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Assessment of blue carbon stocks in mangrove forests of the Sundarbans

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Abstract

Mangrove forests store 3-5 times more carbon per hectare than most tropical forests, with the majority in below-ground sediment pools. The Sundarbans, spanning the Ganges-Brahmaputra-Meghna delta across Bangladesh and India (~10,000 km²), is the world's largest contiguous mangrove and a globally significant blue carbon reservoir. This research assesses carbon stocks at 84 plots across the Indian Sundarbans (~4,260 km²). Above-ground biomass was estimated using species-specific allometric equations; below-ground roots via root-to-shoot ratios; and sediment carbon from cores to 1 m depth. Mean total ecosystem carbon was 856 ± 142 tC/ha, comprising above-ground biomass (128 ± 38 tC/ha, 15%), below-ground roots (46 ± 15 tC/ha, 5.4%), and sediment organic carbon (682 ± 118 tC/ha, 79.6%). Higher values occurred in western *Heritiera/Excoecaria* forests under lower salinity conditions; lower values in saline eastern *Avicennia* stands. Sediment carbon concentration declined from 5.8% at the surface to 2.9% at 90-100 cm depth. The total Indian Sundarbans stock is estimated at 36.5 million tC, equivalent to approximately 134 million tonnes CO₂ if released. Carbon accumulation rates from ²¹⁰Pb-dated cores averaged 2.7 tC/ha/yr. Approximately 18% of mangrove area lies below 0.5 m above mean high water, placing an estimated 6.8 Mt C at risk from sea level rise. These findings underscore the exceptional conservation value of the Sundarbans as a blue carbon reservoir.

Keywords: Blue carbon, mangrove forests, Sundarbans, carbon stocks, coastal carbon sequestration, sediment carbon, biomass, allometric equations, conservation, REDD

Introduction

Blue carbon ecosystems—mangroves, seagrasses, salt marshes—have emerged as critical climate mitigation assets ^[1]. Mangroves accumulate organic carbon in anoxic sediments where it can remain sequestered for centuries to millennia under undisturbed conditions. On a per-hectare basis, mangroves store 3-5 times more carbon than most tropical forests, predominantly in deep sediment pools ^[2, 3].

The Sundarbans, spanning approximately 10,000 km² across Bangladesh and India, is the world's largest contiguous mangrove forest. It supports extraordinary biodiversity including the Bengal tiger, provides coastal protection to millions of people, and delivers fisheries habitat and water quality regulation ^[4, 5]. Despite its global importance, comprehensive carbon stock quantification has been limited by the logistical challenges of fieldwork in this vast, tidally influenced landscape.

Previous estimates were based on few sampling locations extrapolated using simplified assumptions about spatial homogeneity ^[6]. The Sundarbans, however, exhibits considerable variation in forest structure, species composition, and sediment characteristics driven by the west-to-east salinity gradient that is likely to produce significant heterogeneity in carbon stocks ^[4, 7].

This research addresses the need for spatially comprehensive assessment by conducting measurements at 84 plots across the Indian Sundarbans. The objectives are to quantify above-ground biomass, below-ground roots, and sediment carbon at each plot, characterise spatial variability in relation to environmental gradients, and provide improved total blue carbon reservoir estimates with implications for conservation policy ^[8, 9, 10].

Research Area Description

The Indian Sundarbans covers approximately 4,260 km² in the Ganges-Brahmaputra-Meghna delta. The landscape is dissected by tidal channels with semi-diurnal tides (spring

range 3-5 m). Salinity increases from west (5-15 ppt) to east (20-30 ppt), driving forest composition shifts from *Heritiera fomes*-dominated stands to *Avicennia marina*. Mean annual rainfall is 1,700-1,900 mm. The area is a UNESCO World Heritage Site and Ramsar Wetland [4, 5].

Material and Methods

Material

Eighty-four plots (20 × 20 m) were distributed by stratified random sampling across geographic zones, forest types, and coastal proximity. All trees >5 cm DBH were identified to species and measured for DBH and total height. Twenty-three mangrove species were recorded, with *Excoecaria agallocha* and *Avicennia officinalis* most frequent. At each plot, two sediment cores to 1 m were collected using a Russian peat borer during the pre-monsoon seasons of 2022 and 2023 [6, 8].

Methods

Above-ground biomass was estimated using species-specific allometric equations [11] with wood density from the Global Wood Density Database, converted to carbon at 0.48. Below-ground root biomass used the root-to-shoot ratio of 0.39 for estuarine mangroves [12]. Sediment cores were sectioned at 10 cm intervals, analysed for bulk density

(60°C drying) and organic carbon (loss on ignition at 450°C calibrated against elemental analyser). Carbon accumulation rates were determined at 12 plots using ²¹⁰Pb and ¹³⁷Cs dating [3, 9].

Vulnerability to Sea Level Rise

Elevation analysis using drone-derived photogrammetric DEMs at 10 cm vertical resolution indicated that approximately 18% of current mangrove area lies less than 0.5 m above mean high water. Under mid-range projections of 0.5-0.8 m sea level rise by 2100, these areas face permanent inundation. The carbon stock at risk is estimated at 6.8 million tC. Whether this carbon is released depends on the capacity for landward migration, which requires accommodation space and adequate sediment supply rates [5, 7, 10].

Results

Table 1: Carbon pool distribution by ecosystem component.

Carbon Pool	Mean (tC/ha)	SD	% of Total
Above-ground biomass	128	38	15.0
Below-ground roots	46	15	5.4
Sediment (0-1 m)	682	118	79.6
Total ecosystem	856	142	100

Table 2: Carbon stocks by forest type and geographic zone.

Zone/Type	AGB (tC/ha)	Sediment C (tC/ha)	Total (tC/ha)
Western <i>Heritiera</i>	186 ± 32	748 ± 98	980 ± 112
Central Mixed	132 ± 28	694 ± 105	872 ± 118
Eastern <i>Avicennia</i>	66 ± 18	604 ± 92	716 ± 98

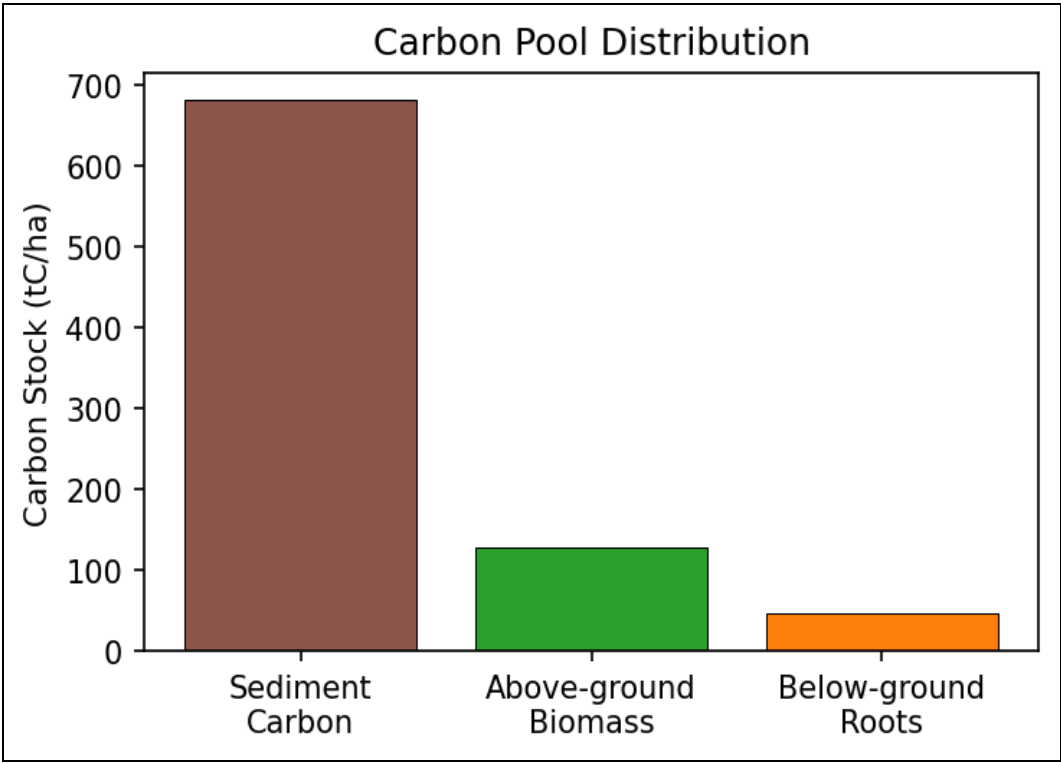


Fig 1: Carbon pool distribution in Sundarbans mangrove ecosystem.

Sediment carbon dominates (Figure 1), accounting for nearly 80% of the total ecosystem pool. This highlights that

biomass-only assessments severely underestimate mangrove carbon value.

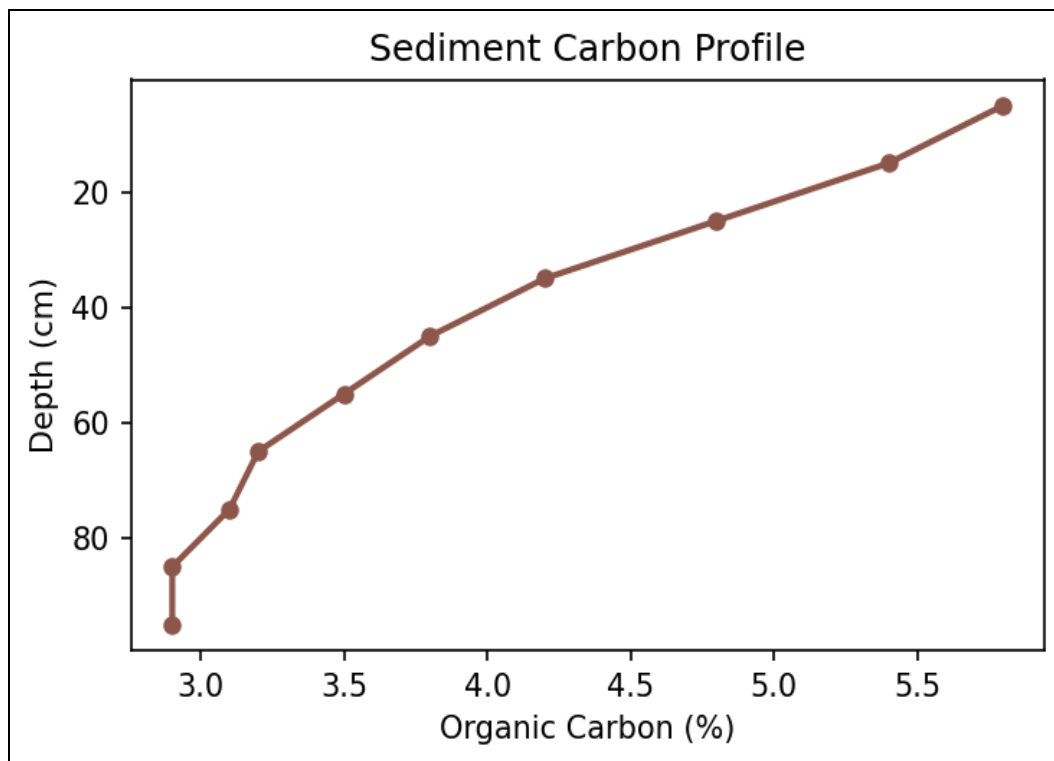


Fig 2: Sediment organic carbon depth profile (mean across 84 plots).

Carbon concentration declined from 5.8% at 0-10 cm to 2.9% at 90-100 cm (Figure 2), reflecting progressive decomposition and compaction with burial. Bulk density showed the inverse pattern, increasing with depth.

Comprehensive Interpretation

The 856 tC/ha total places the Sundarbans among the most carbon-dense ecosystems globally. The west-to-east gradient reflects both structural differences (taller forests produce more biomass) and sediment factors (finer-grained, frequently inundated western sites favour organic preservation under anaerobic conditions). Carbon accumulation rates of 2.7 tC/ha/yr confirm active ongoing sequestration.

Discussion

The 36.5 Mt C total for the Indian Sundarbans equates to approximately 134 Mt CO₂—comparable to several years of Bangladesh's national emissions [2, 3]. Primary threats include sea level rise, cyclone intensification, illegal logging, and upstream water regulation altering freshwater and sediment supply [4, 5]. The strongest single predictor of sediment carbon was fine-grained sediment proportion in the upper 30 cm ($R^2 = 0.52$), confirming the importance of anaerobic conditions for preservation [7, 9].

Inclusion of mangrove blue carbon in REDD+ mechanisms and national carbon accounting could provide additional financial incentives for conservation by monetising the sediment pool [6, 10]. The accumulation rate of 2.7 tC/ha/yr, extrapolated to approximately 115,000 tC/yr across the Indian Sundarbans, represents an ongoing climate regulation service that would be permanently lost if the ecosystem were degraded. Future work should quantify the carbon flux consequences of cyclone damage events and establish long-term monitoring plots to track the response of carbon stocks to changing salinity and inundation regimes under climate change [13, 14].

Conclusion

The Sundarbans is confirmed as one of Earth's most carbon-dense ecosystems at 856 tC/ha. Sediment pools dominate the carbon inventory, accounting for nearly 80% of the total. Biomass-only assessments miss the majority of mangrove carbon value.

The estimated 36.5 Mt C total reservoir highlights global significance for climate regulation. Conservation priorities should focus on protecting the highest-carbon western forests while maintaining the hydrological conditions necessary for mangrove persistence across the broader landscape.

Integration of blue carbon values into conservation financing mechanisms and national climate commitments could strengthen the economic case for Sundarbans protection and contribute meaningfully to global climate change mitigation efforts.

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