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Review

An Overview of the Role of Forests in Climate Change Mitigation

Kyriaki Psistaki, Georgios Tsantopoulos and Anastasia K. Paschalidou *

Department of Forestry and Management of the Environment and Natural Resources, Democritus University of Thrace, 193 Pantazidou Street, 68200 Orestiada, Greece; kpsistak@fmenr.duth.gr (K.P.); tsantopo@fmenr.duth.gr (G.T.)
* Correspondence: apascha@fmenr.duth.gr

Abstract: Nowadays, climate change is recognized as one of the biggest problems the world is facing, posing a potential threat to the environment and almost all aspects of human life. Since the United Nations Framework Convention on Climate Change in 1992, many efforts have been made to mitigate climate change, with no considerable results. According to climate change projections, temperatures will continue to rise, and extreme weather events will become more frequent, prolonged, and intense. Reflecting these concerns, the 2015 Paris Agreement was adopted as the cornerstone for reducing the impact of climate change, aiming to limit global warming below 2 °C and even keep the temperature rise below 1.5 °C. To achieve this international goal, focused mitigation actions will be required. Climate change has a strong impact on forests, enhancing their growth but also posing risks to them. Conversely, forests can mitigate climate change, as they have a considerable impact on global surface temperatures through their influence on the land–atmosphere energy exchange and the absorption of vast amounts of CO_2 through photosynthesis. Consequently, afforestation and reforestation have become integral components of climate change mitigation strategies worldwide. This review aims to summarize the cutting-edge knowledge on the role of forests in climate change mitigation, emphasizing their carbon absorption and storage capacity. Overall, the impact of afforestation/reforestation on climate change mitigation hinges on strategic planning, implementation, and local forest conditions. Integrating afforestation and reforestation with other carbon removal technologies could enhance long-term effectiveness in carbon storage. Ultimately, effective climate change mitigation entails both restoring and establishing forests, alongside reducing greenhouse gas emissions.

Keywords: forest; reforestation; afforestation; climate change; sustainability

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1. Introduction

Climate is in constant interaction with natural ecosystems and humans, affecting all aspects of life, including work, nutrition, health, economy, and general well being. Since the onset of the industrial revolution, excessive use of fossil fuels and changes in land use have resulted in disrupted weather patterns, the impacts of which often surpass the resilience limits of ecosystems. Climate change has been linked to numerous adverse outcomes, including food insecurity, reduced availability and quality of potable water, biodiversity loss, the transmission of infectious diseases, destruction of infrastructure, and public health stress [1]. Consequently, it is regarded as one of the most critical challenges the modern world faces.

Climate change was recognized as a global political issue approximately half a century ago, and since then, mitigation efforts have been steadily increasing. Milestones in this endeavor include the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) during the 1992 United Nations Conference on Environment and Development (UNCED), also known as the Earth Summit, the signing of the Kyoto Protocol in 1997, and the establishment of the Paris Agreement in 2015. The Paris Agreement set ambitious targets, aiming to hold the global average temperature rise to well below 2 °C compared to pre-industrial levels, with aspirations to limit it to 1.5 °C. In line with these efforts, the European Union, through the Green Deal, has taken a leading role in combating climate change, intending to achieve climate neutrality by 2050.

In recent years, as efforts to develop measures and strategies for mitigating and adapting to climate change have intensified, there has been an increasing focus among policymakers and the scientific community on nature-based solutions. These solutions comprise a broad framework of integrated ecosystem-based approaches aimed at addressing societal and environmental challenges while considering environmental, social, and economic aspects and interconnections. Nature-based solutions involve the preservation, restoration, and sustainable management of natural ecosystems, including forests, wetlands, grasslands, and coastal areas [2]. Considering the capacity of forests to sequester atmospheric carbon dioxide (CO_2), reforestation actions, integral to the framework of nature-based solutions, could be very effective in the fight against climate change.

In addition to their impact on climate, trees and forests offer multiple additional benefits, including biodiversity conservation, soil and water retention, air and water pollution mitigation, and economic growth, e.g., refs. [3–7]. It is also worth noting the significant role of urban forests in mitigating the urban heat island effect [8,9], wherein temperatures in urban areas are notably higher compared to surrounding suburban and rural areas [10]. Finally, there is evidence that forests have a positive effect on people's concentration, anxiety and depression management, and overall emotional and mental health [11,12]. In conclusion, forests play a multifaceted role, providing invaluable benefits to both the environment and humans.

This review aims to elucidate the role of forests in climate change mitigation by thoroughly examining the diverse dimensions of the underlying interactions. It delves into the impact of forests on climate, focusing on their carbon removal and storage capabilities, while also assessing the effect of biophysical processes, such as evapotranspiration and surface albedo. The review explores both natural and anthropogenic disturbances that affect forest ecosystems. Furthermore, it evaluates the efficacy of afforestation and reforestation in carbon sequestration while also examining their implications for food security. In addition, it investigates the overall impact of such actions as well as the nuanced factors affecting their effectiveness. Overall, this review contributes to advancing the understanding of the nexus between forests and climate, highlighting the importance of afforestation and reforestation in global efforts to mitigate climate change.

2. The Role of Forests in Shaping Climate

Forests are complex ecosystems teeming with diverse flora and fauna. Although there is no single definition, the Food Agriculture Organization (FAO) of the United Nations (UN) describes a forest as a land area of more than 0.5 ha with trees over 5 m tall, or with trees capable of reaching this height, and a canopy cover of more than 10% [13].

The impact of forests on climate is mainly linked to the biochemical processes of trees (Figure 1), such as photosynthesis, which affect CO_2 levels in the atmosphere, playing an important role in the carbon cycle [14,15]. Trees, along with other plant organisms within forests, sequester CO_2 from the atmosphere during the process of photosynthesis. A proportion of this carbon is stored in the stems, branches, and roots of trees and plants, in dead organic matter, and within soil. The rest is released into the atmosphere as CO_2, mainly through the respiration of trees and plants, as well as through the decomposition of dead organic matter [15]. In addition to the respiration process, CO_2 emissions may be caused by forestry activities related to their management, as well as from deforestation and/or degradation due to natural disturbances (e.g., fires, droughts, etc.) and anthropogenic interventions (e.g., deforestation for land use change and/or exploitation of timber products) [16,17].

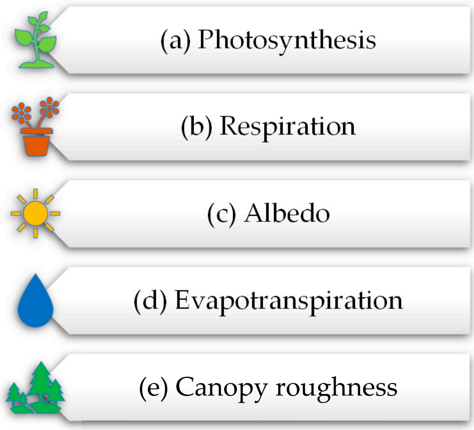

Figure 1. The biochemical (a and b) and biophysical (c, d, and e) mechanisms of trees that affect the climate.

In forest ecosystems, the equilibrium between carbon stocks and emissions has an important impact on climate. A forest is deemed a net carbon sink when it absorbs and stores more carbon than it emits over a defined period. Otherwise, it is considered a net carbon source [18]. Although carbon stocks in different forest ecosystems around the world exhibit notable variations related to various factors, such as biodiversity [19], tree characteristics (e.g., species, age) [20,21], climatic conditions [22], and forest management [23,24], on a global scale, forest ecosystems act as net carbon sinks, contributing to mitigating the increase in global average temperature [25–28]. In 2020, the global forest carbon stock was approximately 662 Gt, with 44% attributed to tree mass (root system, wood, bark, and leaves), 45% to soil organic matter, and the remainder to deadwood and litter [29].

However, some researchers have reported that forests acted as weak net carbon sources at the global level during specific time periods between 1990 and 2020. This was probably related to extensive deforestation and increased forest degradation, mainly due to anthropogenic interventions [30,31]. Additionally, high temperatures and elevated Vapor Pressure Deficits (VPDs) have been observed to affect photosynthesis and respiration in trees, disturbing their balance under certain conditions. This can potentially undermine the role of forests as carbon sinks [32–35]. Nevertheless, it is important to acknowledge that the modeling and quantification of carbon fluxes in forest ecosystems are complex processes. They are influenced by numerous factors, and their results involve a high degree of uncertainty, as they depend on the data used, the methodology followed, and the assumptions adopted [15,30,31,36,37].

Apart from their impact on the carbon cycle, forests influence the climate, primarily at local and regional levels, through biophysical mechanisms, including reflectivity (albedo), evapotranspiration, and canopy roughness [14] (Figure 1). Due to their dark color, forests possess lower albedo than that of soil, snow, grazing lands, cultivated lands, and low vegetation [14]. Consequently, forests absorb a greater percentage of incident solar radiation, enhancing climate warming at local and/or regional levels [38,39]. Additionally, a portion of the incident solar radiation is absorbed during evapotranspiration. This process involves the evaporation of water from the soil surface and plants, as well as transpiration, where water is transferred through the root system from the soil to the leaves and emitted as water vapor. Through evapotranspiration, sensible heat, associated with air temperature rise, is converted into latent heat to change the phase of water from liquid to gas (water vapor) [39,40]. Furthermore, the relatively high roughness of the forest canopy favors vertical mixing of the air and latent heat transfer (via water vapor) to higher altitudes, eventually cooling the soil locally [40]. Under certain conditions, the cooling effect on soil is augmented by the condensation of water vapor, leading to cloud formation and higher albedo. However, as water vapor is a greenhouse gas, it can counteract the cooling effect of clouds, affecting the overall surface energy balance [40].

On the whole, it is evident that the influence of biophysical mechanisms on climate is complex and varies greatly, depending on regional characteristics. As biophysical mechanisms can either enhance or counteract heat storage, they contribute to climate warming or cooling, respectively, e.g., refs. [40–43]. On the other hand, the interactions among biophysical mechanisms and their overall impact on climate exhibit high spatial variability, posing challenges in accurate quantification [40,44]. Generally, due to the low albedo of forests, the intensity of warming increases with latitude, while the intensity of cooling decreases due to evapotranspiration. For example, in tropical regions, the increase in soil temperature resulting from the low albedo of forests is counteracted by the intense cooling caused by high evapotranspiration rates, leading to climate cooling on an annual basis [18,39,45]. On the other hand, in the boreal forest, warming due to low albedo greatly exceeds the cooling caused by evapotranspiration, especially during winter months when snow cover is typically high [14,39,46]. For temperate forests, the impact of their biophysical mechanisms on climate remains uncertain [14,39,46,47]. Irrespective of the climatic zone, though, the biophysical mechanisms of forests play an important role in reducing diurnal and annual temperature fluctuations, as well as moderating extreme temperatures during the summer period, particularly during the day [39,46].

Overall, forests are vital for climate stability and for mitigating climate change, but it should be noted that their ability to continue playing this role is increasingly at risk due to a combination of natural and human-induced pressures.

3. Natural and Anthropogenic Disturbances of Forests

Anthropogenic activities, including deforestation, logging, and harvesting of wood for fuel, combined with natural disturbances, such as storms, fires, droughts, diseases (e.g., from fungi, pests, or insects), and other extreme weather events, put continuous pressure on forest ecosystems [48–52]. As natural disturbances depend on local climate conditions, due to climate change, an increase in their frequency and severity is expected [53]. The combined effect of these disturbances seriously threatens forests' sustainability, impairing their capacity to store carbon. For example, Yang et al. (2018) found that during the period from 2005 to 2008, the Amazonian forests experienced an average carbon loss rate of 0.3 PgC yr^{-1}, primarily attributed to the prolonged 2005 drought [54].

Despite continuous global efforts in recent decades, deforestation remains a major environmental problem [29–31,36]. From 1990 to 2020, approximately 420 million ha of forests were lost globally, with the annual rate of deforestation decreasing by 5.6 million ha from 1990–2000 to 2015–2020 [29]. Notably, over the period of 2012–2021, global CO_2 emissions from deforestation accounted for about 17% of total annual CO_2 emissions, amounting to about 6.6 Gt CO_2 yr^{-1} (≈1.8 GtC), with the tropics making the largest contribution [32]. Tropical deforestation alone has been estimated to be responsible for 2.3–6.2 Gt CO_2 yr^{-1} [23,55,56]. Nevertheless, caution is needed when comparing CO_2 emissions, as these values depend on the method and assumptions adopted for their calculation, as well as the timeframe under consideration [56].

Furthermore, although wildfires, as natural occurrences in forest ecosystems, play a vital role in regulating ecological processes and supporting crucial ecosystem services while promoting biodiversity preservation and enhancement [57,58], they also rank among the most common disturbances affecting forests globally [59,60]. Despite a decrease in global burnt areas over the last two decades, there has been a slight increase in forest fire emissions [61]. According to Zhao et al., (2021b), between 1986 and 2016, CO_2 emissions from wildfires in the Alaskan and Canadian boreal forests were estimated at 57.1 TgC per year [62]. Similarly, the average annual emissions from wildfires in Siberia, between 2002 and 2020, were estimated at 80 ± 20 Tg C/year. However, there were notable sporadic peaks during this period, with 2020 recording the highest emissions at approximately 350 Tg C/year [63]. In addition, the emissions from the Southeast Australian wildfires during the 2019–2020 summer season were estimated to be 715 Tg CO_2 (517–867 Tg CO_2) [64]. From 2001 to 2018, fires affected approximately 7.2 billion ha globally, 29% of which were in tree-covered areas (not necessarily classified as forests) located in the tropics [29]. Additionally, according to Van Lierop et al., (2015), from 2003 to 2012, the annual burned forest area globally averaged 67 million ha, with more than 53 million ha located in the tropics [59]. In 2023, wildfire activity was exceptionally high in many regions worldwide. Canada was affected the most, experiencing intense and persistent fires from May to October. As a result, almost 7.8 million ha of forest land were burned, accounting for over 25% of the total global tree cover loss, and nearly 3 billion tons of CO_2 were emitted [65]. Similarly, Greece faced severe wildfires during the summer of 2023, primarily on the island of Rhodes and in the northeastern part of the country, with the wildfire in the latter being the largest recorded in the history of the European Union. Overall, these wildfires in Greece emitted approximately 2 MtC (Copernicus: https://atmosphere.copernicus.eu/ accessed on 6 June 2024).

Additionally, it is important to highlight that due to climate change, an increase in the frequency of wildfires caused by high temperatures and droughts is predicted, with the Mediterranean region being particularly vulnerable [51,66–69]. In response, efforts by governments and organizations worldwide to enhance protection measures against the threat of forest fires have been burgeoning in recent years (European Commission: https://drmkc.jrc.ec.europa.eu/ accessed on 6 June 2024; European Forest Institute: https://efi.int/ accessed on 6 June 2024; Government of Canada: https://www.canada.ca/ accessed on 6 June 2024). However, strict fire control can impact the structure and functions of forest ecosystems in several ways, including shifts in species composition and biodiversity reduction [70,71]. There is evidence suggesting that aggressive fire suppression policies favor the accumulation of flammable vegetation, increasing the risk of large and intense fires, especially under the impact of ongoing climate warming. Therefore, it is recommended to adopt a holistic forest fire management approach that considers the aforementioned parameters and integrates proactive measures to complement fire suppression efforts [72,73]. In addition to the disturbances mentioned earlier, each year approximately 6 million ha of forest areas are affected by extreme weather events, 4.8 million ha by diseases, and 29 million ha by insects [29]. Considering the challenges associated with accurately recording forest areas affected by these disturbances and the inconsistency in doing so, these rates may potentially be higher in reality [51].

Given the challenges posed by natural and anthropogenic disturbances, the need for proactive measures becomes evident. Transitioning from understanding these threats to addressing them, the focus shifts to exploring the pivotal role of afforestation and reforestation in restoring and enhancing forest ecosystems.

4. Afforestation and Reforestation

The imperative role of forests in removing CO_2 from the atmosphere underscores the importance of their restoration, expansion, and proper management in achieving the Paris Agreement targets and mitigating climate change [27,30,41,74]. According to the international literature, the restoration of degraded forest ecosystems could substantially offset CO_2 emissions resulting from forest degradation and deforestation caused by natural and/or anthropogenic disturbances [15,18,36,49]. Given the environmental and socio-economic impacts of forest degradation, the scientific community has a particular interest in issues related to sustainable forest development and restoration, e.g., refs. [75–78]. Tree planting initiatives to restore and expand forests through afforestation and reforestation campaigns are recognized as an efficient and cost-effective solution, e.g., refs. [41,79–81], and are highly valued by both stakeholders and the general population. It is of note that afforestation refers to the process of planting trees to create new forests in areas devoid of forest cover for at least the past 50 years, while reforestation refers to the restoration of forests that have been impacted by natural or anthropogenic disasters [82]. Nevertheless, the term "reforestation" is often used interchangeably for both activities.

According to FAO [29], in 2020, the area of planted forests created through afforestation and reforestation encompassed approximately 294 million ha, accounting for 7% of the world's total forests. Between 1990 and 2020, the area of planted forests increased by

123 million ha globally, although the average annual growth rate decreased from 5.13 million ha in 2000–2010 to 4.06 million ha 2010–2020. Notably, in Asia, 22% of forests are attributed to tree planting operations, while the equivalent percentage in Africa and South America is only 2%. The percentage of planted forests is slightly higher in North and Central America, reaching 6% of the total forest area in each region. Europe shows higher rates, with human intervention contributing to 30% of forests, excluding the European part of Russia. However, when including Russia's predominantly natural forests, the percentage drops to 7% (Figure 2).

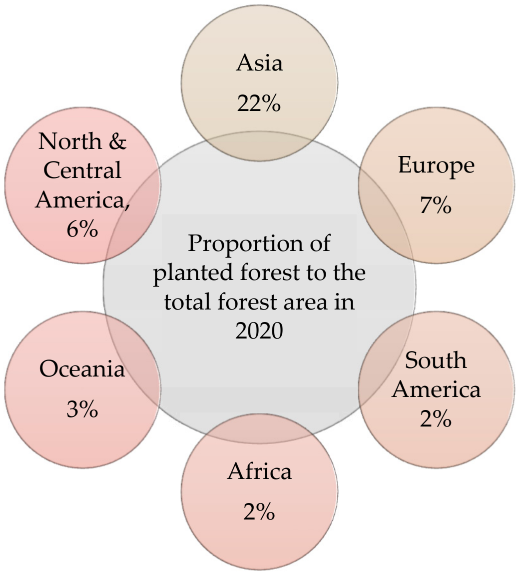

Figure 2. The percentage of forest attributed to tree planting operations in various parts of the world in 2020.

As national agreements on climate change mitigation highlight the crucial role of CO_2 sequestration, large-scale afforestation and reforestation actions are pivotal in addressing climate change, despite variations in specific land requirements and their effectiveness. Numerous researchers have focused on assessing the effectiveness of afforestation/reforestation practices to tackle climate change by quantifying the CO_2 sequestration capacity of forests, e.g., refs. [41,83,84]. For instance, acknowledging the value of urban forests for local communities [4,7,10,11] and spurred by the increasing prevalence of afforestation programs in various urban areas worldwide [85–87], Teo et al. (2021) evaluated the potential contribution of urban forests to climate change mitigation [88]. Specifically, after identifying areas suitable for planting new forests within 7595 urban centers worldwide, they calculated the potential carbon sequestration capacity of the aboveground woody biomass (i.e., carbon stored in trees, branches, leaves, and other aboveground vegetation). According to their findings, approximately 17.6% of the total urban areas studied were potentially suitable for afforestation. This rate corresponds to approximately 10.9 Mha and has the potential to sequester 82.4 $\pm$ 25.7 Mt CO_2 eq annually. Overall, they concluded that afforestation of available urban areas could significantly contribute to CO_2 emissions mitigation, offsetting more than 1/4 of local emissions. However, when comparing the carbon sequestration rates of urban and non-urban forests, they observed that non-urban forests tended to prevail.

Furthermore, a study by Bastin et al. (2019) has sparked considerable interest [75]. They explored the potential changes in tree cover and the carbon storage capacity in forest ecosystems globally, considering the impact of climatic, soil, and topographic parameters. Overall, they concluded that forest ecosystem restoration through afforestation, reforestation, and natural forest regeneration is one of the most effective methods for mitigating climate change. According to their estimates, excluding existing trees, cultivable land,

and urban areas, forests could expand by 0.9 billion ha globally, potentially storing up to 205 GtC. This amount corresponds to approximately 70% of total carbon concentrations in the atmosphere resulting from anthropogenic activities. However, a part of the scientific community [79,89–91] has expressed objections regarding the validity of the aforementioned results. Critics have pointed out simplifications and inaccuracies in calculations, including the omission of existing vegetation and soil organic carbon stocks, as well as the biophysical impact of forests on climate. In response, Taylor and Marconi (2020) [91] estimated that by increasing forests by 0.9 billion ha, global carbon stocks would range between 71.7 and 75.7 GtC, which is approximately 40% less than the estimations provided by Bastin et al. (2019) [75].

Nevertheless, large-scale afforestation/reforestation actions, such as those presented above, require extensive land areas, a portion of which may already serve (or could potentially serve) other uses, such as food production [16,92]. Therefore, extensive tree planting in areas devoid of previous land cover could pose risks to local and global food security. As pointed out by Kreidenweis et al. (2016), increasing forest area by 60% globally would result in the sequestration of approximately 860 Gt CO_2 by the end of the century, causing, however, food prices to more than quadruple [93]. Similar conclusions have been drawn for other land-based climate change mitigation measures, such as bioenergy production [94–97]. It is noteworthy that one-third of the countries participating in the Bonne Challenge face difficulties in meeting their targets without impacting food production. These difficulties stem from their commitment to restore degraded forests and plant trees covering more than 10% of their total land area, as outlined in the Bonne Challenge [98].

Similarly, Doelman et al. (2020) demonstrated that in order to keep the average global temperature increase below 2 °C by the end of the century (compared to pre-industrial times), a total of 410 Gt of CO_2 must be sequestered [80]. They also estimated that to achieve this target, it is necessary to expand forests by approximately 1.1 billion ha. According to their estimates, this would result in reduced food availability and increased food prices, which would put an additional 441 million people worldwide at risk of undernourishment by 2100 compared to 2010 levels. In addition, considering the findings of Doelman et al. (2020) [80] and other similar studies [95–97], it can be concluded that developing regions already facing severe nutrition challenges, particularly Africa and South Asia, are expected to experience the greatest impact. Despite the high uncertainty of these results, it is recommended that climate change mitigation strategies involving large-scale land planting take into account potential risks to food security and adopt suitable mitigation practices [80]. For instance, agroforestry, which integrates the cultivation of trees and shrubs with crops and/or livestock on the same land, constitutes a promising land management practice that effectively addresses the conflict between forest conservation and food production. It supports all four aspects of the food and nutrition security framework (availability, access, utilization, and stability) while delivering positive economic impacts for farmers and offering environmental advantages, such as enhanced biodiversity and water quality, improved soil health, and carbon sequestration. Overall, agroforestry presents a balanced and sustainable solution, favoring both climate change mitigation and adaptation [99–101].

5. Parameters Affecting the Effectiveness of Forests and Afforestation/Reforestation in Climate Change Mitigation

5.1. Factors Related to Forest Characteristics

The ability of forests to sequester and store carbon, and, consequently, the effectiveness of afforestation/reforestation programs in climate change mitigation, exhibit spatial and temporal variations, depending on various factors. These factors include, among others, local climatic conditions, density and diversity of forest vegetation, tree age and species, and soil characteristics, e.g., refs. [15–20,102–106].

Li et al., (2023), who studied a forest with approximately 2000 fir trees in Southern China, gradually planted as part of reforestation efforts in the region, found that the total carbon stocks of the ecosystem increased with increasing tree age [21]. Consistent with findings from previous studies, e.g., refs. [15,24,107], they observed that the CO_2 sequestration rate gradually increased until the middle age of trees, where it peaked and then decelerated considerably, highlighting the role of tree aging in carbon sequestration rates. Bernal et al. (2018), taking into account the impact of various factors, such as climatic conditions, latitude, tree age, and species, assessed the carbon sequestration rate and storage for a set of different forest landscape restoration actions, including natural forest regeneration and afforestation/reforestation [108]. According to their findings, the growth rate of forest biomass, and thus the carbon removal rate from the atmosphere, was higher during the first 20 years of forest restoration. However, in some cases, such as in regions with high annual precipitation in North America, Asia, and Oceania, the growth rate of forest biomass was found to be as high or higher over the period between 20 and 60 years old [108].

Bernal et al. (2018) also observed that the CO_2 removal rates from trees, regardless of their species, exhibited an increasing trend from colder to warmer climates [108]. Similarly, Chiquier et al. (2022) estimated that the maximum CO_2 sequestration potential per ha of boreal forests in the United Kingdom was approximately six times smaller than that of the tropical forests in Brazil [17]. Additionally, they observed that high levels of rainfall enhanced the CO_2 sequestration potential of tropical forests [17]. Similarly, Balima et al. (2021) found that high mean annual precipitation enhances carbon storage in aboveground tree biomass in West Africa, but they observed that increased mean annual temperature has a negative impact [109]. According to Wang and Huang (2020), tropical climate regions presented the highest rate of carbon sequestration from aboveground tree biomass, while the maximum carbon sequestration rate from forest soils was observed for warm temperate climate regions [81]. They also found that latitude, mean annual rainfall, and the number of frost-free days were among the factors determining the carbon sequestration rate from soil, highlighting that their contribution varies, depending on the climate of the region under study [81].

Interestingly, Wen and He (2016) found that temperature and rainfall positively affected carbon storage in the vegetation of forests in eastern China but had a negative impact on soil carbon storage [110]. Overall, the growth rate of trees is related to local climatic conditions, thereby affecting their ability to sequester and store carbon in their biomass [104,106]. This is because the processes of photosynthesis and respiration in trees depend on climatic parameters, such as temperature, precipitation levels, and cloud cover, with the magnitude of their effects varying based on the climatic characteristics of each region [111,112]. For instance, there is evidence that under the influence of hot and dry conditions, respiration can exceed photosynthesis, counteracting the benefits of forests as carbon sinks [32–34]. However, the impact of these climatic parameters on soil carbon stocks in forest ecosystems is complex, mainly depending on the balance between organic matter inputs into the soil and decomposition processes [110].

Other factors that may affect total carbon stocks in forests are the density and species of trees. Consistent with findings from previous studies [77,106], Osei et al. (2022), focusing on European forest ecosystems, observed that stand density, expressed as basal area per hectare, strongly affects the carbon stored in tree woody biomass, whereas its impact on soil carbon stock is negligible [113]. However, contradictory conclusions have emerged from studies focusing on coniferous forests of the Pinaceae family [114,115]. Furthermore, in the study by Osei et al. (2022), it was found that broadleaved species, such as beech and oak, store more carbon in their aboveground woody biomass (stem and branches) than in the soil (forest floor and down to a depth of to 40 cm depth), whereas, in the case of pines, carbon is evenly distributed between these two pools [113]. They also observed that, in all species studied, the carbon stored in their coarse root system is lower compared to the carbon stored in their aboveground biomass. In the same vein, Bernal et al. (2018) observed variations in the carbon sequestration rate of different species in the same climatic zone [108].

In line with the findings of Bernal et al. (2018) [108], numerous studies confirmed that soil carbon stocks vary, depending on tree species [103,116–118]. Such observations presumably stem from the fact that the species of a tree affects both the quantity and the quality of carbon deposition, thereby determining the decomposition rate and the fraction of organic matter that remains in the soil or is released as CO_2 [119–121]. Nevertheless, while species composition, as well as stand density, undoubtably influence total carbon stocks and the distribution between aboveground woody biomass and soil, evidence suggests that they cannot fully account for the variability in soil carbon storage [113]. This indicates that soil carbon stocks in forests may also be affected by other factors [103], such as climatic conditions, soil characteristics (e.g., texture, moisture, chemical composition), and the topography of the area [122].

In addition to the factors previously discussed, there is evidence that increased tree species diversity enhances soil organic carbon (SOC) storage in forests [19,77,123]. For instance, Osei et al. (2021), who studied several mixed stands comprising two different species as well as their corresponding pure stands across seven European countries, discovered that oak–beech pairs promoted carbon storage at soil depths of 0–10 cm, while pine–oak pairs promoted it at depths of 10–40 cm [124]. However, when assessing the total carbon stocks from the soil surface to a depth of 40 cm, they found no significant variation associated with the coexistence of the species under study. Furthermore, while some studies suggest that monocultures exhibit higher CO_2 sequestration rates, especially when appropriate management schemes are implemented [125–127], high tree diversity has also been positively associated with increased aboveground carbon stocks of forests [128–131]. Nevertheless, in agreement with previous studies [77,132], Osei et al. (2021) concluded that although tree diversity may affect soil carbon stocks of forests, its impact is smaller compared to the effect of tree species identity [124].

5.2. Factors Related to the Implementation of Afforestation/Reforestation Actions

Based on the previous discussion, it is evident that forests are complex ecosystems with many, and often interdependent, factors affecting their capacity to sequester CO_2 from the atmosphere. In addition to these factors, various parameters occurring during the implementation of afforestation/reforestation actions, such as soil carbon losses resulting from ground preparation before tree planting, may play an important role. Specifically, the type and intensity of the afforestation/reforestation practices used are determined by soil characteristics (e.g., its mineral content) and may lead to high soil carbon emissions for several years [16]. Furthermore, climatic conditions, soil composition, and moisture levels can affect the decomposition rate of deposits and may contribute to the accelerated mineralization of organic soil carbon, increasing greenhouse gas emissions [133]. All these factors, along with the low CO_2 sequestration rate and deposition rate typical of young trees, are likely to result in a substantial reduction in soil carbon stocks and may impede the ability of new forests to function as net carbon sinks during the first ten years after their establishment [17,133].

Additionally, the amount of carbon stored in the soils of afforested/reforested areas depends, to a large extent, on the previous land use [117,122,134]. For example, there is evidence that tree planting in croplands increases soil carbon stocks, whereas in grasslands and peatlands, soil carbon stocks remain stable or decrease [77]. Similar conclusions were reached by Friggens et al., (2020) while studying soil carbon stocks 12 and 39 years after planting pines and oaks in peatlands in Scotland [135]. In the same vein, Hüblová and Frouz (2021) observed that soil carbon stocks are higher after tree planting in areas previously characterized as forests or agricultural lands compared to areas that had undergone mining activities [136]. Specifically, they found that in forests, agricultural areas, and soils with relatively low pH and/or high sand content, planting coniferous trees contributed to higher organic carbon stocks compared to planting broadleaf trees. Conversely, the opposite trend was observed in areas previously affected by mining activities [136].

5.3. Climate Change

Climate change has a complex effect on forests' growth and health. Higher levels of CO_2 and higher temperatures related to climate change can prolong the growing season and enhance forest productivity, potentially resulting in higher sequestration rates (EPA: www.epa.gov accessed on 6 June 2024). However, this positive impact presents regional variability, varies between tree species, and depends on the level of projected temperature increase (EPA: www.epa.gov accessed on 6 June 2024) [137,138]. Furthermore, the more frequent and intense occurrence of forest disturbances due to climate change, such as insect outbreaks, wildfires, droughts, and storms, can counteract its positive effect on forest growth and productivity (EPA: www.epa.gov accessed on 6 June 2024). Excluding the impact of forest disturbances, climate change is expected to favor carbon sequestration in forests located in the mid to high latitudes of the Northern Hemisphere, particularly in Northeast and Central Asia, Northern Europe, and Northwestern America. On the other hand, forests in South America and Central Africa will probably be adversely affected [28].

In addition, various studies suggest that under the influence of a rapidly changing climate, local habitat suitability for the growth and thriving of species will change, resulting in some species benefiting and others facing challenges [139,140]. It is, therefore, crucial to conduct a thorough long-term assessment of a region's capacity to support each species to be planted, as this has a strong impact on its growth and, overall, the new forest's ability to remove CO_2 from the atmosphere. In general, for forests and afforestation/reforestation actions to effectively contribute to a sustainable and resilient future, a balanced approach is necessary. This approach should combine long-term planning to guide future decision making, as well as the implementation of strategies that yield immediate impacts on climate change mitigation and adaptation to its effects. Reconciling the need for comprehensive long-term assessments with the urgent need to address climate change in the near future presents a critical challenge.

An illustrative example is the study conducted by Baggio-Compagnucci et al., (2022) on the assessment of afforestation as a strategy for CO_2 mitigation in Scotland, where they observed that climate variations have different impacts on carbon stocks in tree biomass, depending on their species [16]. Additionally, they found that by 2050, the lowland areas of Scotland will become more conducive for species that typically thrive in temperate climates with mild temperatures (e.g., Pedunculate Oak, Ash, Wych Elm), while these areas will be less conducive for species that thrive in cold climates and boreal forests (e.g., Betula sp.) [16].

On the other hand, climate change is expected to result in spatially heterogeneous increases in the intensity and frequency of disturbances that afflict forests (e.g., heatwaves, fires, droughts, biotic agents, such as insects, etc.), adversely affecting their CO_2 sequestration capacity and decreasing their carbon stocks [51]. In addition, the impact of climate change on forests, combined with other factors, such as air pollution and invasive species, can exceed their limits of resilience, resulting in their conversion into grasslands or savannahs [141]. Consequently, in regions that are heavily affected by such stressors and where vulnerability is projected to increase due to climate change, the benefits expected from afforestation/reforestation need to be carefully evaluated, and appropriate management measures need to be implemented in order to minimize potential adverse impacts [141].

5.4. Biophysical Mechanisms of Forests

Planting trees in previously non-forested areas usually leads to a decrease in surface albedo. This, in conjunction with other biophysical and biochemical mechanisms of forests, can affect local and regional climate, depending on the latitude [14,40,44]. For instance, in tropical regions, tree planting constitutes an extremely effective way to mitigate temperature rise. In these regions, the prevailing climatic conditions also play an important role, favoring the rapid growth of trees and thus the high CO_2 sequestration rate [40,53,84]. On the other hand, the effectiveness of afforestation in the boreal forest zone is disputed, as the change in surface albedo caused by tree planting is likely to offset the temperature decrease that could be achieved by CO_2 sequestration, causing local temperature increase [40,42].

Of particular interest is a recent study by Breil et al. (2023), which evaluated the climatic impact of covering the entire European continent with trees, assuming greenhouse gas concentrations at pre-industrial levels [43]. According to their findings, the implementation of this hypothetical afforestation would cause climate warming in Europe. This highlights the strong influence of biophysical processes, which exceed that of biochemical processes in the region under study. Therefore, it is crucial to consider the combined effect of biophysical and biochemical processes when assessing the impact of afforestation on local or regional climate [17,43]. However, the overall contribution of forests to carbon sequestration and their role as important carbon sinks highlight the importance of considering the cost/benefit needs on a global scale. In any case, even when forests are associated with local/regional climate warming, they contribute substantially to air and water quality, biodiversity, human well being and leisure, the provision of forest products, etc. [42].

6. Exploring the Overall Impact of Afforestation and Reforestation

As demonstrated in the previous section, to maximize the benefits of afforestation/ reforestation in climate change mitigation, it is crucial to plant the right tree in the right place [124,136]. However, to ensure that afforestation/reforestation is a successful nature-based solution (NBS), its impact on other sectors, such as biodiversity conservation/enhancement and economic enhancement, needs to be also assessed. For example, afforestation of areas, such as savannahs, grasslands, peatlands, and wetlands, contributes to carbon removal from the atmosphere, but it may also lead to devastating impacts on local biodiversity [2]. Additionally, it could jeopardize food security [80] and local water resources, particularly in developing countries and dry regions [142,143]. Therefore, to ensure sustainability and resilience, all potential risks involved need to be considered. Along these lines, priority is suggested to be given to tree planting in degraded or destroyed lands and expanding existing forests [80,144]. This may enhance carbon sequestration and biodiversity while improving the ecosystem's ability to regenerate naturally, thereby positively affecting its resilience [144].

Planting monocultures, often composed solely of non-native tree species, is another example that highlights the importance of thoroughly examining the impacts of afforestation/reforestation. This practice is particularly widespread worldwide, with eucalyptus as well as conifers, primarily pine, and spruce being among the most commonly used species. The highest percentages of monocultures are held, in descending order, by North America, Oceania, Africa, and Asia, where they represent more than 50% of the forested area obtained through afforestation/reforestation [29]. Monocultures offer various advantages, such as rapid growth rates and ease of management, due to their uniformity. Consequently, they are widely used for timber and other forest products, including rubber, paper pulp, charcoal, palm oil, etc. [145]. As a result, they have been associated with local economic development through the exploitation of forest products and services, as well as job creation [146,147]. However, there is evidence suggesting that monocultures do not always have a positive impact on the economy. In several cases, it has been observed that the expansion of these types of forests exacerbates social inequalities and poverty [148,149].

Furthermore, while monocultures are characterized by a rapid carbon sequestration rate, they are likely to cause adverse impacts on soil quality and properties, local flora and fauna, water availability, and forest resilience to extreme weather events, diseases, and pests [2,150–152]. These negative impacts can be further amplified when interventions aimed at enhancing forest biomass productivity, such as thinning, soil fertilization, and harvesting with short rotation lengths, are applied [7]. In recent years, an increasing number of studies have advocated for planting species-rich forests, composed either of native species exclusively or of a combination of non-native and native species. This practice is preferred over monocultures as it promotes biodiversity, exhibits greater resilience, demonstrates better long-term carbon storage performance, enhances the economy, and provides a variety of socio-environmental benefits [80,144,145,152]. In addition, there is evidence that multi-species plantation positively affects forest productivity, linked to increased forest carbon sequestration [153,154]. In the same vein, according to a recent meta-analysis study, young mixed-planted forests, particularly those consisting of four species, exhibit on average 70% higher aboveground carbon stock accumulation than monocultures [155]. In conclusion, poor planning and inadequate implementation of afforestation/reforestation actions can lead to increases in CO_2 emissions and adverse impacts on humans and ecosystems. Given the diversity of tree species, forest types, regional characteristics, and socio-economic impacts of forests, the implementation of afforestation/reforestation projects requires a multidimensional approach. In this regard, Di Sacco et al. (2021) suggested a set of principles to guide the design of such programs, aiming at achieving optimal outcomes for climate change mitigation, biodiversity preservation, and sustainability at both the local and global scales [144]. In agreement with Seddon et al. (2022), they highlighted the importance of involving indigenous populations and local communities in all phases of afforestation/reforestation from the planning stage to subsequent monitoring [156]. Since indigenous people have an in-depth knowledge of local needs, they can help protect their interests and contribute to the overall success of the project. Additionally, Di Sacco et al., (2021) indicated that successful and sustainable afforestation/reforestation projects require collaboration among all stakeholders (governments, private sector, NGOs, etc.) throughout their lifecycle [144].

Moreover, the benefits arising from afforestation/reforestation for climate change mitigation can be strongly enhanced by combining them with industrial carbon removal technologies, such as Bioenergy with Carbon Capture and Storage (BECCS). BECCS is widely regarded as one of the most promising technologies for reducing greenhouse gas emissions. It involves energy production by biomass combustion, coupled with the capture of the produced CO_2 through carbon capture technologies, and its subsequent storage underground or in geological storage sites [17,78]. Estimates suggest that by 2050, BECCS could remove between 0.5 Gt CO_2 and 5 Gt CO_2 per year [53]. BECCS is typically implemented on an industrial scale and is designed to capture CO_2 emissions from industrial processes, particularly in the energy sector [78]. However, it is important to note that the emissions associated with the lifecycle of BECCS, including CO_2 emissions from land use change, biomass cultivation, harvest, CO_2 capture, transport, and storage, need to be thoroughly considered to accurately assess BECCS's carbon footprint and effectiveness [17].

Nevertheless, combining BECCS with afforestation/reforestation, particularly using fast-growing plantations, enhances the overall carbon removal capacity, making it a viable option for achieving ambitious climate targets. This combination ensures long-term carbon storage and improves land use efficiency by addressing the growth limitations associated with afforestation/reforestation. Moreover, it increases carbon sequestration potential through soil organic carbon over the plantation's lifecycle. Overall, integrating afforestation/reforestation with BECCS can significantly mitigate the challenges associated with their individual applications and establish a robust system for carbon removal from the atmosphere [78].

7. Conclusions

Forests, through their biochemical processes, such as photosynthesis, play a key role in removing CO_2 from the atmosphere and constitute important carbon sinks. However, anthropogenic activities and natural disturbances have resulted in the degradation and destruction of extensive forested areas. Coupled with the looming threat of rapid climate change, the future of forests remains uncertain. Given these challenges, along with the multitude of socio-environmental benefits forests offer and the urgent need for immediate and decisive climate change mitigation actions, afforestation and reforestation programs are gaining steadily increasing attention.

The effectiveness of afforestation/reforestation in addressing climate change depends on various factors, some of which are related to the design and implementation of these actions, whereas others pertain to the characteristics of forests and the impacts of climate change on them. While climate change can enhance forest productivity and carbon sequestration by extending the growing season and accelerating tree growth rates, its benefits are doubtful due to the high spatial variability influenced by regional climatic characteristics, tree species, the magnitude of temperature rise, and the frequency and intensity of forest disturbances. Furthermore, during the development of afforestation/reforestation initiatives, the biophysical mechanisms of the forests also affecting the climate, as well as the potential impacts of land use change, must be taken into account. Consequently, appropriate planning and careful implementation of afforestation and reforestation, tailored to the characteristics of the specific area, along with the adoption of suitable forest management strategies, can maximize the benefits of these programs for climate change mitigation and the environment.

However, despite the pivotal role of forests in CO_2 sequestration, depending solely on afforestation and reforestation initiatives to tackle climate change might not offer a comprehensive solution, considering their limitations and the potential risks and trade-offs involved. For instance, factors such as local climatic conditions, tree species, and age influence their carbon sequestration rates. Forests take time to grow and reach their full carbon sequestration potential. In addition, their capacity to sequester carbon is finite, presenting a decreasing trend with years. Moreover, the availability of land poses a major constraint, as competition with agriculture for food production and land suitability issues limit opportunities for reforestation/afforestation. Furthermore, changing temperature and precipitation patterns, as well as extreme weather events, wildfires, pest outbreaks, and disease spread due to climate change jeopardize carbon storage in forest ecosystems.

Nevertheless, forests possess considerable carbon sequestration potential, leveraging their ability to absorb CO_2 through photosynthesis and store it in biomass and soils. This highlights the vital role forests play in global carbon balance, making afforestation and reforestation crucial components in the fight against climate change. In addition, the combination of these actions with other carbon removal technologies would be beneficial, providing an integrated solution that will increase the likelihood of long-term effectiveness in carbon storage. Overall, effective climate change mitigation demands a comprehensive strategy for both restoring degraded forests and establishing new ones, alongside sustained and intensified endeavors to reduce anthropogenic greenhouse gas emissions.

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