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Review

Boosting C Sequestration and Land Restoration through Forest Management in Tropical Ecosystems: A Mini-Review

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Abstract: Soil has a major role in sequestering atmospheric CO_2. This has further benefits and potential to improve soil fertility and food production, mitigate climate change, restore land degradation, and conserve ecosystem biodiversity. However, its health is increasingly being threatened by the growing population, land degradation and climate change effects. Despite its importance, soil organic carbon (SOC) is understudied in the tropics. This paper reviews how managing forests in tropical ecosystems can benefit SOC sequestration and land restoration. Sequestered SOC has the potential to improve soil fertility, as well as to reduce both land degradation and atmospheric CO_2 emissions. It further improves soil structure, aggregation and water infiltration, enhances soil faunal activity and boosts nutrient cycling (C, N, P and S). Managing forest ecosystems is crucial to boost C sequestration, mitigate climate change and restore degraded lands, besides other ecosystem services they provide. Apart from managing natural forests and planted forests, afforesting, reforesting marginal or degraded lands especially when associated with specific practices (organic residue management, introducing nitrogen-fixing species) boost C storage (in both soil and biomass) and foster co-benefits as soil health improvement, food production, land restoration and mitigation of climate change. Improved soil health as a result of sequestered C is confirmed by enhanced physical, biological and chemical soil fertility (e.g., sequestered C stability through its link to N and P cycling driven by soil biota) which foster and sustain soil health.

Keywords: soil organic carbon storage; management practices; soil fertility improvement; land degradation recovery; climate change mitigation; tropical forest ecosystems

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1. Introduction

In twenty-five years, the world's forested area has decreased 31%, i.e., from 4128 million ha in 1990 to 3999 million ha in 2015. The tropical domain comprises the largest proportion of the world's forests (45 percent, i.e., 1.8 billion hectares), followed by the boreal (27 percent), temperate (16 percent) and subtropical (11 percent) domains [1]. Nevertheless, the largest forest loss has been reported in tropical regions, mainly in South America and Africa due to agricultural and/or industrial activities [2]. Africa had the largest annual rate of net forest loss in 2010–2020, i.e., 3.9 million ha, followed by South America, i.e., 2.6 million ha [3]. Pan et al. [4] estimated forest sink to be equal in magnitude to both land-use change sources and the terrestrial sink derived from fossil fuel emissions with subtracted sinks from ocean and atmosphere. Nonetheless, forest ecosystems harbor the largest terrestrial carbon (C) pool [4] with more than 80% of all terrestrial aboveground C and more than 70% of all soil organic C [5].

Managing forest ecosystems for C sequestration, land restoration and climate mitigation is, therefore, crucial [4–6]. There are three main factors to deal with in managing C in forest ecosystems: C dynamics, C pool size and C chemical forms. Managing forest to sequester C depends on human activities such as silviculture (selection of tree species, rotation period), spacing (number of trees at planting), disturbances (pest infestations, wind throw, wild fire), air pollution and water management [5]. Future forest development scenarios simulated for 100 years based on ten case study landscapes across Europe, revealed the potential of managing European forests in guiding the provision of ecosystem services such as carbon sequestration, biodiversity and sustainable wood production [7]. The authors argued that climate change associated disturbances, such as storms and extended drought periods, which were not taken into account in the study, must be integrated in the scenarios.

Unlike in the western United States, stimulation of potential forest carbon sequestration has been performed using the Community Land Model 4.5 (CLM) taking into account the vulnerability to drought and fire to hierarchize forest land for preservation and further relativize the C priority to biodiversity [8]. It appears that the preservation of temperate forest (medium to high potential in storing C) and weak susceptibility to climate change in the western United States, equate with 27–32% of the global mitigation potential formerly determined for temperate and boreal forests for around 8 yr of regional fossil fuel emissions [8]. The potential of boosting C sequestration capacity and mitigating CO_2 emissions using tree planting in the United States has been demonstrated by forest inventory describing nearly 1.4 trillion trees from more than 130,000 national forestlands [9].

Tropical forests store large quantities of C below and above ground [10]. They also have the highest available timber volume (121 m^3 ha^{-1}), C storage (91 t ha^{-1}) and species diversity. Boreal forest ecosystems have the least of these attributes [11], although they have large C stocks in soils [4]. Tropical forest ecosystems possess, therefore, the highest potential to capture and sequester C as they have the highest C density relative to all forests [12]. The overall C cycle in tropical forest ecosystems both natural and planted is roughly schematized (Figure 1 [4]). In fact, their capacity for sequestering atmospheric C estimated using two atmospheric inversion models (MACC-II and Jena CarboScope) and 10 dynamic global vegetation models (TRENDY), has even increased the most over the last two decades, making them crucial in mitigating climate change [13]. According to this study, the less CO_2 ecosystems absorb on a worldwide scale, the warmer the climate is. Amongst these tropical forest ecosystems, there are three main rainforest basins, i.e., the Amazon basin being the largest, the Congo basin and Southeast Asia the second and third, respectively [14]. Managing forest in these regions is, therefore, vital to foster C sequestration with further benefits on land restoration (degraded forests and other lands), mitigating climate change and preserving natural forests and ecosystem biodiversity [15].

The capacity of forests in storing and sequestering C is beyond doubt [4,5,16], the overall C in forests' above- and below-ground biomass was estimated at 296 Gt (or 73 tons per ha) in 2015 [2]. Forest soils contain nearly half of the total organic carbon of terrestrial ecosystems [17]. Soils store approximately three times as much C as found in either the atmosphere or in the living plants, with the largest portion in soils under tropical forests [4]. Forest ecosystems play a vital role in the climate system through C, water and other biogeochemical cycles [18]. Climate change affects forest ecosystems, making their adaptation and resilience essential for their productivity and sustainability [16,19]. It has been argued that tropical forest ecosystems may not be resilient to climate change over the long term, mainly due to predicted depletion in rainfall and increased drought (Malhi et al. 2009 cited in [16]). Nevertheless, an increase in their great capacity to sequester atmospheric C over the last two decades, i.e., in their potential ability to mitigate climate change has been argued [13]. Although, Malhi et al. [18] declared that direct anthropogenic activities, such as land-use change which involves habitat loss and overexploiting have a more pronounced impact on ecosystems than climate change. In addition to climate change impacts on tropical forest ecosystems, soil health including C status is threatened due to the increasingly growing population, soil fertility and food depletion, leading to growing land degradation [19,20].

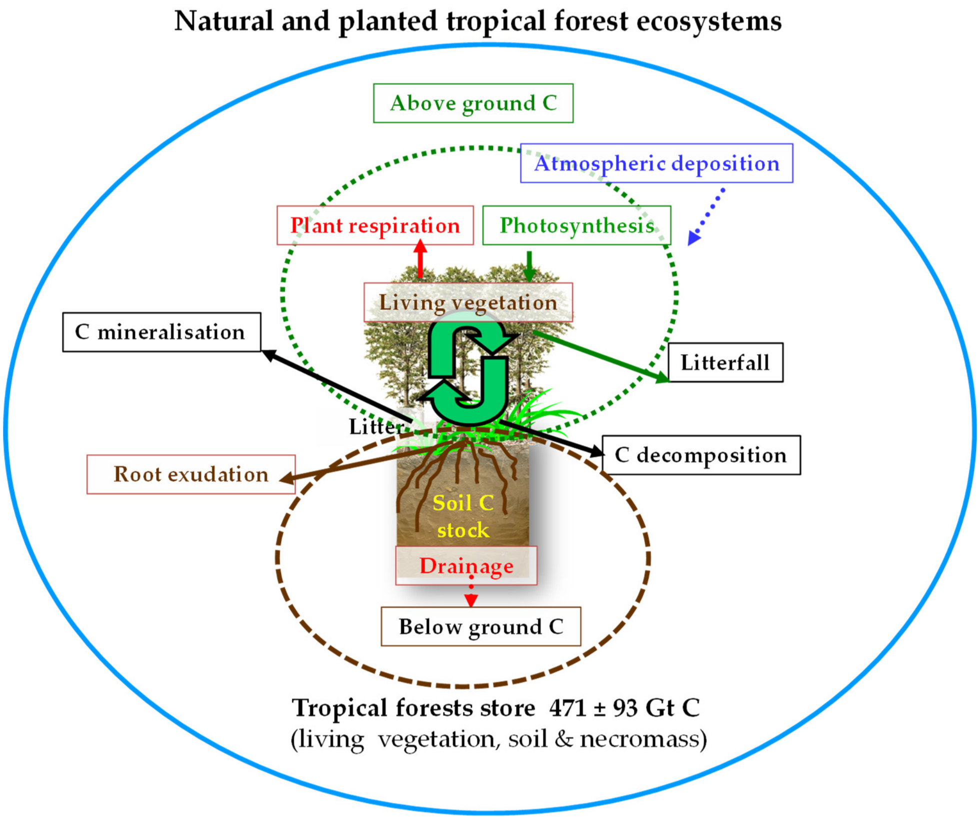

Figure 1. Carbon cycle in tropical forest ecosystems. The information of the amount of overall C Stored is from Pan et al.'s paper [4].

For years, the United Nations has been raising the alarm to prevent, stop and reverse the degradation of land worldwide with the goal to achieve land degradation neutrality and further fulfill the UN-Sustainable Development Goals (UN-SDGs) similar to other international initiatives ('Bonn Challenge' and the 'UN- Decade on Ecosystem Restoration [2021–2030]). Soil degradation may be anthropogenic and/or natural of four main types: (i) physical (compaction, runoff and erosion, desertification, etc.); (ii) chemical (acidification, salinization, leaching, nutrient depletion, pollution, etc.); (iii) biological (loss of soil biodiversity, a decline in soil organic matter, loss soil C sink capacity, etc.); and (iv) ecological (disruption in nutrient cycling, perturbations in the hydrological cycle, decline in use efficiency of inputs, etc.) [21]. Soil and ecosystem C pools, including soil degradation restoration, may be improved by forest management, i.e., integration of trees in degraded lands [12].

In the past two decades, there has been an increase in the number of publications on soil organic carbon (SOC) [17,22]. Most publications deal with the forms and dynamics of SOC, its role in nutrient cycling, soil fertility and crop production, and its link to climate change, management practices for land restoration, and modeling [20,21,23–25]. In November 2015, attention was focused on soil for the first time at the 21st Conference of the Parties (COP) of United Nations Framework Convention on Climate Change (UNFCCC), with the launch of the '4 per 1000′ Initiative, i.e., Soils for Food Security and Climate Change (www.4per1000.org (accessed on 19 January 2022)). In 2016, at the 22nd COP of UNFCCC, a joint workshop on agriculture and soils, taking into account its vulnerabilities to climate change and approaches to addressing food security, was convened at the Koronivia Joint Work on Agriculture (KJWA) on the topic of improved nutrient use and manure management towards sustainable and resilient agricultural systems [25]. Both climate change and land degradation are increasingly threatening sustainable agriculture and forestry, food production and the environment worldwide [19–21,26] www.4p1000.org (accessed 19 January 2022).

Soil organic matter (SOM) is a sink for nutrients and is widely used as an indicator to evaluate chemical, physical and biological soil fertility or soil health [27,28]. Soil organic carbon (SOC) is one of its key components constituting 50–58% of the total SOM amount [29,30]. The stable pool of SOM is large with a mean residence time of several decades, so more than 2 years may be required to assess changes in SOC [31]. However, changes in SOM biodegradability or microbial biomass can be readily detectable in a shorter period of time [32,33]. As the most important reservoir of C, soils can act as both source and sink of C [24]. This depends on climate [34–36], soil texture [37–39], soil acidity [40], vegetation cover [41], biomass inputs and management [42], but also depth [43] and the initial C level and soil type [44,45]. SOC accretion enhances SOM quality when protected by fine soil fractions [46–49]. On the contrary, the decline in SOM quality is characterized by higher C mineralization caused by climate, management practices, or edaphic factors [38,50,51].

Soil C sequestration has the potential to simultaneously improve soil fertility (enhancing the physical, biological and chemical properties), increase food production (amount and quality of crop) and mitigate climate change (reduce greenhouse-house gases) [24,30,43,44,52–56]. Stored SOC also controls, mitigates and halts land degradation [20,21]. Using the global meta-analysis on the restoration of ecosystem services (C pool, soil attributes and biodiversity protection) in tropical forests, Shimamoto et al. [57] reported enhanced restoration in the biodiversity protection (degraded former pasture land), and the C pool (degraded former agricultural plots). The authors argued that the correct strategy broadens the restoration of ecosystem services in degraded tropical forests.

Priorities for SOC research such as monitoring and assessment are needed in areas where its decomposition is accelerated due to its large stocks and climate change [41], such as tropical forest ecosystems where land degradation is worsening [2]. Sustainable soil management through C sequestration is one of the key soil components which is crucial to restoring and sustaining soil health fostering climate change mitigation and land restoration [20,21], www.4per1000.org (accessed on 19 January 2022), especially since the tragedy of the COVID-19 [58]. Deforestation has already been widely studied [2,10], this paper, therefore, will mostly focus on SOC management in tropical forest ecosystems, the more threatened forest ecosystems to date, to both mitigate climate change as well as to halt/restore land degradation. Afforestation from cropland, grassland, or marginal land may impact the environment and the economy. Some practices, such as the introduction of nitrogen-fixing species or organic residue management, ensure good management and sustainability of forest ecosystems, i.e., improve soil fertility and prevent land degradation through enhanced SOC sequestration and nutrient cycling. The link between SOC quantity and quality (link to nitrogen (N) and phosphorus (P), i.e., link between sequestered soil C and other nutrients), and how it may stabilize C sequestration and prevent land degradation in the long term, have been under-researched in tropical regions (Figure 2).

This mini-review addresses two questions: (i) how managing tropical forest ecosystems may boost C sequestration; and (ii) what is the relationship between the SOC quality and quantity (i.e., SOC associated with N or P cycling, C stocks, stable versus labile C forms) on one hand, and the restoration of degraded lands on the other hand in the tropical forest ecosystems over the long term? It is hypothesized that managing tropical forest ecosystems in general, and through reforestation, afforestation of marginal and degraded areas, boosts C sequestration, with the beneficial impacts not only in sustaining soil health, i.e., its quality, but also mitigating both climate change and land degradation in the long term.

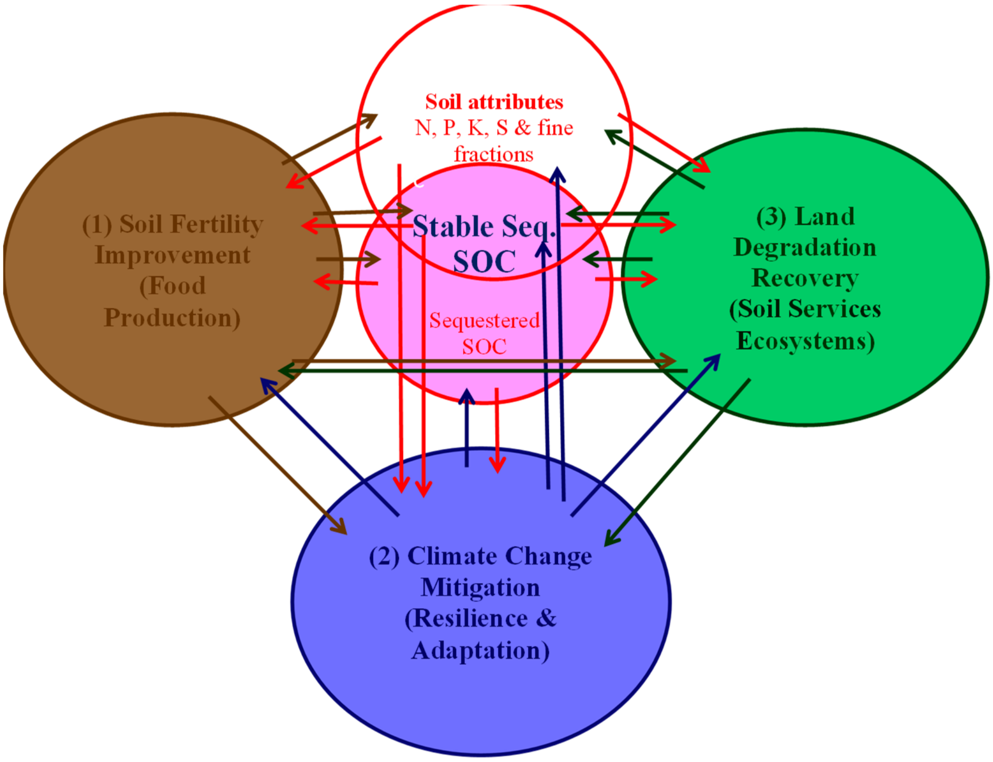

Figure 2. Conceptual scheme (1) Soil fertility improvement (food production); (2) Climate change mitigation (Resilience and adaptation to climate change); and (3) Land degradation recovery (soil services ecosystems: carbon pool, soil attributes and biodiversity): how stable sequestered SOC (linked to other nutrients and/or to fine soil fractions) may sustain soil health through SOC sequestration and its co-benefits in the long term.

2. Material and Methods

2.1. Systematic Literature Review

Interactions between soil carbon management and its storage on one hand, and between land restoration and soil organic carbon and other nutrients on the other hand in tropical forest ecosystems, were undertaken through a systematic literature review. This helped to unveil how sequestered C (quality and quantity) and restored land strongly rely on forest management in tropical ecosystems. The review followed the principles of systematic review according to [59]: (1) draw the field via scoping review; (2) inclusive search; (3) assess quality; (4) extract data; (5) synthesize; and (6) write up.

A number of search terms were created by dividing the research questions into individual concepts to permit an exhaustive and representative search of significant studies that have been conducted on managing soil organic C and its link to climate change and land restoration in tropical forest ecosystems. Synonyms, singular and plural forms, different spellings, broader terms, and classification terms used by databases to sort contents into categories have been taken into account.

2.2. Including and Excluding Criteria

All retrieved publications and papers were pre-screened for inclusion in the review using predetermined criteria for inclusion and exclusion of primary studies comprising:

- Research questions (scope, topic): (i) how managing soil carbon in tropical forest ecosystems may be related to climate change adaptation and resilience; (ii) how land restoration and management in forest ecosystem may be driven by the interaction between SOC and other nutrients cycling and links to land restoration in tropical forest ecosystems in the long term?

- Define and conceptualize (terms and concepts); 'tropical forests', in this study, is a collective name for all forest ecosystems (natural and plantations). 'Natural forest' may be primary or secondary, either humid or dry. 'Forest plantations' are defined as those forest stands established by planting or/and seeding in the process of afforestation or reforestation, marginal and degraded land may be previous cropping or forest systems.
- Qualitative and quantitative measurements and key variables: primary studies that evaluate SOC management related to climate change or land restoration in tropical ecosystems have been considered. In addition, the review also includes a qualitative and quantitative review of secondary data on tropical forest ecosystems.
- Time frame: literature published in the last three decades (1990–2021).
- Data sources: articles, books and book chapters, theses and dissertations, also bibliographies and data available have been reviewed.

Following these guidelines, data and studies were identified using the formal electronic database search; cross-referencing to bibliographies of expert peer reviews and key papers. Thematic and matrix analyses of quantitative and qualitative literature published to date were searched through electronic databases such as Web of Science, Google Scholar, Google. A manual search of key journals and of the reference list by initial searchers was made to lessen the risk of overlooking the relevant articles.

2.3. Primary Studies and Review Search

After a global literature search and careful consideration, the search was concentrated on key sentences, such as "Soil carbon in tropical forest ecosystems in relation to climate change adaptation and resilience" and "Soil carbon in tropical forest ecosystems linked to land management", as these terms are interdisciplinary and can be widely used. Several alternative phrases (i.e., 'tropical forests' instead of 'forest ecosystems', 'land restoration' or 'land reclamation' or 'soil carbon' or 'soil organic carbon') were checked by conducting any text search. Main findings, research method, research aim/objective, place of research, year of publication and author(s) were key search strings. When articles met the search criteria after reading the titles, abstracts and conclusions, they were included in the review.

2.4. Information and Quality Assessment Extraction

The review guaranteed that information extracted from the full articles (meeting the inclusion criteria) and were applicable (useful) and valid (closeness to truth) by assessing the research protocol and questions, sources of data, the scope of the review, although no specific tool for quality assessment was used. Assessment of the quality of studies took into account several variables: appropriateness of study design for addressing the research objectives; conditions of the study; measurement of study variables; appropriate use of statistics; quality of reporting; quality of intervention; generalizations; and author conflict of interest. Nevertheless, there was a need to compare the comprehensiveness of the search against the value of identifying all available studies and time.

3. Results and Discussion

More than nine million unique citations through a systematic review of electronic databases have been identified. Numerous papers recorded by the initial search contained summaries, documentaries, opinions and general comments on soil organic carbon or forest ecosystems or climate change or land restoration. They were not linked to the topic, the working definition and this type of study. Finally, 89 relevant to the topic and 23 others corroborating the global context, were included in the review after further screening based on the relevance of their abstracts, full-text review and hand search process.

3.1. How Forest Management May Boost Soil C Sequestration in Tropical Ecosystems

3.1.1. Forest Management Boosting C Sequestration

Forest management is important to boost C sequestration and favor soil health due to their crucial role in the global C cycle and several ecosystem services, including C sequestration (soil and biomass), they provide to societies [4,12,60]. This ability is enhanced in tropical forest ecosystems since Fernandez-Martinez et al. [13] argued that their capacity in sequestering C has increased over the last two decades. Carbon sequestration may occur or not in different tropical forest ecosystems following forest management (Table 1). SOC sequestration has been widely reviewed [17,61] and is largely related to land use history, while its rate is affected by the tree species, soil type and environment [17], and climate and geographic factors [35,37]. Managing forest ecosystems via afforestation or reforestation often leads to C sequestration in both biomass and soil, while its success strongly depends on edaphic factors in addition to those above [45,62–65].

In central China, afforestation of large uncultivated areas to woodland, shrubland and cropland plantations increased soil C and N storage mainly in macroaggregates (>2000 μm) [65]. Taking into account the potential risk of threatening savanna ecosystems [66,67], afforestation of native tropical savannas to mixed acacia and eucalypt plantation increased soil C stocks in the top 25 cm of the mixed-species (50% acacia and 50% eucalypt) stands (17.8 ± 0.7 t ha^{-1}) relative to pure acacia and eucalypt stands, i.e., 16.7 ± 0.4 t ha^{-1} and 15.9 ± 0.4 t ha^{-1}, respectively, at the end of the first 7-year rotation in the coastal Congolese plains [68,69]. An additional C stock of 15 t ha^{-1} and 64 t ha^{-1} at year 3 (89.9 t ha^{-1}) and 5 (138.9 t ha^{-1}) relative to year 1 (74.9 t ha^{-1}), respectively, was reported on the 0–30 cm of the loamy siliceous soil with low fertility beneath the *A. mangium* plantations in Malaysia [70].

Policies and practices fostering C sequestration in the Makiling forest reserve and the entire Philippines were reviewed and the goal of long-term C sequestration to mitigate climate change through sustainable management of forests was stated [71]. The authors recognized reforestation as one of the strategies for enhancing C sequestration capacity, mainly when it involved plantation of fast-growing species and high-timber-yielding species. Reforestation/afforestation through practices, such as introducing fast-growing NFS or nitrogen-fixing bacteria, or managing organic residues, i.e., leaving them on the field after wood harvest, may increase SOC stocks even in coarse-textured soils where SOC decomposition is otherwise high [17,68,72,73]. This is due to biological changes that result from newly added organic residues [74,75] or the input of N-rich organic matter following the shift in the microbial activity and/or bacterial composition [76–80]. Changes in soil microbial indicators lead to C and N accumulation in eucalypt mixed with acacia stands relative to pure or fertilized stands after 27 months [15]. In fact, N_2-fixing species have the ability to ameliorate soil fertility and enhance carbon sequestration via interactions between biota and nutrient availability in tropical forest plantations [15,69,77,78].

Managing forest plantations of mature (42–47 years) *Aucoumea klaineana*, *Cedrela odorata*, *Tarrietia utilis*, and *Terminalia ivorensis* on long rotations led to a higher biomass accumulation (aboveground C stocks), C sequestration, and timber value, i.e., higher climate mitigation potential in both the moist and wet zones relative to secondary naturally regenerated forest in Ghana [81]. Natural forests still possess a great capacity to sequester and store C in other cases. A review arguing to develop forest management practices that boost C sequestration in forest soils reported an overall amount of 23.48 million tonnes of C with a C sequestration potential of 4 tonnes of C ha^{-1} year^{-1} [82]. However, total soil C accounting for 36–46% in the forest ecosystem of Malaysia was excluded [82]. In other cases, SOC has been considered [83,84]. Estimation of C stock in India's forests reported an increase in SOC, the largest pool, i.e., from 3969 million tonnes (2015) to 3979 million tons (2017), followed by the aboveground (2220 million tons (2015) and 2238 million tons (2017)) and belowground (695 million tons (2015) and 699 million tons (2017)) biomass [83]. In the same line, Joshi et al. [84] evaluated SOC sequestration of degraded and non-degraded community forests in the Terai region of Kanchanpur in Nepal. They reported an increase in C sequestration of 1.97 times higher in the non-degraded community forests (SOC sequestration of 54.21 ± 3.59 t ha^{-1} and total C stock of 301.08 ± 27.07 t ha^{-1}) relative to degraded community forest (SOC sequestration of 42.55 ± 3.10 t ha^{-1} and total C stock of 152.68 ± 22.95 t ha^{-1}). Investigation on forest management in the teak plantation (35 yr) in western Thailand evidenced an average C storage of 63.3 Mg C ha^{-1} and 42% of it stored in the harvest wood products, highlighting its potential to sequester C in aboveground biomass and contribute to mitigating climate change [85]. Potential C sequestration of rubber trees (*Hevea brasiliensis* Müll.Arg.) plantation has been evaluated using eddy covariance technique measuring the net ecosystem exchange (2013–2016) and indicated annual CO_2 sequestration ranked between 28.0 and 43.1 tonnes CO_2 ha^{-1} yr^{-1} with an average of 36.7 tonnes CO_2 ha^{-1} yr^{-1} in Thailand [86]. The study also stated further that these plantations sequestered around 24.9 kg of CO_2 to produce a kilogram of natural-rubber latex.

3.1.2. Limitation to SOC Sequestration in Forest Ecosystems

Although forest ecosystem management usually leads to SOC sequestration, there are cases where it does not. SOC sequestration may have inherent or other limits, such as the age of the forest ecosystems. At San Luis Campus (Monteverde) in Costa Rica, it has been reported that secondary forests harbor greater potential to sequester C compared to older primary forest ecosystems via tree growth, as their biomass increase more rapidly than the older counterparts [87]. Three short rotations (6–8 years) of eucalypt plantation after decades of crop production and pasture decreased soil C stocks along a broad geographic gradient in Brazil [51]. Some factors, such as texture, climate, or vegetation, may boost or limit C sequestration in forest ecosystems [18] reducing its potential to mitigate climate change and restore degraded lands. In mature lowland tropical forest in Panama, [88] reported that 15 years of doubled litter inputs did not increase C stocks, but on the contrary, may have altered processes induced in the stabilization of SOC through its association with soil minerals, which is critical for SOC storage in the humid tropics. A study managing organic residues in the eucalypt plantation on sandy soils in Congolese coastal plains showed that C accretion through C-POM (particulate organic matter) status declined after three rotations, i.e., 21 years after first planting [89]. In another part of the Congolese coastal plains, although C accretion occurred at the end of 7 years of the first rotation of the acacia and eucalypt plantations [68], the percentage of C concentration in POM has decreased at 5 relative to 2 years into the second rotation [90]. This may indicate the creation of more labile soil organic matter with enhanced SOM turnover due to the limited C saturation potential of these sandy soils, to the N richness of the new organic residues from the plantation [75,89,91,92].

C sequestration rates may be limited when decomposition rates are high. This occurs with afforestation [35,74], certain management practices such as leaving organic residues on the field after wood harvest Epron et al. [89], or climatic disturbances (drought, long dry season [35,36,92]. Marin-Spiotta and Sharma [35] compiled and analyzed soil C data from 510 reforestation and afforestation sites in the tropics across 32 countries and territories. They concluded that climatic variation explains more of the variability in soil C in successional and forest plantation than former land-use or forest age does. The authors found that the age of forest was a poor predictor of soil C stocks in tropical forest plantations. Comparing tropical forest soils under various rainfall regimes in Mexico, Campo et al. [93] argued that higher SOC recalcitrance in soils with longer drought periods may be related to a high content of resistant biopolymers [94], inducing organic material accumulation as a consequence of selective preservation [95].

It may take decades to restore SOC stocks in forest ecosystems after its shift to other ecosystems. Cook et al. [49] reported that more than two decades were required to return to soil SOC stocks of native forests after conversion of mature native forests into forest plantations and pastures in South East Brazil. While evaluating C and N dynamics after agricultural abandonment and reforestation of the primary and secondary seasonally dry tropical forests in central Mexico, [96] argued that the full restoration of soil C and N dynamics occurred only after 60 years of secondary succession. Evaluation of SOC after plantation or pasture establishment in 27 sites located in South America (Brazil, Argentina and Uruguay) revealed that changes in SOC amounts were only detected after 30 years [47].

In addition to the limitations stated above, there are some barriers that may attenuate or even halt the capacity of tropical forest ecosystems to sequester C and promote land restoration and climate change mitigation. They may be classified as lack of knowledge and measurement uncertainties in some regions and socio-economic factors (linked to social, political, economic and environmental contexts). For instance, estimation of C stocks in the forests of Kalimantan facing pressure from large-scale land use activities (palm oil plantations or peatland fires), reported a storage potential of degraded forests of around 0.8–1.1 PgC resulting from emission factors calculated from lidar or random forest map [97]. The authors argued that Kalimantan degraded forests harbor significantly greater storage potential per ha (70.2 Mg C ha^{-1}) in a short period relative to second growth forests (1–60 yr, 35.33 Mg C ha^{-1}) in the Latin America (Chazdon et al. 2016, cited in [97]).

3.2. What Is the Relationship between the SOC Quality (i.e., SOC Associated with N or P Cycling, C Stocks, Stable Versus Labile C Forms) and Its Sequestered Quantity on One Hand, and the Land Degradation Restoration on the Other Hand, in Tropical Forest Ecosystems over the Long Term?

Nutrients, such as N and P can determine the quality and stability of sequestered SOC [29,98,99]. SOC sequestration is linked to N availability [100,101]. The importance of N in C sequestration processes has been highlighted in several studies [100]. High C sequestration is often reported in mixed species forest plantations of NFS and non-fixing species, as N-fixation permits C accretion [42,73,76,102,103]. High or increased soil N can enhance SOC accretion by increasing both below– and aboveground biomass and forest growth [76,104]. N-fixing trees might also increase SOM stability due to biological changes stimulated by the input of N-rich litter [76,78,80]. In two tropical forest soils in Puerto Rico, Cusack et al. [105] found that N additions induced an overall increase in SOC stocks. However, the authors also argued that the stability of sequestered SOC in tropical forest ecosystems remains undefined due to interacting global change factors, including N deposition and climate.

SOC sequestration is also linked to phosphorus (P), an essential nutrient for plant growth, wood and food production [106]. Even though P is often limited in tropical forests [107,108], its availability is closely linked to SOC mineralization in these ecosystems [109]. Low concentrations of P in the litter of *A. mangium*, an NFS, produced a stoichiometric (N:P) imbalance, resulting in starvation/inhibition of decomposers and in low microbial biomass and activity [109]. Low C:N:P ratios of microbial communities relative to the soil and material they decompose indicate they require high concentrations of N and P [110]. Consequently, microorganisms will immobilize N and P up to a critical threshold before these nutrients are released [111]. An antagonistic link between P and available soil N has been often reported, i.e., there is a high demand for P to compensate for a greater N supply [110,111]. Yet there is a synergistic effect between P and C accumulation that is often found in mixed-species stands containing NFS species compared to the monoculture stands [112–114].

The quality of sequestered SOC is also influenced by faunal and microbial activities, i.e., linked to biological soil properties [33,77,78,80,109]. In monocultures, litter decomposition was controlled by water-soluble components and lignin content, suggesting that decomposer activity may be energy limited or limited by P as commonly observed in tropical forest ecosystems [109]. In general, the change in soil microbial and bacterial communities are strongly correlated to soil N, C and P contents, which reveals an enhanced nutrient cycling due to the greater stimulation of microbial activity in litter and soil [33,77–79].

Cusack et al. [115] reported that interactions between microbial community composition, enzymatic capability, and soil C chemistry seemed to drive changes in C cycling, as a response to N deposition in two N-rich tropical forest soils in Puerto Rico. It shows the beneficial effects of microorganisms to enhance SOC sequestration and strengthen the link between sequestered SOM and N and P. These soil processes are crucial in sequestering SOC in tropical forest ecosystems in the long term, as the stable, i.e., less mineralized sequestered C has a beneficial effect on climate change mitigation [23,116] and land restoration [20].

Overall processes, links and interactions are illustrated in Figure 2, and show how stable sequestered SOC (linked to other nutrients and/or to fine soil fractions) may sustain SOC sequestration and its co-benefits.

Stable sequestered SOC and its benefits on land restoration are boosted by other nutrient dynamics, such as N, P and S [23,76,100,117]. Lal [23] emphasized the link between C and N, P, and S, to improve physical (aggregation) and chemical soil fertility (N, P and S availability), and to convert labile C from crop and animal residues into stable SOM. Availability of inorganic nutrients, such as N, P and S, are crucial to sequester C into the more stable fine fraction of SOM pool irrespective of soil types and C inputs [118]. McDonald et al. [112] demonstrated the strong relationships between photosynthesis, decomposition rates, and soil C, N, and P storage capacity (also see [48,76,118]). This answers partly to the second question of mini-review, i.e., it shows the relationship between the sequestered SOC quality (its link to other N, P nutrients) and land recovery and its benefits in the long term in the forest tropical ecosystems.

Restoration of degraded forests into rehabilitated areas that sequester C using the combination of legume trees, nitrogen-fixing bacteria and arbuscular mycorrhizal fungi re-established the nutrient cycling processes of the systems such as C and N in Brazil [119]. Assuming C stocks of the deforested area were equivalent to that of the restored area prior to legume tree planting, the authors reported an increase in soil C stock by 23 Mg ha^{-1} and by 1.7 Mg ha^{-1} for N stock over 13 years [119]. To restore marginal, degraded lands or unsuitable soils for agriculture, NFS is often used due to their ability to improve soil chemical fertility mainly by increasing nitrogen (N) contents but also C status [62,63,69,120,121]. Restoration of degraded lands in southern China using *Acacia mangium* and *A. auriculiformis*, two NFS, led to reconditioned soil C and N cycling processes [62]. Chen et al. [63] reported that *Acacia crassicarpa* stands had large carbon sinks with higher SOC stocks relative to *Eucalyptus urophylla*, i.e., 330 $\pm$ 76 C m^{-2} yr^{-1} vs 1960 $\pm$ 178 g C m^{-2} yr^{-1} in Guangdong Province in Southern China. Comparison of *A. mangium* and *E. urophylla* plantations, secondary forests and pastures, revealed positive correlations between aboveground biomass production and soil C, N and P amounts along edaphic and climatic gradients in Vietnam [48] (Table 1). Ahmed et al. [122] reported an accumulation in total C and P concentration with time, i.e., from 0- to 6-, 12-, and 17-year-old in Malaysia. This shows and qualifies the rehabilitated forests with indigenous trees as a sink of C and P.

In some cases, neither the C sequestration nor the land restoration using NFS plantations may occur due to other factors [123]. This may be also true for other species as eucalypt plantations in Brazil where soil C stocks depend on soil clay content, precipitation, and mean annual temperature [51]. Based on an average of 29 Mg ha^{-1} ($\pm$0.70 Mg ha^{-1}) in the 0–30 cm layer beneath the 18 to 26 years eucalypt plantations, Cook et al. [51] reported SOC stock decrease with the plantation age in tropical and subtropical sites ($-$0.87 Mg ha^{-1} yr^{-1}, $p < 0.0001$, Espirito Santo state). The management of organic residues or introducing NFS in the rehabilitation or restoration processes of degraded lands or forests leads to SOC sequestration with further impact on land restoration and responds to the second question of this paper; what is the relationship between the SOC quality and its sequestered quantity and what is its impact on land reclamation, in tropical forest ecosystems over the long term?

Table 1. C Sequestration in some forest (natural and planted) ecosystems and locations in the tropics.

Location & Climate Zone	Soil Type	Forest Type	Baseline	Sequestered C	Duration (Year, Yr)	More Information	References
Ghana/Tropical	ND	Mature plantation of *Aucoumea klaineana*, *Cedrela odorata*, *Tarrietia utilis*, *Terminalia ivorensis*	Secondary forest 103 Mg ha^{-1} -	70 Mg C ha^{-1} (primary forest) 56 Mg C ha^{-1} (timber plantation) -	42–47 years & secondary	Higher aboveground biomass C stocks in managed forest plantations compared to naturally regenerated secondary forests,	(Brown et al. 2020)
Thailand/Tropical monsoon climate	ND	Plantation of teak	-	19.1 Mg C ha^{-1} 82.1 Mg C ha^{-1} 73.0 Mg C ha^{-1} 45.4 Mg C ha^{-1}	17 yr 24 yr 31 yr 35 yr	Average C storage in standing trees of 63.3 Mg C ha^{-1}, of which 42% in the harvest wood products	(Chayaporn et al. 2021)
India/Overall	ND	All forest types		3969 million tonnes (2015) 3979 million tonnes (2017)	-	Largest C stock followed by aboveground and belowground biomass	(Indian State of Forest, 2017)
Nepal/Tropical	ND	Community degraded and non-degraded forests	Degraded forests (SOC = 42.55 ± 3.10 t ha^{-1} & TC = 152.68 ± 22.95 t ha^{-1})	Non degraded forests (SOC = 54.21 ± 3.59 t ha^{-1} & TC= 301.08 ± 27.07 t ha^{-1})	-	Better forest management in community forests: 1.97 times > in non-degraded than in degraded forests	(Joshi et al. 2020)
Republic of the Congo/Subtropical	Ferralic Arenosols	Plantation of *A. mangium* and eucalypt	Plantation of eucalypt (15.9 tC ha^{-1} yr^{-1})	0.9 tC ha^{-1} yr^{-1}	7 yr	Soil C stock in plantation of *A. mangium* (16.7). 0–25 cm	(Koutika et al. 2014)
				1.8	7 yr	Soil C in plantation of eucalypt and *A. mangium* (17.8). 0–25 cm	

Table 1. *Cont.*

Location & Climate zone	Soil Type	Forest Type	Baseline	Sequestered C	Duration (Year, Yr)	More Information	References
Malaysia/Tropical	Well drained Bekenu series (loamy siliceous, with low fertility status)	Plantation of *A. mangium*	Plantation of *A. mangium* (1 year) (74.9)	15 tC ha^{-1} yr^{-1}	3 yr	Plantation of *A. mangium* 3 yr (89.9) 0–15, 15–30 cm	(Lee et al. 2015)
				64 tC ha^{-1} yr^{-1}	5 yr	Plantation of *A. mangium* 5 yr (138.9) 0–15, 15–30 cm	
Costa Rica/Hu-mid tropical	ND	Mature natural forest	-	Estimated total CO_2 sequestered 18,210 ton (2019)	50 yr		(Paniagua-Ramirez et al. 2021)
Brazil, (Subtropical)	Ferralsol of sandy texture	Plantation of *A. mangium* and Eucalypt	ND	C accretion	2.25–3.25 y	Changes in microbial attributes and a strong effect on Soil C and N dynamics	(Pereira et al. 2018)
Vietnam/Tropical	Ferralic Acrisols, Dystric Cambisols	Plantation of Eucalypt and *A. mangium*	Plantation of Eucalypt (50.9)	11.5 tC ha^{-1} yr^{-1}	7–16 yr	Plantations of *A. mangium* (62.4) 0–30 cm	(Sang et al. 2013)

Key: ND (not determined).

4. Conclusions

This review highlighted forest management, i.e., practices that enhance SOC sequestration and land restoration, and their potential to favor the quality (interactions to other nutrients driven by soil biota) of sequestered SOC in tropical forest ecosystems. However, since SOC depends on edaphic and other factors, such as climate, land-use history, environment and even inherent factors, SOC sequestration may not occur in some cases. Managing forest ecosystems leading to C sequestration is crucial to sustain soil health and foster climate change mitigation and restoration of degraded lands in tropical ecosystems. The creation of stable sequestered C is driven by soil biota and strongly linked to other nutrients (N, P and S) and soil fractions. Managing forest ecosystems (natural or plantations) associated with some practices (introducing NFS, managing organic residues, etc.) mostly boosts SOC sequestration and its quality (stable C, link to N, P, and soil fractions) and also the conservation of forest C stocks, which benefits to both climate change mitigation and land restoration in the long-term.

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