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Carbon Sequestration Potential of Rubber Plantations as a Complementary Approach to Tropical Forest Conservation Strategies. A Review

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Abstract: Tropical forest ecosystems play a significant role in carbon storage and climate regulation. However, these ecosystems are threatened by deforestation through slash-and-burn agriculture, logging, and mining. Consequently, there is a pressing need to assess the carbon storage potential of tropical perennial plantations, particularly rubber plantations, as a sustainable alternative to deforestation and tropical forest degradation. This study utilizes a systematic review of the extant literature to assess the carbon sequestration potential of rubber plantations and to explore their viability as a complementary alternative to tropical forests in the context of climate change mitigation. The carbon stocks present in rubber plantations have been documented to range from 30 to over 100 tons of carbon per hectare in total dry weight. In comparison, dense tropical forests have been shown to store up to over 300 tons of carbon per hectare, placing rubber plantations in a competitive range, particularly when managed effectively. The potential for carbon sequestration varies considerably based on factors such as plantation age, tree density, environmental conditions, and land management practices, including crop rotation, tapping frequency, plantation maintenance, and biomass management. Optimizing plantation density and regulating water inputs to avoid excessive irrigation are among the management practices that have been shown to enhance carbon sequestration potential, maximize biomass storage, and preserve optimal physiological conditions for rubber trees. Notwithstanding their substantial carbon sequestration potential, rubber plantations are unable to fully compensate for the ecological functions and storage capacity of tropical forests. This limitation stems from their simplified structure and the reduction in biodiversity that is characteristic of monoculture. The findings of this study have the potential to inform the implementation of public policies that promote the adoption of rubber plantations in high-risk deforestation areas. These policies could be developed in conjunction with the development of sustainable management techniques, such as agroforestry, with the aim of maximizing carbon storage and biodiversity preservation. In this context, rubber plantations emerge as a complementary alternative to tropical forest conservation initiatives, offering an economically viable option while contributing significantly to carbon sequestration.

Keywords: sequestration potential; tropical plantation; rubber tree; conservation; tropical forest

1. Introduction

Climate change is regarded as one of the most significant environmental challenges of our era, with substantial ramifications for ecosystems and human societies [1,2]. A critical strategy for mitigating the adverse effects of climate change is the promotion of carbon sequestration, defined as the process of capturing and storing carbon dioxide (CO2) in plant biomass and soil [2]. The release of greenhouse gases, predominantly from the combustion of fossil fuels, has led to an increase in global temperatures, resulting in detrimental effects on natural systems and human societies [3]. The Intergovernmental Panel on Climate Change (IPCC) has underscored the pivotal function of forests in carbon sequestration. According to the Sixth Assessment Report (AR6) of the IPCC, which was published in 2023, the estimated annual carbon storage capacity of forests worldwide is approximately 289 gigatons [4]. Tropical forests are recognized for their exceptional capacity to store carbon; however, they are facing increasing pressure from deforestation, land-use change, and economic development [5]. These anthropogenic activities release carbon into the atmosphere, contributing to climate change [4,6]. Specifically, deforestation and forest degradation contribute significantly to greenhouse gas emissions, accounting for approximately 10-15% of global emissions [4,7]. A decline in global forest area from 4.13 billion hectares (ha) in 1990 to 4.06 billion ha in 2020 has been observed, indicating a net loss of approximately 178 million ha over the past three decades [8]. This represents a shift from 31.6% of the world's land area in 1990 to 30.8% in 2020 [9].

In this critical context of constant threat of deforestation and degradation of tropical forests, it is essential to explore sustainable alternatives that could contribute to conservation efforts while supporting local economies [10]. Industrial tropical plantations, including rubber plantations, have garnered significant interest due to their capacity to sequester carbon, address economic imperatives, and preserve biodiversity [10]. These plantations, which are frequently established on a substantial scale for the purpose of rubber production, also function in the absorption of CO2 from the atmosphere [11]. They possess distinct characteristics in terms of floristic composition, structure, and land management practices [11]. Rubber plantations are of particular interest due to their growing economic importance and wide distribution in tropical regions. The global extent of these plantations currently encompasses more than 11 million hectares, with projections indicating a further expansion in the coming years [1,3,11].

Rubber plantations offer ecological advantages over other monoculture systems, such as maize or rice, which are often associated with significant biodiversity loss and soil degradation [10,12]. These intensive farming practices have been shown to release carbon into the atmosphere, in addition to reducing soil organic matter [12]. Despite their classification as monocultures, rubber plantations present a valuable opportunity to integrate agroforestry practices and intercropping, enhancing carbon sequestration and improving soil health. In contrast to monocultures, which exhibit a paucity of biodiversity, rubber plantations can promote biodiversity through these integrated practices [13]. However, when compared with tropical forests, rubber plantations have a lower carbon sequestration capacity. This is due to the complexity and resilience of tropical forest ecosystems, which ensure sustainable carbon storage [14]. These forests have the potential to achieve higher levels of sequestration due to their high species diversity and structure, which optimize carbon uptake [15]. Furthermore, tropical forests have demonstrated a capacity to adapt to climate change, thereby enhancing their resilience over time. In contrast, rubber plantations continue to be heavily reliant on human intervention for their sustained productivity and carbon storage capacity [16].

In numerous tropical nations, rubber plantations assume a pivotal function as a source of wood products, thereby mitigating pressure on natural forests and, by extension, contributing to their indirect preservation from overexploitation [11]. Furthermore, these plantations often serve as habitats for spontaneous biodiversity, with native species colonizing the interstitial spaces. Despite the lower diversity of this spontaneous vegetation compared to that found in natural forests, it can provide ecosystem services such as improving soil fertility, retaining water, and protecting against erosion [17]. These services contribute to enhancing the ecological value of rubber plantations [3]. Consequently, rubber plantations serve a dual role, functioning economically while contributing to significant environmental dynamics. These plantations are often established with the dual objectives of providing shelter for livestock and preventing erosion caused by wind or water [3]. Additionally, they offer a diverse array of non-timber products [17]. In recent years, some researchers have proposed developing rubber plantations as "carbon sinks" to mitigate the effects of global warming linked to greenhouse gases [3,11,18].

Rubber plantations play an essential economic role, supporting the livelihoods of approximately 40 million people worldwide [3]. Natural rubber is a strategic material with applications in over 5,000 different products, ranging from tires to medical equipment and building materials [3]. Furthermore, Hevea leaves are utilized as fodder, while the seeds are incorporated into poultry feed. Furthermore, rubber plantations contribute to the sequestration of a significant amount of carbon through the production of latex [19]. However, the majority of studies carried out to date on rubber plantations focus mainly on the consequences of deforestation in relation to previous land cover, which is generally dominated by natural forests. Consequently, the analysis of the impacts of rubber plantations is frequently constrained, with a narrow focus on the adverse effects associated with forest loss. Consequently, there is an urgent need for specific studies that assess the consequences of converting formerly forested land to rubber plantations. It is also imperative to explore the contribution of former rubber plantations to biodiversity conservation, carbon sequestration, and climate change mitigation. The objective of this study is to examine the potential of rubber plantations in terms of carbon sequestration, with a particular focus on the influence of agricultural practices, environmental conditions, and land management policies on this potential.

2. Methodology of the Literature Review

The methodological approach employed (Figure 1) is predicated on a meticulous evaluation of the scientific rigor of extant studies concerning the carbon sequestration potential of rubber plantations in comparison with that of tropical forests. This approach involves a systematic analysis that considers various factors, including ecological structure, species diversity, tree density, environmental conditions, sample size, methods for measuring carbon sequestration, and the validity of the conclusions drawn. The analysis encompassed a comprehensive review of the extant methodological tools, including simulation models, direct and indirect sequestration measurements, and remote sensing techniques. This comprehensive analysis enabled us to identify the advantages, disadvantages, and inherent limitations of each method, thereby facilitating a nuanced understanding of their respective uses. A comparative analysis of the results and conclusions of the various studies in relation to geographical areas, measurement methods, and climatic conditions was carried out. The studies included in this analysis focus specifically on the carbon sequestration potential of non-traditional perennial plantations and tropical forests. To carry out this analysis, various databases were consulted, including Web of Science, Scopus, and Google Scholar. The following keywords were used in the searches: "rubber," "tropical plantations," "carbon sequestration," "tropical forests," and "climate change." The review encompasses studies published in English, Chinese, French, and Spanish. To mitigate potential biases arising from linguistic differences, these articles were translated reliably.

The selection of articles and keywords was methodical, ensuring the relevance and comprehensiveness of the research. Preference was given to scientific articles published in peer-reviewed journals, as well as technical reports and recognized academic publications. Experimental studies, meta-analyses, and systematic reviews were accorded particular value. Research that primarily targeted the tropical regions where these plantations are located was selected. To ensure the currency of the data, only recent publications (from 2005 onwards) were considered. The articles selected offer a comprehensive, high-quality overview of the scientific literature on the carbon sequestration potential of natural forests and tropical plantations, with a particular emphasis on industrial crops and rubber plantations.

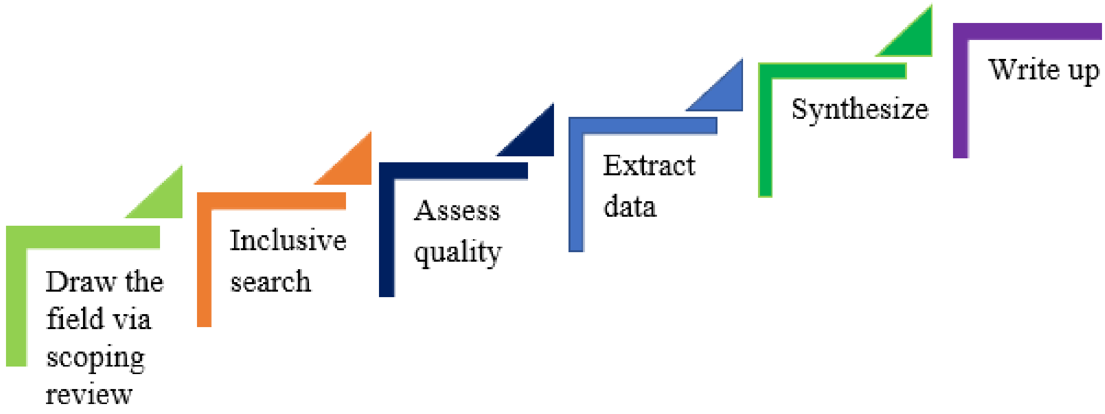

Figure 1. The procedure of systematic review conducted by the study.

3. Results and Discussion

3.1. Carbon Sequestration in Non-Traditional Tropical Plantations

Carbon sequestration in non-traditional tropical plantations is defined as the capacity of perennial agricultural plantations to remove carbon dioxide from the atmosphere [6,20]. Such crops include non-traditional agricultural plantations, such as rubber, cocoa, coffee, oil palm, or pasture plantations, which play an important role in carbon sequestration [20]. The process of carbon sequestration is initiated by the absorption of carbon dioxide by trees, plants, and crops through the process of photosynthesis. These organisms subsequently store the carbon in the biomass of their trunks, branches, foliage, roots, and soils [21]. The process commences with photosynthesis, during which plants capture carbon dioxide (CO2) from the atmosphere using sunlight. Within the cells of leaves, known as chloroplasts, this CO_2 is converted into glucose, a form of chemical energy, while oxygen is released. This stage is predominantly active during daylight hours and is subject to variation according to factors such as season, environment, and climate [15]. The fixed carbon is then incorporated into various plant tissues (i.e., biomass), including leaves, stems, and roots. This carbon remains stored in the biomass as long as the plant is alive. The duration of this storage can vary from a few years to several decades, depending on the type of vegetation [22].

As plants undergo growth, carbon is transferred to older or decomposing parts, contributing to long-term storage [15]. Upon the demise of plants, the release of biomass carbon into the soil is initiated through the decomposition process. In this process, micro-organisms and decomposers (e.g., fungi and bacteria) transform organic matter into humus [23]. This process is continuous and can take from a few months to several years, depending on the soil and climatic conditions (temperature, humidity, soil type). Subsequent to the decomposition process, certain elements combine with soil particles to form organic complexes, thereby contributing to the long-term storage of carbon in the soil [23]. This carbon can persist in the soil for extended periods, ranging from centuries to millennia [2].

Carbon is also found in the form of humus, which is defined as stable organic matter that plays a crucial role in soil fertility and long-term carbon sequestration. [24]. The formation of humus, a byproduct of decomposition and transformation processes, can extend over the course of decades [25]. Soil organic carbon has been observed to interact with minerals, forming stable complexes that retard decomposition and enhance permanence in the soil [24]. The amount of carbon stored in soil organic matter is influenced by the addition of carbon from dead plant matter and carbon losses due to respiration, decomposition, and natural and human disturbance of the soil [26]. The process of carbon sequestration is dynamic and temporal. Photosynthesis and biomass storage are rapid processes, with timescales ranging from days to years, while soil storage and humus formation are

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slower processes, with timescales ranging from months to centuries [20]. The duration of storage is influenced by numerous factors, including climate, soil type, crop type, vegetation cover, land management practices, ecosystem composition, and environmental disturbances, such as climate change [3,11,27].

A number of studies have demonstrated the beneficial impacts of agricultural practices on carbon sequestration, providing concrete examples of their effectiveness in various environmental contexts. For instance, crop rotation, accomplished by diversifying crop species, has been shown to enhance soil health and fertility, reduce erosion, and promote microbial biodiversity [1]. These practices contribute to the decomposition of organic matter, thereby increasing carbon storage capacity. A study conducted in Europe, for instance, demonstrated that the rotation of crops such as wheat and legumes could enhance soil organic carbon by up to 20% over a period of five years [28]. In terms of soil management, practices such as reduced tillage, mulching, and soil cover have been shown to limit the rapid decomposition of organic matter, protect the soil against erosion, and increase its carbon content [29]. Research in sub-Saharan Africa has demonstrated that the implementation of enhanced management techniques, such as conservation tillage and mulching, has resulted in a 30-50% increase in soil organic carbon [30]. Agroforestry practices, which integrate trees into farming systems, have been shown to improve soil structure and water retention, thereby promoting both productivity and carbon storage [11,29,31]. A study by Singh et al. [32] demonstrated that rubber plantations in Southeast Asia, notably in Indonesia and Malaysia, have the capacity to sequester up to 30 tons of carbon per hectare per year, both in the biomass and in the soil. This finding underscores the potential of rubber-based agroforestry systems to enhance carbon sequestration while generating sustainable income for farmers. Furthermore, annual crops such as maize and rice have been observed to exhibit substantial carbon sequestration rates over brief periods [12]. The rapid growth cycle of these crops contributes to their capacity to sequester a substantial amount of carbon during the growing season [12]. For instance, research has demonstrated that specific intensive agricultural practices can result in increases in soil organic carbon of the order of 5 to 10 tons per hectare per year [12,33]. However, this benefit is often short-lived, as once harvested, biomass decomposition and plowing can lead to a rapid release of stored carbon [33]. Conversely, non-traditional, or perennial crops, notably rubber plantations, function as long-term carbon reservoirs [34].

Despite the potential for lower annual sequestration of rubber plantations in comparison to certain fast-growing annual crops, the capacity of rubber plantations to store carbon over extended periods is influenced by numerous distinct factors [12]. Firstly, the long rotation period of rubber trees, spanning up to 25 to 30 years before they are harvested for timber, enables a gradual yet sustained accumulation of biomass in trunks, branches, and roots [35]. Secondly, the perennial structure of rubber trees facilitates continuous sequestration, in contrast to the frequent renewal required by annual crops, which often disrupts soil and results in carbon emissions [32,35]. Furthermore, rubber plantations contribute to the sequestration of organic carbon in soils through the constant supply of litter, which consists of leaves, dead branches, and root exudates [36]. This process enriches soil carbon stocks, especially when soils are well managed and conservation practices, such as reduced tillage or the integration of vegetation cover, are adopted [37,38]. Furthermore, the prolonged maintenance of rubber plantations has been shown to mitigate land degradation, thereby contributing to the stabilization of the carbon already sequestered within the ecosystem [35]. Finally, rubber plantations are notable for their potential for indirect sequestration [18,39]. By providing a sustainable source of latex and wood, they can reduce pressure on natural forests, which play a key role in global carbon sequestration [39]. However, to optimize their function as carbon sinks, it is imperative to implement sustainable management practices, such as optimizing planting density, integrating complementary species into agroforestry systems, and utilizing resistant clones adapted to local conditions [35,40,41].

For instance, rubber plantations have been shown to sequester carbon over time due to their substantial biomass and prolonged rotation periods [35,42,43]. Furthermore, rubber plantations offer

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considerable potential for additional soil storage and indirect carbon preservation through sustainable, integrated management [35]. These factors contribute to rubber plantations' status as a promising alternative for enhancing sequestration efforts in tropical regions, while addressing the economic and social needs of the areas where they are cultivated [3,39].

It is imperative to acknowledge that each system type exhibits distinct carbon sequestration characteristics, accompanied by a range of advantages and disadvantages. These factors must be meticulously considered when formulating sustainable management strategies, as outlined in Table 1.

Table 1. Comparison of sequestration rates in agroforestry systems, secondary forests, and pastures.

Type de systèmes	Rate of Carbone sequestered $tCO2/ha/year$	Advantages	Disadvantages	References
Agroforestry systems	5 à 20	Biological diversity Improvement of soil fertility	Competition between crops	[44,45]
Secondary forests	10 à 50	Biological diversity Vegetation restoration Biodiversity Ecosystem services	Dépendance on environmental conditions Vunerability to fire	[46,47]
Rubber plantations	5 à 30	Vegetation restoration Air retention Biodiversity enchancement	Dependance on humain intervention	[48,49]
Abandoned pastures	2 à 10	Restoration of vegetation Air retention Biofiversity enchancement	Risk of invasion	[50,51]

Looking at Table 1, agroforestry is characterized by productive diversity but requires rigorous management, while secondary forest is a natural asset with vulnerability issues. Abandoned pasture offers an opportunity for regeneration, but faces challenges related to invasion by non-native species. Each of these systems therefore has advantages and limitations that need to be considered according to the sustainability objectives being pursue [12]. Perennial plantations, whether in agroforestry, monoculture, or pasture systems, play a key role in capturing carbon dioxide from the atmosphere during their growth and storing it in the biomass (trees, roots, etc.) and in the soil [52]. This process contributes significantly to climate change mitigation by reducing the concentration of greenhouse gases [12]. By stabilizing the soil with their roots, plants limit erosion caused by heavy rainfall and run-off, which is particularly important in regions prone to extreme climatic events [53]. Agroforestry systems promote biodiversity, which increases the resilience of ecosystems to climatic stress [54]. This diversity also helps to maintain vital ecosystem services such as pollination and regulation of water cycles [55].

In addition, tropical plantations are a source of income for local communities, providing resources such as timber, fruit, and other non-timber products [56]. This helps people to diversify their income sources and reduce their economic vulnerability to the impacts of climate change. By improving food security and strengthening economic resilience, these ecosystems effectively support communities in their adaptation process [57]. Non-traditional plantations also help regulate the water cycle by promoting the infiltration and retention of water in the soil, which is crucial for adequate drinking water supplies and agriculture, especially in drought-prone areas [55]. In this way, non-traditional plantations play a multifunctional role in carbon sequestration and adaptation to climate change, strengthening the resilience of ecosystems and supporting local communities [58].

However, an understanding of monoculture, plantation and agroforestry systems is essential for analyzing studies and quantitative data on carbon sequestration in rubber plantations [35,39]. Monoculture systems are characterized by the cultivation of a single plant species over large areas for long periods of time [12]. This model, often used in industrial agriculture and forest plantations, favors resource homogeneity. However, it can lead to a reduction in biodiversity and increased vulnerability of ecosystems to pests and diseases [59]. Forest plantations, on the other hand, are man-made forests, usually composed of species selected for their rapid growth or economic value [12]. These plantations can include a wide variety of species. Although they can play an important role in carbon sequestration, their effectiveness depends largely on management practices and the biodiversity present in the ecosystem [52].

Finally, agroforestry is an integrated approach that combines agriculture and forestry by integrating trees into crop or livestock systems [32]. This model not only promotes biodiversity, but also improves ecosystem resilience while optimizing carbon sequestration through better land use [26,35]. In addition, agroforestry systems can increase agricultural productivity and provide economic benefits to local communities [60]. There is a wealth of information on carbon sequestration in forest plantations, agroforestry, and natural forests. In contrast, information on monoculture tree plantation systems is incomplete. A few studies have been carried out, mainly in Latin America, Southeast and East Asia, on the carbon content of oil palm [5,61–63] and rubber plantations [31,64]. In Africa, only a few studies have been carried out on tree monoculture systems, for example [65] on rubber and [66] on cocoa in an agroforestry system. Some authors note that the combination of trees and food crops not only optimizes resource use but also promotes system resilience to change but call for further research to better understand the behavior of these systems in different African contexts [32,38].

Estimated sequestration values vary widely depending on the species planted, the management of the plantation and the age of the trees [32]. For example, some studies suggest that plantations of fast-growing species such as eucalyptus or teak can store between 10 and 30 tons of carbon per hectare per year [13]. In addition, floristic diversity within plantations can improve not only ecological resilience but also carbon storage potential [35]. Research has shown that increased diversity can lead to significant increases in carbon sequestration in soil and above-ground biomass [37]. The study by Lan et al [35] on Hainan Island in China showed that semi-natural rubber plantations, also known as 'rubber forests', can support floristic diversity very similar to that of forests. Another critical factor is the interaction between these agricultural and forestry systems and their environment [32].

Agroforestry practices integrating food or feed crops with trees have the potential to enhance carbon sequestration, thereby promoting food security [12]. These mixed systems facilitate the optimal utilization of natural resources while preserving biodiversity. However, a comprehensive evaluation of the immediate potential and long-term sustainability of these systems is imperative. Large-scale deforestation can nullify the benefits derived from afforestation efforts [2]. It is imperative to explore the integration of these practices within a comprehensive framework of sustainable land use to circumvent competition between food production and carbon sequestration.

Table 2 presents a selection of case studies that demonstrate the carbon sequestration potential of atypical rainforest-like ecosystems.

Table 2. Some case studies of carbon sequestration in atypical tropical forest ecosystems.

Type	Age (years)	Area (tC/ha)	Location	Source
Rubber	Mature plantation	275,1	Brazil	Shorrocks [55]
Rubber	20	257,95	Philippines	Onofore et al. [67]
Rubber	35	246,23	Philippines	
Agroforestry system	-	195	Dioïla/Mali	Siriki et al. [68]

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Rubber	Mature plantation	198,4	Ngobo, Indonesia	Yuda & Danoedoro [69]
Rubber	15	146,30	Parana State/Brazil	Maggiotto et al. [70]
Rubber	34	169,22	Brazil	Cotta et al. [71]
Rubber	40	186,65	China	Nizami et al. [63]
Rubber	8 - 20	156	Colombia	Orjuela et al [72]
Agroforest/rubber	8 - 20	159	Colombia	
Rubber	-	214	Ghana	Kongasager & Mertz [73]
Cocoa	-	65	Ghana	
Orange	-	76	Ghana	
Oil palm	-	45	Ghana	
Oil palm	Mature plantation	173,81	Yangambi/DRC	Bustillo et al. [74]
Rubber	Mature plantation	337,33	Yangambi/DRC	

An analysis of Table 2 reveals that, although dense tropical rainforests are widely recognized as the primary terrestrial carbon sink, perennial plantations also fulfill an indispensable role in the carbon cycle. Rubber plantations have been found to sequester approximately 100 to 275 tons of carbon per hectare in cumulative total dry weight. This is in contrast to other tropical industrial crops, such as cocoa (65tC/ha), orange (76tC/ha), oil palm (45tC/ha), and agroforestry systems (195tC/ha). However, the sequestration potential of rubber plantations is contingent on factors such as rotation length, tree age, tree density, management practices (e.g., sustainable tapping), and soil and climate conditions.

According to the findings of the Intergovernmental Panel on Climate Change (IPCC), the judicious management of agricultural land has the potential to curtail the global carbon dioxide (CO2) emissions by approximately 0.4 to 1 gigatons per year by the year 2030 [4]. For instance, the rotation period of rubber plantations plays a pivotal role in determining their carbon sequestration potential. In essence, the duration of the rotation period directly correlates with the amount of biomass accumulated by the plantations, thereby enhancing carbon sequestration [75]. Furthermore, optimal tree density fosters competition for resources such as water, nutrients, and light, thereby enhancing ecosystem productivity. This competitive dynamic has been shown to stimulate tree growth, thereby increasing their capacity to sequester carbon [64]. Conversely, intensive management practices, such as fertilization and irrigation, have been shown to enhance tree growth, thereby increasing total carbon sequestration and soil carbon [76]. Conversely, extensive management practices may not maximize this potential [77]. Furthermore, diversified systems, exemplified by agroforestry practices, have been shown to enhance resilience in the face of environmental stresses, thereby facilitating more efficient carbon sequestration [78]. Finally, it is important to note that soil and climate factors, such as variations in temperature, precipitation, and humidity, can have a significant impact on tree growth and, consequently, on their ability to sequester carbon [79]. However, it is imperative to acknowledge the limitations of extant research on carbon sequestration in rubber plantations. Firstly, the utilization of disparate data collection methodologies, encompassing varied measurement techniques and sampling protocols, can result in the introduction of biases and inconsistencies into the results. For instance, certain studies may rely on point measurements that overlook the temporal and spatial variability of carbon stocks [52]. Additionally, the paucity of research in Africa, where rubber plantations are of strategic importance to local economies and natural resource management, is a matter of concern. This dearth of data hinders our comprehension of carbon sequestration dynamics within a tropical context. Conducting longitudinal research in these understudied regions is therefore imperative to better assess the real potential for carbon sequestration and provide a sound basis for sustainable management policies [3,11]. By enhancing our understanding in these areas, we can not only contextualize current results but also guide future efforts towards more effective and sustainable management of biodiversity and forest resources.

3.2. Comparative Analysis of Rubber Plantations and Tropical Forests

Comparées aux plantations d'hévéa, les forêts tropicales sont les écosystèmes terrestres les plus efficaces pour la séquestration du carbone (Tableau 3). En effet, elles jouent un rôle crucial dans la régulation du climat et l'atténuation du changement climatique [26,80–82]. Ces forêts sont capables de séquestrer jusqu'à 30 % des émissions mondiales de CO_2 d'origine anthropique et représentent environ 59 % des stocks mondiaux de carbone [83]. Elles stockent en moyenne entre 250 et 300 tonnes de carbone par hectare, ce qui en fait l'un des puits de carbone les plus importants de la planète [49,82,84–86]. Il existe une forte variation spatiale de la biomasse au sein des forêts tropicales et notamment entre les trois bassins forestiers tropicaux avec des valeurs plus élevées en Afrique tropicale et en Asie, respectivement 418 ± 91 et 393 ± 109 Mg.ha-1, que dans les forêts d'Amérique du Sud, 287 ± 105 Mg.ha-1 [87]. Ces variations s'expliqueraient par la fréquence plus élevée d'arbres de plus de 70 cm de diamètre dans les forêts Paléotropicale (Afrique et Asie). Au sein du continent africain, il existe aussi d'importantes variations spatiales de biomasse.

As demonstrated in Table 3, tropical forests have been shown to exhibit superior efficacy in terms of carbon sequestration in comparison to rubber plantations. These forests play a crucial role in climate regulation and mitigation [26,80–82]. It has been determined that these forests are responsible for sequestering up to 30% of global anthropogenic CO_2 emissions and accounting for approximately 59% of global carbon stocks [83]. On average, these forests store between 250 and 300 tons of carbon per hectare, making them one of the planet's most significant carbon sinks [49,82,84–86]. A substantial spatial variation in biomass is observed within tropical forests, particularly between the three tropical forest basins, with higher values recorded in tropical Africa and Asia (418 ± 91 and 393 ± 109 Mg.ha-1, respectively) compared to South American forests (287 ± 105 Mg.ha-1) [87]. These variations can be attributed to the higher frequency of trees with a diameter greater than 70 centimeters in tropical forests of the Paleotropical region, which includes Africa and Asia. Within the African continent, significant spatial variations in biomass are also observed. Lewis et al. [88] present biomass estimates for Central Africa (429 Mg.ha-1) that are considerably higher than those for West Africa (305 Mg.ha-1) and East Africa (274 Mg.ha-1). The disparities in biomass can be attributed to the prevalence of hyper dominant species in Central Africa, which contribute more than 50% of biomass stocks [89]. On a local scale, several authors have also demonstrated significant variations in biomass between different types of African tropical forests (Table 3). For instance, Day et al. [90] documented variations in above-ground biomass among distinct types of dense rainforest in Central Africa, while Kuyah et al. [91] examined differences in biomass among Miombo forest types in East Africa. These variations can be attributed to structural differences associated with anthropogenic disturbances and/or edaphic and altitudinal gradients. However, the floristic composition and structural variables (basal area, height-diameter allometry, etc.) explain the majority of the spatial variation in biomass observed in African tropical forests [92,93]. Conversely, spatial variations in biomass can be attributed to the distinct specific compositions of forest types [89,92–98]. Mature forests where *Gilbertiodendron dewevrei* (Fabaceae - Caesalpinioideae) forms monodominant stands store as much or more above-ground biomass than younger mixed forests in Cameroon [99] and the DRC [88,100]. Furthermore, forests dominated by trees from the Olacaceae, Caesalpiniaceae, and Burseraceae families have been shown to have significantly higher above-ground biomass compared to those dominated by the Burseraceae, Myristicaceae, and Euphorbiaceae families [101]. In contrast, Fayolle et al. [102] posit that the disparities in above-ground biomass between evergreen and semi-deciduous forests in Cameroon can be attributed to variations in floristic composition, forest structure (stem density per hectare and basal area), and height-diameter allometry. A study conducted in the semi-deciduous forests of Yangambi, and Yoko in the Democratic Republic of the Congo (DRC) demonstrates that height-diameter allometry is the primary factor contributing to the variation in spatial patterns of above-ground biomass [103]. The interaction between floristic composition, forest

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structure, and environmental factors (soils) has been identified as a primary driver of variations in above-ground biomass among mature Central African forests, distinguishing those with rich soils from those with poor soils or soils with physical constraints [89,104].

It is imperative to acknowledge the potential influence of other environmental factors on the spatial distribution of biomass. Miombo-type forests, located at intermediate elevations, have been observed to accumulate greater biomass compared to those found at lower or higher elevations [92,93]. Rainfall has been identified as a primary driver of spatial variation in biomass among tropical montane forest types in Tanzania [105]. This underscores the imperative for a comprehensive understanding of tropical forests, as they are poised to play a pivotal role in sequestering additional terrestrial carbon [81].

However, it is imperative to acknowledge that tropical deforestation contributes significantly to greenhouse gas emissions [81,82]. These ecosystems are subject to rapid, widespread, and irreversible land-use change, particularly as a result of deforestation and anthropogenic degradation [106–108]. A substantial decrease in the area of tropical forests has been observed in recent decades, particularly from 2010 to 2020. This decline is evident in Africa, where the loss amounted to 3.9 million hectares, and in South America, with a loss of 2.6 million hectares [9].

In light of these observations, the establishment of non-traditional perennial plantations, such as rubber plantations, emerges as a promising strategy for enhancing carbon storage. This approach is regarded as a sustainable alternative to the restoration of tropical forests in areas experiencing significant deforestation or undergoing the transition from agricultural crops to plantation or agroforestry systems.

Table 3. Comparative table of sequestration levels in different rubber plantations compared to tropical forests and plantations forests.

Type of Ecosystem	Carbon stock Tons of Mg C/ha	References
Primary tropical forest	> 300	OFAC [109]
Mature rubber plantation (Brasilia)	80 - 150	Lan et al. [35]
Young rubber plantation ≤ 10 years old (Sub-Saharan Africa)	30 - 50	Onoji et al. [110]
Mono-dominant forest (Ituri/DRC)	267,5	Makana et al. [100]
Mono-dominant forest (Yangambi/DRC)	165,5	Kearsley et al. [111]
Mixed forests (DRC)	160,5 to 199,5	Panzou et al. [112]
Young forests (DRC)	202	Panzou et al. [112]
Plantation forest (Ethiopia)	223	Dick et al. [98]
Secondary forest (Congo-Brazzaville)	167	Ekoungoulou et al. [97]
Teak plantation (Panama)	3 - 41	Derwish et al. [113]
Mixed forest (Colombia)	122 - 141	Saatchi et al. [114]
Mixed forest (Venezuela)	118 - 139	
Mixed forest (Bolivia)	84 - 94	
Mixed forest (Myanmar)	146 - 157	
Mixed forest (Papua New Guinea)	147 - 153	
Acacia magium and Eucalyptus plantation (Vietnam)	11,5	Sang et al. [115]
Production forest (Indonesia)	46,32	Situmorang et al. [116]
Mixed forest (Cameroon)	318	Zapfack et al. [117]
Plantation forests (Ghana)	56 - 70	Brown et al. [118]

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Community forests (Nepal)	301	Joshi et al. [119]
Agroforestry (Peru)	106	Aragon et al. [120]
Teak plantation (Thailand)	45 - 82	Chayaporn et al. [121]
All types of forests (Malaysia)	157,5	Raihan [122]
Peatland (Congo)	634	Crezee et al. [123]

Table 3. Estimate (mean ± standar error / standar deviation) of aboveground biomass and /or total (in bold) for the different types of tropical forests. n: number of the sampled. DRC: Democratic Republic of Congo, RCA: Republic Central African.

Type of forest	Location	Country	Sampling		Tree diameter threshold (cm)	Biomass (Mg ha^{-1})	Reference
			Size (ha)	n			
Mono-dominant forest	Dja	Cameroun	1	5	D ≥ 10	596 ± 62	Djuikouo et al. [99]
	Ituri	DRC	10	2	D ≥ 1	535	Makana et al.[100]
	Yangambi	DRC	1	5	D ≥ 10	331 ± 28	Kearsley et al. [111]
Mixed forest	Dja	Cameroun	1	5	D ≥ 10	402 ± 58	Djuikouo et al. [99]
	Ituri	DRC	10	2	D ≥ 1	399	Makana et al. [100]
	Yangambi	DRC	1	8	D ≥ 10	321 ±48	Kearsley et al.[111]
Mature forest	Kakamaga	Kenya	0,04	46	D ≥ 5	**498 ± 45**	Glenday [124]
	Yangambi	DRC	1	1	D ≥ 10	163	Kearsley et al. [111]
Young forest	Kakamaga	Kenya	0,04	16	D ≥ 5	**202 ± 40**	Glenday [124]
	Yangambi	DRC	1	3	D ≥ 10	37 ± 4	Kearsley et al. [111]
Semi-caducifolia forest on rich soils	South-east	RCA	0,5	324	D ≥ 20	248 ± 10	Gourlet-Fleury et al. [104]
Semi-caducifolia forest on poor soils	South-east	RCA	0,5	101	D ≥ 20	198 ± 18	
Semi-caducifolia forest (logged)	M'Baïki	RCA	4	3	D ≥ 10	375 ± 58	Gourlet-Fleury et al. [104]
Semi-caducified forest (logged + thinned)	M'Baïki	RCA	4	4	D ≥ 10	356 ± 64	
Semi-caducifolia forest (not exploited)	M'Baïki	RCA	4	3	D ≥ 10	375 ± 40	
Semi-deciduous forest	Mindourou	Cameroun	0,5	5 152	D ≥ 10	348	Fayolle et al. [102]
Evergreen forest	Ma'an	Cameroun	0,5	2 101	D ≥ 10	260	
Natural forest	Hawassa	Ethiopia	0,12	10	D ≥ 5	200	Wondrade et al. [98]
Plantation forest	Hawassa	Ethiopia	0,12	38	D ≥ 5	223	
Semi-deciduous mixed forest	Yangambi	DRC	1	5	D ≥ 10	326 ± 38	Doetterl et al. [103]
	Yoko	DRC	1	5	D ≥ 10	382 ± 56	
Agro-forestry	Campo-Ma'an	Cameroun	0,5	8	D ≥ 5	**231 ± 45**	Djomo et al. [95]
Production forest	Campo-Ma'an	Cameroun	0,5	8	D ≥ 5	**283 ± 51**	
Protected forest	Campo-Ma'an	Cameroun	0,5	8	D ≥ 5	**278 ± 48**	
Secondary forest	Lesio-louna	Congo	0,12	3	D ≥ 10	**167 ± 15**	Ekoungoulou et al. [97]
Forest gallery	Lesio-louna	Congo	0,12	3	D ≥ 10	**92 ± 29**	
Olacaceae, Caesalpiaceae, Burseraceae forest	Center	Gabon	0,3	766	D ≥ 5	333 ± 7	Maniatis et al.[101]
Burseraceae, Myristicaceae, Euphorbiaceae	Center	Gabon	0,3	885	D ≥ 5	324 ± 5	

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Mountain forest	Monts de Cristal Park	Gabon	1	5	D ≥ 10	456 ± 88	
Lowland and mountain tropical forest	Park Waka Park Monte Mitra	Gabon Equatorial Guinea	1 1	5 3	D ≥ 10 D ≥ 10	394 ± 169 384 ± 42	
Forests under mountains, plains, and riparian forests	Park Takamanda	Cameroun	1	10	D ≥ 10	351 ± 147	Day et al. [125]
Semi-deciduous tropical forest	Park Nouabalé Ndoki	Congo	1	5	D ≥ 10	281 ± 52	
Atlantic coastal and swamp forest	Park Campo Ma'an	Cameroun	1	3	D ≥ 10	250 ± 64	
Atlantic evergreen forest	Reserve Ejaghan	Cameroun	1	2	D ≥ 10	247 ± 128	
Miombo-type forest with medium-sized trees	Kasangu	Malawi	1,35	15	D ≥ 5	8 ± 5	
Forest with low diversity of large canopy trees	Neno	Malawi	0,9	10	D ≥ 5	5 ± 4	Kuyah et al. [91]
Mountain forest	Hanang	Tanzania	0,08	60	D ≥ 5	**55 ± 6**	
Miombo forest	Kiolombero	Tanzania	0,08	162	D ≥ 5	**26 ± 1**	
Low-level natural forest	Mount Kilimanjaro	Tanzania	0,25	5	D ≥ 10	**361 ± 88**	
Natural mountain forest	Mount Kilimanjaro	Tanzania	0,25	5	D ≥ 10	**357 ± 22**	Ensslin et al. [105]
Mountain-level natural forest	Mount Kilimanjaro	Tanzania	0,25	5	D ≥ 10	**372 ± 4**	
Miombo-type open forest at 791 m altitude	Nyanganje	Tanzania	1	1	D ≥ 10	**61 ± 2**	
Miombo-type open forest at 502 m altitude	Nyanganje	Tanzania	1	1	D ≥ 10	**56 ± 2**	
Miombo-type open forest at 1 333 m altitude	Kitonga	Tanzania	1	1	D ≥ 10	**48 ± 2**	Shirima et al. [93]
Miombo-type open forest at 1 500 m altitude	Kitonga	Tanzania	1	1	D ≥ 10	**28 ± 1**	
Plain forest (< 750 m altitude)	Udzungwa	Tanzania	1	5	D ≥ 10	**14**	
Transition forest (750 – 1 200 m altitude)	Udzungwa	Tanzania	1	5	D ≥ 10	**23**	Marshall et al. [92]
Afromontane forest (> 1200 m altitude)	Udzungwa	Tanzania	1	8	D ≥ 10	**21**	

Recent studies have indicated a trend of increasing above-ground biomass and carbon stocks in mature and undisturbed tropical forests [94], including in Africa [126]. These forests serve as carbon sinks, indicating that they sequester more carbon than they emit. For instance, Makana et al. [100] demonstrated that biomass increased by an average of 1.1 Mg.ha-1.yr-1 in mature *Gilbertiodendron dewevrei* mono-dominant forests and by 3 Mg.ha-1.yr-1 in mixed forests (young forest) in Ituri, DRC,

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over a period of 12 years. A monodominant forest is a type of plant formation in which a single tree species is predominant, accounting for the majority of tree cover and biomass. In such a forest, the presence of other tree species is minimal, with low densities of additional tree species present [100]. This discrepancy can be attributed to a comparatively diminished tree growth rate in mono-dominant forests, where the degree of maturity is more advanced. However, it has been observed that the biomass of mature forests exceeds that of young forests [126]. However, it is critical to acknowledge the deleterious impact of human activities, such as slash-and-burn agriculture and logging, on biomass and carbon stocks [96]. In Central Africa, tropical forests cover approximately 180 million hectares, and 26% of this area is developed for commercial use by logging companies [127]. Selective logging, a practice that is particularly prevalent in this region, has been shown to result in a reduction of 17 to 20 Mg.ha-1 of initial biomass [128].

Given the temporal nature of these biomass losses, the optimization of skidding track layouts has the potential to exert a considerable influence on the mitigation of logging-related biomass losses [129]. However, a period of approximately 30 years is required to restore the initial biomass levels of tropical forests in Central Africa [126,130]. The rate of forest biomass recovery following logging appears to be influenced by the intensity and type of logging [129,131]. However, a study by Lung et al. [132] found no significant difference in biomass between four regions of Kenya employing different logging techniques. A similar can be drawn between the carbon stocks present in logged forests and those found in unlogged forests within the Tanzanian context [92,105]. Furthermore, Gatti et al. [133] observed that the biomass of logged forests is comparable to that of primary forests in African tropical forests. In sum, these findings suggest that tropical forests possess a greater carbon stock compared to rubber plantations. Conversely, rubber plantations could serve as a preliminary step in the restoration of a tropical forest that has been deforested.

A thorough investigation into the immediate and long-term consequences of various agronomic practices on carbon sequestration is imperative. Such practices include crop rotation, agroforestry, and the utilization of organic fertilizers in lieu of chemical alternatives [1]. It is also imperative to elucidate two pivotal indicators: the total stock of carbon accumulated, and the amount of carbon sequestered annually [35]. The former quantifies the total amount of carbon stored in a given system, while the latter evaluates the system's annual carbon capture capacity. While these two measures are complementary in understanding the dynamics of carbon sequestration, particular attention must be paid to the annual sequestration rate [35]. This is particularly salient for initiatives associated with voluntary carbon markets, wherein credits are derived based on the quantity of carbon captured annually [7]. The exploration of diverse agronomic practices holds potential in identifying strategies that optimize the economic viability and ecological sustainability of these systems [10]. Furthermore, it is imperative to adapt plantations in anticipation of the impending effects of climate change, which may encompass a decline in productivity and an impaired capacity to effectively sequester carbon [32].

Although rubber plantations may not fully replicate the complexity and biodiversity of dense tropical rainforests, they can nevertheless contribute significantly to carbon sequestration through the effective enhancement of biomass productivity and soil nutrient accumulation [1]. However, the role of rubber plantations is nuanced and contingent on several factors, including the species cultivated, forest management practices, and the ecological context [1]. In this regard, concerted efforts are imperative to harmonize the conservation of natural forests with the cultivation of sustainable plantations, thereby ensuring the optimal benefits for climate and biodiversity [134]. Integrating practices such as reforestation, assisted regeneration, and exotic species management has the potential to increase carbon storage and enhance biodiversity and ecosystem resilience [135].

Research has demonstrated that sustainable management practices, such as agroforestry, have the capacity to enhance carbon sequestration. For instance, the implementation of agroforestry systems, which integrate food crops and trees, has been demonstrated to enhance income diversification while augmenting carbon storage potential [60]. Integration of such strategies by

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forest managers represents a dual approach, contributing to both the mitigation of climate change and the enhancement of forest sustainability [1].

The significance of carbon sequestration in global initiatives to mitigate the effects of climate change is of paramount importance. The debate surrounding rubber plantations has been substantial. Some consider them a responsible alternative to deforestation, while others have expressed concerns over their potential impact on biodiversity [1]. However, this analysis reveals that rubber plantations can play a significant role in carbon sequestration and therefore present themselves as a complementary option to tropical forest conservation efforts. According to Lan et al. [35], rubber plantations have the capacity to accumulate substantial amounts of carbon, comparable to those observed in certain natural forests that are managed in a sustainable manner. The biomass of rubber trees has been observed to reach up to 160 tons per hectare after 25 years, as reported by Lan et al. [35].

This potential is especially salient in regions where logging has resulted in substantial deforestation. In this regard, it is noteworthy that certain researchers contend that, despite the immediate economic and ecological benefits these plantations provide to local farmers through latex production [11], they do not fully supplant the role of natural tropical forests with respect to biodiversity and ecosystems. Consequently, it is imperative that they be integrated into a broader framework that also includes the active protection of existing forest ecosystems [39]. This analysis underscores the socio-economic importance of rubber plantations as a means of enhancing local living standards and contributing to the global effort against climate change by storing carbon. The financial yield from such plantations has the potential to enhance rural communities' economic well-being, thereby reducing their reliance on detrimental practices such as shifting cultivation or illegal logging [136]. This underscores the pressing need to formulate policies that integrate sustainable agriculture and conservation to ensure a viable future for local populations while safeguarding global biodiversity [1].

Nevertheless, it is also important to recognize certain limits associated with the massive development of rubber plantation monocultures. Their proliferation can result in ecological homogenization on land that was previously characterized by a diverse array of plant species or natural ecosystems [32]. Consequently, there is an imperative for rigorous environmental monitoring to be implemented in order to ensure that these farming systems do not lead to systematic soil degradation or a significant loss of local biological diversity over time [134].

A review of the extant literature indicates that natural forests have been demonstrated to be unrivaled in their capacity to execute a multitude of ecological functions, including the regulation of hydrological cycles, the maintenance of biodiversity, and the long-term storage of carbon. This superior performance can be attributed to their complex structure and biological diversity [131]. Conversely, rubber plantations, due to their monocultural nature and simplified structure, have been shown to provide a lesser degree of ecosystem services [35]. Notwithstanding, rubber plantations have been demonstrated to possess considerable carbon sequestration potential, largely attributable to their perennial biomass, extended rotation period, and contribution to soil carbon storage [137]. These findings underscore the role of rubber plantations as a transitional solution, particularly in regions where deforestation or natural forest degradation severely compromise sequestration capacities [35]. Consequently, rubber plantations should not be regarded as a substitute for natural forests; rather, they should be regarded as a complementary mitigation opportunity that can reduce pressure on these ecosystems while generating economic benefits for local populations [11,138].

3.3. Long-Term stability of Carbon Stocks in Rubber Plantations

The long-term stability of rubber plantations as carbon sinks is contingent on numerous interconnected factors [134]. Among these factors, climate variability, market dynamics, and pest epidemics play a crucial role in the sustainability and effectiveness of these plantations as climate solutions [1]. Climate variability directly influences the growth of rubber trees, thereby affecting their capacity to store carbon [35]. Changes in rainfall patterns, temperature extremes, and the increased

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occurrence of extreme weather events can affect tree development in these plantations [31]. A study by Hazir et al. [139] demonstrates that substantial variations in rainfall patterns can impact not only annual growth but also the physiological cycle of rubber trees. The authors further emphasize that prolonged periods of drought can substantially diminish productivity, consequently leading to reduced carbon sequestration [139].

It has been demonstrated that elevated temperatures can induce water stress in these plants, thereby reducing their photosynthetic capacity [140]. This phenomenon can result in a decline in overall carbon storage over time [141]. Furthermore, economic profitability emerges as a pivotal factor in the long-term sustainability of carbon stocks within rubber plantations [142]. The reliance on markets for natural rubber exerts a substantial influence on decisions regarding the maintenance of existing plantations or the initiation of new ones [143,144]. During periods of elevated rubber prices, there is a possibility of increased pressure to convert more forest land to rubber plantations [145]. Furthermore, the policies governing international trade, particularly those that influence the global market, have the potential to either promote or impede the sustainable or intensive expansion of farms, which could initially serve to mitigate the adverse effects of climate change [144].

Epidemics caused by various bio-aggressors also represent a grave threat to long-term sustainability. For instance, certain fungal diseases, such as *Chordomyia* spp., have been demonstrated to rapidly devastate an entire cultivated batch of rubber plantations if not adequately managed [146]. This phenomenon is associated with a decline in production and a potential loss of substantial carbon stocks [147]. The integration of biodiversity within rubber plantations through agroforestry practices has been demonstrated to be a viable strategy for mitigating the adverse effects associated with predators and pests. However, it is important to note that intensive monocultural practices render rubber plantations particularly susceptible to various diseases [148].

3.4. The Role of Rubber Plantations in the Context of Climate Change

Rubber plantations play an ambivalent role in the context of climate change (Figure 2). On the one hand, they offer significant opportunities for carbon sequestration and the provision of renewable resources; on the other hand, they are exposed to environmental risks that could compromise their long-term benefits [144]. Due to their rapid growth, these plantations can act as a complementary sink for carbon dioxide if managed sustainably [35]. Natural rubber is emerging as an environmentally friendly product in an agroforestry system [149]. In fact, while it takes between 108 and 174 GJ of energy to produce one ton of synthetic rubber, it takes only 13 GJ to produce one ton of natural rubber [150,151]. Each ton of natural rubber that replaces synthetic rubber results in a reduction of 4.8 tons of carbon in the atmosphere [151].

Adding together the carbon sequestered in the shoot biomass and in the rubber itself, this gives around 1,019.2 tons of CO2 fixed per hectare in 33-year-old rubber plantations [152]. In addition, greenhouse gas (GHG) emissions from rubber plantations can be lower than from other crops, particularly when land use and agricultural practices are considered [11]. For example, rubber plantations, when managed sustainably, can generate less than 0.5 tons of CO2 equivalent per hectare per year in emissions linked to agricultural inputs and practices [153]. In contrast, intensive corn and soybean cultivation can generate emissions of 2 to 4 tons of CO2 equivalent per hectare per year due to the use of chemical fertilizers and deforestation to expand farmland [154]. In addition, natural rubber remains essential for the manufacture of essential products such as condoms, surgical gloves, and aircraft tyres [155]. Currently, global demand, particularly in Asia and China, is outstripping supply of both synthetic and natural rubber [155]. Although Brazil is the historical cradle of rubber, it accounts for only about 1.2% of global natural rubber production and 3.3% of synthetic rubber production [155]. In contrast, China's consumption of natural and synthetic rubber reaches 3.5% and 38% respectively [155]. This analysis shows that rubber plantations can play an important role in the fight against climate change and can effectively contribute to mitigating the effects of climate change, provided they are managed sustainably [35].

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However, it is important to adopt policies and practices that promote the sustainable management of these plantations in order to maximize their positive contribution to reducing greenhouse gas emissions while preserving the environment and promoting sustainable development [11]. These include agroforestry practices, the adoption of cultural practices such as the selection of species adapted to local conditions, high planting densities, appropriate fertilization, pest and disease control, and the promotion of longer plantation rotation cycles [32]. In addition, the inclusion of native species in plantations can enhance biodiversity and ecosystem services while contributing to carbon sequestration [1].

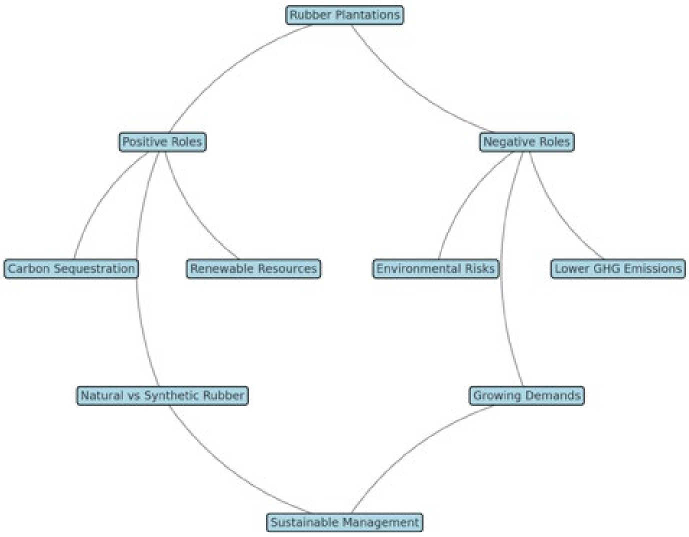

Figure 2. Ambivalent role of rubber plantations in climate change context.

3.5. Measuring Carbon Sequestration in Rubber Plantations

Carbon sequestration in rubber plantations is generally estimated using above-ground biomass, assuming that 50% of this biomass is carbon [156]. Biomass is calculated by combining harvested and standing biomass, as above-ground biomass is easier to measure than below-ground biomass [157]. The traditional approach (direct measurements) to estimating biomass in tropical ecosystems involves harvesting whole trees, separating their various parts (stem, leaves, roots, etc.) and then determining the dry weight [15,94,131]. The data collected are used to develop allometric equations using variables such as diameter at breast height (dhp) and total tree height [15]. Although this method is accurate, it is also very laborious, especially for large trees, and is often used to validate less invasive methods (indirect measurements) [94,131,158].

Accurate assessment of carbon storage in rubber plantations often relies on the use of established allometric models linking diameter at breast height (dbh), height and wood density [31. These models allow not only rapid estimation, but also the standardization needed for comparative studies between different tropical sites or systems [15,157].. However, many of the existing models do not always take into account species-specific variability or local conditions, which can lead to significant under- or overestimation of actual storage in these plantations [157]. An analysis of the literature shows a high degree of variability in parameter values and allometric equations for rubber plantations (Table 4). This uncertainty is due to bioclimatic variability, the effects of clone type, plantation management, tapping methods and measurement methods [159].

Table 4. Carbon stocks (Mg C ha^{-1}) in plant biomass and soil for rubber plantations of different locations.

Carbon stock, (Mg C ha^{-1})	Pool description	Rotation	Tree density per ha	Location	Refence

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		length (years)			
51.2a	Above – and belowground biomass	1 - 35	469	Brazil, Mato Crosso	Wauters et al. [65]
63.7a	Above – and belowground biomass	1 - 25	419	Thailand	Pestri et al. [160]
42.4b	Above – and belowground biomass	1 - 25	No data	China, Xishuangbanna	Tang et al. [43]
45.3b	Above – and belowground biomass	1 - 30	375	China, Hainan	Cheng et al. [64]
40.4a	Above – and belowground biomass	1 - 30	Variable	Sri Lanka, wet zone	Munasinghe et al.[161]
43.2a	Above – and belowground biomass	1 - 30	Variable	Sri Lanka, intermediate zone	Munasinghe et al. [161]
65.1a	Above – and belowground biomass	1 - 38	450	China, Xishuangbanna	Yang et al. [162]
41.7b	Above – and belowground biomass	1 - 20	500 - 680	Thailand, Nong Khai	Saengruksawong et al.[163]
42.0c	Above – and belowground biomass	1 - 20	500	Indonesia, Sumatra	Sone et al. [164]
38.2b	Aboveground biomass	1 - 30	No data	Indonesia	Lusiana [165]
46.2b	Aboveground biomass	1 - 30	Jungle rubber	Indonesia	Palm et al. [166]
23.0b	Above – and belowground biomass	1 - 15	500	Brazil, Parana	Maggioto et al. [70]
52.7	Soil, 0-60 cm depth	14	433	Ghana	Wauters et al. [65]
105.6	Soil, 0-60 cm depth	14	469	Brazil, Mato Grosso	Wauters et al. [65]
79.3	Soil, 0-60 cm depth	15	460	Brazil, Parana	Maggioto et al.
72.0d	Soil, 0-40 cm depth	15	375	China, Hainan	Cheng et al. [64]
147.2	Soil, 0-100 cm depth	19	450	China, Xishuangbanna	Yang et al. [162]

Time averaged C stocks are in bold. Superscript letters in the first column designate the method used for the calculation of carbon stocks: a—plant growth described by the logistic function used by Wauters et al. [65] and Pestri et al. [160] ; b—linear models were used for the description of biomass development or c—time averaged C stock was derived from estimated annual increments; d—soil C stocks were recalculated based on Cheng et al. [64] using published SOM content data (conversion factor 0.58) and the relationship between SOM content and bulk density was calculated according to Post and Kwon.

The allometric relationship has been used by several authors to estimate plant biomass in plantations of different ages from diameter at breast height (dbh) measurements and to construct an empirical equation for the temporal and spatial evolution of plant biomass [43,65,160]. It is clear that the carbon stocks in rubber biomass increase over time due to the development of seedlings up to the time when a plantation is harvested [35]. The full life cycle of a rubber plantation is approximately 25 to 35 years, depending on tree growth conditions and harvesting patterns [63,64]. Analysis shows that the main changing component is the above ground biomass of the trees. To account for the temporal variation of this carbon stock in a rubber plantation, it is necessary to estimate the time-averaged carbon stock (TAC) [167].

Such an estimate allows the average carbon stock to be quantified over the entire rotation cycle, from rubber plantation establishment to timber harvest, thus providing an integrated assessment of its contribution to carbon sequestration [157,168]. It is necessary to scale up measurements from the plot level of plantations of different ages to the landscape and regional level for long-term comparisons [157]. The simplest way to calculate TACs is to divide the maximum carbon stock (at the time of harvest) by 2, assuming a linear increase in biomass [167].

If more detailed data are available, i.e., carbon stocks in plantations of different ages, a regression equation for the increase in biomass over time can be derived [157]. In this case, the TAC is equal to the stock value calculated by the equation, adjusted to the midpoint of the rotation cycle [157]. The TAC values presented in Table 4 were calculated using two types of equations, either linear or sigmoid functions, depending on data availability and best fit results, or directly using expressions derived by the authors in their publications [160].

It is also important to compare a number of allometric equations that have been developed, as the equations differ mainly by tree species and geographical region [15]. As most equations use conversion factors developed by the IPCC, it is important to develop local conversion factors or use equations developed for local species conditions [169]. Measuring carbon sequestration in rubber plantations is complex and requires the use of adapted allometric equations and accurate inventory data [169]. Little information is available on allometric variations specific to rubber plantations in Africa, highlighting the need to develop specific allometric equations based on local data to accurately assess the sequestration potential of these plantations [157].

Recent studies have highlighted the importance of considering species-specific data and local conditions to accurately estimate carbon sequestration in rubber plantations. For example, Ren et al. [170] showed that management of the underlying vegetation significantly affects soil carbon and nitrogen storage in rubber plantations, highlighting the need for management practices adapted to local contexts. In addition, Ma et al [34] reviewed different methods for assessing carbon sinks in rubber plantations, highlighting the challenges associated with the sometimes-blurred dynamics between carbon sources and sequestration, and the importance of accurate monitoring technologies adapted to specific conditions. In addition, a study by Lan et al. [171] showed that the complexity of the soil bacterial network is lower in rubber plantations than in tropical forests, suggesting that microbial community structures differ significantly between these ecosystems and may influence carbon cycling processes. Finally, research by Sun et al. [172] has shown that conversion of tropical forests to rubber plantations has significant negative impacts on soil quality, such as accelerated acidification and reduced soil fertility, highlighting the need to integrate species- and site-specific considerations into plantation management.

3.6. Future Research Needs for Policy Formulation to Enhance Carbon Sequestration in Rubber Plantations

In order to maximize the carbon sequestration potential of rubber plantations, it is imperative that a focused effort be devoted to scientific research. This will not only improve our understanding of the underlying ecological dynamics but will also enable us to develop informed and effective policies. A thorough understanding of carbon storage at different stages of the rubber tree life cycle is essential. Methods such as the combined use of specific allometric models and advanced technological tools such as LiDAR or remote sensing should be explored to provide a more accurate and contextual assessment [157]. In addition, it would be relevant to study the differential effects of crop varieties, agricultural practices, and local environmental conditions on total sequestration. It is necessary to study the long-term and short-term effects on carbon sequestration of rubber plantations using different agricultural practices, such as crop rotation, agroforestry, and organic versus chemical use. Testing these approaches could show how to optimize these systems so that they are not only economically viable but also ecologically sustainable. Plantations need to be adapted to foreseeable climate changes that could affect their productivity and ability to sequester carbon [12].

Future research should focus on (i) genetic identification, i.e. exploring which varieties or hybrids are more resilient to abiotic stresses such as excessive heat or prolonged drought; (ii) climate

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modeling, attempting to develop predictive models that link climatic variations with their potential impacts on growth and therefore stored biomass; (iii) integrative policy, ensuring that any policy aimed at improving carbon sequestration is not only based on sound science, but is also designed to respond to local socio-economic realities. Studies should examine how to effectively integrate economic needs by balancing agricultural profitability with environmental objectives such as CO2 storage [1].

4. Conclusion

This study highlights the potential of rubber plantations as a complementary alternative to tropical forest conservation efforts, particularly in terms of carbon sequestration. Evidence from the literature suggests that these plantations can not only provide a sustainable source of income for local communities but can also contribute to the mitigation of greenhouse gas emissions if managed sustainably. However, the effectiveness of carbon sequestration in these systems is highly dependent on a variety of factors, including the forest management practices employed, the age of the plantations, the frequency and methods of harvesting, and the specific soil and climatic conditions. It is also important to recognize the challenges associated with rubber cultivation, such as biodiversity loss and soil degradation, which can result from poorly managed monocultures. Therefore, further research is crucial to better understand the mechanisms of carbon sequestration in rubber plantations and to optimize their management to maximize their positive impacts on climate and biodiversity.

In this regard, future research should prioritize the development of integrated agroforestry practices that combine rubber cultivation with local species conservation and ecosystem regeneration. These approaches must also support the livelihoods of local communities while preserving the environment. In addition, it is imperative to conduct in-depth studies on the most diverse and reliable models to accurately determine the rate of carbon sequestration in rubber-growing ecosystems. These efforts will help optimize plantation management and maximize their role in combating climate change. A systems approach is essential to ensure that these dense tropical forest-like ecosystems can make a sustainable contribution to today's environmental challenges. In this way, in addition to their direct interest in latex production, rubber plantations could play a key role not only in combating climate change, but also in conserving biodiversity and improving the livelihoods of the people who depend on them.

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