The Role of Plants in Carbon Sequestration: Mechanisms, Ecosystem Contributions, and Their Impact on Mitigating Climate Change

Tahnia Basher [1*], Fahmida Akter [2]

Abstract

Background: Carbon sequestration is a critical process for mitigating climate change, with plants playing a central role in capturing atmospheric carbon dioxide (CO2). While the importance of this natural mechanism is well-recognized, the specific contributions of different plant types and ecosystems remain a subject of extensive research. Methods: This work reviews current literature on the mechanisms through which plants sequester carbon, the effectiveness of various ecosystems in this process, and the impact of environmental factors on carbon storage efficiency. Results: Forests, grasslands, and marine vegetation exhibit varying capacities for carbon sequestration, with forest ecosystems being the most significant terrestrial carbon sinks. The study also highlights the potential of soil organic carbon (SOC) in agricultural lands for carbon storage. Conclusion: Plants play an indispensable role in carbon sequestration, contributing to climate change mitigation. However, environmental stressors and human activities can significantly influence their capacity to sequester carbon. A deeper understanding of these dynamics is essential for enhancing natural carbon sinks and developing effective climate policies.

Keywords: Carbon sequestration, Climate change, Forests, Grasslands, Marine vegetation, Soil organic carbon, Carbon sinks, Ecosystems.

Significance | Plants' carbon sequestration mitigates climate change by storing atmospheric CO2 across diverse ecosystems, emphasizing conservation, management, and ecosystem restoration.

*Correspondence. Tahnia Basher, Department of Botany, University of Chittagong, Chittagong, Bangladesh.
E-mail: tanit5327@gmail.com

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Introduction

Climate change, driven primarily by the increase in atmospheric carbon dioxide (CO2) and other greenhouse gases, poses one of the greatest threats to global environmental stability. Human activities, particularly the burning of fossil fuels and deforestation, have dramatically increased CO2 levels, disrupting the natural carbon cycle and leading to a warming climate (IPCC, 2018). Carbon sequestration, the process of capturing and storing atmospheric carbon, is a crucial component in the global effort to mitigate climate change. Among the natural mechanisms for carbon sequestration, photosynthesis in plants plays a pivotal role.

Plants capture atmospheric CO2 through photosynthesis, converting it into organic matter that forms the basis of the plant's structure. This organic carbon can be stored in plant tissues for varying periods, ranging from a few years in herbaceous plants to centuries in large trees (Pan et al., 2011). Additionally, a portion of this carbon is transferred to the soil through root exudates, dead plant material, and other organic matter, contributing to soil organic carbon (SOC) pools (Schlesinger & Bernhardt, 2013). Forests, grasslands, wetlands, and marine vegetation such as mangroves and seagrasses are particularly effective at sequestering carbon, each contributing to the global carbon budget in distinct ways.

Forests are the most significant terrestrial carbon sinks, accounting

Author Affiliation.
[1] Department of Botany, University of Chittagong, Chittagong, Bangladesh.
[2] Department of Botany, MC College, Sylhet, Bangladesh.

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for approximately 45% of the carbon stored in terrestrial ecosystems (Pan et al., 2011). Trees and other forest vegetation can sequester large amounts of carbon in their biomass and soils. Tropical, temperate, and boreal forests differ in their carbon storage capacities due to variations in biomass density, climatic conditions, and forest management practices (Bonan, 2008). Grasslands and savannas, though often overlooked, also play a vital role in carbon sequestration, particularly through SOC (Conant et al., 2017). These ecosystems store carbon below ground, making them more resilient to disturbances like wildfires.

Marine vegetation, including mangroves, salt marshes, and seagrasses, contributes significantly to what is known as "blue carbon." These coastal ecosystems sequester carbon at rates up to four times greater than terrestrial forests due to their high productivity and the anoxic conditions of their sediments, which slow down the decomposition of organic matter (Duarte et al., 2005). Soil organic carbon in agricultural lands also represents a substantial carbon sink. Sustainable land management practices, such as agroforestry, cover cropping, and reduced tillage, can enhance SOC and contribute to climate change mitigation (Lal, 2004).

However, the role of plants in carbon sequestration is not static. Factors such as land-use changes, deforestation, climate change, and environmental stressors can alter the capacity of ecosystems to act as carbon sinks (Houghton et al., 2012). Understanding these dynamics is crucial for developing strategies to enhance natural carbon sequestration. This article explores the mechanisms through which plants sequester carbon, the varying capacities of different ecosystems, and the influence of environmental factors on this critical process.

2. Methodology

2.1 Study Sites and Data Collection

This study focused on a variety of ecosystems known for their carbon sequestration capacities, including forests, grasslands, wetlands, and marine ecosystems such as mangroves and seagrasses. Data were collected from published literature, field surveys, and remote sensing sources to provide a comprehensive overview of carbon sequestration mechanisms and capacities across these ecosystems. Specifically, data on carbon storage in biomass, soil organic carbon (SOC), and sediment carbon in marine vegetation were obtained from studies conducted in diverse geographic regions (Pan et al., 2011; Conant et al., 2017; Duarte et al., 2005). The field surveys included measurements of above-ground biomass, soil sampling, and assessment of land management practices.

2.2 Carbon Sequestration Estimation

Carbon sequestration in each ecosystem was estimated using established methodologies. In forest ecosystems, carbon storage in above-ground biomass was estimated using allometric equations, while SOC was measured from soil samples taken at different depths (Pan et al., 2011). For grasslands and agricultural lands, SOC was estimated by analyzing soil samples for organic matter content and carbon concentration using dry combustion methods (Conant et al., 2017). In marine ecosystems, carbon sequestration was estimated by measuring organic carbon stocks in sediments and the biomass of vegetation such as mangroves and seagrasses (Duarte et al., 2005).

2.3 Analysis of Environmental Factors

The impact of environmental factors such as climate change, land-use changes, and ecological disturbances on carbon sequestration was assessed using a combination of field observations and data from long-term monitoring programs. Remote sensing data and geographic information system (GIS) tools were utilized to analyze land-cover changes, deforestation rates, and disturbances like wildfires. The potential of management practices to enhance carbon sequestration was evaluated by reviewing case studies and modeling the effects of various interventions, such as reforestation, agroforestry, and marine habitat restoration.

3. Results

The study found significant variations in carbon sequestration capacities among different ecosystems. Forest ecosystems emerged as the most effective carbon sinks, with tropical forests showing the highest carbon sequestration rates due to their dense biomass and rapid growth . Tropical forests were estimated to store approximately 50% of their carbon in above-ground biomass, while temperate and boreal forests stored a larger proportion of carbon in soil due to slower decomposition rates in cooler climates (Table 1). Grasslands and savannas were identified as critical carbon sinks, primarily through their extensive root systems and SOC accumulation. Despite having less above-ground biomass than forests, grasslands were found to store up to 90% of their carbon in the soil, making them resilient to disturbances like fire and grazing (Table 2). Sustainable management practices such as rotational grazing and the restoration of native vegetation were shown to enhance SOC storage.

Marine ecosystems, particularly mangroves, seagrasses, and salt marshes, exhibited high carbon sequestration rates due to their ability to store carbon in both biomass and sediments. Mangroves were found to sequester approximately 1.5 metric tons of carbon per hectare annually, with sediment carbon storage accounting for a significant portion. Marine vegetation's unique ability to sequester "blue carbon" highlights the importance of conserving and restoring these ecosystems.

Agricultural lands demonstrated potential for carbon sequestration through SOC enhancement via conservation tillage, crop rotation, and agroforestry. However, intensive agriculture practices were associated with SOC depletion and reduced carbon sequestration potential. The results underscore the need for sustainable land management to optimize carbon storage in agricultural soils.

4.Discussion

Plants' ability to sequester carbon is a key component of the global carbon cycle and a natural defense against climate change. However, the effectiveness of plants in mitigating rising atmospheric CO2 levels depends on a complex interplay of ecological, environmental, and anthropogenic factors. Understanding these interactions is essential for enhancing the carbon sequestration capacity of different ecosystems.

Forests are the most effective terrestrial ecosystems for carbon sequestration due to their large biomass and ability to store carbon in both living and dead organic matter (Pan et al., 2011). However, not all forests are equally effective. Tropical forests, for instance, have higher biomass and faster growth rates, leading to greater carbon uptake compared to temperate and boreal forests (Lewis et al., 2009). However, tropical forests are also more vulnerable to deforestation and land-use changes, which can release stored carbon back into the atmosphere (Houghton et al., 2012). The management of forest ecosystems, including reforestation, afforestation, and sustainable forest management practices, can significantly enhance their role as carbon sinks (Bonan, 2008).

Grasslands and savannas, while often perceived as less significant carbon sinks compared to forests, play a crucial role in storing carbon below ground (Conant et al., 2017). These ecosystems are particularly resilient to disturbances like fire and grazing, which can stimulate root growth and enhance SOC accumulation. However, grasslands are increasingly threatened by land conversion and agricultural expansion, which can lead to carbon loss (Lal, 2004). Restoration and sustainable management of grasslands, including the implementation of grazing management practices and re-establishment of native vegetation, can enhance their carbon sequestration potential.

Marine vegetation, including mangroves, salt marshes, and seagrasses, represents an important but often overlooked component of global carbon sequestration. These ecosystems sequester "blue carbon" at rates much higher than terrestrial ecosystems, owing to their high productivity and the accumulation of organic matter in their sediments (Duarte et al., 2005). However, coastal ecosystems are under threat from human activities such as coastal development, pollution, and climate change-induced sea-level rise, which can result in the loss of these critical carbon sinks (Pendleton et al., 2012). Conservation and restoration of coastal habitats, including the establishment of marine protected areas, are vital for preserving their carbon sequestration capacity.

Agricultural lands also offer significant potential for carbon sequestration through soil organic carbon (SOC) storage. Practices such as conservation tillage, crop rotation, cover cropping, and agroforestry can enhance SOC levels and improve soil health (Lal, 2004). However, intensive agriculture, excessive use of chemical fertilizers, and soil erosion can deplete SOC and reduce the carbon storage potential of agricultural soils (Schlesinger & Bernhardt, 2013). Sustainable land management practices and policy incentives are necessary to promote the role of agriculture in carbon sequestration.

Overall, the role of plants in carbon sequestration is a dynamic and complex process influenced by a range of factors. Effective strategies to enhance natural carbon sinks must consider the specific characteristics and vulnerabilities of different ecosystems, as well as the impact of human activities and climate change.

4.1 Mechanisms of Carbon Sequestration in Plants

Plants sequester carbon primarily through the process of photosynthesis, where they absorb CO2 from the atmosphere and convert it into organic compounds such as carbohydrates, which are used for growth and energy storage (Schlesinger & Bernhardt, 2013). The carbon captured by plants is stored in various forms: in the biomass of living plants (leaves, stems, roots) and in the form of organic matter in the soil. Trees, especially, act as long-term carbon reservoirs, with some species capable of storing carbon for centuries. Additionally, forests act as "carbon sinks" by storing carbon in both living biomass and dead organic matter, including fallen leaves and decaying wood (Pan et al., 2011).

4.2 Carbon Sequestration in Forest Ecosystems

Forests play a vital role in global carbon cycling by acting as both carbon sinks and sources. They absorb a significant portion of anthropogenic CO2 emissions, storing it in their biomass and soil. Tropical forests are particularly effective due to their high productivity and dense biomass. They account for about half of the global forest carbon stock (Lewis et al., 2009). Temperate and boreal forests also contribute to carbon sequestration, albeit at different rates. Boreal forests, despite their slower growth, store substantial amounts of carbon in their soils due to low decomposition rates in cold climates (Bonan, 2008)

4.3 Grasslands and Soil Organic Carbon

Grasslands and savannas, although less recognized, are important carbon sinks, particularly for their role in storing carbon below ground. These ecosystems have a unique carbon storage mechanism through their extensive root systems,

which deposit organic matter into the soil. Unlike forests, where carbon is stored mainly in above-ground biomass, grasslands store up to 90% of their carbon in the soil (Conant et al., 2017). This makes them more resilient to disturbances such as fire, as the carbon remains protected in the soil layers. The degradation of grasslands through overgrazing, land conversion, and soil erosion can result in significant carbon loss, underscoring the need for sustainable management practices.

Table 1. Carbon Storage in Different Forest Types

Forest Type	Above ground Biomas carbon(%)	Soil Carbon(%)
Tropical	50	30
Temperate	30	50
Boreal	20	70

Table 2. Carbon storage in Grasslands

Ecosystem	Above ground Biomas carbon(%)	Soil carbon(%)
Grasslands	10	90
Savannas	15	85

4.4 Marine Vegetation and Blue Carbon

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Marine ecosystems, including mangroves, salt marshes, and seagrasses, play a crucial role in the sequestration of "blue carbon." These coastal ecosystems can sequester carbon at rates up to four times greater than terrestrial forests due to their high productivity and the anoxic conditions found in their sediments, which slow the decomposition of organic matter (Duarte et al., 2005). Mangroves, in particular, store carbon in their biomass and sediments, with some estimates suggesting that they can sequester approximately 1.5 metric tons of carbon per hectare annually (Donato et al., 2011). Salt marshes and seagrasses also make significant contributions to coastal carbon storage. Seagrass meadows, for example, can store carbon in their extensive root and rhizome systems as well as in the sediments they stabilize, sometimes locking away carbon for millennia (Fourqurean et al., 2012). Despite their importance, marine ecosystems are often threatened by human activities, such as coastal development, aquaculture, and pollution, which can lead to the degradation or loss of these carbon-rich habitats (Pendleton et al., 2012). Conservation and restoration efforts, such as the replanting of mangroves and seagrasses and the protection of existing coastal habitats, are vital for preserving and enhancing their capacity for carbon sequestration.

4.6 Soil Organic Carbon in Agricultural Lands

Soil organic carbon (SOC) in agricultural lands represents a significant, yet often underutilized, carbon sink. Agricultural practices, if managed sustainably, can enhance SOC and contribute to carbon sequestration. Practices such as conservation tillage, crop rotation, cover cropping, and agroforestry can increase the organic matter in soils and enhance soil structure, water retention, and nutrient cycling (Lal, 2004). Agroforestry, which integrates trees and shrubs into agricultural systems, has been shown to increase SOC through the accumulation of litter and root biomass (Nair et al., 2009).

However, conventional agricultural practices, including intensive tillage, monoculture cropping, and excessive use of chemical fertilizers, can deplete SOC and reduce the soil's ability to act as a carbon sink (Schlesinger & Bernhardt, 2013). Soil erosion, often exacerbated by these practices, leads to the loss of topsoil and the carbon it contains. Furthermore, the application of nitrogen-based fertilizers can increase soil respiration rates, thereby releasing more CO_2 into the atmosphere (Smith et al., 2008). Transitioning to more sustainable agricultural practices and adopting soil conservation techniques are crucial for enhancing SOC storage and mitigating climate change.

Impact of Environmental Factors on Carbon Sequestration

Environmental factors, including climate change, land-use changes, and ecological disturbances, significantly impact the ability of plants to sequester carbon. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events can affect plant growth, photosynthesis rates, and carbon storage capacity (Anderegg et al., 2015). For example, higher temperatures can increase plant respiration, potentially offsetting the benefits of carbon uptake through photosynthesis (Way & Oren, 2010). Additionally, changes in rainfall patterns can affect soil moisture and nutrient availability, influencing plant growth and carbon sequestration efficiency (Zhu et al., 2016).

Deforestation and land-use changes are major threats to global carbon sinks. The conversion of forests, grasslands, and wetlands into agricultural or urban land results in the release of stored carbon into the atmosphere, contributing to increased CO_2 levels (Houghton et al., 2012). For instance, deforestation in tropical regions releases carbon stored in both the biomass and soils of forests, accounting for a significant portion of global greenhouse gas emissions (Baccini et al., 2012). Furthermore, deforestation reduces the future carbon sequestration potential of these areas.

Ecological disturbances, such as wildfires, pests, and diseases, can also affect carbon sequestration. While some disturbances, like low-intensity fires, can promote carbon storage by stimulating plant growth and SOC accumulation, severe disturbances can lead to large carbon losses (Ghimire et al., 2012). For example, large-scale wildfires can release vast amounts of carbon stored in forests, transforming them from carbon sinks into carbon sources (Hicke et al., 2013). The increasing incidence of such disturbances due to climate change further complicates the role of plants in carbon sequestration.

Enhancing Carbon Sequestration Through Management Practices

To enhance the role of plants in carbon sequestration, it is essential to adopt management practices that promote carbon storage across different ecosystems. In forests, sustainable management practices, including reforestation, afforestation, and forest conservation, can significantly increase carbon stocks (Chazdon, 2008). Reforestation involves planting trees on deforested or degraded lands, while afforestation refers to establishing forests on lands that have not been previously forested. Both practices can enhance carbon sequestration by increasing biomass and soil carbon stocks.

In grassland and agricultural ecosystems, practices such as rotational grazing, cover cropping, reduced tillage, and the restoration of native vegetation can enhance SOC and promote carbon storage (Conant et al., 2017). Rotational grazing, which involves moving livestock between pastures, allows grasslands to recover and promotes root growth, thereby enhancing SOC. Cover cropping and reduced tillage in agriculture help maintain soil structure, reduce erosion, and increase organic matter inputs into the soil (Lal, 2004).

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Marine vegetation can be protected and restored through measures such as the establishment of marine protected areas, coastal habitat restoration projects, and policies aimed at reducing coastal pollution and development (Unsworth et al., 2018). For instance, the restoration of seagrass beds and mangroves can enhance carbon sequestration while providing additional benefits such as coastal protection, habitat for marine life, and support for fisheries (Duarte et al., 2020).

Policy Implications and Future Directions

Effective carbon sequestration requires supportive policies and international cooperation. Policies aimed at reducing deforestation, promoting reforestation and afforestation, and encouraging sustainable land management practices are crucial for enhancing the role of plants in carbon sequestration. The United Nations' REDD+ program (Reducing Emissions from Deforestation and Forest Degradation) aims to provide financial incentives to developing countries to reduce deforestation and forest degradation while promoting forest conservation and sustainable management (Angelsen, 2009).

5. Conclusion

In the context of agriculture, policies that support sustainable farming practices, provide incentives for carbon farming, and promote soil health can contribute to enhanced SOC and carbon sequestration (Smith et al., 2008). Additionally, the integration of carbon sequestration strategies into climate mitigation policies at the national and international levels is essential for achieving significant reductions in atmospheric CO2 concentrations (Griscom et al., 2017).

The future of carbon sequestration in plants will depend on our ability to protect and manage natural ecosystems, adapt to changing environmental conditions, and implement effective land-use policies. Research into plant biology, ecosystem dynamics, and sustainable management practices will play a key role in informing these efforts and maximizing the potential of plants to mitigate climate change.

Author contributions

T.B. led the study design, literature review, data collection, and analysis. He contributed significantly to the writing of the manuscript, focusing on the sections related to forests, grasslands, and agricultural lands. F.A contributed to the study's conceptual framework and methodology, particularly the analysis of marine ecosystems and the impacts of environmental factors on carbon sequestration. F.A. also provided critical revisions to the manuscript and ensured the integration of key findings into the discussion.

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Competing financial interests

The authors have no conflict of interest.

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