

Biochar Utilization as a Forestry Climate-Smart Tool

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Abstract: Carbon (C) in gaseous form is a component of several greenhouse gases emitted during the combustion of fossil fuels. C movement between the atmosphere, land (biosphere and lithosphere), and ocean (hydrosphere) alters the total amount in each pool. Human activities accelerate C movement into the atmosphere, causing increases in temperature. This shift from terrestrial and oceanic C pools to the atmosphere causes an increase in the intensity, frequency, and duration of catastrophic climate disturbances. Although society hears and reads about C emissions, there is a lack of understanding of its importance and the need to decrease it in the atmospheric pool to avoid exacerbating climate change. Forests and biochar are two biological methods to retain C in the terrestrial pool for a long time and at a very low cost. However, forest harvesting, the use of woody biomass as a source of renewable C for different applications, and the relationship with decreasing C emissions have created a highly controversial topic among governments, the scientific community, society in general, and social groups. The main objective of this review is to highlight the importance of C, forests, and biochar, including the benefits of C sequestration to decrease the impacts of climate change and promote sustainable forests and healthy soils in the future. The main findings show strong evidence that climate-smart forest management practices are an efficient option for managing C and increasing C stocks. This review suggests that forest management mitigation actions are another efficient C management approach with high potential. The findings show that biochar is a climate-smart tool that contributes to climate change mitigation by increasing soil carbon sequestration and reducing soil GHG emissions, including other associated benefits.

Keywords: carbon; climate change; sequestration; mitigation; biochar



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1. Introduction

Carbon (C) is one of the most common elements in the universe and on Earth, is the fourth most abundant element by mass, and is the basic building block of humans, animals, plants, and soils [1]. Carbon abundance in organic compounds and polymers makes it the chemical foundation of all life. There are one million organic compounds containing only C and hydrogen (H). When a C atom combines with two oxygen (O) atoms, it forms carbon dioxide (CO₂), one of the greenhouse gases (GHGs) causing warming on Earth and influencing climate change [2]. Carbon dioxide is one of the anthropogenic GHG emissions responsible for increased temperatures that influence climate change on Earth [3].

There is widespread recognition of climate change and its impacts on humans, plants, and animals. Increasing temperatures are linked to extreme environmental disturbances all over the world, such as extreme droughts, hurricanes, snowstorms, and intense precipitation, among others. These disturbances cause environmental imbalances in forest ecosystems affecting their health, vigor, and productivity. Forest consequences are manifested as widespread or prolonged insect and disease attacks, high tree mortality, and

increases in extreme wildland fires, with further negative effects on the soil, ecosystem services (e.g., erosion and water storage), and rural communities. Further, changes in precipitation patterns may decrease soil organic C (SOC) pools, structural integrity, and nutrient cycles, with adverse impacts on biomass productivity, biodiversity, and the environment [4].

The International Paris Agreement (2015) seeks to limit the increase in average global temperature to 2 °C, with efforts to limit the increase to 1.5 °C. Controlling and mitigating CO₂ emissions are a priority for sustainability and global economic development, but also for sustainable natural resources. Forests and soils provide climate forcing feedback [5] that helps move C from atmospheric to terrestrial pools. However, there is a societal lack of awareness about the importance of C, its role in climate change, and the need to decrease atmospheric C. Although awareness about the impacts of climate change on urban populations is increasing, there are many people who do not fully understand the impacts caused by increased temperatures. Notwithstanding these misunderstandings, leaders representing a majority of countries have recognized the urgency of taking action to limit global temperature increases. This is the goal of the agreement signed by 196 countries at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. However, to limit global warming to 1.5 °C, GHG emissions must reach their highest value before 2025 and begin to decline by 43% until 2030 [6].

Carbon, forests, and biochar are highly interrelated by a common element (C). Their interactions are a potential solution to help mitigate the impacts of climate change and support the current international policies to limit the increase in temperature to 1.5 °C by the end of this century. The objective of this systematic literature review is to highlight the importance of C, forests, and biochar, including the benefits of C sequestration to decrease the impacts of climate change and promote sustainable forests and healthy soils into the future.

2. Historic Atmospheric Conditions

The amount of CO₂ in Earth's atmosphere has been correlated with the increase in temperature causing global warming. Many studies have described this correlation through reconstruction studies of Earth's historical atmosphere characteristics by using ice cores. The amount of atmospheric CO₂ four billion years ago is unknown, but it is believed to have been as much as 100 times the current atmospheric level. This would have been necessary to keep the Earth's surface temperature above freezing because of reduced solar luminosity [7,8]. Three billion years ago, the amount of CO₂ in the atmosphere was estimated between 25 and 50%. However, the Earth was not warmer because of the presence of lower nitrogen (N) partial pressure, resulting in a lower surface temperature that allowed for glaciation [9].

From the Middle Miocene to Pleistocene (23 million to 5.3 million years ago), global CO₂ levels declined by more than 50 parts per million by volume (ppmv), suggesting that when CO₂ concentrations decrease, temperatures also decrease [10,11]. In the Late Pliocene (3.264 to 3.025 million years ago), atmospheric CO₂ concentrations were comparable to present-day values (~400 ppm), and estimated global mean temperatures were elevated by 2–3 °C relative to the pre-industrial period [12].

The lowest CO₂ concentration during eight glacial cycles, as measured in an ice core that spanned the late Quaternary (650,000 and 750,000 years before present day), ranged from 10 ppmv equivalent to 172–300 ppmv [13]. Further, atmospheric CO₂ concentrations from 430,000 years ago, as measured on the Dome Concordia ice core, found that the partial pressure of atmospheric CO₂ was within the range between 260 and 180 ppmv, showing that CO₂ was stable through six glacial cycles and that the Antarctic climate was rather constant over this same interval [14]. However, assessments conducted 10 years ago indicated that during the last 800 thousand years, atmospheric CO₂ ranged from 300 ppm in the interglacial period to a minimum of 180 ppm in the glacial periods. However, in 2011,

measurements from ice cores revealed GHG concentrations of 390.5 ppm of CO₂, exceeding the range of measurements for the past 800 thousand years [15].

Since the beginning of industrialization, the amount of atmospheric CO₂ has progressively increased from ~280 ppmv to ~368 ppmv in 2001 [16]. The National Oceanic and Atmospheric Administration (NOAA) pointed out that in 2022, global average atmospheric CO₂ was 417.06 ppm, setting a new record high, in May 2023, it was at 424 ppm [17], and it is currently estimated at 422.5 ppm [18]. The measured increases have resulted in 2023 being the warmest year on record, with a temperature that is approximately 1.5 °C above pre-industrial levels [19].

Terrestrial and Atmospheric C Exchange

Although it is important to understand atmospheric conditions, understanding C exchange between the land and atmosphere is also critical since the amount of C on Earth has not changed for millions of years [20].

Terrestrial C has been found in analyses of the oldest rocks on Earth and indicates that water-laid sediments, with an age of 3.8 billion years, contain organic C (OC) and carbonate minerals. In addition, microfossils and other sedimentary features convincingly demonstrate that life had arisen on Earth by that time, indicating that based on the distribution of ¹²C and ¹³C, living organisms started the global C cycle. These data, along with the presence of sedimentary carbonates, indicate that there was CO₂ in the Earth's atmosphere at that time [21].

All C forms (gas, liquid, and solid) are stored (sink) or released (source) through the respiration of living organisms and by human activity, primarily when fossil fuels are burned, and matter transformations occur [22]. Movement from one C form or pool to another occurs when it is transformed or combined with other minerals or gasses (e.g., calcium carbonate (CaCO₃), dolomite (CaMg(CO₃)₂), bicarbonate (HCO₃[−]), carbonate ion (CO₃^{2−}), CO₂, methane (CH₄), and formaldehyde ((CH₂O)_n). Each C pool has varied amounts of organic and inorganic C, and the residence time of each pool varies from years to centuries [23].

The lithosphere (the rocky outer part of the Earth), with 10²³ g C, is the largest reservoir of C contained in sedimentary rocks as carbonate minerals, and this C is considered inactive [23] and not addressed in this review.

Active C reservoirs (Figure 1) contain approximately 47,972 Pg C, which is separated between the atmosphere with 829 Pg C, the terrestrial biosphere with 6690 Pg C, and the ocean with 40,453 Pg C [24]. Soils represent the largest terrestrial OC pool and will likely drive the C climate feedback in the coming centuries. Although the amount of C in active reservoirs is maintained in a near-steady state by slow geological processes, rapid biogeochemical processes can result in redistribution among the pools (e.g., C from fossil fuels (inactive) added to the biologically active reservoirs during combustion) [25].

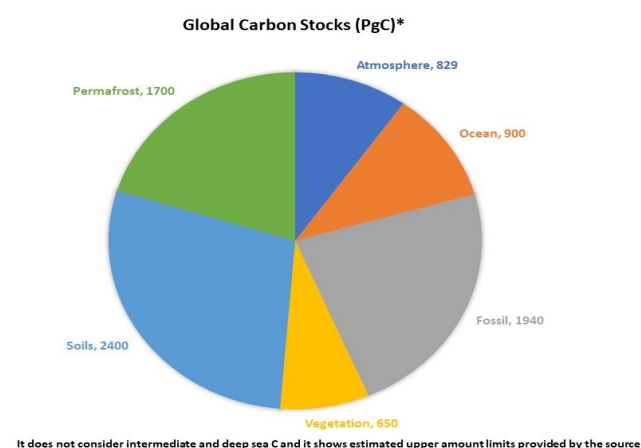


Figure 1. Global C stock (Pg) pools * [24].

The degree to which GHGs affect the climate is dependent on how much heat that particular gas absorbs and reradiates [26]. The atmosphere naturally contains GHGs, but they are increased by human activities. The most influential GHGs on the global warming potential (GWP) are H₂O vapor, CO₂, nitrous oxide (N₂O), CH₄, and ozone (O₃). Methane (23×) and N₂O (296×) have greater potential than CO₂ to increase Earth's temperature. In the absence of a natural greenhouse effect, the heat emitted from Earth would go directly into space and the average surface temperature of 14 °C would be as low as −18 °C [26]. Current global atmospheric CO₂ concentrations are greater than 400 ppm and the magnitude of climate change beyond the next few decades will depend on the amount of GHGs (especially CO₂) emitted globally [27]. Without major reductions in emissions, the increase in annual average global temperature relative to pre-industrial times could reach 9 °F (5 °C) or more by the end of this century. With significant reductions in emissions, the increase in annual average global temperature could be limited to 3.6 °F (2 °C) or less [27]. Since the 1950s, annual emissions from burning fossil fuels have increased every decade, from close to 11 billion tons of CO₂/yr in the 1960s to an estimated 36.6 billion tons of CO₂ in 2022 [17].

In addition to geological processes, C is assimilated into vegetation through photosynthesis and released through respiration. Animals, fires (wild and prescribed), and fossil fuels also release C into the atmosphere. Another factor affecting the C cycle is that it is generally 50% of the dry weight of living organisms and when they die, this C is moved into another pool (terrestrial or atmospheric). Further, in the ocean sink, there is passive absorption of CO₂ and associated dissolution, mixing C from algae and animal biomass, and dissolved CO₂ and carbon-containing plant and animal matter. When atmospheric C pools increase, particularly with CO₂ and CH₄, then these GHGs increase global temperature [28,29]. Other assessments indicate that from 2021 to 2022, global GHG emissions increased by 1.2 percent, reaching 57.4 gigatons of CO₂ equivalent [30].

3. Forest Vegetation and Soil

Reducing GHG emissions alone is not sufficient to avoid atmospheric temperature increases, and therefore, natural climate solutions (e.g., forests, high C biochar) must also be used to mitigate climate change. Forests are estimated to cover 4.5 billion ha and equal approximately 31% of the Earth's total land area [31–33]. Tropical forests comprise 45% of the total area, followed by boreal forests at 27%, temperate forests at 16%, and subtropical forests at 11% [34].

Forest vegetation accounts for 92% of all terrestrial biomass globally, storing approximately 400 Gt of C [35], although the more recent literature indicates that forest C stocks are much larger at 662 Gt [36]. Forests are a large C sink in most places because net forest C uptake is greater than losses associated with harvesting or wildfires, and they absorb a large portion of anthropogenic CO₂ emissions [37]. Data from a 20-year (2001–2019) 30 m resolution study that used ground and Earth global observation data for mapping annual forest C emissions and removals confirm the importance of forests as a net C sink. During the 20-year study, the C sink was calculated as -7.6 ± 49 Gt CO₂e/yr, indicating a balance between gross CO₂ removals (-15.6 ± 49 GtCO₂e/yr) and gross emissions from deforestation and other disturbances (8.1 ± 2.5 GtCO₂e/yr) [38].

Forest harvest operations change the amount of aboveground C, but they can also change soil physical, chemical, and biological properties that subsequently alter below-ground C pools. Sustaining the soil C stock can maintain soil fertility and water-holding capacity, leading to increased aboveground productivity [39]. A detailed review of the impact of various forest management practices on soil C pools can be found in Mayer et al. [39].

Forests are an important means of capturing large amounts of C at low cost, because carbon can be sequestered through the growth of trees [40], especially when compared to other C sequestration options such as geologic sequestration. One potential option to sequester atmospheric CO₂ is biological sequestration using photosynthesis to remove

atmospheric C and sequester it for several decades in living biomass and mass timber structures [41]. Promoting photosynthesis of existing forest trees through active forest management to increase forest ecosystem resilience and decrease competition between plants is an available method to reduce atmospheric CO₂. More options for biological C removal also could be achieved through afforestation, reforestation, and urban forestry [42]. Moreover, utilizing forest residues from logging operations for different products like cross-laminated timber, pulp for paper, wood pellets, biofuels, biochar, and other products could enhance the opportunities for removal and long-term sequestration of C [43].

In the case of forest management, the sustainability and long-term capacity of forest ecosystems to capture and store C depends largely on their health, productivity, resilience, and adaptive capacity. Forest ecosystems are dynamic and are affected by multi-year droughts, insect and disease epidemics, wildfires, catastrophic storms, and human activity. For example, storing C in overly dense forests that remain unthinned increases the risk of losing the C through fire and the decomposition of fire-killed trees following large wildfires, as well as affecting the vegetation dynamics and influencing future forest vegetation composition. Dense unthinned stands are less vigorous and more susceptible to insect attack (largely documented in the book on forest stand dynamics by Chadwick and Larson [44]).

Traditionally, forest management was focused on optimizing the volume of wood harvested per surface unit. In the case of C, the same approach can be taken, and therefore, optimizing, not maximizing, C capture in forest ecosystems can be a sustainable, long-term solution for responding to climate change that sustains other forest ecosystem services. Forest ecosystems that are capable of adapting to changing conditions will capture C and store it more securely over the long term while also furnishing woody materials to help reduce fossil fuel use, when one of the uses is for producing bioenergy [45]. Atmospheric CO₂ limited by terrestrial C sequestration is an ecosystem service with both social and economic value, as it can help limit climate warming [46].

Globally, soils store two to three times as much C in organic form as in the atmosphere, and soil stocks exceed those in plants in most climatic regions [46]. Soil OC can persist for decades, or longer, and is considered a stable C pool. The ability to store C in the soil is one reason there are many efforts to increase soil C. In a 2007 assessment, the combined mineral and surface organic matter C stocks in boreal forests was 202 Pg, in temperate forests, it was 69 Pg, and in tropical forests, it was 155 Pg, and these soil stocks comprise 30–70% of ecosystem C [47]. However, the forest harvest method and intensity can influence both above and belowground C stocks [48,49].

The benefits of C sequestration include the forests' ability to store significant amounts of C both above and belowground, which makes it imperative to understand how humans alter C pools. Understanding the linkages among the various C pools and management can help reduce wildfire risk, increase water infiltration, retention, and availability, provide habitat for wildlife and other macro and microorganisms, and sustain biodiversity [43].

Overall, land use practices have the potential to alter the global distribution of C, contributing as much as 20% of global C emissions [50]. Deforestation is one activity that can increase atmospheric CO₂, with the annual forest loss from 2010 to 2020 estimated to be 4.74 million ha per year globally [34]. The projected amount of CO₂ released through deforestation was estimated at 3.9 billion tons per year in 2022.

The afforestation of degraded land can restore ecological functions and sequester atmospheric C. In addition to C sequestration, afforestation helps many communities restore a source of food and fiber while also supplying a source of firewood for cooking [51]. In addition, afforestation on cropland may result in significant C stocks over 100 years [52]. However, Nave et al. [53] indicated that at least 35 years are required to significantly increase SOC content and to achieve ~15% increase in soil C stocks could take 100 years. Increased aboveground growth increases litterfall to build the surface organic horizons. This layer is susceptible to disturbances (e.g., wildfire and harvesting), and therefore, increasing mineral soil C pools is also important. Specifically, mineral soil C sequestration can be high when broadleaved species are planted [54].

Many forest management practices can increase soil C pools over time, especially those that balance the volume of material aboveground with the ability of the soil to support nutrient cycling, water supply, and microbial diversity. For example, afforestation has been shown to increase soil C over decades [55], while clearcut harvesting results in a loss of soil C, particularly in the surface organic horizons [56]. The need for food and fiber from forest stands means that they will be harvested at some point in the future. One method to retain ecosystem C on-site after harvesting, insect or disease outbreak, or wildfire is to retain coarse (>7 cm diameter) woody debris. This material is a significant C source, but the timeframe for incorporation into the soil can be decades to centuries [57]. Depending on the climatic regime, this pool could also be lost to decomposition and have little benefit to the soil [58]. Considering these facts, it is critical to develop additional methods to increase forest soil C.

There are also forest management technologies to increase C sequestration. As noted previously, C retention and silvicultural practices that manage forest-growing space to promote optimum vegetation growth increase aboveground C sequestration. For example, improved forest management can increase C sequestration from 0.03 to 1.6 Gt/yr and afforestation and reforestation efforts can increase C sequestration in a range from 0.001 to 2.25 Gt/yr of CO₂ for the United States [42]. Afforestation, with reduced deforestation and sound forest management, could vary the amount of C sequestered globally from 1.9 to 5.5 Gt of CO₂e per year in 2040 [59].

4. Biochar from Low-Value Woody Residues

Large amounts of charcoal remain in soils today as relics from indigenous burning or past wildfires. It is estimated that the total C storage of charcoal in soil is as high as 250 Mg C ha⁻¹ m⁻¹ compared to typical values of 100 Mg C ha⁻¹ m⁻¹ in Amazonian soils derived from similar parent material [60]. Globally, up to 12% of anthropogenic C emissions (0.21 Pg C) can be offset annually in soil if slash-and-burn agriculture is replaced by slash-and-char methods, and it is estimated that by 2100, this change from burning to charring could increase C sequestration to between 5.5 and 9.5 Pg C yr⁻¹ [61]. Further, adding biochar to soils can result in global CO₂ removal, with the potential to remove 6.23 ± 0.24% of total GHG emissions in the 155 countries studied over a 100-year timeframe (base year 2020) [62]. The authors also pointed out that biochar could remove more than 10% of national emissions in 28 countries.

Biochar applications to forest soils are a rapid method to increase soil C and mitigate atmospheric GHGs, particularly CO₂. This, combined with sustainable harvesting, is a path toward for climate-smart forest operations. In addition to biochar increasing C sequestration when combined with sustainable biomass production, this can be a C-negative opportunity and therefore used to actively remove CO₂ from the atmosphere, with potentially major implications to mitigate climate change [63–67]. Biochar is a C-rich material formed through thermal decomposition of biomass at high temperature (<700 °C) under reduced oxygen conditions [62,68,69]. When producing biochar from organic materials, the proportion of the amount of biomass transformed into carbon as total solid carbon in biochar varies from approximately 5% when using gasification technologies to approximately 35% when using slow pyrolysis technologies [70]. When added to the soil, biochar remains relatively stable for an extended period of time [71] when determined by the oxygen O/C ratio. When the O/C is lower than 0.2, then the biochar half-life is approximately 1000 years [72]. Biochar longevity is a result of a large proportion of condensed aromatic C [73].

Biochar is particularly well suited for improving degraded soils and improving ecosystem services. However, knowledge of biochar and soil properties is critical for developing application rates that affect plant productivity [74]. Biochar can improve soil physical, chemical, and biological properties while also reducing soil GHG emissions and subsequently stabilizing C pools [63,75,76].

Biochar also has potential applications in waste management, renewable energy, C sequestration, GHG emission reduction, and soil and water remediation, but its best

use in forestry is in the potential for enhancing soil health and C sequestration. Place-based biochar production and its use on local degraded soils is one strategy that, when combined with various silvicultural treatments, can restore a variety of ecosystem services, in addition to building the soil C stock [64]. Biochar can improve water quality, bind heavy metals, decrease toxic chemical concentrations, and improve soil health to establish sustainable plant cover that results in less soil erosion, leaching, or other unintended, negative environmental impacts [65]. In addition to applying untreated biochar to degraded soils, there has been efforts made to design biochar tailored for specific environmental hazards. For example, to increase the adsorption capacity of biochar, a bimetal-doped biochar was created as an absorbent to better remove Hg from contaminated substrates [66].

During all forest harvest operations, there is a large volume of non-merchantable woody residues that are generally left in a pile and burned. Burning these piles also creates smoke, releases CO₂ into the atmosphere, can cause long-term damage to the soil, and can effectively eliminate forest vegetation production in that area. However, the production of biochar from the non-merchantable woody residues can occur at a variety of scales that range from small-scale conservation burns to fixed bioenergy facilities. Other C sequestration opportunities for both merchantable and non-merchantable woody biomass include combining bioenergy production with C capture and sequestration, which can lead to net negative emissions as the C stored in photosynthesizing biomass is sequestered rather than released into the atmosphere [42].

In summary, depending on the method used to create biochar, technologies exist to generate heat, create negative C emissions, and sequester C. Biological C sequestration can be achieved through changes in forest practices such as afforestation, the application of biochar to soil, and the combination of biochar and bioenergy production with C capture and storage, where biochar has a moderate potential for delivering negative emissions which are estimated to be about 0.7 Gt of C_e per year [77]. In addition to the potential soil benefits of biochar, other co-products of combustions, such as bio-oil and biogas, can provide climate change mitigation benefits.

5. Discussion

There is no doubt that changes in the C balance between atmospheric and terrestrial sources are the cause of increased CO₂ in the atmosphere [42,78]. For example, burning fossil fuels (terrestrial source) was estimated to contribute 68% (37.5 GtCO₂) of the total GHG emissions (atmospheric sink) in 2018 [79]. Alone, natural resource management will not be enough to decrease global warming through biological sequestration and climate-smart practices, but it could make a large contribution to mitigating climate change impacts if there is an inclusion of increased biochar production and its application as one of the climate-smart tools.

Dynamic forest management techniques consider the cumulative effects at temporal and space scales. Across time, it factors in management risk, severity, scale, and the likely outcome of harvest operations. Natural disturbances, especially wildfires, insect and disease outbreaks, and prolonged drought, threaten resource sustainability and increasingly disrupt our ability to implement forest management programs. Because of the volume of standing dead trees killed by insects, disease, and drought, wildfires are the existential threat to life and property and are a major cause of GHG emissions. Globally, 3 to 5 million km² per year are affected by landscape fires which emit 2.2 Pg/yr of C to the atmosphere. However, a significant portion of the burned biomass remains as standing dead trees or on the soil surface as pyrogenic C. Over time, pyrogenic C accumulates in soils, contributing to C sequestration, which has been estimated to be approximately 12% of the total C emissions from landscape fires in the world [80]. In boreal forests, increasing fires are result of warmer and drier fire seasons. Boreal fires normally account for 10% of the global C emissions, but in 2021, this increased to 23% (0.48 billion metric tons) and was the highest increase in the last 21 years [81]. A recent example was the 2023 Canadian wildfire that burned nearly 20 million hectares and resulted in the release of 290 megatons of C from May to August.

This represented over 25% of the global total for 2023, as reported in August [82]. One way to decrease C emissions and the intensity of damage to the forests from wildland fires is sustainable C management. This involves effectively managing forest and soil C stocks by restoring, maintaining, and enhancing health and productivity through silvicultural practices such as the application of climate-smart practices to balance stand density and disrupt the ability of fire to be carried through the vegetation, decrease fire intensity, and reduce C emissions. The results of these practices create growing conditions that enhance forest ecosystem resistance and resilience to climate change.

An integral factor of climate-smart forest management is that wood products, which are high in C, can be considered another method to retain C in the terrestrial pool. Climate-smart actions can also decrease supply chain emissions. Assessments have demonstrated that in 2007, the net emission and removal effect of CO₂ in wood products was 424 million tons of CO₂e, offsetting 86% of the GHG emissions from manufacturing wood products and close to 50% of the value chain total emissions [59]. More recent assessments indicate larger global impacts of the harvested wood products with an annual potential of 2.8 Pg/yr of C storage [83].

The National Academy of Sciences [77] and several other authors [43,84–87] emphasize that some management strategies for forests, grasslands, or soils impact their ability to absorb and sequester C. Actions that restore forests to healthy and productive conditions will ensure the long-term maintenance and transformation of forest C stocks. Responsible and sustainable managed forests result in healthy forests with an increased resistance, resilience, and capacity to mitigate and adapt to the impacts of climate change and increasing C sequestration. However, when forests are mismanaged through degradation or deforestation, it could result in the release of up to 20% of the global C emissions [88]. Although forests are not the whole solution, they are important for solving the climate change crisis, together with other sustainable alternatives such as wood-based renewable energy as a substitute for fossil fuels. As noted previously, forest management options such as reforestation, afforestation, reducing deforestation, the application of biochar to soil, and employing practices that improve soil health are all climate-smart actions to improve terrestrial C sequestration.

Currently, climate-smart forest management uses a threefold approach to climate change: adaptation, mitigation, and restoration of forest ecosystems. Restoration includes conditioning and repairing key ecosystem functions to increase resilience to stresses and uncertainties associated with extreme climatic patterns. The focus of climate mitigation is to sequester additional C belowground through the increased production and use of biochar in combination with forest practices. Examples of adaptation and mitigation actions to restore healthy, resilient forest and grassland ecosystems while also actively managing terrestrial C stocks over time are as follows:

- Manage stand density to decrease competition for space, water, and nutrients, and to increase resilience to droughts, insects, and disease, thereby decreasing mortality, wildland fire risk, and vulnerability to extreme weather events.
- Where possible, control pest outbreaks when they occur outside the norm.
- Restore forest ecosystems impacted by catastrophic disturbances such as wildland fires, hurricanes, and other disturbances, consistent with land management laws and regulations.
- Develop programs that enhance C sequestration potential through afforestation, reforestation, and practices that increase and maintain vegetation productivity and ecosystem health.
- Encourage cities to retain green space and to plant and maintain trees.
- Use available tools to understand management impacts on C stocks and fluxes, such as exploring the possibilities to increase rotation length, and the implementation of best management practices to decrease impacts on C soil pools to protect biodiversity and decrease erosion.

There are synergies to be gained from combining silvicultural prescriptions for wildfire risk reduction or for creating healthy forests with biochar production and use at a variety of scales. Biochar can be a method for C sequestration while also building resilient soil that supports healthy forest growth. On-site production used instead of burning large piles also increases C sequestration. There are numerous options for using biochar on local degraded soils, but if produced in large quantities, it could be transported to agricultural sites to obtain the associated benefits. The concomitant benefits of using biochar are C sequestration, increased water-holding capacity and nutrient retention, decreased erosion and GHG emissions, and other ecosystem services provided by a healthy soil.

Biochar is now reaching economic importance in the global biochar market and is expected to reach USD 3 billion by 2025. The Grand View Research, Inc. (GVRI) report indicates that increasing consumption of organically grown food is a major factor driving market growth. This, combined with a growing awareness regarding the advantages of biochar as a soil amendment, is further supplementing the demand for the global biochar market [89]. A more recent assessment indicates that the global biochar market was valued at USD 1.6 billion in 2021 and is expected to reach USD 5.2 billion in 2030, growing with a compound annual growth rate of 13.53% for the forecasted period [90]. These studies show the potential importance of producing biochar for agricultural applications only and do not include the benefits of biochar for sustaining forest soils and vegetation or restoring degraded mine soils.

There is controversy surrounding forest tree removal at local, regional, and global scales. The opinions about C storage in forest sites revolve around the removal of either dead or live trees. There are also strong opinions about the impacts of harvesting on forest soil C, soil erosion, water retention, and biodiversity. Other relevant objections relate to not cutting down trees in old-growth forests because of diverse views on esthetics, biodiversity, and C. There are also different opinions surrounding the use of harvested trees for creating pellets, torrefied wood, cellulosic biofuels, and biochar. However, biochar is usually created from unmerchantable woody residues or as a byproduct of other production systems and therefore is not part of high-value wood products. In general, the strongest points of disagreement are related to C neutrality and C debt, with different scientific and societal opinions.

Carbon neutrality means that bioenergy is an integrated part of the C cycle through a forest stand rotation, and it suggests that trees are equally effective in preventing the accumulation of atmospheric CO₂, if they are a living tree, or the C is sequestered in a wood building [91]. Various countries' governments address C neutrality concerns by enforcing forest C sequestration policies to ensure that they are C neutral, that forest C stocks are maintained, and that natural forest areas are not converted to forest plantations or other land uses. The legal framework for forest biomass C neutrality was stipulated by the United States Government [92] in the Consolidated Appropriations Act, 2018 (H. R. 1625-348), for policies relating to biomass energy section 431. In addition, C neutrality of woody biomass for energy production in the United States of America was detailed in a statement issued by the Environmental Protection Agency [93].

Carbon neutrality was upheld by the IPCC's [94] accountability system for C accounting from forests and it has been confirmed by the IPCC's assessments from 2011 and 2018 [95,96]. In addition to the IPCC accepting C neutrality of woody biomass, the European Union has accepted the concept since 2009 [97]. Currently, the European Union supports the concept of woody biomass as C neutral as long as the raw material comes from sustainable forest management sources with chains of custody certified under the current REDII directives enacted by the European Commission [98]. This implies that all wood bioenergy will have C emissions accounted for factors such as transportation or processing at various stages in the production cycle, regardless of the C neutrality assumption. With these policies in place, the Paris Agreement signatory countries [99] have endorsed nature-based forest management practices for C sequestration and have included them in their national contributions toward reducing net C emissions reports [100].

Despite all of these policies and scientific advances made about C knowledge and the actions that could be taken to limit global temperature increases, controversy persists. The utilization of forest biomass for renewable energy production as a C-friendly option is still challenged, but sustainable forest management and increasing tree cover is still a need in many countries. Options are available to promote sustainable forest management, enjoy food and fiber benefits, maintain healthy forests, and continue enjoying ecosystem services while also decreasing the impacts of climate change as suggested in this review.

6. Conclusions and Future Directions

- There is strong evidence that climate-smart forest management practices are an efficient option for managing C, increasing C stocks, decreasing impacts of climate change, and promoting sustainable forest ecosystems with other associated benefits.
- Forest management actions, such as afforestation, reforestation, restoration, and utilization of woody biomass residues for biochar, are efficient C management approaches with high mitigation potential.
- Biochar is a climate-smart tool that contributes to climate change mitigation, increasing soil C sequestration, reducing soil GHG emissions, storing water, and providing other associated benefits.

Biological C sequestration is a critically important tool to increase the terrestrial C pool. Current technological alternatives for establishing and manipulating vegetation to enhance C sequestration and the utilization of byproducts could be improved by additional research. New research could include technology transfer tools to support climate-smart decisions to increase forest practice success in increasing C storage (e.g., afforestation and reforestation) and assessing potential species that are better adapted to future environmental conditions.

Innovations in using woody residues from forest management practices to create biochar are in place, but new developments or technological advances are another avenue for research and development. In addition, knowledge about using woody biomass or biochar as a substitute for fossil fuels is still needed. Additional long-term studies that evaluate different biochar in different soils and their C sequestration potentials are also critical for moving this tool forward. Other research needs include the optimization of forest operations with electric logging equipment and charging stations, methods to decrease transportation costs, the development of innovative wood processing hubs, and economic analyses for forest innovations markets, including biochar. The assessment of current policies and regulations can identify potential barriers for improving supply chain operation processes. A significant amount of biochar research has been conducted in recent years, but still, there are specific research areas that need to be addressed, such as long-term woody biochar and soil–plant interactions, the assessment of biochar types for different purposes including highly polluted soil remediation, chronic wasting disease in cervids, low OC soils, and other agricultural or industrial uses of biochar created from woody biomass.

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