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Review

Carbon Sequestration Potential in Rubber Plantations: A Complementary Approach to Tropical Forest Conservation Strategies, a Review

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Abstract: The adverse effects of climate change, which are associated with the rise in greenhouse gases, impact all nations worldwide. In this context, tropical forests play a critical role in carbon sequestration. However, the significant anthropogenic pressure on these forests contributes to accelerated deforestation and a decrease in their capacity to regulate the climate. This study uses a comprehensive review of 176 published scientific articles and reports to assess the carbon sequestration capacity of rubber plantations, comparing their effectiveness with that of natural tropical forests. The findings are largely consistent and indicate that agricultural systems, such as rubber plantations, which were not traditionally associated with carbon sequestration, play a significant role in this area. Rubber plantations present a complementary alternative to the rapid deforestation of tropical forests, with the capacity to sequester substantial amounts of carbon. The range of carbon storage potential for rubber plantations, spanning from 30 to over 100 tons per hectare, rivals that of natural tropical forests, which can store over 300 tons per hectare. Furthermore, rubber plantations are notable for their indirect carbon sequestration potential. By providing a sustainable source of latex and wood, and thus income, they can reduce the pressure on natural tropical forests. However, challenges remain, particularly concerning sustainable management and the integration of rubber plantations into sustainable tropical forest management strategies. This analysis focuses on the opportunities and challenges of rubber plantations as an offset solution for carbon sequestration. It highlights the prospects for effectively integrating these plantations into sustainable tropical forest management policies.

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

1. Introduction

1.1. Context and Justification of Study

Climate change is regarded as one of our era's most significant environmental challenges, with substantial ramifications for ecosystems and human societies [1]. Carbon sequestration, the process by which carbon dioxide (CO_2) is absorbed and stored in plant biomass and soil, is emerging as a pivotal strategy for mitigating these effects [1]. The release of greenhouse gases, primarily from the combustion of fossil fuels, is responsible for the escalating global temperatures, which exert adverse effects on natural systems and human societies [1–3]. The IPCC underscores the pivotal role of forests in carbon sequestration, as outlined in its Sixth Assessment Report (AR6) published in 2022. This report estimates that forests globally store approximately 289 gigatons of carbon annually [1].

Tropical forests are renowned for their exceptional capacity to store carbon; however, they are facing face increasing pressure from deforestation, land-use change, and economic development [4,5]. These anthropogenic activities release carbon into the atmosphere, contributing to climate change [6,7]. Deforestation and forest degradation contribute significantly to greenhouse gas emissions, accounting for around 10–15% of global emissions [8,9]. 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 [10]. This decline represents a shift from 31.6% of the world's land area in 1990 to 30.8% in 2020 [5]. Concurrently, the total area of tropical forests has diminished by 150 million hectares, constituting approximately 12% of the total tropical forest area at that time [10].

The cultivation of industrial rubber plantations has garnered mounting interest, primarily due to their capacity to sequester carbon, stimulate local economic growth, and enhance biodiversity [11,12]. These plantations, cultivated on a substantial scale for rubber production, assume a pivotal role in the absorption of carbon dioxide. They are distinguished by their unique structural characteristics and management methodologies [13–16]. Presently, these plantations encompass an area of over 13 million hectares, with ongoing expansion driven by the escalating demand for latex [13,17–21].

Rubber plantations offer ecological advantages over monoculture systems, such as maize or rice, which are often associated with significant biodiversity loss and soil degradation [22,23]. These intensive farming practices not only release carbon but also reduce soil organic matter [24]. Despite the common perception of rubber plantations as monocultures, they present a valuable opportunity to integrate agroforestry practices and intercropping, enhancing carbon sequestration and improving soil health. In contrast to monocultures, which hinder biodiversity, these integrated practices can promote ecological diversity [25]. However, when evaluated against tropical forests, rubber plantations demonstrate a comparatively lower carbon sequestration capacity. This discrepancy can be attributed to ecosystems' intricate and resilient nature, which ensures sustainable carbon storage [26]. The capacity of these forests to achieve higher levels of sequestration is attributable to their high species diversity and structure, which optimize carbon uptake [27]. Furthermore, tropical forests can adapt to climate change, thereby ensuring their resilience in the long term [28]. In contrast, rubber plantations remain highly dependent on human intervention to maintain their productivity and carbon storage capacity [29–31].

In many tropical countries, rubber plantations play a significant role in providing wood products, thereby reducing pressure on natural forests and helping preserve them from overexploitation [32]. Additionally, these plantations often serve as habitats for spontaneous plant biodiversity, including native species colonizing interstitial spaces [11,12]. Despite their lower diversity compared to natural forests, these plantations can offer numerous ecosystem services, including firewood collection, traditional pharmacopeia, soil fertility improvement, water retention, and protection against erosion [11]. This reinforces the ecological value of rubber plantations, highlighting their multifaceted role in economic and environmental dynamics [30].

Rubber plantations are frequently managed to protect livestock, limit erosion, and provide various Non-Timber Forest Products (NTFPs) [33]. Recently, their potential as carbon sinks has been highlighted as a means to mitigate the effects of greenhouse gas-induced climate change [13,17,34]. These plantations play an essential economic role, supporting the livelihoods of around 40 million people worldwide [17]. Natural rubber is a strategic material used in over 5000 products, ranging from tires to medical equipment and building materials [17]. Rubber leaves are also used as fodder, while the seeds are incorporated into poultry feed. In addition, rubber plantations contribute to the sequestration of a significant amount of carbon through the production of latex [35].

Most studies on rubber plantations concentrate on their deleterious impacts, such as deforestation and conversion of natural tropical forests. This bias precludes a comprehensive evaluation of their potential benefits. To objectively appraise their role in carbon sequestration and climate change mitigation, it is imperative to undertake in-depth research on their ecological and climatic contributions. This research should encompass carbon storage dynamics, biodiversity, and sustainable management practices. This study aims to assess the carbon sequestration potential of rubber plantations and their complementary role in tropical forest conservation strategies to combat climate change. It is based on the central assumption that rubber plantations when managed sustainably and optimally, can play a significant role in CO_2 sequestration. However, the efficacy of this process is contingent on the management practices employed as well as on the prevailing ecological characteristics of the locale, including soil type, climate, and surrounding biodiversity.

This study employs a methodological approach predicated on an exhaustive literature review. It synthesizes current knowledge and proposes recommendations for integrating rubber plantations into sustainable land management policies. The study utilizes a comparative approach to carbon stocks between rubber plantations and tropical forests, incorporating key parameters. The assessment considers plantation age, tree density, silvicultural management practices, and environmental conditions. These factors are systematically analyzed to quantify carbon sequestration potential and identify optimal conditions for maximizing this ecological function.

1.2. Objectives of the Study

The objective of this study is to evaluate the capacity of rubber plantations in tropical regions to sequester carbon. In addition, the study will analyze how this approach could complement and reinforce tropical forest conservation strategies, contributing to reducing greenhouse gas emissions and preserving biodiversity. The specific objectives of this study are as follows:

- Quantify the CO_2 sequestration potential of rubber plantations compared to tropical forests and other plantations;
- Evaluate the factors influencing this potential, including silvicultural management, climate, and soil;

- Examine the ecological and socio-economic implications of integrating rubber plantations into conservation strategies.

2. Methodology of the Literature Review

2.1. Methodological Approach

The methodological approach (Figure 1) employed is predicated on a thorough evaluation of extant studies concerning the carbon sequestration potential of rubber plantations in comparison with other non-traditional tropical plantations and tropical forests. A systematic analysis incorporated various factors such as ecological structure, species diversity, tree density, soil and climatic conditions, and sequestration measurement methods. This analysis encompassed simulation models, direct and indirect sequestration measurements, and the utilization of remote sensing. To ensure the relevance and completeness of the data collected, we consulted various databases (Web of Science, Scopus, Google Scholar, ScienceDirect, and SpringerLink). We used targeted keywords such as "rubber", "tropical plantations", "agroforestry systems", "carbon sequestration", and "climate change". The inclusion criteria were established with two fundamental principles: scientific relevance and methodological quality. In addition, the criteria included the requirement of publication in peer-reviewed journals. Conversely, studies that did not meet these methodological requirements, notably those based on hypotheses that had not been empirically validated, were excluded (relevant references). A body of research has been published over the past two decades and has been used to update our knowledge. To refine the results, search operators such as union (OR) and intersection (AND) were used to combine and refine terms, resulting in a precise selection of articles.

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

The evaluation of each source was conducted with meticulous scrutiny, encompassing a comprehensive evaluation of its methodology, sample size, and the robustness of its conclusions. The focus of this evaluation was directed toward experimental studies, meta-analyses, and systematic reviews. To mitigate the potential for interpretation bias, non-English publications were meticulously translated. The analysis encompassed 176 scientific articles and reports, ensuring comprehensive coverage and a robust methodological approach.

2.2. Overview of the Study Logic

The logical structure of the study is illustrated in Figure 2 below.

As illustrated in Figure 2, the study's logic is outlined, demonstrating the potential of rubber plantations as a complementary strategy to tropical forest conservation initiatives. The figure emphasizes the logical progression of the argument, tracing its trajectory from the issue of deforestation to the recommendations for sustainable management. This structured presentation enables the reader to swiftly comprehend the scientific approach and the study's primary outcomes.

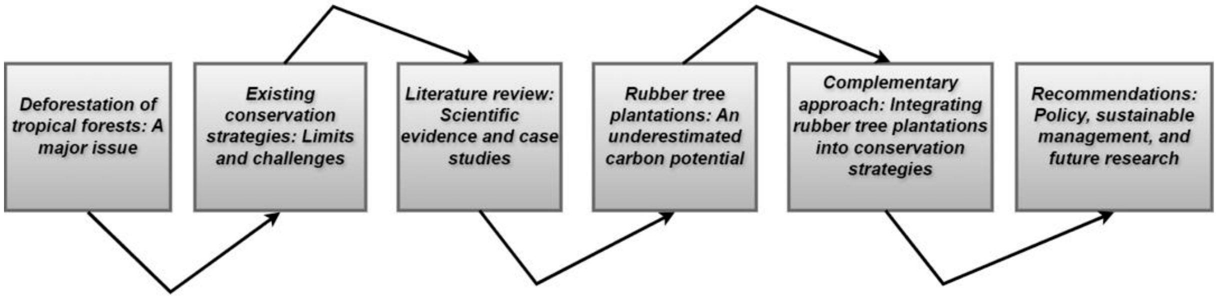

Figure 2. The following diagram illustrates the logical structure of the study.

2.3. Review of the Literature and Conceptual Framework of the Study

2.3.1. Carbon Sequestration in Rubber Plantations

This study employs the term "carbon sequestration" to denote the process by which CO_2 is captured and stored in plant biomass and soil, thereby contributing to climate change mitigation. This mechanism is based on the absorption of CO_2 by plant photosynthesis and its subsequent storage in above-ground (e.g., trunks, branches, leaves) and below-ground (e.g., roots and soil organic matter) biomass [12,18]. A tropical plantation is an agricultural ecosystem located in tropical regions where perennial crops such as rubber, cocoa, and oil palm are cultivated on a large scale for industrial use [36]. Heveaculture refers to the cultivation of the rubber tree (*Hevea brasiliensis*), a tropical tree mainly grown for the production of latex, which is used to manufacture natural rubber.

2.3.2. Biological Mechanisms of Carbon Fixation in Biomass and Soil

Figure 3 below illustrates the carbon sequestration mechanism in rubber plantations, highlighting the key processes involved, from CO_2 uptake to storage in biomass and soil.

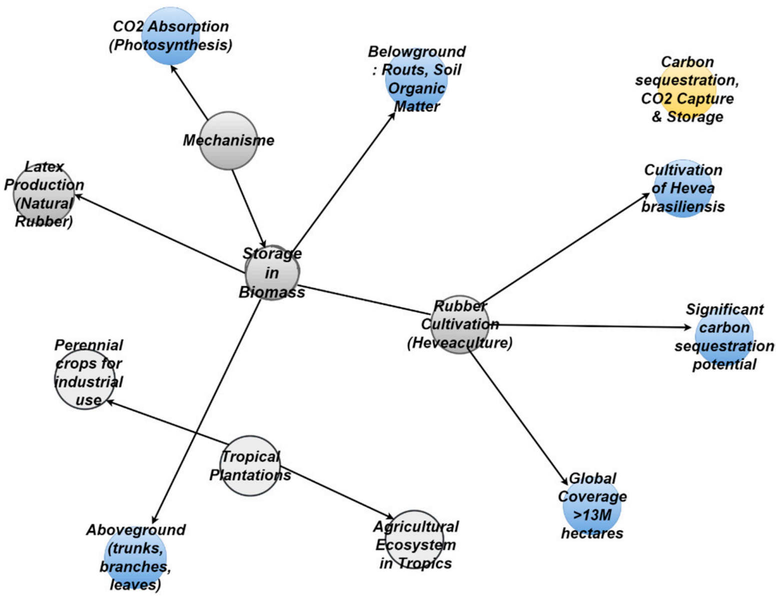

Figure 3. Carbon sequestration mechanisms in rubber plantations.

In the context of rubber plantations, the process of CO_2 absorption is initiated by trees, plants, and crops through the process of photosynthesis, which subsequently stores this gas as carbon within the biomass of various plant components, including trunks, branches, foliage, roots, and soils [37]. The process of photosynthesis, which involves the capture of

CO_2 from the atmosphere using sunlight, is the initial step in this process. Within the cells of leaves, known as chloroplasts, the CO_2 is converted into a form of chemical energy known as glucose while concurrently releasing oxygen. This stage is predominantly active during daylight hours and can be influenced by seasons, environment, and climate [27]. The fixed carbon is then incorporated into various plant tissues (e.g., leaves, stems, and roots), where it becomes part of the plant's biomass. This carbon remains stored in the biomass until the plant dies. This storage can range from a few years to several decades, depending on the type of vegetation [38,39]. Carbon is transferred to older or decomposing parts as vegetation grows, contributing to long-term storage [27]. Upon the demise of plants, the carbon contained within their biomass is released into the soil through decomposition. During this process, microorganisms, and decomposers (e.g., fungi and bacteria) transform organic matter into humus [40,41].

This continuous process can take from a few months to several years, depending on pedoclimatic conditions (temperature, humidity, and soil type). Once decomposed, certain elements combine with soil particles to form organic complexes. These complexes contribute to the long-term storage of carbon in the soil. This carbon can remain in the soil for centuries, even millennia [42].

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. Humus formation results from decomposition and transformation processes that can last for decades [43]. Soil organic carbon can interact with minerals, forming stable complexes that slow its decomposition and increase its permanence in the soil [44]. 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, the decomposition process, and natural and human disturbance of the soil [45]. Photosynthesis and biomass storage are rapid processes (days to years), while soil storage and humus formation are slower processes (months to centuries) [46]. The duration of storage is further influenced by many factors, including climate, soil type, crop type, vegetation cover, land management practices, ecosystem composition, and environmental disturbances, such as climate change [13,17,47].

Several studies have been conducted that demonstrate the beneficial effects of agricultural practices on carbon sequestration. These studies provide substantial evidence of these practices' efficacy in various environmental settings. For instance, crop rotation, which involves cultivating diverse crop species, has been shown to enhance soil health and fertility, reduce erosion, and promote microbial biodiversity [18]. These practices contribute to the decomposition of organic matter, thereby increasing carbon storage capacity [47].

3. Results and Discussion

3.1. Measuring Carbon Sequestration in Rubber Plantations

The estimation of carbon sequestration in rubber plantations is typically conducted using above-ground biomass under the assumption that 50% of this biomass consists of carbon [48]. The calculation of biomass is performed by integrating harvested and standing biomass, as the measurement of above-ground biomass is often more straightforward than that of below-ground biomass [30]. The conventional approach (direct measurements) to estimating biomass in tropical ecosystems involves the harvesting of entire trees, followed by the separation of their various components (stem, leaves, roots, etc.) and subsequent determination of dry weight [27,38,49]. The collected data are then utilized to develop allometric equations, employing variables such as diameter at breast height (dhp) and total tree height [27]. While this method is accurate, it is also very laborious, especially for large trees. Consequently, it is often used to validate less invasive methods (indirect measurements) [38,49,50].

Accurately assessing carbon storage in rubber plantations frequently necessitates the utilization of established allometric models that link diameter at breast height (dbh), height, and wood density [30]. These models facilitate rapid estimation and the standardization required for comparative studies between disparate tropical sites or systems [27,30]. However, many existing models do not always consider species-specific variability or local conditions, which can lead to significant under- or over-estimation of actual storage within these plantations [30]. In addition, a literature review reveals considerable variability in parameter values and allometric equations for rubber plantations (Table 1). This uncertainty stems from bioclimatic variability, the effects of clone type, plantation management, tapping methods, and measurement methods [51].

Table 1. 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 Length (Years)	Tree Density per ha	Location	References
51.2 [a]	Above- and below-ground biomass	1–35	469	Brazil, Mato Crosso	Wauters et al. [40]
63.7 [a]	Above- and below-ground biomass	1–25	419	Thailand	Pestri et al. [52]
42.4 [b]	Above- and below-ground biomass	1–25	No data	China, Xishuangbanna	Tang et al. [53]
45.3 [b]	Above- and below-ground biomass	1–30	375	China, Hainan	Cheng et al. [54]
40.4 [a]	Above- and below-ground biomass	1–30	Variable	Sri Lanka, wet zone	Munasinghe et al. [55]
43.2 [a]	Above- and below-ground biomass	1–30	Variable	Sri Lanka, intermediate zone	Munasinghe et al. [55]
65.1 [a]	Above- and below-ground biomass	1–38	450	China, Xishuangbanna	Yang et al. [56]
41.7 [b]	Above- and below-ground biomass	1–20	500–680	Thailand, Nong Khai	Saengruksawong et al. [57]
42.0 [c]	Above- and below-ground biomass	1–20	500	Indonesia, Sumatra	Sone et al. [58]
38.2 [b]	Above-ground biomass	1–30	No data	Indonesia	Lusiana [59]
46.2 [b]	Above-ground biomass	1–30	Jungle rubber	Indonesia	Palm et al. [60]
23.0 [b]	Above- and below-ground biomass	1–15	500	Brazil, Parana	Maggioto et al. [61]
52.7	Soil, 0–60 cm depth	14	433	Ghana	Wauters et al. [40]
105.6	Soil, 0–60 cm depth	14	469	Brazil, Mato Grosso	Wauters et al. [40]
79.3	Soil, 0–60 cm depth	15	460	Brazil, Parana	Maggioto et al. [61]
72.0 [d]	Soil, 0–40 cm depth	15	375	China, Hainan	Cheng et al. [54]
147.2	Soil, 0–100 cm depth	19	450	China, Xishuangbanna	Yang et al. [56]

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. [40] and Pestri et al. [52]; [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. [54] 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.

Numerous researchers have employed the allometric relationship to estimate plant biomass in plantations of varying ages, with measurements of breast height (dbh) serving as the primary data source. This approach has led to the development of empirical equations that facilitate calculating plant biomass dynamics over time and space [40,52,53]. Carbon stocks in rubber biomass increase over time, attributable to the development of tree seedlings until a plantation is harvested [12]. The complete life cycle of a rubber plantation is approximately 25 to 35 years, contingent on tree growth conditions and harvesting patterns [54,62]. The analysis indicates that the primary component changing is the above-ground biomass of the trees. To account for the temporal variation of this carbon stock in a rubber plantation, it is imperative to estimate what is known as the time-averaged carbon stock (TAC) [63]. Estimating these variables allows for the calculation of the average carbon stock throughout the rotation cycle, from the establishment of rubber plantations to timber harvesting. This provides an integrated assessment of their contribution to carbon sequestration [30,64]. The spatial and temporal scale is essential for comparing these long-term dynamics and sustainable plantation management strategies in the context of combating climate change.

To facilitate long-term comparisons, it is necessary to expand the scale of measurement from the plot level of plantations of different ages to the landscape and regional level [30]. The most straightforward method for calculating total above-ground carbon (TAC) stocks is to divide the maximum carbon stock (at the time of clearing) by 2, under the assumption of a linear increase in biomass [63]. When more detailed data are available, such as carbon stocks in plantations of varying ages, a regression equation can be derived to calculate the increase in biomass over time [30]. In such cases, the TAC is equivalent to the stock value calculated by the equation adjusted to the midpoint of the rotation cycle [30]. The TAC values presented in Table 1 were calculated using two types of equations: either linear or sigmoid functions, depending on data availability and best-fitting results or directly using expressions derived by the authors in their publications [52]. A comparison of several developed allometric equations is also important, as these equations differ mainly according to tree species and geographical region [27]. Since 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 [65]. Measuring carbon sequestration in rubber plantations is complex and requires adapted allometric equations and accurate inventory data [65]. The paucity of information regarding allometric variations specific to rubber plantations in Africa underscores the necessity to develop customized allometric equations based on local data for an accurate assessment of the sequestration potential of these plantations [30].

Recent studies have underscored the necessity of incorporating species-specific data and local conditions of plantations. For instance, Ren et al. [66] demonstrated that the management of the underlying vegetation substantially influences soil carbon and nitrogen storage in rubber plantations, underscoring the need for management practices adapted to local contexts. Furthermore, Ma et al. [67] conducted a comprehensive review of methodologies employed for assessing carbon sinks in rubber plantations, underscoring the intricacies inherent in distinguishing the dynamics of carbon sources and sequestration and emphasizing the necessity of employing precise monitoring technologies tailored to specific conditions. Furthermore, a study by Lan et al. [68] revealed that the complexity of the soil bacterial network in rubber plantations is lower than in tropical forests. This suggests that microbial community structures vary considerably between these ecosystems and may influence carbon cycling processes. Finally, research by Sun et al. [69] has indicated that the conversion of tropical forests to rubber plantations results in significant negative impacts on soil quality, such as accelerated acidification and reduced soil fertility, reinforcing the need to integrate species- and site-specific considerations into plantation management.

The necessity for developing specific allometric equations is evident, given the need to account for each geographical zone's ecological and climatic particularities. The adaptation of these equations to specific regions will provide more precise and relevant estimates of sequestered carbon, thereby encouraging optimal management of rubber plantations and strengthening their role in the fight against climate change.

3.2. Comparing Sequestration Rates in Rubber Plantations, Agroforestry Systems, Secondary Forests, and Pastures

A comparison of the carbon sequestration rates in rubber plantations, agroforestry systems, secondary forests, and pastures is imperative to comprehend the impact of these disparate land management systems on climate change mitigation. Each of these systems contributes a unique aspect to the carbon capture and storage process, contingent upon their specific management, ecological composition, and the environmental conditions under which they operate. This comparative analysis offers prospects for optimizing carbon sequestration strategies, particularly in tropical regions where these systems are common. For example, some studies highlight that rubber plantations store carbon over the years thanks to their biomass and extended rotation duration [12,53,70]. They also offer significant potential for additional soil storage and indirect carbon preservation through sustainable, integrated management [12]. These factors underscore the significance of rubber plantations as a promising alternative for enhancing sequestration efforts in tropical regions while concurrently addressing the economic and social imperatives of the regions where they are cultivated [17,32]. It is imperative to acknowledge that each system type possesses unique carbon sequestration characteristics, accompanied by distinct advantages and disadvantages. These considerations must be meticulously evaluated when formulating sustainable management strategies, as delineated in Table 2.

Table 2. Comparison of sequestration rates in agroforestry systems, secondary forests, and pastures.

Type of Systems	Rate of Carbone Sequestered tCO_2/ha/year	Advantages	Disadvantages	References
Agroforestry systems	5–20	Biological diversity Improvement of soil fertility	Competition between crops	[71,72]
Secondary forests	10–50	Biological diversity Vegetation restoration Biodiversity Ecosystem services	Dépendance on environmental conditions Vulnerability to fire	[73,74]
Rubber plantations	5–30	Vegetation restoration Air retention Biodiversity enhancement	Dependance on humain intervention	[75,76]
Abandoned pastures	2–10	Restoration of vegetation Air retention Biodiversity enhancement	Risk of invasion	[77,78]

As demonstrated in Table 2, the agroforestry system is notable for its high productivity level, though it requires meticulous management. In contrast, the secondary forest is a natural asset susceptible to various forms of vulnerability. Abandoned pastureland, while presenting an opportunity for regeneration, is confronted with challenges associated with the infestation of non-native species. Perennial plantations, whether in agroforestry, monoculture, or grazing systems, are pivotal in sequestering carbon dioxide from the atmosphere during their growth, storing it in the biomass (e.g., trees, roots) and the soil [79]. This process contributes substantially to climate change mitigation by reducing the concentration of greenhouse gases [23]. By stabilizing the soil with their roots, plants mitigate erosion caused by heavy rainfall and runoff [79]. Agroforestry systems have been shown to promote biodiversity, thereby enhancing the resilience of ecosystems to climatic stress [80]. This biodiversity is also crucial for maintaining vital ecosystem services, such as pollination and the regulation of water cycles [81].

In addition, tropical plantations serve as a source of income for local communities, providing resources such as timber, fruit, and other non-timber products [11,82]. This contributes to the diversification of local incomes and the mitigation of economic vulnerability in the face of climate change. Furthermore, non-traditional plantations contribute to regulating the water cycle by facilitating the infiltration and retention of water in the soil, a process vital for ensuring an adequate supply of drinking water and for agriculture, particularly in drought-prone regions [81]. Consequently, non-traditional plantations are multifunctional in carbon sequestration and climate change adaptation, enhancing ecosystem resilience and supporting local communities [83]. However, a comprehensive understanding of monoculture, plantation, and agroforestry systems is imperative for the analysis of studies and quantitative data on carbon sequestration in rubber plantations [12,32].

Monoculture systems are defined as cultivating a single plant species across extensive areas over an extended period. However, this practice can result in a decline in biodiversity and an increased susceptibility of ecosystems to diseases and pests [84]. In contrast, forest plantations constitute man-made forests, typically comprising species selected for their rapid growth or economic value [23]. Conversely, while rubber plantations are regarded as monocultures with minimal ecological ramifications, recent research, and methodologies have emerged that promise to enhance their capacity to sequester carbon while concomitantly fostering biodiversity and augmenting other ecosystem services [11].

3.3. Comparing Sequestration Rates in Rubber Plantations and Tropical Perennial Plantations

A substantial body of literature exists on carbon sequestration in forest plantations, agroforestry, and natural forests. However, the literature on monoculture tree plantation systems remains limited. A few studies have been conducted, predominantly in Latin America, Southeast Asia, and East Asia, on the carbon content of oil palm [62,85–87] and rubber plantations [30,54]. In Africa, the research on monoculture tree crop systems is limited, with only a few studies conducted on rubber [40] and cocoa [88] in agroforestry. Some authors have noted that the integration of trees and food crops not only optimizes resource use but also enhances system resilience in the face of change. However, they have called for further research to understand better the behavior of these systems in various African contexts [89,90].

The sequestration values of various plantations are known to vary considerably, contingent on the species of vegetation cultivated, the management of the plantation, and the age of the trees [89]. Studies have shown that plantations of fast-growing species, such as eucalyptus or teak, can sequester between 10 and 30 tons of carbon per hectare each year. [25]. Furthermore, the presence of diverse flora within plantations has been demonstrated to enhance not only ecological resilience but also the potential for carbon storage. Research has demonstrated that increased diversity can significantly increase carbon sequestration in soil and above-ground biomass [91]. The study conducted by

Lan et al. [12] on Hainan Island in China demonstrated that rubber plantations with close-to-natural management, also known as "rubber forests", can harbor a floristic diversity and carbon sequestration potential comparable to that of forests. Another critical factor is the interaction between these agricultural and forestry systems and their environment [89]. Integrating food or feed crops with trees by agroforestry practices can further increase carbon sequestration while improving food security [23].

Indeed, mixed systems have been demonstrated to facilitate enhanced utilization of natural resources while ensuring the preservation of biodiversity [11,12]. However, a comprehensive evaluation of these systems is imperative, encompassing their immediate potential and long-term sustainability. It is imperative to acknowledge that substantial deforestation can nullify the advantages derived from afforestation initiatives [42]. It is imperative to explore integrating these practices within a comprehensive framework of sustainable land use, thereby averting the competition between food production and carbon sequestration.

Table 3 presents a series of case studies that explore the potential for carbon sequestration in rubber plantations and tropical perennial plantations.

Table 3. Some case studies of carbon sequestration in total dry weight in rubber plantations and tropical perennial plantations.

Type	Age (Years)	Area (tC/ha)	Location	Source
Rubber	Mature plantation	275.1	Brazil	Shorrocks [81]
Rubber	20	257.95	Philippines	Onofore et al. [92]
Rubber	35	246.23	Philippines	
Agroforestry system	-	195	Dioïla/Mali	Siriki et al. [93]
Rubber	Mature plantation	198.4	Ngobo, Indonesia	Yuda & Danoedoro [94]
Rubber	15	146.30	Parana State/Brazil	Maggiotto et al. [61]
Rubber	34	169.22	Brazil	Cotta et al. [95]
Rubber	40	186.65	China	Nizami et al. [62]
Rubber	8–20	156	Colombia	Orjuela et al. [96]
Agroforest/rubber	8–20	159	Colombia	
Rubber	-	214	Ghana	Kongasager & Mertz [97]
Cocoa	-	65	Ghana	
Orange	-	76	Ghana	
Oil palm	-	45	Ghana	
Oil palm	Mature plantation	173.81	Yangambi/DRC	Bustillo et al. [98]
Rubber	Mature plantation	337.33	Yangambi/DRC	

An analysis of Table 3 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, a notable distinction from other tropical industrial crops such as cocoa (65 tC/ha), orange (76 tC/ha), oil palm (45 tC/ha), and agroforestry systems (195 tC/ha). However, the sequestration potential of rubber plantations is contingent on factors such as rotation length, age, tree density, management practices (e.g., sustainable tapping), and soil and climate conditions. Studies referenced by the IPCC suggest that enhancing farmland management could result in a global reduction of approximately 0.4 to 1 gigaton of CO_2 per year by 2030 [8]. The rotation period of rubber plantations, for instance, 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 their capacity for carbon sequestration [99].

Furthermore, optimal tree density fosters competition for resources such as water, nutrients, and light, thereby stimulating tree growth and enhancing their capacity to sequester carbon [54]. Conversely, intensive management practices, including fertilization and irrigation, are likely to promote tree growth, consequently increasing total carbon sequestration and soil carbon [100]. Conversely, extensive management practices may not fully maximize this potential [101]. Furthermore, diversified systems, such as those implemented in agroforestry practices, can enhance resilience to environmental stresses, facilitating more efficient carbon sequestration [102]. 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 biases and inconsistencies in results. For instance, certain studies may rely on point measurements that fail to capture the temporal and spatial variability of carbon stocks [103]. Additionally, the dearth of specific research in Africa, where rubber plantations hold strategic importance in local economies and natural resource management, is a matter of concern.

This dearth of data represents a substantial impediment to the comprehension of carbon sequestration mechanisms in tropical environments, thereby compromising the capacity to accurately assess their long-term potential. It is, therefore, imperative to establish in-depth longitudinal studies in these ecosystems, which remain inadequately documented, with the objective of rigorously quantifying carbon fluxes and identifying the biophysical and anthropogenic factors influencing their dynamics [13,17]. A more profound comprehension of these processes will facilitate the contextualization of current results with greater precision and enable the development of strategies for mitigating climate change and optimizing the management of forest ecosystems in a more effective and sustainable manner.

3.4. Comparative Analysis of Rubber Plantations and Tropical Forests

Tropical forests are the most efficient terrestrial ecosystems for carbon sequestration when compared with rubber plantations (Table 4). This disparity can be explained by differences in ecosystem structure, floristic composition, and tree growth dynamics [38,49]. Tropical forests are distinguished by their high species diversity and complex, multi-layered structure, which provides a variety of carbon sinks, including trees of different sizes and ages, dense undergrowth, litter, and soils rich in organic matter [38,76]. This favors high carbon sequestration [7]. In contrast, rubber plantations, often monocultures, have a simplified floristic composition and a homogeneous structure [92,97,104]. The sequestration of carbon is predominantly concentrated within the rubber trees themselves, with a comparatively lesser contribution from the undergrowth and soils [30,83,97]. Notwithstanding the capacity of rubber plantations to store substantial quantities of carbon [98], their potential is, as a general rule, lower than that of tropical forests due to the low diversity and simplified structure of these ecosystems [30].

Indeed, these forests play a crucial role in climate regulation and mitigation [45,105–107]. They are capable of sequestering up to 30% of global anthropogenic CO_2 emissions and account for around 59% of global carbon stocks [108]. 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 [76,107,109–111]. Significant spatial variation in biomass is observed within tropical forests, particularly among the three tropical forest basins, with higher values recorded in tropical Africa and Asia, at 418 ± 91 and 393 ± 109 Mg·ha^{-1}, respectively, compared to South American forests, at 287 ± 105 Mg·ha^{-1} [112]. These variations can be attributed to the higher frequency of trees with a diameter greater than 70 cm in tropical forests of the Paleotropical region, which encompasses Africa and Asia. Significant spatial variations in biomass are also observed within the African continent. Lewis et al. [113] report biomass estimates for Central Africa (429 Mg·ha^{-1}) that are significantly higher than those for West Africa (305 Mg·ha^{-1}) and East Africa (274 Mg·ha^{-1}). These disparities in biomass can be attributed to the prevalence of hyper-dominant species in Central Africa, which contribute over 50% of biomass stocks [114].

On a local scale, several authors have demonstrated significant variations in biomass between different African tropical forest types. Day et al. [115] report variations in above-ground biomass between different types of dense rainforest in Central Africa, and Kuyah et al. [116] report variations between Miombo forest types in East Africa. These variations are essentially explained by structural differences linked to anthropogenic disturbances and/or edaphic and altitudinal gradients. However, the variation in biomass across African tropical forests is predominantly explained by floristic composition and structural variables, such as basal area and height–diameter allometry [117,118]. Conversely, spatial variations in biomass can be attributed to the distinct specific compositions of forest types [49,114,117–122]. Mature forests where *Gilbertiodendron dewevrei* (Fabaceae—Caesalpinioideae) forms mono-dominant stands store as much or more above-ground biomass than younger mixed forests in Cameroon [122] and the DRC [113,123].

According to Maniatis et al. [124], forests dominated by trees from the Olacaceae, Caesalpiniaceae, and Burseraceae families exhibit significantly higher above-ground biomass than forests dominated by the Burseraceae, Myristicaceae, and Euphorbiaceae families. Fayolle et al. [125] 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 predominant factor contributing to spatial variations in above-ground biomass [126]. The interaction between floristic composition, forest structure, and environmental factors (soils) has been identified as a contributing factor to the variation in above-ground biomass observed between mature Central African forests on rich soils or poor soils and those on soils with physical constraints [114,127]. Additional environmental factors have been posited as potential influencers of the spatial distribution of biomass. Miombo-type forests at mid-altitude have been found to store greater biomass compared to those at low and high altitudes [117,118].

The prevailing interest in tropical forests is therefore fully justified, as these ecosystems have the greatest potential to store additional terrestrial carbon [106]. However, tropical deforestation is a significant source of greenhouse gas emissions [106,107]. These ecosystems are subject to rapid, widespread, and irreversible land-use change, particularly as a result of deforestation and anthropogenic degradation [36,128,129]. The net reduction in tropical forest area has been particularly marked over the decade 2010–2020, notably in Africa (with a loss of 3.9 million hectares) and South America (with a loss of 2.6 million hectares) [5]. In this context, perennial plantations, such as rubber plantations, offer a promising potential in terms of carbon storage as a sustainable alternative to the complementary efforts of tropical forests in areas heavily affected by deforestation or in the transition from an agricultural crop to a plantation in an integrated or agroforestry system.

Table 4. Comparative table of sequestration levels in different rubber plantations compared to tropical forests and plantation forests.

Type of Ecosystem	Carbon Stock Tons of Mg C/ha	References
Primary tropical forest	>300	OFAC [130]
Mature rubber plantation (Brasilia)	80–150	Lan et al. [12]
Young rubber plantation $\leq$ 10 years old (Sub-Saharan Africa)	30–50	Onoji et al. [131]
Mono-dominant forest (Ituri/DRC)	267.5	Makana et al. [123]
Mono-dominant forest (Yangambi/DRC)	165.5	Kearsley et al. [132]
Mixed forests (DRC)	160.5 to 199.5	Panzou et al. [49]
Young Forests (DRC)	202	Panzou et al. [49]
Plantation forest (Ethiopia)	223	Dick et al. [122]
Secondary forest (Congo-Brazzaville)	167	Ekoungoulou et al. [121]
Teak plantation (Panama)	3–41	Derwish et al. [133]
Mixed forest (Colombia)	122–141	Saatchi et al. [134]
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. [135]
Production forest (Indonesia)	46.32	Situmorang et al. [136]
Mixed forest (Cameroon)	318	Zapfack et al. [137]
Plantation forests (Ghana)	56–70	Brown et al. [138]
Community forests (Nepal)	301	Joshi et al. [139]
Agroforestry (Peru)	106	Aragon et al. [140]
Teak plantation (Thailand)	45–82	Chayaporn et al. [141]
All types of forests (Malaysia)	157.5	Raihan [142]
Peatland (Congo)	634	Crezee et al. [39]

An analysis of Table 4 indicates that, despite their inability to reproduce the complexity and biodiversity of dense tropical rainforests, rubber plantations can nevertheless contribute significantly to carbon sequestration by effectively increasing biomass productivity and soil nutrient accumulation [18]. However, the role of rubber plantations is nuanced and contingent on several factors, including the species planted, forest management practices, and the ecological context. In this context, a multifaceted approach that integrates the conservation of natural forests with the development of sustainable plantations is imperative to optimize the benefits for climate and biodiversity [143]. The integration of practices such as reforestation, assisted regeneration, and exotic species management has the potential to not only augment carbon storage but also enhance biodiversity and ecosystem resilience [144].

The significance of carbon sequestration in global initiatives to mitigate the impacts of climate change cannot be overstated. Rubber plantations have frequently been regarded as a contentious solution, occasionally perceived as a responsible alternative to deforestation, and at times criticized for their potential to diminish biodiversity. However, a comparative analysis reveals that rubber plantations can play a substantial role in carbon sequestration, thereby presenting themselves as a complementary option to tropical forest conservation efforts. According to Lan et al. [12], rubber plantations can sequester substantial amounts of carbon, comparable to those observed in some natural forests that are managed sustainably. The biomass of rubber trees has been documented to reach up to 160 tons per hectare after 25 years of rotation [12], making them a significant component in regions where deforestation has led to a substantial loss of forest cover.

In this respect, it is interesting to note that some researchers argue that, despite the immediate economic and ecological value these plantations offer local farmers through latex production [13], they do not completely replace the role of natural tropical forests in terms of biodiversity and ecosystems. Consequently, they must be integrated into a broader framework that also includes the active protection of existing forest ecosystems [32]. 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 income generated by these plantations can support rural communities and reduce their dependence on destructive activities such as shifting cultivation or illegal logging [19]. This underscores the urgent need to develop policies that integrate sustainable agriculture and conservation to ensure a viable future for local populations while protecting global biodiversity. However, it is imperative to acknowledge the inherent limitations associated with the extensive development of rubber plantation monocultures. The proliferation of these farming systems has the potential to result in ecological homogenization in areas that previously exhibited a high degree of biodiversity and natural ecosystem diversity [89]. To mitigate the potential adverse ecological consequences of these farming systems, it is imperative to implement rigorous environmental monitoring programs. Such monitoring is essential to prevent the long-term systematic degradation of soil quality and the substantial loss of local biological diversity [143].

This comparative analysis demonstrates that natural tropical forests continue to be unrivaled in their capacity to fulfill a multitude of ecological functions, including regulating hydrological cycles, maintaining biodiversity, and storing carbon over extended periods. This superior performance can be attributed to their intricate structure and biodiversity [38]. In contrast, rubber plantations, due to their monocultural nature and simplified structure, are unable to provide a similar level of ecosystem services [12]. However, rubber plantations have been shown to offer significant carbon sequestration potential, largely attributable to their perennial biomass, extended rotation duration, and contribution to soil carbon storage [145]. These findings underscore the role of rubber plantations as an intermediate solution, particularly in regions where deforestation or natural forest degradation severely compromises sequestration capacities [12]. Consequently, rubber plantations should not be regarded as a substitute for natural tropical 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 [13,17].

3.5. Impact of Management Practices on Carbon Sequestration in Rubber Plantations

3.5.1. Impact of Sustainable Intensification Techniques on Rubber Plantations

The application of sustainable intensification techniques has emerged as a solution for increasing the productivity of rubber plantations while reducing their ecological impact. These techniques include practices such as agroforestry, efficient management of water resources, and genetic improvement of rubber cultivars. A comprehensive analysis of the effect of these sustainable intensification practices on rubber plantations is essential to better understand their potential to reconcile productivity and environmental sustainability.

Research in sub-Saharan Africa has demonstrated that the implementation of enhanced management techniques, including conservation and mulching, has resulted in a 30–50% increase in soil organic carbon in rubber plantations [146]. Agroforestry practices, which integrate trees into farming systems, have been shown to enhance soil structure and water retention, thereby promoting both productivity and carbon storage [30,32,147]. A study by Singh et al. [89] demonstrated that rubber plantations in Southeast Asia, notably Indonesia and Malaysia, can sequester up to 30 tons of carbon per hectare per year, both in the biomass and in the soil. This suggests that rubber-based agroforestry systems enhance carbon sequestration while generating sustainable income for farmers. Additionally, annual crops such as maize and rice have been observed to exhibit high carbon sequestration rates over brief periods [23]. The rapid growth cycle of these crops contributes to their capacity to sequester a substantial amount of carbon during the growing season [23]. For instance, studies have demonstrated that specific intensive agricultural practices can result in increases in soil organic carbon of 5 to 10 tons per hectare per year [23,148].

Despite the lower annual sequestration of rubber plantations in comparison to certain fast-growing annual crops, their capacity to store carbon over an extended timeframe is influenced by numerous distinct factors [148]. Primarily, the prolonged rotation period of rubber trees, spanning up to 25 to 30 years before harvesting timber, facilitates a steady yet continuous accumulation of biomass in trunks, branches, and roots [67]. Secondly, the perennial structure of rubber trees facilitates continuous sequestration [12], a trait that distinguishes them from annual crops [23], which require frequent renewal and often disrupt soil, potentially leading to carbon emissions [12,89]. Furthermore, rubber plantations contribute to the sequestration of organic carbon in soils through the constant supply of litter comprising leaves, dead branches, and root exudates [149]. The process of rubber cultivation has been shown to enhance soil carbon stocks, particularly when coupled with effective soil management and conservation practices, such as reduced tillage or the incorporation of vegetation cover [90,91]. Furthermore, the sustained cultivation of rubber plantations has been demonstrated to mitigate land degradation, thereby contributing to the stabilization of the carbon already sequestered within the system [12].

Additionally, rubber plantations have been identified as a significant source of indirect sequestration potential [32,34]. By providing a sustainable source of latex and wood, they help to sequester carbon indirectly, reducing pressure on natural forests, which play a key role in global carbon sequestration [32]. However, to maximize their effectiveness as carbon sinks, it is essential to adopt sustainable management practices, such as optimizing planting density, integrating complementary species into an agroforestry system, and using resistant clones adapted to local conditions [12,70,150].

3.5.2. Comparison Between Conventional and Certified Rubber Plantations (FSC, Rainforest Alliance)

Certification of rubber plantations to standards such as those established by the Forest Stewardship Council (FSC) and the Rainforest Alliance (RA) has emerged as a pivotal mechanism for ensuring the environmental and social sustainability of production [151,152]. Rubber plantations that have obtained certification from the FSC and the Rainforest Alliance are obligated to adhere to criteria pertaining to the sustainable management of natural resources and the establishment of harmonious relations with local communities [152]. These certifications mandate adherence to stringent standards concerning forest management, protection of sensitive ecosystems, and respect for workers' rights. According to Kennedy et al. [152], FSC-certified plantations are obligated to reduce chemical use, minimize soil erosion, maintain primary forests, and preserve biodiversity and carbon sequestration while ensuring decent working conditions for employees. Conversely, conventional plantations, while capable of adopting certain sustainable practices, are not subject to such stringent constraints, potentially resulting in more intensive farming practices that exhibit a lesser degree of environmental and labor respect [151–155].

Certified plantations have been shown to promote practices that not only sequester carbon in the biomass but also augment the organic carbon content of soils, thereby reducing the overall carbon footprint of plantations. Conversely, conventional plantations, with their heavy reliance on the use of chemical fertilizers and intensive cultivation practices, tend to release more CO_2 into the atmosphere, increasing greenhouse gas emissions, particularly when soils are poorly managed [151,152]. This comparative analysis of two types of plantations (conventional and certified) demonstrates that certification, notably through labels such as FSC or Rainforest Alliance, can be an effective tool for promoting sustainable management of rubber plantations while contributing to carbon sequestration and sustainable latex production [152]. By optimizing both yields and environmental impact, this certification approach offers a mutually beneficial solution where latex production and climate protection are synergistic while contributing to the well-being of local populations [11].

3.6. Integrating Rubber Plantations into Conservation Strategies

3.6.1. Long-Term Stability of Carbon Stocks in Rubber Plantations

The long-term stability of rubber plantations as carbon sinks is contingent on a multitude of interconnected factors [143]. 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 [18]. Climate variability exerts a direct impact on the growth of rubber trees and, consequently, on their capacity to store carbon [12]. Changes in rainfall patterns, temperature extremes, and the increased occurrence of extreme weather events can affect tree development in these plantations [30]. A study by Hazir et al. [156] shows that significant variations in rainfall patterns can affect not only annual growth but also the physiological cycle of rubber trees. These authors point out that prolonged periods of drought can significantly reduce productivity, resulting in lower carbon sequestration [156]. Furthermore, elevated temperatures have been demonstrated to induce water stress in these plants, thereby reducing their photosynthetic capacity [157]. This, in turn, can result in a decline in overall carbon storage over time [158].

Furthermore, economic profitability has been identified as a pivotal factor in the long-term sustainability of carbon stocks within rubber plantations [159]. The dependency on markets for natural rubber has been demonstrated to exert a substantial influence on decisions regarding the maintenance or clearance of existing plantations [160,161]. During periods of elevated rubber prices, there is a potential for increased pressure to convert a greater proportion of forest land to rubber plantations [162]. Furthermore, the policies that govern 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 have adverse effects on climate change mitigation efforts [161]. In addition, epidemics caused by various bio-aggressors pose a significant threat to long-term sustainability. For instance, certain fungal diseases, such as *Chordomyia* spp., have been observed to rapidly devastate entire rubber plantations if not effectively managed [163]. The consequences of this phenomenon include a decline in production levels and the possible forfeiture of substantial carbon reserves [164]. The incorporation of biodiversity within these plantations through agroforestry practices has been demonstrated to serve as a mitigating factor against the deleterious effects associated with the presence of predators and pests. Nevertheless, the intensification of monocultural practices has rendered rubber plantations susceptible to a range of diseases [165].

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

Rubber plantations play an ambivalent role in the context of climate change (Figure 4). On the one hand, they offer significant opportunities for carbon sequestration and the provision of renewable resources, while on the other, they are exposed to environmental risks that could compromise their long-term benefits [161]. Because of their rapid growth, these plantations can act as complementary sinks for carbon dioxide when managed sustainably [12]. Natural rubber is emerging as an environmentally friendly product in an agroforestry system [70].

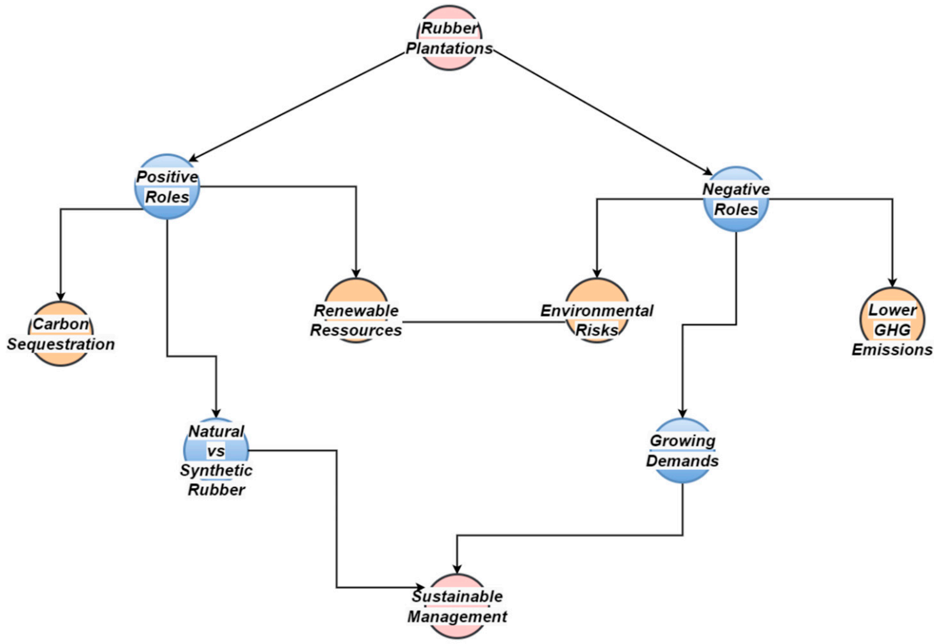

Figure 4. Ambivalent role of rubber plantations in climate change context.

Indeed, while the production of synthetic rubber requires between 108 and 174 GJ of energy per ton, the production of natural rubber requires only 13 GJ [166]. The substitution of synthetic rubber for natural rubber results in a reduction of 4.8 tons of carbon in the atmosphere per metric ton of natural rubber [167]. The carbon sequestered in the shoot biomass and in the rubber, itself adds up to approximately 1019.2 tons of CO_2 fixed per hectare in 33-year-old rubber plantations [166]. Additionally, greenhouse gas (GHG) emissions from rubber plantations can be lower than from other crops, particularly when land use and agricultural practices are considered [13]. For instance, when managed sustainably, rubber plantations can generate less than 0.5 tons of CO_2 equivalent per hectare per year in emissions associated with agricultural inputs and practices [168].

Conversely, intensive corn and soybean cultivation has been shown to generate emissions of 2 to 4 tons of CO_2 equivalent per hectare per year, primarily due to the use of chemical fertilizers and deforestation to expand farmland [169]. Furthermore, natural rubber remains indispensable for the manufacture of essential products such as condoms, surgical gloves, and aircraft tires [170]. The present moment is characterized by a discrepancy between global demand, particularly in Asia and China, and the supply of both synthetic and natural rubber [170]. Brazil, while historically recognized as the origin of rubber, contributes a mere 1.2% of global natural rubber production and 3.3% of synthetic rubber production [170]. In contrast, China's consumption of natural and synthetic rubber stands at 3.5% and 38%, respectively [170]. This analysis demonstrates that, within the broader context of the global effort to combat climate change, rubber plantations have the potential to play a significant role in mitigating climate impacts, provided that they are managed in a sustainable manner [12].

3.6.3. Toward an Integrated Approach: Landscape Mosaics and Ecological Corridors

Ecological corridors are defined as natural or restored vegetation zones that facilitate species mobility and dispersal by linking fragmented habitats. They are essential for maintaining genetic connectivity between plant and animal populations and ensuring their survival in fragmented landscapes [171,172]. In the context of rubber plantations, corridors can be used to connect different fragments of natural forest and other protected habitats [173]. For instance, in rubber plantations, the creation of corridors could facilitate the movement of forest species between residual forests, thereby ensuring the continuity of access to food resources and breeding sites [173,174]. Furthermore, ecological corridors have been shown to play a pivotal role in carbon storage, linking existing carbon sinks such as natural forests and mitigating the impact of ecological isolation [175].

This analysis demonstrates that rubber plantations, far from being simple monocultures, can play a crucial role as landscape mosaics and ecological corridors in transition zones between protected forests and human activities. Their structure, although less complex than that of primary tropical forests, offers a diversity of habitats for flora and fauna, contributing to ecological connectivity between fragments of natural forest. By acting as buffer zones, they reduce the direct pressure of human activities on protected forest ecosystems while enabling species dispersal and promoting natural regeneration. Furthermore, the incorporation of agroforestry practices within rubber plantations serves to reinforce their role as ecological corridors, thereby increasing species diversity and providing additional resources for local wildlife.

In this context, the integration of landscape mosaics and ecological corridors into rubber plantations can be regarded as a holistic approach to sustainable land management, wherein conservation and production objectives are reconciled. Mosaic-based landscape management that incorporates interconnected ecological corridors has the potential to mitigate the adverse impacts of rubber plantations while maximizing economic profitability [173]. For instance, Harich et al. [173] have demonstrated that the incorporation of ecological corridors into rubber plantations can enhance ecosystem resilience to the impacts of climate change while fostering local biodiversity.

The implementation of a combination of landscape mosaics and ecological corridors within rubber plantations has been demonstrated to be a viable strategy for achieving a balance between agricultural production, biodiversity conservation, and soil protection. This approach, when adopted, has the potential to play a pivotal role in combating deforestation, soil degradation, and biodiversity loss in tropical regions. Additionally, it has the capacity to sequester carbon and support local economies. It is, therefore, imperative that rubber plantations are managed in a sustainable manner, incorporating agroforestry practices that integrate natural elements into the landscape.

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

In order to optimize the capacity of rubber plantations to sequester carbon, it is essential to allocate resources to scientific research. This initiative will facilitate a more profound comprehension of the underlying ecological dynamics, thereby enabling the formulation of informed and effective policies. A comprehensive understanding of carbon storage at the various stages of the rubber tree life cycle is imperative. The utilization of combined allometric models and advanced technological tools, such as LiDAR or remote sensing, is essential to obtain a more precise and contextual assessment [30]. Furthermore, it is imperative to investigate the differential impact of crop varieties, farming practices, and local environmental conditions on overall storage.

It is imperative to investigate the long-term and short-term ramifications of rubber plantations on carbon sequestration, particularly when employing diverse agricultural practices, such as crop rotation, agroforestry, and the comparison of organic versus chemical utilization. Through rigorous experimentation, these methodologies can be assessed for their potential to enhance the economic viability and ecological sustainability of these systems. Additionally, it is crucial for plantations to adapt to imminent climate shifts, as these shifts may have a profound impact on their productivity and the capacity to sequester carbon [23]. Future research should prioritize the following areas: (i) genetic identification, i.e., the exploration of varieties or hybrids that demonstrate superior resilience to abiotic stresses such as excessive heat or prolonged drought; (ii) climate modeling, aimed at developing predictive models that link climatic variations with their potential impacts on growth and, consequently, on stored biomass; and (iii) integrative policies. The development of policy aimed at enhancing carbon sequestration should be based not only on a sound scientific foundation but also designed to respond to local socio-economic realities. The development and validation of rubber-specific allometric equations to accurately estimate the carbon sequestration potential of rubber plantations in Africa, particularly in the Central African region, is also essential. Studies must examine how to effectively integrate economic needs by balancing agricultural profitability with environmental objectives such as CO_2 storage [18].

4. Conclusions

This study underscored the potential of rubber plantations as a complementary alternative to tropical forest conservation efforts. A comprehensive literature review of 176 published scientific articles and reports was conducted to assess the capacity of rubber plantations to store carbon, and their effectiveness was compared with that of natural tropical forests. The results are largely consistent and indicate that agricultural systems such as rubber plantations, while not traditionally associated with carbon conservation, do play an important role in carbon uptake and storage. A distinguishing feature of rubber plantations is their high potential for indirect carbon sequestration, attributable to their capacity to provide a sustainable source of latex and wood and, consequently, income. This attribute mitigates pressure on natural forests, which play a pivotal role in global carbon sequestration and storage. However, it is crucial to acknowledge that these plantations remain dependent on human intervention. The findings of this study indicate that rubber plantations have the potential to serve as a complementary alternative to tropical forests experiencing significant deforestation, with a carbon storage capacity ranging from 30 to over 100 tons per hectare. This suggests that the storage potential of rubber plantations is comparable to that of tropical forests, which have been observed to store up to 300 tons per hectare. However, challenges persist, particularly with regard to sustainable management and the integration of rubber plantations into tropical forest conservation and sustainable management strategies. It is imperative to acknowledge the challenges associated with rubber cultivation, including biodiversity loss and soil degradation, which can result from poorly managed monocultures.

To enhance the ability of rubber plantations to sequester CO_2 effectively, it is essential to adopt management practices that harmonize ecological, social, and economic goals. Key recommendations include diversifying plantations by incorporating native species and implementing agroforestry systems that foster biodiversity while improving carbon sequestration capacity. The development of long-term management plans, incorporating sustainable financing mechanisms, monitoring, and evaluation frameworks, and public–

private partnerships, is also imperative. Additionally, implementing certification policies like those from the Rainforest Alliance and the Forest Stewardship Council (FSC), along with comprehensive environmental performance monitoring, will help ensure long-term sustainable management.

Despite its significance, this study is not without its limitations, which must be considered in the context of future research. Primarily, the analysis is predominantly focused on a literature review, thereby constraining the applicability of the findings to the available data and the geographical contexts examined. The paucity of empirical data from experimental fields or long-term monitoring further restricts the ability to gain a profound understanding of the dynamics particular to different regions or rubber plantation management contexts. Therefore, future research should prioritize the development of integrated agroforestry practices that combine rubber cultivation with local species conservation and ecosystem regeneration. These initiatives are essential for optimizing plantation management and enhancing their role in addressing climate change. A systems approach is crucial to ensure that these plantations contribute sustainably to contemporary environmental challenges. This study lays the groundwork for innovative management strategies that could enable rubber plantations to assume a more prominent role in combating climate change, complementing natural tropical forests.

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