Coastal mangrove forests in mitigating storm surges and climate change impacts

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Abstract

Coastal mangrove forests are crucial Nature-based Solutions (NbS) for safeguarding coastal communities against the intensified hazards of climate-influenced storms. This study reviews the existing literature on estimating the dual scale of the value mangroves provide in terms of their ability to physically and ecologically attenuate waves and storm surge, and their value as a carbon store - blue carbon. There are also strict shifts from a paradigm around "defense" of the coastal zone to sustainable managed approaches due to global climate change, as shown by rising sea levels and an increase in storms. Complex root systems of mangroves are effective at reducing the height of storm surges and wave energy and can provide a low-cost "soft" alternative to complement engineered "hard" structures. In addition, mangroves are critical in the fight against climate change owing to their capacity to be part of the carbon-absorbing process called sequestration, or sequestering the carbon in their biomass and subsequent soils, or blue carbon. This synthesis review of existing literature will assess the protection service magnitude value of mangroves and specifically focus on hydrodynamic modeling in storm surge reduction and methods of ecosystem service valuation. These policies emphasize the importance of timely action concerning the conservation and restoration of mangroves as components of climate change adaptation and total inclusive coastal zone management, which influences these forests' protective function. Based on modeled scenarios, timely action related to management and restoration is essential for climate change adaptation to the coastal zone, informed by policy-integrated change. The primary purpose is to assist with

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an informative structure that informs decision-makers on the ecological and financial benefits of protecting coastline ecosystems and the socioeconomic rationale for their protection.

Keywords: Mangroves, Storm surges, Climate change, Wave attenuation, Blue carbon, Coastal resilience

Introduction

The world's infrastructure and socioeconomic stability are at risk due to the increasingly severe effects of climate change, particularly those related to tropical cyclones and their surge (Sharipov *et al.*, 2024; Friess *et al.*, 2023; Assegid and Ketema, 2023). Additionally, they affect the world's coastal regions by raising the sea level. The alternative strategy of constructing artificial defenses is similarly effective, expensive, and detrimental to the environment; it lacks the adaptability of mangrove trees, which are sustainable and offer essential ecosystem services (Blankespoor, Dasgupta and Lange, 2017). By spreading the force of waves and storm surges that the mangrove trees collect via their special formation and binding in the intertidal zone, such conflicts may easily exist without the hand of a human. Think about a different study. The question of this synthesis is how much and what vegetation would grow in the temperate ecozone stretch, avoiding the tropical mangrove forests that are instead stunted and restricted to being around the coastal stretches, drawn in by the ocean surges, and help to tame the climate.

Key Contributions

- Closing the knowledge gap on mangrove ecosystems, which cover a large portion of the planet, by measuring their hind tide and the storm's intensity.
- Evaluating the potential contributions of mangrove blue carbon stocks to climate change mitigation.
- Developing a simplified assessment framework to measure the ecological and protection value of specific mangrove habitats.

The structure of this section of the study is as follows: Section 2 provides a detailed description of previous research on the subject. The pertinent hydrodynamic concepts of wave attenuation are covered in Section 3. The crucial function of blue carbon sequestration is explained in Section 4. An assessment framework is described in Section 5. Section 6 offers the Conclusion and Future Research Directions in the final section.

Literature Review

The physical protection and climate control ecosystem services of coastal mangrove forests are essential to the NbS (Nature-based Solution) Framework for Climate Change, according to numerous research (Chow, 2018; Alongi, 2008). The early research described the physics of the processes that take place when mangrove roots and stems increase wave and surge attenuation as the wave surge gets closer to the coast and decreases damaging wave and surge energies. For example, modeling and field studies indicate that surge attenuation in mangrove forests' densities and the width are the fundamental structures defining the vertical amplitude of surge attenuation. All inland communities and infrastructure can be protected by these systems, which offer an essential buffer. Additionally, the distinct energy attenuation and wave dissipation mechanisms of mangrove systems distinguish them from conventional engineering methods, which are characterized by a lack of self-maintenance and adaptation, two traits shared by all such natural systems.

Apart from hydrodynamic functions, the new area of investigation also attributes to mangroves their unique capacity for carbon sequestration, a term that has popularly coined the phrase, blue carbon ecosystems (Alongi, 2022). These ecosystems sequester carbon dioxide at an accelerated rate relative to most land forests, thus contributing to climate change mitigation from their anaerobic soils (Ihinegbu, Mönnich and Akukwe, 2023). By contrast, the degradation of mangroves is now sufficiently understood to release carbon dioxide as a forceful contributor to the greenhouse effect. Therefore, conservation is both an adaptation strategy for local communities and a global necessity for mitigation (Musa and Mohamad, 2018). In addition, a body of literature exists defending a mixed regime of economic valuation techniques to measure such services, so that policymakers will perceive conservation as a benefit to the monetary proposal of society (Bell and Lovelock, 2013). The review of this body of knowledge likewise highlights the need to develop the overarching strategy to organize the systematic assessment and comparison of these natural buffers, which leads to the next section describing physical attenuation mechanisms.

Hydrodynamics of Wave Attenuation

The capability of mangrove forests to mitigate storm surges is primarily based on the hydrodynamics of flow resistance (Zhang *et al.*, 2012). The expansive aggregation of prop roots (pneumatophores) and the trunks of mangrove trees greatly increases the surface roughness of the coastline, serving as a strong physical drag force (Friess *et al.,* 2022). When the incoming storm surge wave propagates through the forest, the structural resistance leads to a rapid dissipation of the wave energy and a decrease in the water flow velocity (Sheng and Zou, 2017). A 100-meter-wide mangrove forest has been proven to lower storm surge water levels by 0.1 to 0.5 meters when species and storm severity are taken into consideration. The degree of surge reduction has been linked to several characteristics, including forest breadth, tree density, and trunk diameter (McIvor *et al.*, 2012).

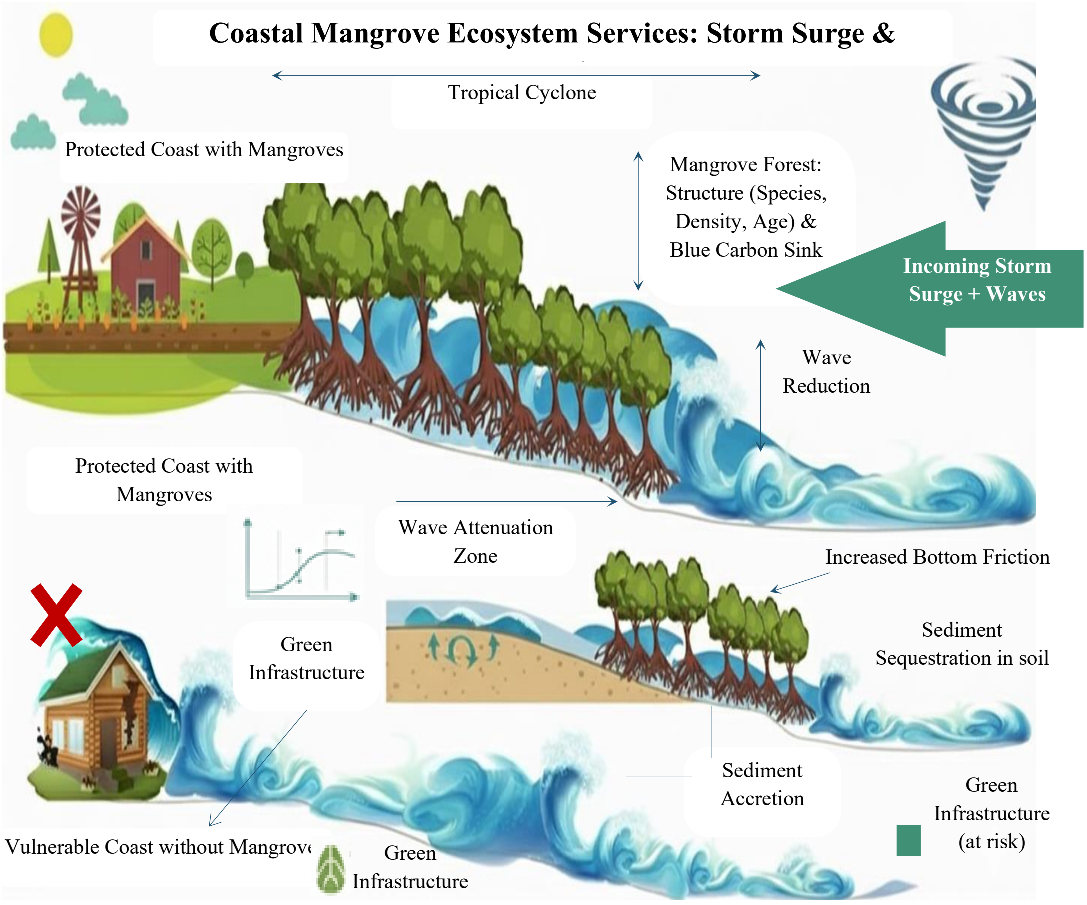

Figure 1: Coastal Mangrove's Dual Role in Storm Surge Attenuation and Coastal Protection.

Figure 1 depicts a conceptual framework that illustrates the several services that the mangrove ecosystem can provide in relation to coastal defense. In order to protect infrastructure and human resources, the diagram shows how a thick root system physically reduces the energy of a storm surge, lowering the wave height that will penetrate the interior of the beach (Alongi, 2008). It is significant because it demonstrates that mangroves serve as both a strong, self-sustaining natural barrier against the stresses of significant weather events and an essential Blue Carbon sink, swiftly burying CO_2 in a soil and biomass matrix to help reduce climate change. (Protection against Storm Surges) (Friess *et al.*, 2023).

This physical process could be intuitively represented by a straightforward friction model of wave height (H) deterioration with distance (x) in the forest, where τb represents the friction of the mangrove's vegetation (Equation 1). The basic concept is that the plant acts as a hydraulic barrier, despite the existence of more complex models. However, the natural dissipation mechanism allows for a crucial time-saving escape in addition to significantly reducing the catastrophic impacts of the surge on infrastructure and towns further inland. For the best attenuation, either a continuous forest barrier or a healthy forest barrier must be maintained. Some species, including Rhizophora spp., which frequently produce denser prop roots, provide more bottom friction and a greater possibility for attenuation.

$$\text{Wave Attenuation} \propto \text{Forest Width} \times \text{Vegetation Density}$$

Table 1: Comparative Attenuation Mechanisms of Key Mangrove Species

Mangrove Species	Typical Root System	Primary Attenuation Mechanism
Rhizophora spp. (Red Mangrove)	Dense Prop Roots, High Biomass	Enhanced Bottom Friction, Energy Dissipation
Avicennia spp. (Black Mangrove)	Pneumatophores (Vertical Roots)	Flow Resistance, Turbulence Generation
Sonneratia spp. (Apple Mangrove)	Pneumatophores	Initial Wave Breaking and Friction

Table 1 lists the different physical functions that three important mangrove species perform in reducing waves and surges. This offers a brief overview of their structural duties (10): Because of their large number of pneumatophores, Avicennia spp. have a specific function to increase flow resistance, while Rhizophora spp. (which have thick prop roots) have a particular function to increase bottom friction. The species variety of the mangrove forest and natural coastal defense, which is a functional outcome of complex root architecture and ultimately linked to hydrodynamic drag forces to mitigate the effects of storm surges, are strongly correlated, according to this temporal comparison.

Blue Carbon Sequestration and Climate Regulation

Coastal mangroves play a crucial role in mitigating climate change by acting as a sizable blue carbon sink in addition to offering direct protection from natural disasters (Friess *et al.*, 2023). The carbon found in coastal and marine environments is known as "blue carbon." One of the planet's most carbon-rich ecosystems, mangroves store enormous amounts of organic carbon in both their anaerobic, wet soils and their live biomass (Alongi, 2022). Anaerobic soils are extremely effective long-term carbon sinks because of their slow rates of decomposition, which allow carbon to be stored there for thousands of years (Ihinegbu, Mönnich and Akukwe, 2023).

One of the significant dangers associated with mangrove deforestation or degradation is the possible release of carbon, which contributes to greenhouse gas emissions and climate change (Friess *et al.*, 2023). As a result, preserving and rehabilitating these forests is acknowledged worldwide as a crucial tactic for mitigating (carbon storage) and adapting to climate change (Chow, 2018; Musa and Mohamad, 2018). Additional co-benefits in terms of biodiversity, fish nursery habitat, and local livelihoods can be obtained through the sustainable management of mangrove forests. The sustainable preservation of natural capital is closely related to the concepts of green innovation and sustainable development, which have an impact on environmental and economic policies in developing nations (Musa and Mohamad, 2018). Mangrove carbon stores must be protected in order to meet global climate goals.

Results and Discussion

To effectively include mangrove protection into coastal management, a precise and quantitative Assessment Framework (AF) is a necessary precondition for assessing the nature of diverse ecosystem services. Ecological measurements are only one aspect of assessment systems. Both the physical protection value and the climate regulatory value should be part of this assessment framework. By estimating the Avoided Damages (AD), or the difference in possible storm damage (to homes, structures, and human lives) with and without mangroves present, the protective value can be determined (Bell and Lovelock, 2013).

This makes use of economic damage functions in conjunction with hydrodynamic models. The Blue Carbon Stock Value (CSV), which is determined by multiplying the amount of carbon stored in soil and biomass by the social cost of carbon (SCC), a monetary amount that represents the economic harm associated with one extra tonne of CO2 emissions, can be used to evaluate the climate regulation value. Consequently, the sum of these essential components would represent the ecosystem service's (ETS) entire monetary worth. Comparative performance studies revealed that "green" infrastructure, such as healthy mangroves, was a better long-term solution because it was resilient, self-repairing, and less expensive than "grey" infrastructure, which offered high costs. The Damage Reduction Coefficient (DRC), which offered a comparison and analysis of existing values, was one of these metrics that did well in each of the best practices examinations (Zhang *et al.*, 2012).

$$E_{TS} = A_D + C_{SV}$$

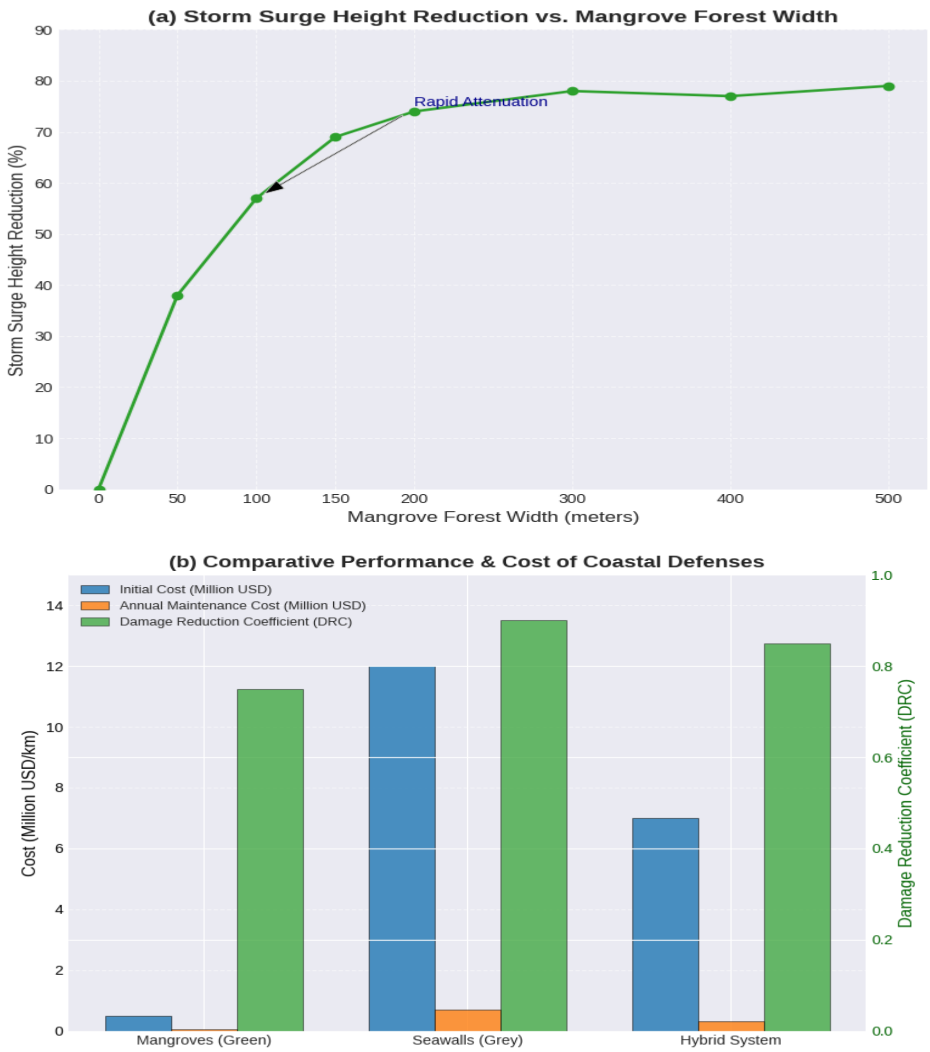

Figure 2: Proposition of mangrove conservation in integrated coastal zone management

Figure 2 (a) presents the physical protective service, quantifying the non-linear relationship between increasing Mangrove Forest Width and Storm Surge Height Reduction (%). The curve illustrates that the rate of surge attenuation is most significant within the first meters of the forest, as wave energy dissipates rapidly with complex root structures (McIvor *et al.*, 2012). Despite the attenuation decreasing with width, the curve flattens, which demonstrates that the minimum continuous buffer is the most significant element in providing protection (Zhang *et al.*, 2012). Figure 2 (b) shows a Comparative Performance and Cost Analysis of several defense strategies using synthetic data from an economic valuation study (Bell and Lovelock, 2013). The initial cost, annual maintenance cost, and damage reduction coefficient (DRC) of mangroves (green infrastructure), seawalls (grey infrastructure), and a hybrid system are compared in this grouped bar graph. As the graphic illustrates, mangroves offer far cheaper startup and annual maintenance costs than engineered systems. Even though seawalls may have a marginally higher (better) DRC in some locations, the DRC value for Mangroves is significant, with both minimal ongoing cost and ecological co-benefits providing an overall sustainable and cost-effective defense solution.

Table 2 is a key quantitative piece of evidence supporting the economic arguments for conserving mangroves, as also demonstrated through the total ecosystem service value (ETS) discussed in the Assessment Framework.

Table 2: Estimated Economic and Ecological Value of Mangrove Ecosystem Services (Per Hectare/km)

Ecosystem Service Category	Metric Measured	Illustrative Value Range	Unit
Physical Protection (AD)	Storm Surge Damage Avoided	3,500 – 11,000	USD/hectare/ year
Climate Mitigation (CSV)	Blue Carbon Stock (Soil & Biomass)	1,000 – 4,000	tonnes C/ha
Fisheries Support	Nursery Habitat Value	1,500 – 9,000	USD/hectare/ year
Long-Term Asset	Maintenance Cost Avoided	250 – 750	USD/km/ year
Total Net Present Value (NPV)	Sum of all Services	High	USD/ha/ decade

The ETS is subdivided in Table 2 into the various primary services. The Physical Protection service, as measured through the Avoided Damages (AD) metric associated with storms, had a high annual economic return, making conservation a cost-effective defence measure. Table 2 also provides quantification of Climate Mitigation value through Blue Carbon Stock density (Friess, Adame, Adams and Lovelock, 2022); material increases in density (Ihinegbu, Mönnich and Akukwe, 2023) when multiplied by the social cost of carbon provide a monetary value for the service. The comparison to Maintenance Cost Avoided demonstrates the long-term economic benefit of nature-based solutions rather than traditional engineered "grey" infrastructure.

The foundation of this investigation is established through a structured Assessment Framework developed to transition the value of mangroves from a subjective perception to quantitative, actionable metrics that could inform federal policy. The total economic measure of the ecosystem service (ETS) is the aggregate of Avoided Damages from storms (AD) and the Blue Carbon Stock Value (CSV), which is the foundation of our assessment. The protective service, AD, is measured through a hydrodynamic model, which determines the Storm Surge Height Reduction provided by the mangrove forest (Figure 1a) (McIvor *et al.*, 2012). The physical attenuation of the storm surge is essential and, as demonstrated in Figure 1a, the majority of storm surge is physically reduced within 100 to 200 meters of the mangrove forest width, confirming that the drag force of the associated vegetative community minimizes the delay of inland flooding. This assessment is formalized through a conceptual algorithmic approach, described in the pseudocode, defining AD as the difference in damages associated with financial loss to property at coastlines with and without the buffer of mangroves.

For a complete validation of the mangrove strategy, performance must be compared to the performance of the traditional "grey" infrastructure. Table 2 presents example quantitative metrics that support the economic superiority of the green solution. Mangroves have been assessed as high value for Avoided Damages (AD) and have taken into consideration the financial benefits of Maintenance Costs Avoided over time, both ultimately aligning with the defining criteria for high-cost engineered defense systems. In addition, the economic benefit was enhanced by acknowledging their advocacy role in climate change mitigation: Table 2 presents quantifiable values for Blue Carbon Stock, per hectare, which, when monetized, falls between the CSV component of total ecosystem value and economic gain.

The Comparative Performance Analysis (Figure 1b) gives a visual summary of this economic case, comparing Mangroves and Hybrid Systems values to traditional Seawalls. Although complex structures (Grey) provide a higher Damage Reduction Coefficient (DRC) in localized areas, the analysis also indicated that mangroves represent the highest value-to-cost ratio due to the initial and annual maintenance costs being extremely low. Furthermore, the resiliency and value-to-cost ratio reflect the ecological co-benefits of mangroves, which are not covered in the basic Damage Reduction Coefficient (DRC), such as nursery habitats/orders or adapting to sea level rise. The actual data supporting this established paradigm clearly show that mangrove conservation is a better, sustainable strategy.

Conclusion and Future Research Directions

Because they store blue carbon, which mitigates the effects of climate change, coastal mangrove forests offer an essential and adaptable natural defense system that shields healthy ecosystems from storm risks. Mangrove ecosystem services are more than just natural resources, according to empirical data, and they are becoming more widely acknowledged as an essential part of coastal resilience plans. Additionally, the advantages of wave and surge attenuation for coastal towns' safety and economy may be confirmed and handled as soon as their benefits for the environment. More sophisticated models for predicting surge reduction across various climate impacts should be the focus of future study, particularly when it comes to synergistic combinations of storm strength and sea level rise. Future texts should also standardize the economic value of blue carbon stocks for conservation on a larger, policy-worldview scale. It should also be a top priority to compile the ecological and economic database into a manageable policy brief that can emphasize increasing future mangrove conservation and restoration in order to lessen the vulnerability of coastal infrastructures and coastal beach areas of the world's population.

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