Research Support in Analysing Mangrove Responses to Climate Change: The Interplay of Anthropogenic Impacts and Blue Carbon Mitigation

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Abstract

Mangrove forests are highly efficient natural carbon sinks, playing a crucial role in mitigating anthropogenic carbon dioxide emissions through the sequestration and long-term storage of organic carbon (C_{org})—a function highlighted by the "blue carbon" concept. However, these ecologically and economically valuable ecosystems are under immense pressure from dual stressors: global climate change, particularly accelerated sea-level rise (SLR), and localized anthropogenic activities such as coastal eutrophication, deforestation, and aquaculture expansion. This review synthesizes current peer-reviewed literature to systematically analyze the dual response of mangroves to these interconnected stressors, with a focus on the interplay between anthropogenic nutrient loading, carbon sequestration capacity, and climate resilience. While the global climate mitigation potential of mangrove blue carbon remains relatively small due to their limited spatial extent, the integration of blue carbon strategies is highly effective at the national scale, especially for countries with extensive coastlines and moderate fossil fuel emissions. Furthermore, local anthropogenic impacts (e.g., urban effluents, deforestation) significantly alter mangrove nutrient accumulation rates (nitrogen and phosphorus), which in turn modulate the overall resilience of mangrove ecosystems to SLR and other climate-driven disturbances. We conclude that understanding localized nutrient dynamics and the phenomenon of "coastal squeeze"—the restriction of mangrove landward migration by human infras-

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tructure—is essential for accurate national carbon emission modeling, the formulation of targeted conservation policies, and the effective integration of mangroves into the Paris Agreement's Nationally Determined Contributions (NDCs).

Keywords: Blue carbon, Climate change, Nutrient accumulation, Sea-level rise, Mangrove conservation, Coastal squeeze, Anthropogenic stressors

1. Introduction

Mangrove forests occupy the dynamic coastal-land interface of subtropical and tropical seas, spanning approximately 81,484 km^2 globally across 118 countries and territories [1, 2, 3]. These unique ecosystems serve as critical biogeochemical barriers, regulating nutrient fluxes between terrestrial and marine environments, supporting high biodiversity, and providing essential ecosystem services such as coastal protection against storms and erosion [4, 5, 6]. The concept of "blue carbon"—coastal carbon sequestered and stored by ocean ecosystems—highlights the role of mangroves, alongside salt marshes and seagrasses, in absorbing anthropogenic CO_2 emissions to mitigate climate change [4, 7, 8, 9].

Despite their small global area (less than 0.4% of terrestrial land), mangroves sequester exceptionally high amounts of C_{org} per unit area, primarily stored in deep, waterlogged soil horizons that prevent organic matter decomposition and CO_2 release [1, 10, 11]. Mean mangrove C_{org} stock is estimated at 738.9 Mg C_{org} ha^{-1}, with 76.5% of this stock vested in soils to a depth of at least 1 m [4, 12]. However, the capacity of mangroves to act as reliable, long-term carbon sinks is increasingly threatened by two interconnected sets of stressors: global climate change (notably accelerated SLR) and localized anthropogenic activities (eutrophication, deforestation, aquaculture, and urban development) [13, 14, 15, 16, 17].

Accelerated SLR poses a severe threat to mangrove survival, as these ecosystems rely on sediment accretion to keep pace with rising sea levels; when relative SLR exceeds critical thresholds, mangroves face "drowning" unless they can migrate landward [14, 18, 19]. Concurrently, localized anthropogenic stressors alter mangrove biogeochemistry: eutrophication from urban effluents and aquaculture increases nutrient (nitrogen and phosphorus) accumulation rates, while deforestation reduces carbon storage capacity and disrupts sediment dynamics [13, 20, 21]. These stressors interact syn-

ergistically—for example, eutrophication-induced changes in root structure can reduce mangrove resilience to SLR and storm damage, while deforestation exacerbates coastal squeeze by eliminating potential landward migration routes [14, 1, 22].

To properly integrate mangroves into global climate change mitigation strategies and the Paris Agreement's NDCs, it is crucial to analyze their responses to these localized and global changes, and to clarify the scale-dependent effectiveness of blue carbon sequestration [1, 23]. While previous reviews have focused on either global blue carbon potential or localized anthropogenic impacts, this study synthesizes these lines of research to explore their interplay, filling a gap in understanding how local stressors modulate mangrove responses to climate change and the implications for national-scale mitigation policies.

2. Objectives

The primary objective of this review is to evaluate the response of mangrove ecosystems to climate change scenarios, specifically focusing on the impacts of SLR and the modulatory role of localized anthropogenic nutrient loading (eutrophication, deforestation) on mangrove resilience. This objective includes three specific sub-goals:

(a) Quantify the effects of different anthropogenic stressor intensities (conserved vs. eutrophied vs. deforested) on mangrove nutrient (nitrogen, phosphorus) accumulation rates and sediment accretion dynamics;

(b) Identify critical thresholds for SLR survival in mangroves, and analyze how localized anthropogenic stressors alter these thresholds;

(c) Clarify the coupling relationship between nutrient accumulation and carbon sequestration capacity in mangroves under varying stress conditions.

A secondary objective is to assess the viability of mangrove blue carbon sequestration as a climate change mitigation tool at the national versus global scales, with a focus on how localized stressors influence the effectiveness of blue carbon strategies in contributing to NDCs [24, 25]. Specifically, this review aims to provide actionable insights for policy-makers by linking global blue carbon science to local management practices.

3. Methodology

This review was conducted by synthesizing peer-reviewed academic literature published between 2010 and 2024, focusing on three core themes: mangrove carbon sequestration rates and storage capacity, nutrient accumulation dynamics under anthropogenic stress, and climate change projections (particularly SLR) for mangrove ecosystems. Literature searches were performed using Scopus and Web of Science databases with the following key search strings: ("mangrove" AND "blue carbon" AND "carbon sequestration"), ("mangrove" AND "nutrient accumulation" AND "anthropogenic impact"), and ("mangrove" AND "sea-level rise" AND "resilience"). Only studies with rigorous methodology (e.g., replicated field sampling following standardized protocols [26]) and clear reporting of data were included to ensure reliability.

Data were extracted and synthesized from three key studies that provide comprehensive insights into the research themes: Pérez et al. (2021), which focuses on anthropogenic impacts on mangrove nutrient accumulation and sediment accretion; Alongi (2020), which quantifies global mangrove carbon stocks and sequestration rates; and Taillardat et al. (2018), which assesses the scale-dependent effectiveness of blue carbon mitigation. Extracted data included:

(a) Total ecosystem organic carbon (C_{org}) stocks (Mg C_{org} ha^{-1}) and carbon sequestration rates (g C_{org} m^{-2} yr^{-1}) across different regions and environmental conditions;

(b) Nitrogen (TN) and phosphorus (TP) accumulation rates (g m^{-2} yr^{-1}) in conserved, eutrophied, and deforested mangrove ecosystems;

(c) Sediment accretion rates (SAR, mm yr^{-1}) and their relationship with nutrient accumulation and carbon sequestration;

(d) Threshold limits for SLR survival (mm yr^{-1}) and the influence of coastal squeeze on mangrove migration;

(e) National-scale mangrove blue carbon mitigation potential (percentage of national fossil fuel emissions offset by mangrove sequestration).

Data were compared across conserved and impacted environments to identify trends in mangrove responses to stressors. The analysis focused on downscaling global observations to assess the practical value of blue carbon mitigation at the national scale, using case studies from countries with significant

mangrove cover (e.g., Bangladesh, Colombia, Nigeria, Papua New Guinea) [1, 27]. A sensitivity analysis was conducted to account for variability in reported data and to ensure the robustness of the review's conclusions.

4. Literature Review (Findings)

4.1. Carbon Sequestration and Storage

Mangroves are among the most efficient natural carbon sinks on Earth: except for tundra and peatlands, they store more C_{org} per unit area than any other terrestrial or coastal ecosystem [4, 28]. The global mean C_{org} stock for mangroves is approximately 738.9 ± 27.9 Mg C_{org} ha^{-1} (±1SE), with a median value of 702.5 Mg C_{org} ha^{-1}, based on 224 measurements across 52 countries [4, 29]. This stock is distributed across three main pools: above-ground biomass (living and dead), below-ground root biomass (live and dead), and soil organic carbon (SOC) .

As detailed in Table 1, the majority of mangrove carbon (76.5%) is stored in soils, with a mean SOC stock of 565.4 ± 25.7 Mg C_{org} ha^{-1} to a depth of at least 1 m [4, 30]. Above-ground biomass C averages 109.3 ± 5.0 Mg C_{org} ha^{-1}, while below-ground root biomass C averages 80.9 ± 9.5 Mg C_{org} ha^{-1}. Regional differences in C_{org} stocks are notable: for example, mangroves in Cameroon have total C_{org} stocks of 2102.1 Mg C_{org} ha^{-1}, while those in South Africa have much lower stocks (234.8 Mg C_{org} ha^{-1}), reflecting variations in forest age, geomorphology, and environmental conditions [4, 31].

Table 1: Global mean organic carbon (C_{org}) stocks in mangrove ecosystems across different carbon pools (data sourced from Alongi, 2020 [4]).

Carbon Pool	**Mean C_{org} Stock (Mg ha^{-1})**
Above-ground biomass (living and dead)	109.3 ± 5.0
Below-ground root biomass	80.9 ± 9.5
Soil organic carbon (to 1 m depth)	565.4 ± 25.7
Total Ecosystem C_{org}	738.9 ± 27.9

Per unit area, mangroves sequester around 179.6 g C_{org} m^{-2} yr^{-1} globally, translating to approximately 15 Tg C_{org} yr^{-1} at the global scale [4, 28]. This sequestration rate is significantly higher than that of terrestrial forests [1]. However, the limited spatial extent of mangroves means their global climate mitigation potential is relatively small: blue carbon ecosystems together

buffer only 0.42% of global fossil fuel CO_2 emissions [1, 22]. Mangroves alone account for approximately 13.7 ± 11 TgC yr^{-1} of global carbon sequestration [4, 1].

4.2. Anthropogenic Influences on Nutrient Accumulation

Localized human activities—including urban effluent discharge, aquaculture expansion, deforestation, and agricultural runoff—dramatically alter mangrove biogeochemistry, particularly nutrient accumulation rates [13, 32, 33]. These changes have cascading effects on mangrove carbon sequestration, sediment dynamics, and resilience to climate change.

Conserved mangrove ecosystems, with minimal anthropogenic disturbance, present relatively low but stable TN and TP accumulation rates, averaging 5.8 ± 2.1 and 0.8 ± 0.5 g m^{-2} yr^{-1}, respectively [13, 34]. In these systems, nutrient accumulation is primarily driven by natural processes [13]. Sediment accretion rates in conserved mangroves average 2.8 ± 1.0 mm yr^{-1} [13].

In contrast, mangroves impacted by coastal eutrophication exhibit significantly higher nutrient accumulation rates: TN and TP burial rates increase to 21.5 ± 8.6 and 17.9 ± 2.4 g m^{-2} yr^{-1}, respectively [13, 35, 36]. This significant over-enrichment triggers eutrophic conditions in adjacent coastal waters [13, 17]. While increased nutrient availability may temporarily boost mangrove biomass [21], it can also disrupt microbial processes, increasing the emission of greenhouse gases like methane (CH_4) and nitrous oxide (N_2O) [13, 4].

Regional differences in anthropogenic impacts on nutrient accumulation are notable. Oceania's mangroves have higher nitrogen and phosphorus accumulation capacities reflecting lower overall anthropogenic pressure compared to Asia and South America [13]. Deforestation also significantly reduces nutrient accumulation capacity [13, 20]. Forest type (mixed vs. monospecific) influences nutrient accumulation, with mixed forests generally exhibiting higher TN, TP, and SAR [13].

4.3. Climate Change and Sea-Level Rise (SLR)

Mangroves possess natural resilience to tidal changes and moderate SLR, primarily through sediment accretion and landward migration. However, accelerated SLR poses a severe threat to their survival [14, 37, 38]. Figure 1 illustrates the complex interactions and thresholds associated with these climate drivers.

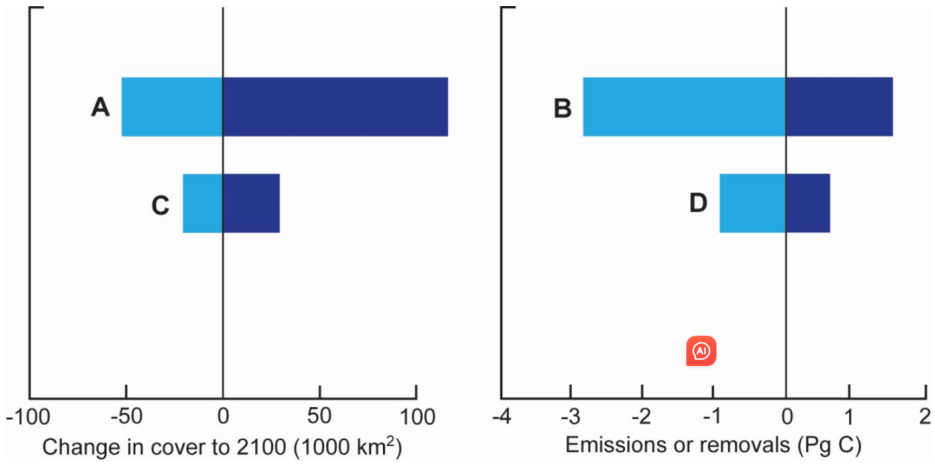


Figure 1: Impacts of climate change drivers, particularly sea-level rise and elevated temperatures, on mangrove blue carbon stocks and fluxes. (Sourced from Alongi, 2022, Figure 1) [14]

Literature identifies a critical threshold for mangrove survival : mangroves are highly likely unable to sustain accretion when relative SLR exceeds 6.1 mm yr^{-1} [14, 39]. This threshold varies slightly by region, depending on factors such as sediment supply and hydrological regime [14, 40]. Sediment accretion rates typically range from 1–5 mm yr^{-1}, with impacted mangroves averaging 5.5 ± 2.0 mm yr^{-1} due to sudden deposition of particulate material from anthropogenic sources [13].

Survival under accelerated SLR depends heavily on "coastal squeeze" [14, 41]. In areas where coastal squeeze is severe, mangroves cannot migrate landward, leading to rapid loss even if sediment accretion rates are sufficient [1].

Environmental drivers such as storms and frequent flooding also interact with SLR. Mangroves impacted by storms exhibit high TN accumulation rates, which promotes sediment accretion [13, 42]. However, TP accumulation is not significantly different, reflecting higher efficiency in accumulating phosphorus compared to nitrogen [13].

5. Discussion

The literature reviewed highlights a critical dichotomy: while mangrove blue carbon is statistically insignificant globally, it is highly impactful at the

national level [1, 43]. This is aligned with the Paris Agreement's NDCs [1, 23]. As demonstrated in Table 2, mangroves mitigate a substantial proportion of national fossil fuel emissions for countries with extensive coastlines.

Table 2: National-scale mangrove blue carbon mitigation potential for selected countries, expressed as the percentage of national fossil fuel emissions offset (data sourced from Taillardat et al., 2018 [1]).

Country	**National Emissions Offset (%)**
Gabon	11.3
Cameroon	8.4
Panama	8.3
Nigeria	1.6
Bangladesh	1.5
Ecuador	1.2
Colombia	1.1

In contrast, high deforestation rates (e.g., Malaysia, Myanmar) lead to negative mitigation potential [1, 44]. Preventing deforestation not only maintains carbon sequestration but avoids emissions from biomass and soil decomposition [4, 45].

Evaluating carbon sequestration in a vacuum is insufficient; anthropogenic effluents directly interact with resilience. Eutrophied mangroves exhibit significantly higher TN, TP, and SAR [13]. Severe eutrophication compromises root structures, increasing susceptibility to storm damage and drowning [13, 18].

Table 3: Comparative analysis of conserved vs. eutrophied mangrove accumulation rates and sediment accretion (adapted from Pérez et al., 2021 [13]). Values are presented as mean ± standard deviation.

Environmental Condition	**TN Accumulation** ($g\ m^{-2}\ yr^{-1}$)	**TP Accumulation** ($g\ m^{-2}\ yr^{-1}$)	**Sediment Accretion (SAR)** ($mm\ yr^{-1}$)
Conserved Mangroves	5.8 ± 2.1	0.8 ± 0.5	2.8 ± 1.0
Impacted by Eutrophication	21.5 ± 8.6	17.9 ± 2.4	5.5 ± 2.0

Previous global assessments often overlook regional differences in anthropogenic stressors, leading to inaccurate mitigation estimates [1, 22]. Oceania's mangroves have more stable carbon sequestration potential than Asia's [13]. This highlights the need for downscaled, region-specific models [1].

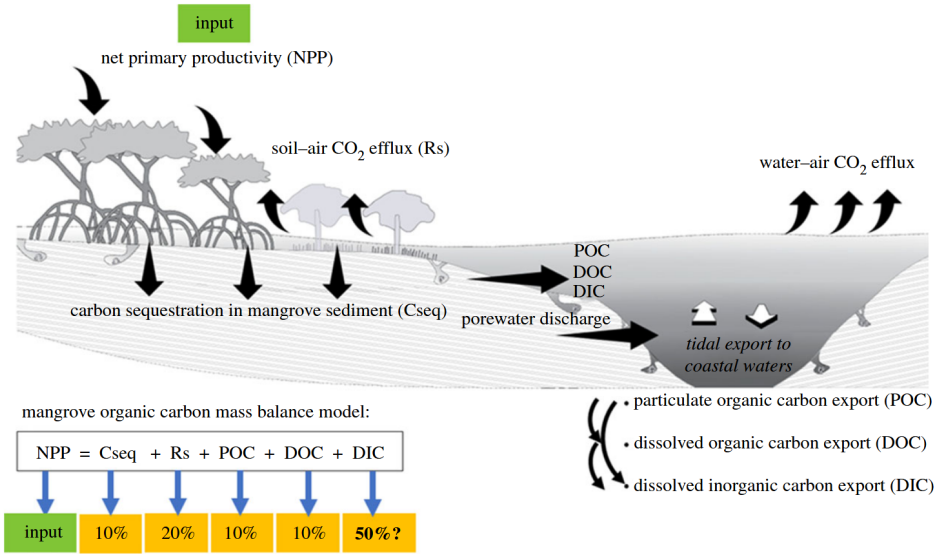


Figure 2: Conceptual model of carbon dynamics in mature mangrove ecosystems, illustrating the balance between carbon input (net primary productivity, NPP) and outputs (soil–air CO_2 efflux, tidal export of particulate and dissolved organic carbon, dissolved inorganic carbon). Estimates of output proportions are included (adapted from Taillardat et al., 2018, Figure 2) [1].

Data limitations remain. Plot scale estimates may be overestimated due to bioturbation and remineralization [1]. Poor estimates of mangrove extent and inconsistent methodologies hinder accurate assessments [1, 26].

6. Conclusion

Mangroves are a highly efficient, spatially limited tool for climate change mitigation, most pronounced at the national scale. Blue carbon strategies must be implemented nationally, integrated into NDCs [24, 46].

Climate predictions regarding mangrove survival must account for local anthropogenic stressors. The interplay between nutrient accumulation and SLR resilience is critical. Eutrophication undermines long-term resilience by altering root structures and promoting greenhouse gas emissions [18, 20].

Policy-makers should: (1) strengthen conservation to prevent deforestation and reduce coastal squeeze; (2) implement nutrient management strategies to mitigate eutrophication; and (3) integrate region-specific blue carbon data into national climate models.

Future research should standardize measurement protocols, expand long-term monitoring, and explore synergistic effects of multiple stressors on mangrove ecosystems. Integrating these insights can effectively leverage mangroves as a nature-based solution to climate change.

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