, *151*(9), 1214-1225.
Chinade, A. A., Siwar, C., Ismail, S. M., & Isahak, A. (2015). A review on carbon sequestration in Malaysian forest soils: Opportunities and barriers. *International Journal of Soil Science*, *10*(1), 17.
Cook, R. L., Binkley, D., Mendes, J. C. T., & Stape, J. L. (2014). Soil carbon stocks and forest biomass following conversion of pasture to broadleaf and conifer plantations in southeastern Brazil. *Forest Ecology and Management*, *324*, 37-45.
Cook, R. L., Binkley, D., & Stape, J. L. (2016). Eucalyptus plantation effects on soil carbon after 20 years and three rotations in Brazil. *Forest Ecology and Management*, *359*, 92-98.
Cusack, D. F., Torn, M. S., McDOWELL, W. H., & Silver, W. L. (2010). The response of heterotrophic activity and carbon cycling to nitrogen additions and warming in two tropical soils. *Global Change Biology*, *16*(9), 2555-2572.
Derwisch, S., Schwendenmann, L., Olschewski, R., & Hölscher, D. (2009). Estimation and economic evaluation of aboveground carbon storage of Tectona grandis plantations in Western Panama. *New Forests*, *37*, 227-240.
Domke, G. M., Oswalt, S. N., Walters, B. F., & Morin, R. S. (2020). Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. *Proceedings of the national academy of sciences*, *117*(40), 24649-24651.
Dou, X., Xu, X., Shu, X., Zhang, Q., & Cheng, X. (2016). Shifts in soil organic carbon and nitrogen dynamics for afforestation in central China. *Ecological Engineering*, *87*, 263-270.
Dubiez, E., Freycon, V., Marien, J. N., Peltier, R., & Harmand, J. M. (2019). Long term impact of Acacia auriculiformis woodlots growing in rotation with cassava and maize on the carbon and nutrient contents of savannah sandy soils in the humid tropics (Democratic Republic of Congo). *Agroforestry Systems*, *93*, 1167-1178.
Eclesia, R. P., Jobbagy, E. G., Jackson, R. B., Biganzoli, F., & Piñeiro, G. (2012). Shifts in soil organic carbon for plantation and pasture establishment in native forests and grasslands of South America. *Global Change Biology*, *18*(10), 3237-3251.
Epron, D., Mouanda, C., Mareschal, L., & Koutika, L. S. (2015). Impacts of organic residue management on the soil C dynamics in a tropical eucalypt plantation on a nutrient-poor sandy soil after three rotations. *Soil Biology and Biochemistry*, *85*, 183-189.
FAO. (2020). Global Forest Resources Assessment 2020. FAO, Rome, Italy, 2020. http://www.fao.org/forest-resourcesassessment/2020 (Accessed: 11 February 2023).
Fernández-Martínez, M., Sardans, J., Chevallier, F., Ciais, P., Obersteiner, M., Vicca, S., ... & Peñuelas, J. (2019). Global trends in carbon sinks and their relationships with CO_2 and temperature. *Nature climate change*, *9*(1), 73-79.
Ferraz, A., Saatchi, S., Xu, L., Hagen, S., Chave, J., Yu, Y., ... & Ganguly, S. (2018). Carbon storage potential in degraded forests of Kalimantan, Indonesia. *Environmental Research Letters*, *13*(9), 095001.
Forest Survey of India. (2017). Carbon stock in India's Forests. Indian State Forest Report, 8, 120-127.

F Fornara, D. A., Banin, L., & Crawley, M. J. (2013). Multi-nutrient vs. nitrogen-only effects on carbon sequestration in grassland soils. *Global Change Biology*, *19*(12), 3848-3857.

Jaafar, W. S. W. M., Maulud, K. N. A., Kamarulzaman, A. M. M., Raihan, A., Sah, S. M., Ahmad, A., Saad, S. N. M., Azmi, A. T. M., Syukri, N. K. A. J., & Khan, W. R. (2020). The influence of forest degradation on land surface temperature–a case study of Perak and Kedah, Malaysia. *Forests, 11*(6), 670.

Joshi, R., Singh, H., Chhetri, R., & Yadav, K. (2020). Assessment of carbon sequestration potential in degraded and non-Degraded community forests in Terai Region of Nepal. *Journal of forest and environmental science*, *36*(2), 113-121.

Lal, R. (2013). Soil carbon management and climate change. *Carbon Management*, *4*(4), 439-462.

Lee, K. L., Ong, K. H., King, P. J. H., Chubo, J. K., & Su, D. S. A. (2015). Stand productivity, carbon content, and soil nutrients in different stand ages of Acacia mangium in Sarawak, Malaysia. *Turkish Journal of Agriculture and Forestry*, *39*(1), 154-161.

Lu, X., Vitousek, P. M., Mao, Q., Gilliam, F. S., Luo, Y., Turner, B. L., ... & Mo, J. (2021). Nitrogen deposition accelerates soil carbon sequestration in tropical forests. *Proceedings of the National Academy of Sciences*, *118*(16), e2020790118.

Liu, J., Yang, Z., Dang, P., Zhu, H., Gao, Y., Ha, V. N., & Zhao, Z. (2018). Response of soil microbial community dynamics to Robinia pseudoacacia L. afforestation in the loess plateau: a chronosequence approach. *Plant and Soil*, *423*, 327-338.

Macedo, M. O., Resende, A. S., Garcia, P. C., Boddey, R. M., Jantalia, C. P., Urquiaga, S., ... & Franco, A. A. (2008). Changes in soil C and N stocks and nutrient dynamics 13 years after recovery of degraded land using leguminous nitrogen-fixing trees. *Forest Ecology and Management*, *255*(5-6), 1516-1524.

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M. G., Field, C. B., & Knowlton, N. (2020). Climate change and ecosystems: Threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B*, *375*(1794), 20190104.

Marín-Spiotta, E., & Sharma, S. (2013). Carbon storage in successional and plantation forest soils: a tropical analysis. *Global Ecology and Biogeography*, *22*(1), 105-117.

Mayer, M., Prescott, C. E., Abaker, W. E., Augusto, L., Cécillon, L., Ferreira, G. W., ... & Vesterdal, L. (2020). Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. *Forest Ecology and Management*, *466*, 118127.

McDonald, C. A., Delgado-Baquerizo, M., Reay, D. S., Hicks, L. C., & Singh, B. K. (2018). Soil nutrients and soil carbon storage: modulators and mechanisms. In *Soil carbon storage* (pp. 167-205). Academic Press.

Ontl, T. A., Janowiak, M. K., Swanston, C. W., Daley, J., Handler, S., Cornett, M., ... & Patch, N. (2020). Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, *118*(1), 86-101.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., ... & Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science*, *333*(6045), 988-993.

Paniagua-Ramirez, A., Krupinska, O., Jagdeo, V., & Cooper, W. J. (2021). Carbon storage estimation in a secondary tropical forest at CIEE Sustainability Center, Monteverde, Costa Rica. *Scientific reports*, *11*(1), 23464.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49-57.

Pereira, A. P., Zagatto, M. R., Brandani, C. B., Mescolotti, D. D. L., Cotta, S. R., Gonçalves, J. L., & Cardoso, E. J. (2018). Acacia changes microbial indicators and increases C and N in soil organic fractions in intercropped Eucalyptus plantations. *Frontiers in microbiology*, *9*, 655.

Raihan, A. (2023a). The dynamic nexus between economic growth, renewable energy use, urbanization, industrialization, tourism, agricultural productivity, forest area, and carbon dioxide emissions in the Philippines. *Energy Nexus*, *9*, 100180.

Raihan, A. (2023b). Toward sustainable and green development in Chile: dynamic influences of carbon emission reduction variables. *Innovation and Green Development*, *2*(2), 100038.

Raihan, A. (2023c). Artificial intelligence and machine learning applications in forest management and biodiversity conservation. *Natural Resources Conservation and Research, 6*(2), 3825.

Raihan, A. (2023d). A review of tropical blue carbon ecosystems for climate change mitigation. Journal of *Environmental Science and Economics, 2*(4), 14-36.
Raihan, A. (2023e). Sustainable development in Europe: A review of the forestry sector's social, environmental, and economic dynamics. *Global Sustainability Research, 2*(3), 72-92.
Raihan, A. (2023f). A review of the global climate change impacts, adaptation strategies, and mitigation options in the socio-economic and environmental sectors. *Journal of Environmental Science and Economics, 2*(3), 36-58.
Raihan, A. (2023g). The influences of renewable energy, globalization, technological innovations, and forests on emission reduction in Colombia. *Innovation and Green Development, 2*, 100071.
Raihan, A. (2023h). A concise review of technologies for converting forest biomass to bioenergy. *Journal of Technology Innovations and Energy, 2*(3), 10-36.
Raihan, A. (2023i). A review on the integrative approach for economic valuation of forest ecosystem services. *Journal of Environmental Science and Economics, 2*(3), 1-18.
Raihan, A. (2023j). The contribution of economic development, renewable energy, technical advancements, and forestry to Uruguay's objective of becoming carbon neutral by 2030. *Carbon Research, 2*, 20.
Raihan, A. (2023k). An econometric evaluation of the effects of economic growth, energy use, and agricultural value added on carbon dioxide emissions in Vietnam. *Asia-Pacific Journal of Regional Science, 7*, 665-696.
Raihan, A. (2024a). The potential of agroforestry in South Asian countries towards achieving the climate goals. *Asian Journal of Forestry 8*(1), 1-17.
Raihan, A. (2024b). A Systematic Review of Geographic Information Systems (GIS) in Agriculture for Evidence-Based Decision Making and Sustainability. *Global Sustainability Research, 3*(1), 1-24.
Raihan, A., Begum, R. A., Said, M. N. M., & Abdullah, S. M. S. (2018). Climate change mitigation options in the forestry sector of Malaysia. *J. Kejuruter*, *1*(6), 89-98.
Raihan, A., Begum, R. A., Mohd Said, M. N., & Abdullah, S. M. S. (2019). A review of emission reduction potential and cost savings through forest carbon sequestration. *Asian Journal of Water, Environment and Pollution*, *16*(3), 1-7.
Raihan, A., Begum, R. A., & Said, M. N. M. (2021a). A meta-analysis of the economic value of forest carbon stock. *Geografia–Malaysian Journal of Society and Space*, *17*(4), 321-338.
Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2021b). Assessment of carbon stock in forest biomass and emission reduction potential in Malaysia. *Forests*, *12*(10), 1294.
Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022a). Dynamic impacts of energy use, agricultural land expansion, and deforestation on CO_2 emissions in Malaysia. *Environmental and Ecological Statistics*, *29*(3), 477-507.
Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022b). Relationship between economic growth, renewable energy use, technological innovation, and carbon emission toward achieving Malaysia's Paris agreement. *Environment Systems and Decisions*, *42*(4), 586-607.
Raihan, A., & Bijoy, T. R. (2023). A review of the industrial use and global sustainability of Cannabis sativa. *Global Sustainability Research*, *2*(4), 1-29.
Raihan, A., Muhtasim, D. A., Farhana, S., Hasan, M. A. U., Pavel, M. I., Faruk, O., ... & Mahmood, A. (2023a). An econometric analysis of Greenhouse gas emissions from different agricultural factors in Bangladesh. *Energy Nexus*, *9*, 100179.
Raihan, A., Muhtasim, D. A., Farhana, S., Pavel, M. I., Faruk, O., Rahman, M., & Mahmood, A. (2022c). Nexus between carbon emissions, economic growth, renewable energy use, urbanization, industrialization, technological innovation, and forest area towards achieving environmental sustainability in Bangladesh. *Energy and Climate Change*, *3*, 100080.
Raihan, A., Muhtasim, D. A., Farhana, S., Rahman, M., Hasan, M. A. U., Paul, A., & Faruk, O. (2023b). Dynamic linkages between environmental factors and carbon emissions in Thailand. *Environmental Processes*, *10*(1), 5.
Raihan, A., Muhtasim, D. A., Pavel, M. I., Faruk, O., & Rahman, M. (2022d). An econometric analysis of the potential emission reduction components in Indonesia. *Cleaner Production Letters*, *3*, 100008.

Raihan, A., Pavel, M. I., Muhtasim, D. A., Farhana, S., Faruk, O., & Paul, A. (2023c). The role of renewable energy use, technological innovation, and forest cover toward green development: Evidence from Indonesia. *Innovation and Green Development*, *2*(1), 100035.

Raihan, A., & Said, M. N. M. (2022). Cost–benefit analysis of climate change mitigation measures in the forestry sector of Peninsular Malaysia. *Earth Systems and Environment*, *6*(2), 405-419.

Raihan, A., & Tuspekova, A. (2022a). Dynamic impacts of economic growth, energy use, urbanization, tourism, agricultural value-added, and forested area on carbon dioxide emissions in Brazil. *Journal of Environmental Studies and Sciences*, *12*(4), 794-814.

Raihan, A., & Tuspekova, A. (2022b). Nexus between energy use, industrialization, forest area, and carbon dioxide emissions: New insights from Russia. *Journal of Environmental Science and Economics*, *1*(4), 1-11.

Raihan, A., & Tuspekova, A. (2022c). Toward a sustainable environment: Nexus between economic growth, renewable energy use, forested area, and carbon emissions in Malaysia. *Resources, Conservation & Recycling Advances*, *15*, 200096.

Raihan, A., & Tuspekova, A. (2022d). Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: New insights from Kazakhstan. *World Development Sustainability*, *1*, 100019.

Raihan, A., & Tuspekova, A. (2022e). Dynamic impacts of economic growth, renewable energy use, urbanization, industrialization, tourism, agriculture, and forests on carbon emissions in Turkey. *Carbon Research*, *1*(1), 20.

Raihan, A., & Tuspekova, A. (2022f). Nexus between emission reduction factors and anthropogenic carbon emissions in India. *Anthropocene Science*, *1*(2), 295-310.

Raihan, A., & Tuspekova, A. (2023). Towards net zero emissions by 2050: the role of renewable energy, technological innovations, and forests in New Zealand. *Journal of Environmental Science and Economics*, *2*(1), 1-16.

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T., Salas, W., ... & Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the national academy of sciences*, *108*(24), 9899-9904.

Sang, P. M., Lamb, D., Bonner, M., & Schmidt, S. (2013). Carbon sequestration and soil fertility of tropical tree plantations and secondary forest established on degraded land. *Plant and Soil*, *362*, 187-200.

Santos, F. M., Balieiro, F. D. C., Fontes, M. A., & Chaer, G. M. (2018). Understanding the enhanced litter decomposition of mixed-species plantations of Eucalyptus and Acacia mangium. *Plant and soil*, *423*, 141-155.

Satakhun, D., Chayawat, C., Sathornkich, J., Phattaralerphong, J., Chantuma, P., Thaler, P., ... & Kasemsap, P. (2019). Carbon sequestration potential of rubber-tree plantation in Thailand. In *IOP Conference Series: Materials Science and Engineering,* 526(1), 012036.

Sang, P. M., Lamb, D., Bonner, M., & Schmidt, S. (2013). Carbon sequestration and soil fertility of tropical tree plantations and secondary forest established on degraded land. *Plant and Soil*, *362*, 187-200.

Sayer, E. J., Lopez-Sangil, L., Crawford, J. A., Bréchet, L. M., Birkett, A. J., Baxendale, C., ... & Schmidt, M. W. (2019). Tropical forest soil carbon stocks do not increase despite 15 years of doubled litter inputs. *Scientific Reports*, *9*(1), 18030.

Saynes, V., Hidalgo, C., Etchevers, J. D., & Campo, J. E. (2005). Soil C and N dynamics in primary and secondary seasonally dry tropical forests in Mexico. *Applied Soil Ecology*, *29*(3), 282-289.

Schleuss, P. M., Widdig, M., Heintz-Buschart, A., Kirkman, K., & Spohn, M. (2020). Interactions of nitrogen and phosphorus cycling promote P acquisition and explain synergistic plant-growth responses. *Ecology*, *101*(5), e03003.

Situmorang, J. P., & Sugianto, S. (2016). Estimation of carbon stock stands using EVI and NDVI vegetation index in production forest of Lembah Seulawah sub-district, Aceh Indonesia. *Aceh International Journal of Science and Technology*, *5*(3), 126-139.

Shimamoto, C. Y., Padial, A. A., da Rosa, C. M., & Marques, M. C. (2018). Restoration of ecosystem services in tropical forests: A global meta-analysis. *PloS one*, *13*(12), e0208523.

Soussana, J. F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., ... & Lal, R. (2019). Matching policy and science: Rationale for the ‘4 per 1000-soils for food security and climate’initiative. *Soil and Tillage Research*, *188*, 3-15.
Wang, F., Li, Z., Xia, H., Zou, B., Li, N., Liu, J., & Zhu, W. (2010). Effects of nitrogen-fixing and non-nitrogen-fixing tree species on soil properties and nitrogen transformation during forest restoration in southern China. *Soil Science & Plant Nutrition*, *56*(2), 297-306.
Zapfack, L., Noiha, N. V., & Tabue, M. R. B. (2016). Economic estimation of carbon storage and sequestration as ecosystem services of protected areas: a case study of Lobeke National Park. *Journal of Tropical Forest Science*, 406-415.