Mangrove sediment ecological and biogeochemical significance for blue carbon sequestration

Naina Bhoyar[1]; Harish Jaiswal[2]; Manvi Pant[3]

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Abstract

Carbon sequestered by vegetated coastal environments (Blue Carbon (BC)) helps alleviate anthropogenic CO2 emissions. However, its efficacy varies with the geographic region of concern. A literature analysis aggregating Carbon Sequestration (CS) levels across essential communities establishes that BC environments represent the most effective natural carbon sinks at the plot size. Still, specific neglected biogeochemical processes result in overestimation. The restricted spatial distribution of coastal ecosystems constrains their worldwide impact, mitigating merely 0.46% of the global fossil fuel carbon dioxide released in 2024. BC is significant for nations with modest fossil fuel production and substantial coastal areas. In 2024, mangroves reduced more than 2% of national fossil fuel pollution. Given that the Paris Agreement relies on locally decided investments, the research suggests that mangrove BC could aid in environmental abatement with other BC habitats.

Keywords: Mangrove sediment, Blue carbon sequestration, Ecology, Biogeochemistry

1- Assistant Professor, Kalinga University, Raipur, India. Email: ku.nainabhoyar@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0000-0999-8741

2- Assistant Professor, Kalinga University, Raipur, India. Email: ku.harishjaiswal@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0000-8183-4944

3- Assistant Professor, New Delhi Institute of Management, New Delhi, India.
Email: manvi.pant@ndimdelhi.org, ORCID: https://orcid.org/0009-0002-4239-5146

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Introduction

Signatories of the Paris Accord have committed to 'attain a balance among anthropogenic emissions from sources and removals by sources by 2100' (Chlela and Selosse, 2023). Given the intense competition among land uses and the delay in achieving fossil fuel independence, protecting and expanding environments with significant Carbon Sequestration (CS) (Guo *et al.,* 2024) capacity represents a viable strategy to fulfill this goal. The research presented here defines CS as the capacity of an environment to absorb and retain greater quantities of carbon in biomass, debris, or water than is emitted into the atmosphere via combustion (Baraković, 2018; Rao and Menon, 2024).

Blue Carbon (BC) habitats (McHarg *et al.,* 2022), comprising salt marshes, ocean grasses, and mangroves, are distinguished by their significant organic carbon preservation, predominantly within deposits across thousands of years, even at maturity. BC has garnered global recognition as a sustainable environmental mitigation strategy because of its significant carbon absorption and storage potential at the plot level. A comprehensive evaluation of BC potential necessitates an assessment of its contributions at broader scales to correspond with regulators' expectations (Yang and Chen, 2022).

Effective management reactions to these shifts necessitate an in-depth knowledge of the various and frequently interconnected ecosystem benefits at the local level. In the southeastern United States, where mangrove invasion has been an annual tendency for over fifty years, deliberate elimination of mangroves to safeguard bird habitats has grown more common (Ravshanova *et al.,* 2024). This could jeopardize the long-term viability of the wetlands if mangrove invasion is demonstrated to be a means of raising the wetland area. Mangrove substitution of salt marsh enhances elevation by trapping sediments and storing atmospheric carbon in below-ground root matter, which negatively responds to rising sea levels (Conroy, Kelleway and Rogers, 2025). Mangroves are more successful than salt marshes in achieving the dual benefits of carbon reduction and coastline adaptation by storing carbon from the atmosphere at greater rates.

The present research examines the scale at which BC is an effective climate change mitigating technique. The study examines this by (i) assessing whether ecosystems containing BC represent the most significant sources of carbon at the plot level; (ii) evaluating the worldwide impact of BC; and (iii) analyzing BC at the national level, particularly about national contributions under the Paris Protocol.

Background

BC

The term BC was initially employed as a metaphor to emphasize the substantial role of coastal environments in storing organic carbon (Corg) alongside terrestrial trees, referred to as "green carbon" (Foroutan *et al.,* 2023; Choudhary, Dhar and Pawase, 2024). BC was first utilized ten years ago to denote aquatic communities, which play a significant role in global CS. It is commonly termed a "ocean carbon sink," indicating the carbon sequestered in the vegetation-dense coastal ecosystem by marine organisms and processes, such as mangrove swamps, seagrass meadows, and salt marshlands. BC's capacity to mitigate warming temperatures while providing ancillary advantages, including coastal preservation and enhancements in fisheries, has garnered global interest. As delineated in the United Nations Environment Programme (UNEP) study, green carbon refers to carbon that organisms have assimilated via photosynthesis and into Organic Matter (OM) (Rajalakshmi *et al.,* 2024). BC is precisely defined as green carbon in marine environments. Plants rapidly assimilate atmospheric carbon dioxide (CO2) in terrestrial environments to produce Corg. The amount of Corg in terrestrial ecosystems can be correlated with the amount of genuine green carbon.

Despite its evolution as a paradigm, certain aspects of BC study continue to be contentious, including divergent opinions regarding the significance of carbonate production in BC and the role of seaweed in its contribution (Mendes *et al.,* 2024). Significant efforts have been dedicated to comprehending BC environments and their potential contributions to climate change prevention. This review aims to encapsulate all facets of BC in mangroves, including its significance, change, methodologies for estimating CS, mechanisms, and environmental role. This research offers comprehensive insights into various conservation techniques, determinants influencing blue CS, and anthropogenic effects on the mangrove environment.

The saline, hypoxic conditions inhibit bacterial decomposition, resulting in the sluggish breakdown of soil carbon. Soil builds, resulting in increasingly deeper deposits as time passes. These attributes distinguish BC habitats from other coastal environments, such as coral reefs and kelp forest communities (Hollarsmith *et al.,* 2022). Mangroves are plants that photosynthesize by utilizing CO2 from both water and air. Seagrass utilizes inorganic absorbed carbon. The substantial amount of sequestered Corg and its rapid accumulation have heightened interest in the possibilities for BC environments to mitigate the effects of climate change. Augmenting the quantity of flora and rehabilitating BC habitats can enhance the CS rate, providing a "nature-based" solution. On the contrary, protecting BC habitats can reduce emission levels, as their degradation can lead to the release of CO2 and methane (CH4), both potent greenhouse gases, into the environment (Chandravanshi and Neetish, 2023).

Significance of BC

Coastal habitats require protection and rehabilitation due to their role as significant global carbon sinks. Despite their relatively tiny size compared to other ecosystems, they trap and store substantial carbon in their soil globally. These natural settings are perpetually being destroyed and lost, resulting in increased greenhouse gas (GHG) emissions from human activities. Coastal environments, such as tropical forests and peatlands, exemplify how nature can enhance efforts to mitigate climate change. They facilitate chances for countries to achieve their carbon reduction targets and Nationally Determined Commitment (NDCs) as specified in the Paris Agreement. These coastal ecosystems provide numerous benefits and resources for addressing climate change, including coastal protection and food availability for diverse populations worldwide.

CS Processes in Mangroves

To combat global warming, countries and regions vigorously enact carbon-neutral policies focused on "carbon reduction and CS." The biogeochemical processes of the coastline rely on mangroves, which are among the biological communities with the most significant carbon concentration on Earth. Although carbon intake and outputs continually fluctuate, the mangrove environment sequesters carbon when the total photosynthesis exceeds the total respiration and decomposition. The remarkable CS capacity of the mangrove BC environment can mitigate the increase in atmospheric CO2 concentrations. Broad-leaved woods, predominant in mangrove vegetation, are located in tropical and temperate coastal intertidal regions. Approximately 1.5×10^7 hectares of mangroves exist globally, surpassing the extent of salt marsh wetland areas covering 6.69×10^7 hectares. Each hectare of broad-leaved forest is anticipated to sequester 1100 kg of CO2 and emit 750 kg of oxygen daily throughout the growing season. This mangrove swamp contains a substantial concentration of sulfuric acid (H2S). In illuminated conditions, a significant population of anaerobic bacteria in mud flats employ H2S as a reducing agent to convert CO2 into organic material, a process absent in forests on land. Worldwide, mangrove sediments sequester approximately 39.4 Tg C per annum, far exceeding the 13.7 Tg C per annum sequestered by salt marshes. Mangroves are thus considered the most efficient marine BC environment for CS. It is undeniably essential for atmospheric purification, reducing the factors contributing to greenhouse gases, and maintaining the equilibrium of CO2.

Materials and Methods

The present mangrove swamp was a salt marsh in images from the 1930s and 1950s, but it became overgrown by mangroves in the 1970s. In the 1980s, the inland colonization of mangrove forests was impeded by the accumulation of brick ash from a nearby building site, resulting in mangrove decay and the resurgence of salt marsh. Mangroves commenced re-sprouting and recolonizing this region in the early 2000s. In 2000, the research established surface elevation databases and tourmaline marker layers in the salt marsh, hybrid salt marsh-mangrove, the ecological tone, and mangrove zones of Powells Creek to assess patterns of surface elevation shift and vertical erosion. In the last phases of the study, the research extracted cores from the mangrove and previous saltmarsh environments to record alterations in carbon amount and origin (utilizing δ13C studies), sediment density in bulk, and to conduct dating using radiocarbon.

Techniques for Quantifying Carbon Reserves in Mangrove Ecosystems

By quantifying above- and below-ground carbon dioxide, one can determine the carbon (C) sequestered in forest ecosystems and assess the capture of carbon, emissions, and storage. Understanding the stock of carbon is the initial step in modeling the productivity of CS. The Above-Grounded Biomass (AGB), Below-Grounded Biomass (BGB), dead trash, woody debris, and soil OM constitute the five carbon reservoirs of the earthly environment, as delineated by the Framework Convention on Climate Change. These various carbon pools facilitate the transfer of CO2 sequestered by plants throughout the photosynthesis process. The predominant component of the carbon reservoir consists of biomass found above ground in plants. The most substantial and prominent carbon reservoir within the lowland forestry environment. The below-ground biomass, comprising all living roots, significantly contributes to the carbon cycle by facilitating the movement and storage of carbon in the earth's soil. The decaying mass of litter and decaying wood constitutes a negligible fraction of the carbon stored in trees, rendering it an insignificant carbon sink. Soil organic matter substantially contributes to forest carbon reserves, and soils represent a primary source of carbon releases following deforestation. The projected biomass elements are as follows:

- outside live cellulose
- deceased above-ground energy
- below-ground energy

Measuring the woody matter of the forest environment enables the assessment of the quantity of CO2 that the tree can sequester from the atmosphere. Precisely quantifying a forest's productivity is essential for numerous uses, including producing lumber, monitoring alterations in forest carbon reserves, and determining the worldwide carbon cycle.

Anthropogenic Impacts and Risks to Mangrove Ecosystems

Mangroves globally are threatened by human activity, with urban growth, aquaculture, farming, mineral extraction, contamination, and unsustainable timber cutting recognized as the principal causes of this degradation. Compared to undamaged regions, CS rates were decreased in damaged sites.

Numerous human activities negatively affect the efficacy of CS in mangroves, resulting in their degradation and loss. The deforestation of mangrove swamps for fuel, growth, and manufacturing diminishes mangrove cover. Water contamination from the release of residual herbicides from croplands results in mangrove infertility, hindering reproduction and population growth. The killing and elimination of aquatic life and other organisms, along with the excavation and completion of mangrove areas, contribute to the decline of mangroves, adversely affecting their CS capabilities.

Conservation Methodologies

Although such advantages arise due to the carbon tactics, a carbon-centric conservation approach does not inherently choose areas most esteemed for wildlife or strive to deliver broader benefits for interrelated organisms, environments, and lifestyles, an optimal coastal management approach should enhance both CS and biodiversity, encompassing advantages for fisheries and the economic viability of communities nearby, due to the significant combined value of cultivated coastal environments in delivering services and products and sequestering carbon. Embracing this method would not significantly increase costs and, in time, would generate greater economic and social benefits on investments. A global partnership between the Comprehensive Convention on the Control of Climate Change and the Convention on Biological Diversity should ideally integrate biodiversity and CS strategies. At a national level, it would provide countries struggling to fulfill the stipulations of various agreements with a chance to align their strategy for conserving biodiversity and combating climate change.

An optimal financing system should offer compensation for carbon reduction, preservation of biodiversity, sustainable utilization, adaptation to climate change, and the encouragement of coastal income, considering that coastal ecosystems deliver numerous services and products beyond their carbon storage potential. These financial options would facilitate coordinated coastal development and oversight, integrating the distinct efforts of biodiversity conservation with climate mitigation.

One such learning is the importance of integrating the knowledge of community members and indigenous populations into processes for planning and handling. It is essential to acknowledge that programs are top-down efforts from governments, international bodies, financial entities, and significant conservation Non-Governmental Organizations (NGOs) when implementing the restoration of mangroves within the framework. Although robust scientific information is essential for planning and management, the enduring success of these efforts, especially in densely populated regions, relies on financial, social, and cultural factors.

Results

All three areas exhibited linear accretion patterns throughout the 18 years (Figure 1). The accretion ratio in the mangroves and hybrid ecotone areas was double that of the previous salt-marsh area, and the accumulation rate in the initial salt-marsh area was not significantly affected by the densification of mangrove growth.

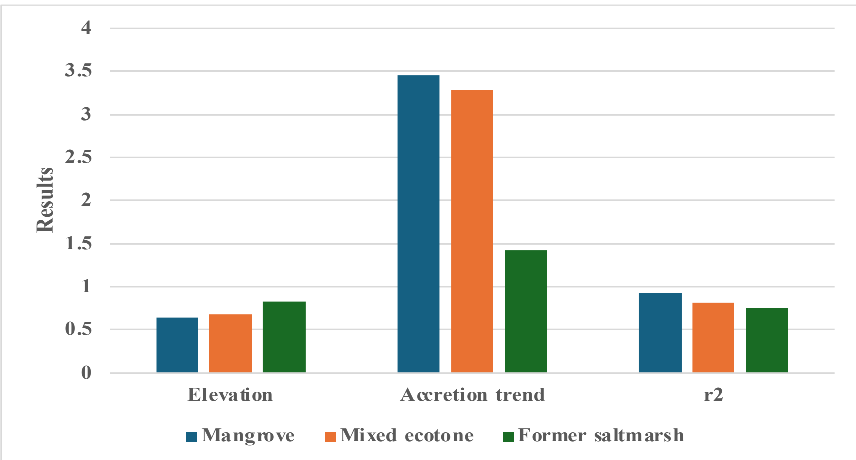

Figure 1: Linear accretion pattern analysis.

Notwithstanding the comparable carbon density in surface debris, the buildup above the mean high water mark indicates divergent carbon buildup rates in the mangrove and previous saltmarsh regions (Figure 2). The projections of carbon buildup are likely modest in the mangrove zone, considering the proof of new root development at depth. The elevated deposition rate in the mangroves and mixture ecotone areas resulted in a rise in elevated surfaces over time, leading to a gradual equalization in surface height among the three regions. Despite the growing number of mangroves, the persistent low deposition rate in the previous salt marsh area did not result in a notable elevation increase.

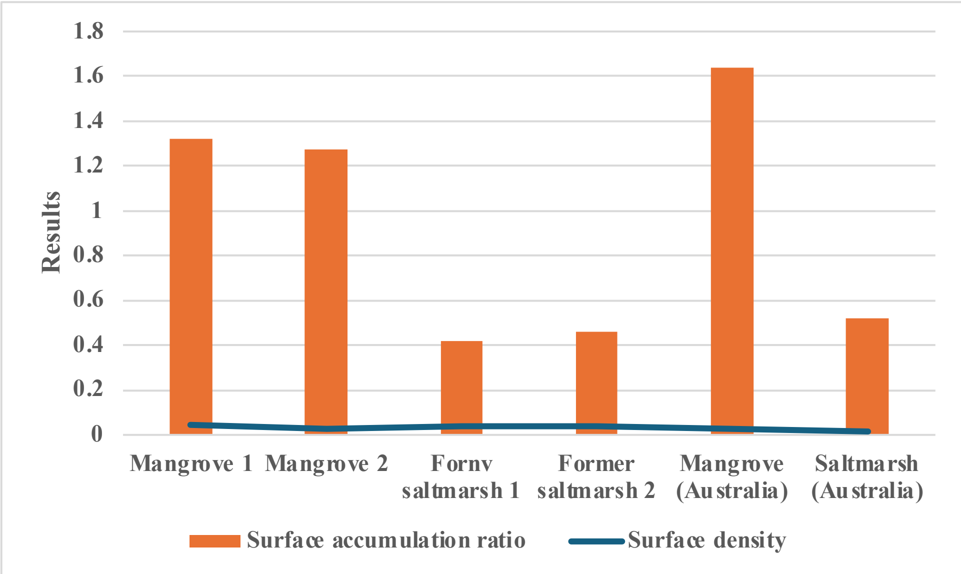

Figure 2: Surface accumulation ratio analysis.

Mangrove sediments exhibit elevated carbon content and reduced bulk density within the upper 28 cm layer. This is the contemporary mangrove rooting zone, evidenced by the continuous 12C signature. A secondary C peak at roughly 0.2m AHD, with comparable C content and diminished 815C signals to surface strata, was considered ancient; it included contemporary material, yielding radiocarbon ages of 1250 and 45 years. Sediments once dominated by salt marsh exhibit greater bulk density than mangrove sediments within the upper 45 cm. Below 45 cm in the two salt marsh cores, the material exhibits a progressive enrichment in $\delta^{13}C$, correlated with an elevated %C and diminished volumetric density.

BC can Aid in Achieving the Paris Agreement at the National Level

Although BC habitats hold less global significance, they exert considerable influence at the national level. The cautious assessment of the national mangrove sequestration capability indicates that they can aid in pollution mitigation, provided that reducing the mangrove remains minimal. Mangroves mitigated over 2% of national GHG emissions in nations. In contrast, in nations experiencing elevated rates of mangrove forest destruction, the CS capacity of the surviving intact mangroves was inferior to the GHG produced by mangrove destruction. These countries lack contributions to emissions reduction but possess significant potential if conservation measures can avert additional emissions from their degradation and promote future CS via restoration. Carbon dioxide reduction at the national level is congruent with the Paris Agreement and related Nationally Determined Contributions for certain countries.

Significant Data Constraints in Evaluating the Function of BC

Limitations on data are unavoidable, given the several scales employed in this investigation. These constraints underscore the necessity of adopting a cautious approach when assessing carbon storage. As demonstrated by the research and others, it is challenging to ascertain a realistic average CS rate at the plot size. Every ecosystem exhibits significant variety, since factors such as plant type or density, geomorphology, hydraulics, and temperature affect primary production and CS. Likewise, studies on sedimentary carbon burial frequently rely on site-specific evaluations that do not comprehensively represent the examined ecosystem. All land and aquatic environments will encounter these challenges. Extensive research can still demonstrate comparative variations in CS among ecosystems. Inaccurate estimations of environmental coverage impede assessments of national and worldwide CS.

Assessing the scale of ecosystems poses a problem due to technology limitations and ambiguous boundaries, especially with salt marshes and seaweeds. The absence of such knowledge affects the accuracy of predictions of ecosystem supply and alterations, particularly in mangroves. The research addressed this issue by employing conservative numbers alongside a sensitivity analysis for the worldwide estimates. Notwithstanding these constraints, national and global investigations facilitate the identification of research deficiencies and policy suggestions. Consistent methods for carbon dioxide dynamics ought to be established and implemented within and outside environments, whereas surface cover, particularly for seaweeds and salt marshes, must be more accurately defined.

Conclusion

BC has garnered global attention for its potential in reducing CO2 emissions. The evaluation indicates that blue CS holds minimal global significance; however, it can contribute in nations with vast coastlines when integrated with supplementary mitigation strategies and deforestation decreases. Preserving BC habitats will ensure ongoing carbon absorption and mitigate emissions resulting from land-use alterations. Significant data deficiencies must be rectified to illustrate BC's contribution to achieving the Paris Accord's objectives.

References

Baraković, D., 2018. Potential of Carbonate Raw Materials of Gračanica, Deposit" Sklop. *Archives for Technical Sciences*, *2*(19), pp.19-28.

Chandravanshi, N. and Neetish, K., 2023. Diurnal Variations in Greenhouse Gas Emissions from a

Macrophyte-Covered River. *Aquatic Ecosystems and Environmental Frontiers*, *1*(1), pp.11-15.

Chlela, S. and Selosse, S., 2023. Carbon Dioxide Removal in SDGs and Nationally Determined Contributions. In *SDGs in the European Region* (pp. 425-444). Cham: Springer International Publishing.

Choudhary, B., Dhar, V. and Pawase, A.S., 2024. Blue carbon and the role of mangroves in carbon sequestration: Its mechanisms, estimation, human impacts and conservation strategies for economic incentives. *Journal of Sea Research*, *199*, p.102504. https://doi.org/10.1016/j.seares.2024.102504

Conroy, B.M., Kelleway, J.J. and Rogers, K., 2025. Root productivity contributes to carbon storage and surface elevation adjustments in coastal wetlands. *Plant and Soil*, pp.1-27. https://doi.org/10.1007/s11104-025-07204-0

Foroutan, B., Bashi Amlashi, H.R., Partani, A., De los Ríos, P. and Nasrollahzadeh Saravi, H., 2023. Determination and comparisons of heavy metals (Cobalt and Iron) accumulation in muscle, liver, and gill tissues of Golden Mullet (Chelon aurata) in coastal areas of the Caspian Sea (Mazandaran and Golestan provinces of Iran). *International Journal of Aquatic Research and Environmental Studies*, *3*(1), pp.1-15. https://doi.org/10.70102/IJARES/V3I1/1

Guo, Y., Ren, Z., Wang, C., Zhang, P., Ma, Z., Hong, S., Hong, W. and He, X., 2024. Spatiotemporal patterns of urban forest carbon sequestration capacity: Implications for urban CO2 emission mitigation during China's rapid urbanization. *Science of the Total Environment*, *912*, p.168781. https://doi.org/10.1016/j.scitotenv.2023.168781

Hollarsmith, J.A., Andrews, K., Naar, N., Starko, S., Calloway, M., Obaza, A., Buckner, E., Tonnes, D., Selleck, J. and Therriault, T.W., 2022. Toward a conceptual framework for managing and conserving marine habitats: A case study of kelp forests in the Salish Sea. *Ecology and Evolution*, *12*(1), p.e8510. https://doi.org/10.1002/ece3.8510

McHarg, E., Mengo, E., Benson, L., Daniel, J., Joseph-Witzig, A., Posen, P. and Luisetti, T., 2022. Valuing the contribution of blue carbon to small island developing states' climate change commitments and Covid-19 recovery. *Environmental Science & Policy*, *132*, pp.13-23. https://doi.org/10.1016/j.envsci.2022.02.009

Mendes, M., Cotas, J., Pacheco, D., Ihle, K., Hillinger, A., Cascais, M., Marques, J.C., Pereira, L. and Gonçalves, A.M., 2024. Red Seaweed (Rhodophyta) Phycocolloids: A road from the species to the industry application. *Marine Drugs*, *22*(10), p.432. https://doi.org/10.3390/md22100432

Rajalakshmi, A.R., Jayakani, S., Shanmugam, H., and Ramakrishnan, P.R., 2024. A Study on Green Entrepreneurship and Electronic Word of Mouth: Special Reference with Kanchipuram District. *Indian Journal of*

Information Sources and Services, *14*(3), pp.270–276. https://doi.org/10.51983/ijiss-2024.14.3.35

Rao, A. and Menon, P., 2024. A Review of Membrane Filtrating Methods for Contaminant/Pollution Removal in Water and Sewage Treatment. *Engineering Perspectives in Filtration and Separation*, *2*(4), pp.1-6.

Ravshanova, A., Akramova, F., Saparov, K., Yorkulov, J., Akbarova, M. and Azimov, D., 2024. Ecological-Faunistic Analysis of Helminthes of Waterbirds of the Aidar-Arnasay System of Lakes in Uzbekistan. *Natural and Engineering Sciences*, *9*(1), pp.10-25. https://doi.org/10.28978/nesciences.1471270

Yang, L. and Chen, J., 2022. A comprehensive evaluation of microbial differential abundance analysis methods: current status and potential solutions. *Microbiome*, *10*(1), p.130. https://doi.org/10.1186/s40168-022-01320-0