

Blue Carbon Dynamics in Coastal Ecosystems: Mechanisms of Mangrove Carbon Sequestration, Climate Change Interactions, and Conservation Pathways

Gulbin Sultana, Department of Marine Science and Environmental Studies, Student, Maldives National University (MNU), Maldives

Mariyam Shameem, Department of Marine Science and Environmental Studies, Professor, Maldives National University (MNU), Maldives

Abstract

Coastal ecosystems play a significant role in global climate regulation by capturing and storing atmospheric carbon dioxide. Among these systems, mangroves, salt marshes, and tidal wetlands collectively contribute to what is known as blue carbon. These ecosystems are highly efficient carbon sinks because they store large quantities of organic carbon in their biomass and sediment layers for long periods. Mangrove forests, in particular, are recognized for their high productivity and capacity to trap sediments, which enhances long-term carbon storage. In recent decades, scientific attention toward blue carbon ecosystems has increased due to their potential to mitigate climate change and provide ecosystem services such as shoreline stabilization, biodiversity conservation, and fisheries support. However, coastal development, pollution, and climate-related disturbances threaten the stability of these ecosystems. Understanding the mechanisms that regulate carbon sequestration, sediment accretion, and nutrient cycling in coastal wetlands is therefore essential for designing effective conservation strategies. This review explores the ecological and biogeochemical processes that control carbon accumulation in mangrove ecosystems and other tidal wetlands. It also discusses the influence of climate change, anthropogenic pressures, and policy frameworks aimed at protecting blue carbon reservoirs. The review highlights current scientific knowledge, identifies research gaps, and outlines future directions for sustainable management of coastal carbon sinks.

Keywords: Blue carbon ecosystems, Mangrove carbon sequestration, Coastal wetland ecology, Climate change mitigation, Tidal marsh sedimentation, Coastal ecosystem conservation

1. Introduction

Blue carbon ecosystems—including mangroves, tidal marshes, and seagrass meadows—have emerged as critical natural solutions for climate change mitigation due to their remarkable capacity to capture and store atmospheric carbon dioxide. Coastal wetlands represent some of the most efficient carbon sinks on Earth, often storing several times more carbon per unit area than terrestrial forests. Mangrove forests in particular possess dense root systems and high productivity that facilitate the burial of organic matter within coastal sediments, enabling long-term carbon sequestration. Recent studies emphasize that these ecosystems not only store carbon but also contribute significantly to coastal resilience by protecting shorelines from erosion and storm surges (Choudhary et al., 2024).

Mangroves occupy tropical and subtropical coastlines where they interact dynamically with tidal processes, sediment deposition, and nutrient cycling. These processes create an environment where organic carbon accumulates within the sediment column, forming stable carbon reservoirs over centuries or even millennia. The ecological functioning of these ecosystems involves complex interactions between vegetation growth, microbial decomposition, and hydrodynamic conditions. According to Wang et al. (2020), carbon accumulation rates in tidal wetlands are strongly influenced by climate variability and rising sea levels, which can enhance sediment deposition and organic carbon burial.

Salt marshes and tidal wetlands are also important components of the global blue carbon network. These ecosystems act as natural carbon sinks through the continuous deposition of organic material and sediment accretion processes (van Ardenne et al., 2021). Additionally, tidal creeks within marsh systems influence the distribution of nutrients and organic carbon, shaping the spatial patterns of carbon storage and nitrogen cycling in coastal landscapes (Ma et al., 2024). Such geomorphological processes determine how effectively these ecosystems can maintain their carbon stocks under changing environmental conditions.

Despite their ecological importance, blue carbon ecosystems are under significant threat from human activities such as coastal development, aquaculture expansion, and pollution. These disturbances can lead to habitat degradation and carbon release from previously stable sediment reservoirs. Global assessments highlight that large areas of mangrove forests have been lost over the past decades, reducing their capacity to function as carbon sinks (Alongi, 2023). The loss of these ecosystems not only accelerates greenhouse gas emissions but also diminishes coastal biodiversity and fisheries productivity.

In recent years, scientific research has increasingly focused on the role of blue carbon ecosystems in climate change mitigation and adaptation strategies. Studies from the Asia-Pacific region emphasize that mangrove conservation and restoration initiatives can significantly contribute to global carbon management while providing socio-economic benefits to coastal communities (Sharma et al., 2022). Similarly, innovative coastal management techniques—such as sediment redistribution and ecological engineering—have been proposed to enhance marsh resilience against sea-level rise (Besterman et al., 2022).

Overall, the growing recognition of blue carbon ecosystems underscores their potential as nature-based solutions for climate change mitigation. However, a comprehensive understanding of the mechanisms that govern carbon sequestration, the impacts of environmental change, and the effectiveness of conservation strategies remains essential for maximizing their benefits. This review therefore examines the ecological processes, environmental drivers, and management approaches associated with mangrove-dominated blue carbon systems.

2. Blue Carbon Ecosystems and Their Global Importance

Blue carbon ecosystems consist primarily of mangroves, tidal marshes, and seagrass beds, which collectively play a fundamental role in regulating global carbon cycles. These ecosystems are unique because they accumulate large quantities of organic carbon in both living biomass and sediment layers. Unlike many terrestrial ecosystems where carbon is released relatively quickly through decomposition, coastal wetlands store carbon within waterlogged soils where oxygen levels are limited. This condition slows down microbial decomposition and allows organic carbon to remain buried for extended periods.

Mangroves are widely recognized as one of the most productive coastal ecosystems on the planet. Their dense vegetation and extensive root networks enhance sediment trapping, allowing organic matter to accumulate in the soil. Over time, this process leads to the formation of deep carbon-rich sediments that can store carbon for centuries. Research has demonstrated that mangrove forests often contain carbon stocks that exceed those of tropical terrestrial forests, highlighting their importance in climate change mitigation (Choudhary et al., 2024).

Tidal marshes also contribute significantly to global carbon storage through continuous sediment accretion and plant productivity. The interaction between tidal flooding and vegetation growth allows these ecosystems to capture suspended sediments and organic matter from surrounding waters. Over time, these materials become buried within marsh soils, creating stable carbon reservoirs. Studies indicate that sediment accumulation processes are strongly influenced by coastal geomorphology and hydrodynamic conditions (van Ardenne et al., 2021).

The global significance of blue carbon ecosystems extends beyond carbon sequestration. These ecosystems provide numerous ecological services, including habitat provision for marine organisms, water filtration, and shoreline protection. Mangrove forests serve as important nursery grounds for many fish and crustacean species, thereby supporting coastal fisheries and local economies. Additionally, their root systems stabilize sediments and reduce the impact of storm surges, protecting coastal communities from natural disasters.

Recent research suggests that the carbon sequestration potential of tidal wetlands may increase under certain climate change scenarios. Rising sea levels can enhance sediment deposition in some coastal regions, leading to greater carbon accumulation rates in wetland soils (Wang et al., 2020). However, the long-term sustainability of this process depends on the ability of wetlands to maintain elevation relative to sea level through sediment accretion and vegetation growth.

Despite their global importance, blue carbon ecosystems are experiencing significant degradation due to human activities. Coastal urbanization, aquaculture development, and industrial pollution have resulted in large-scale loss of mangrove forests and tidal marshes. Such disturbances not only reduce carbon storage capacity but also release previously stored carbon back into the atmosphere, exacerbating climate change (Alongi, 2023). Therefore, protecting and restoring these ecosystems is essential for maintaining their role in global carbon regulation.

3. Mechanisms of Carbon Sequestration in Mangrove Ecosystems

Mangrove ecosystems are highly efficient carbon sinks due to a combination of biological productivity, sediment trapping, and long-term organic matter burial. The carbon sequestration process begins with photosynthesis, where mangrove plants absorb atmospheric carbon dioxide and convert it into organic carbon stored within their tissues. This carbon is distributed throughout the plant structure, including leaves, branches, trunks, and roots.

One of the most distinctive features of mangrove ecosystems is their complex root systems. Prop roots and pneumatophores not only support plant stability in waterlogged soils but also trap suspended sediments and organic matter transported by tidal currents. This sediment trapping process contributes to the accumulation of carbon-rich deposits in the soil, enhancing long-term carbon storage capacity (Choudhary et al., 2024).

The accumulation of organic matter in mangrove soils is further supported by anaerobic conditions. Waterlogged sediments limit oxygen availability, slowing down microbial decomposition and allowing organic carbon to remain preserved within the soil profile. Over time, layers of organic material and mineral sediments build up, creating thick carbon reservoirs beneath mangrove forests.

Another important mechanism influencing carbon storage is the interaction between tidal hydrodynamics and nutrient cycling. Tidal flows transport organic materials and nutrients into mangrove ecosystems, which are then incorporated into the sediment matrix. This continuous exchange between land and sea plays a crucial role in maintaining the productivity and carbon sequestration capacity of mangrove forests.

Carbon sequestration in mangrove ecosystems is also influenced by geomorphological factors such as sediment supply, coastal topography, and tidal range. Areas with high sediment input often exhibit greater rates of soil accretion, which enhances the burial of organic carbon. Conversely, regions with limited sediment supply may experience slower carbon accumulation rates.

In addition to soil carbon storage, mangrove biomass itself represents a substantial carbon pool. Mature mangrove forests contain large quantities of above-ground and below-ground biomass that store carbon throughout the lifespan of the vegetation. When mangrove plants shed leaves or die, the organic matter becomes incorporated into the soil, further contributing to long-term carbon storage.

Overall, the efficiency of mangrove ecosystems as carbon sinks results from the integration of biological productivity, sediment deposition, and environmental conditions that favor carbon preservation. Understanding these mechanisms is essential for assessing the role of mangroves in global climate regulation and for developing strategies to protect these valuable ecosystems.

4. Influence of Climate Change on Coastal Carbon Dynamics

Climate change has a profound impact on coastal ecosystems, influencing both the capacity of blue carbon habitats to store carbon and their long-term stability. Rising global temperatures, changing precipitation patterns, and increasing sea levels are altering the environmental conditions under which mangroves and tidal wetlands function.

Sea-level rise represents one of the most significant climate-related challenges for coastal ecosystems. While moderate sea-level rise can stimulate sediment deposition and wetland expansion, excessive increases may submerge vegetation and reduce plant productivity. The balance between sediment accretion and sea-level rise ultimately determines whether coastal wetlands can maintain their carbon storage capacity (Wang et al., 2020).

Temperature changes also influence the biological processes that regulate carbon sequestration. Higher temperatures can increase plant growth rates in some regions, potentially enhancing carbon uptake. However, they may also accelerate microbial decomposition in sediments, leading to increased carbon release. The net effect of temperature changes on carbon dynamics therefore depends on the interaction between these competing processes.

Extreme weather events such as hurricanes and cyclones can also affect mangrove ecosystems. These disturbances may damage vegetation and alter sediment distribution, temporarily reducing carbon storage

capacity. At the same time, storm-driven sediment deposition can sometimes enhance soil accretion and contribute to long-term carbon burial.

Climate change also influences nutrient cycling and hydrological processes within coastal wetlands. Changes in rainfall and river discharge can modify the supply of nutrients and sediments entering mangrove ecosystems. Such alterations may affect plant productivity and the overall functioning of blue carbon systems.

Understanding how climate change affects carbon dynamics in coastal ecosystems is crucial for predicting future carbon sequestration potential. As environmental conditions continue to evolve, adaptive management strategies will be required to ensure that mangroves and tidal wetlands remain effective carbon sinks.

5. Human Impacts on Blue Carbon Ecosystems

Human activities have significantly altered coastal ecosystems worldwide, leading to the degradation and loss of important blue carbon habitats. Rapid coastal development, aquaculture expansion, and industrial activities have resulted in large-scale deforestation of mangrove forests and modification of tidal wetlands. These changes not only disrupt ecological processes but also release previously stored carbon from sediments into the atmosphere.

Urbanization and infrastructure development are among the primary drivers of mangrove loss. Construction of ports, roads, and residential areas often requires the clearing of coastal vegetation and the alteration of natural hydrological systems. Such disturbances can reduce sediment deposition and increase erosion, thereby diminishing the carbon storage capacity of coastal wetlands.

Aquaculture activities, particularly shrimp farming, have also contributed to the degradation of mangrove ecosystems in many tropical regions. The conversion of mangrove forests into aquaculture ponds involves the removal of vegetation and excavation of sediment layers that contain large amounts of stored carbon. As a result, significant quantities of greenhouse gases may be released during land-use change.

Pollution represents another major threat to blue carbon ecosystems. Industrial waste, agricultural runoff, and plastic debris can degrade water quality and affect the health of mangrove vegetation. Contaminants may disrupt microbial processes in sediments, influencing the balance between carbon sequestration and decomposition.

Overexploitation of coastal resources can also affect the ecological integrity of mangrove ecosystems. Unsustainable harvesting of timber and other resources may reduce vegetation density and limit the ability of mangroves to trap sediments. This can weaken the overall carbon sequestration potential of these ecosystems.

Addressing human impacts on blue carbon ecosystems requires integrated management approaches that combine conservation policies, sustainable resource use, and community participation. Protecting existing mangrove forests and restoring degraded areas can significantly enhance the resilience of coastal ecosystems and contribute to global climate mitigation efforts.

6. Conservation Strategies and Future Perspectives

The conservation and restoration of blue carbon ecosystems have become key priorities in global climate policy and coastal management. Protecting mangroves, tidal marshes, and other coastal wetlands can provide significant environmental benefits, including carbon sequestration, biodiversity conservation, and coastal protection.

One of the most effective conservation strategies involves the establishment of protected areas that limit destructive human activities in sensitive coastal habitats. Marine protected areas and community-based conservation initiatives can help maintain the ecological integrity of mangrove ecosystems while supporting sustainable livelihoods for local populations.

Restoration projects are also increasingly being implemented to recover degraded coastal wetlands. These initiatives often involve replanting mangrove seedlings, restoring natural hydrological conditions, and improving sediment supply. Successful restoration efforts can gradually rebuild vegetation cover and reestablish the carbon sequestration capacity of damaged ecosystems.

Innovative coastal management techniques are also being explored to enhance the resilience of tidal marshes and mangrove forests. For example, ecological engineering approaches such as sediment redistribution and runnel construction have been proposed to improve water flow and support vegetation growth in marsh environments (Besterman et al., 2022).

Economic incentives may also play an important role in promoting blue carbon conservation. Carbon credit programs and payment-for-ecosystem-services schemes can provide financial support for communities that protect or restore mangrove forests. Such initiatives encourage sustainable land management practices while contributing to global climate mitigation goals.

Future research should focus on improving methods for measuring carbon stocks and understanding the long-term dynamics of coastal carbon storage. Advances in remote sensing, ecological modeling, and field monitoring will help scientists assess the effectiveness of conservation strategies and predict how blue carbon ecosystems will respond to environmental change.

Conclusion

Blue carbon ecosystems, particularly mangrove forests and tidal wetlands, represent some of the most efficient natural carbon sinks on Earth. Their ability to capture and store atmospheric carbon within biomass and sediments makes them vital components of global climate regulation. These ecosystems also provide numerous ecological and socio-economic benefits, including biodiversity conservation, fisheries support, and coastal protection. However, increasing environmental pressures and human activities threaten the stability of these valuable habitats. Strengthening conservation policies, implementing restoration initiatives, and promoting sustainable coastal management are essential for maintaining the long-term functionality of blue carbon ecosystems. Continued scientific research and international

collaboration will play a crucial role in enhancing our understanding of coastal carbon dynamics and ensuring the preservation of these ecosystems for future generations.

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