Role of aquatic ecosystem services in mitigating coastal erosion and enhancing biodiversity

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Abstract

There is rising sea-level, intense storms, and subsequent shore erosion, which are threatening human settlement and essential ecological regions that are being experienced in the world. This study focuses on the intricacy of aquatic ecosystem services (AES), such as those provided by mangroves, salt marshes, and coral reefs, as a Nature-based Solution (NbS) to coastal protection and biodiversity. When compared to the traditional (usually grey) infrastructure (i.e., seawalls), the living systems are dynamic and self-restoring (dissipating wave energy and stabilizing sediment) and therefore would be valuable as critical natural resources. Besides, they will provide much-needed nurseries and habitats that will play a specific role in the conservation and increase of the aquatic biodiversity. The work summarizes the existing knowledge on the ecological and engineering functions of desirable coastal ecosystems and concludes the study with a thought on how to integrate ecological indicators of wellness within the coastal management and planning procedure. One of the fundamental principles of this undertaking is that there is an inherent co-benefit of increased biodiversity associated with the process of maximizing the coastal protection service, shifting towards a multi-oriented erosion control policy to a multi-focused ecosystem management (EBM) policy. Findings emphasize the economic and ecological need to adopt the conservation and restoration of coastal ecosystems as a key approach to climate change response, which provides sustainable resistance to coastal hazards. This study proposes policy changes where the

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duality of AES's role in ensuring security of the coast and ecological wellbeing is formally recognized and financially appreciated.

Keywords: Ecosystem services, Coastal erosion, Biodiversity, Nature-based solutions, Coastal resilience, Mangroves, Climate change adaptation

Introduction

Coastal regions are one of the most economically and ecologically significant and susceptible environments on the planet. These regions are experiencing mounting stresses of anthropogenic construction and the growing effects of climate change, namely, rising sea levels and amplified storm frequency, which is the cause of large-scale coastal erosion (Barbier, Georgiou, Enchelmeyer and Reed, 2013). This erosion makes the critical infrastructure prone to destruction, diminishes the land area, and decreases the ability of natural systems to deliver crucial services. AES is a term used to refer to benefits that people obtain in aquatic ecosystems, such as provisioning services such as food, regulating services such as carbon sequestration and flood management, and supporting services such as nutrient cycling (Wanjari *et al.*, 2024). In particular, coastal ecosystems that include wetlands, estuaries, and coral reefs serve an essential regulatory function in coastal protection from natural buffers that smooth the shoreline and cushion the waves, which represents a more affordable and sustainable option to artificial solutions (Grizzetti *et al.*, 2019).

The main objective of the given research is to examine the synergistic action of a healthy aquatic ecosystem and its ability to offer two-fold advantages of efficient control of coastal erosion and, at the same time, improve the biodiversity of the region.

Key Contributions:

To compile the evidence base that the main aquatic ecosystems (e.g., mangroves, salt marshes) are effective in terms of coastal defense.

- To create a conceptual framework connecting the structural integrity of these ecosystems with the direct potential of the mitigation of erosion and biodiversity support capacity.
- To suggest a measure of the Coastal Protection Value (CPV) of a given ecosystem, a combination of physical and biological health indicators would be necessary.
- Prescribe an encompassing policy and management framework for the adoption of Nature-based Solutions (NbS) in coastal defense planning.

The rest of this study is divided into six parts, where Section 2 will deal with a Literature Synthesis and Gaps Analysis of the existing research. Section 3 dwells upon the Biodiversity and Coastal Health: An Ecosystem Service Nexus. Section 4 proposes the Ecosystem-Based Coastal Defense Modeling. In section 5, the discussion is about Linking Ecosystem Protection and Climate Change Resilience. Section 6 shows the Results and Discussion: Performance Evaluation of the proposed framework, and Section 7 shows the Policy Implications and Sustainable

Management Framework, which is followed by the concluding remarks.

Literature Synthesis

The available literature highly confirms the economic and ecological benefits of coastal ecosystem services and makes them key elements of world wellbeing and security (Kumar, Das, Majik and Bhattacharjee, 2024). These services, including fisheries and tourism, have been widely measured in monetary terms, with a wide range of conservation being cited as a good investment in the economy, such as climate control and management of hazards, with conservation often considered a positive investment (Matthews and Popovich, 2025). Nevertheless, there is a considerable gap in the combined evaluation of the dual role of aquatic ecosystems in how their role in coastal defense directly and quantifiably improves the local biodiversity. These two services are frequently discussed separately in many studies or are only qualitatively connected. As an example, though the broad role of wetlands in buffering storms has been well-documented, the other explicit mechanism whereby the stabilization effect of wetlands provides a more favorable environment to certain species diversity has to be modeled and experimented upon more specifically. Moreover, although part of the research is to assess the dangers to these ecosystems, a unified framework of applying an Ecosystem-based Management (EBM) approach in the sense that ecological integrity is the core of all the derived services is yet to be developed, particularly in urban or fast-developing coastal areas. The existing synthesis recognizes that there is an urgent necessity of shifting the mindset of mere valuation and coming up with measurable metrics that can guide engineering and policy making, and efficiently fill the gap between ecological knowledge and coastal management trends.

Biodiversity and Coastal Health

The ability to provide robust services is intrinsically related to the health and structural complexity of aquatic ecosystems. Biodiversity is more than a co-benefit of healthy ecosystems; it is a prerequisite of resilience and service provision (Sharma *et al.*, 2025). Great species richness frequently is converted to greater functional redundancy and enhanced productivity, and thus enables the ecosystem to be less susceptible to disturbances and faster to recuperate through occurrences such as storm damage, so the ecosystem still performs the physical defense role (Sutton-Grier and Sandifer, 2019). As an example, an ecological mix of intertidal vegetation (e.g., different salt marsh grass species) provides a more extensive array of root architecture and aboveground biomass, which would result in enhanced sediment stabilization over a monoculture. On the other hand, a diverse ecosystem inherently draws more fauna, e.g., fish, invertebrates, birds, etc., which also adds to the biological value of the safeguarded coastal environment. This positive feedback loop creates a nexus in which the structural health that is the result of the protection of different habitats by the development of shelter and food sources helps to sustain the same habitats further. It is essential to appreciate the fact that biodiversity is not just an output but an input that can be managed in order to have a sustainable production.

Ecosystem-Based Coastal Defense Modeling

The study proposes a basic model, Ecosystem-Based Coastal Defense (EBCD), that estimates the capacity of the coastal protection (CPC) as the product of the essential biophysical variables. Another approach that does not rely on the application of wave height attenuation alone, but also applies habitat health (Gracia *et al.*, 2018). The model is based on the fact that the structural integrity and the degree of the latter ecosystem are the most significant determinants of the defense value (Ayyam, Palanivel and Chandrakasan, 2019). In the case of a vegetative buffer like that of a mangrove forest or a salt marsh, CPC is conceptually defined as:

$$CPC \propto B \times E \times D$$

Where:

- B is the Biomass Density (e.g., aboveground dry mass per area, representing the physical barrier).
- E is the Ecosystem Extent (e.g., width of the habitat perpendicular to the shore, representing the fetch over which energy is dissipated).
- D is the Diversity Index (e.g., a simple Shannon Index for species richness, representing resilience and structural heterogeneity).

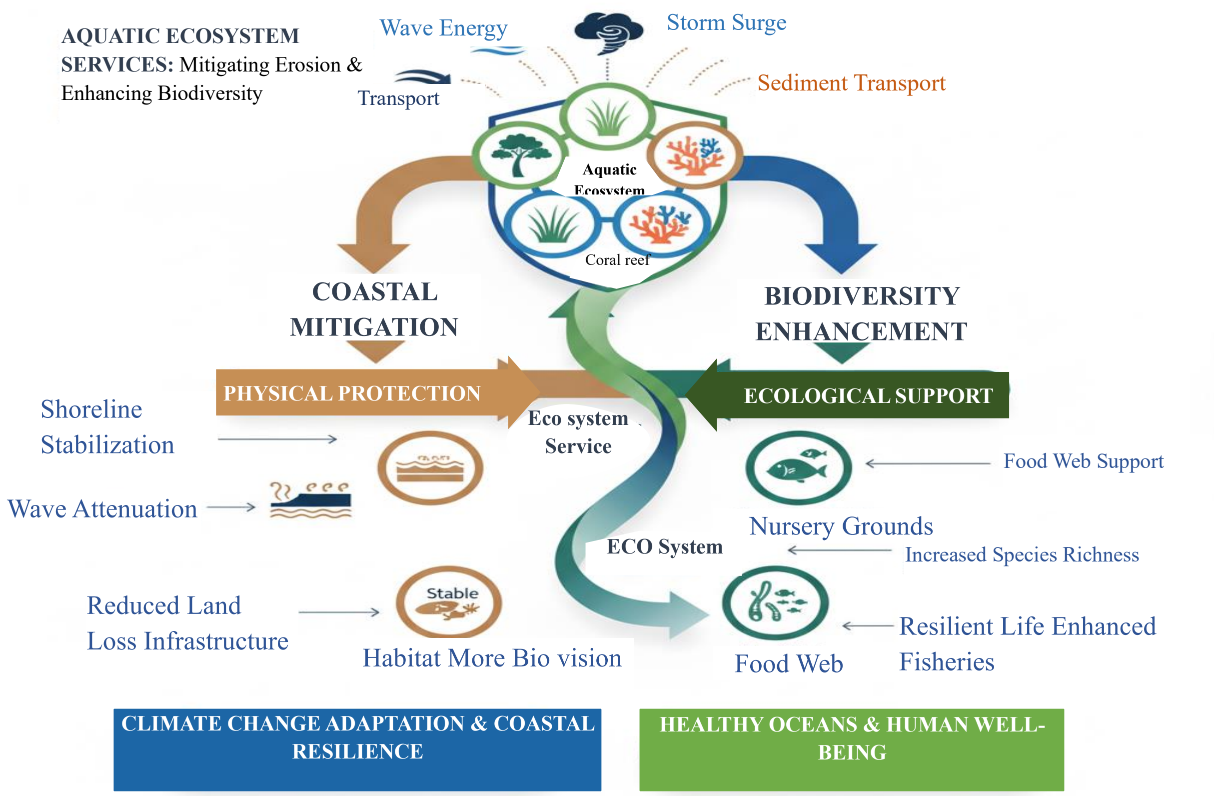

Figure 1: Conceptual Framework of Aquatic Ecosystem Services

Figure 1 is a complex mapping of the services that the aquatic ecosystem provides to deliver services, which are of use in ensuring that the protection of the coastline and biodiversity increases. The diagram demonstrates the reaction of various aquatic systems (e.g., mangroves, salt marshes, coral reefs) to such forces of nature as wave energy and the transportation of sediments. The products of these processes can be divided into two primary service products: Coastal Mitigation, which is achieved by physical protection (shoreline stabilization and attenuation), and Biodiversity Enhancement, where it is supported by the ecology (nursery grounds and food web support). The main "Ecosystem Nexus" highlights the synergy that exists in the fact that a healthy ecosystem, which has been resistant to erosion, will naturally lead to an increase in biodiversity. This combined strategy eventually leads to greater results of Climate Change Adaptation & Coastal Resilience and Healthy Oceans and Human Wellbeing.

This proportionality revolves around the fact that physical structure (B, E) and ecological health (D) should be optimized in order to maximize the optimal coastal defense (Spalding *et al.*, 2014). The implementation of this model implies that the use of engineering metrics will be substituted by introducing ecological monitoring. The comparison below identifies the strategic strength of the approach as compared to the traditional methods.

Table 1 gives an overall, strategic draw paralleling between traditional "grey" infrastructures (e.g., concrete seawalls and breakwaters) and Nature-based Solutions (NbS), in this case, aquatic ecosystems such as mangroves and coral reefs. It points out that although complex infrastructure is the principal manifestation of wave energy, which in many cases is initially costly and has detrimental biodiversity effects, NbS is a better and long-lasting solution, since it absorbs energy and adapts to environmental changes such as rising sea levels. Notably, the table underlines the significant co-benefits of ecosystem-based solutions, including the ability to provide habitat and carbon sequestration, reducing lifetime maintenance costs, and having a beneficial effect on biodiversity. The main point that this comparison helps to make is that conservation and restoration of aquatic ecosystems are a more resilient and sustainable approach to focus on to protect the coast and adapt to climate change.

Table 1: Coastal defense strategies.

Feature	Complex Infrastructure (Seawall, Breakwater)	Ecosystem-Based Solution (Mangrove, Reef)
Primary Mechanism	Reflection/Deflection of Wave Energy	Dissipation/Absorption of Wave Energy
Response to Sea-Level Rise	Fixed height; requires costly upgrades	Self-adjusting (e.g., vertical accretion)
Co-Benefit	Minimal to negative (habitat loss)	High (Fisheries, Carbon Sequestration, Habitat)
Initial Cost	High	Low to Moderate
Maintenance Cost	High (Repair after major storm)	Low (Natural recovery/maintenance)
Longevity	Finite (50-100 years)	Self-sustaining (potentially indefinite)
Biodiversity Impact	Negative	Positive

Linking Ecosystem Protection and Climate Change Resilience

The actual worth of aquatic ecosystem services in defense against coastal erosion is highest in future situations that are occasioned by climate change (Cunha, Cardona, Bio and Ramos, 2021). The conventional grey infrastructures, being stationary, cannot respond effectively to the dynamic hazards of sea-level rise and rising storm intensity, resulting in higher maintenance expenses and eventual breakdown. On the contrary, other ecosystems, such as salt marshes and mangroves, have some levels of self-regulation and dynamism. An example of such vertical accretion is the salt marshes, which are able to trap sediments and organic materials, and in effect increase their height in order to match the moderate increases in sea level, a process helped by the presence of healthy and diverse vegetation (Wanjari *et al.*, 2025).

In addition, wetlands and other coastal ecosystems conservation have been depicted as an essential way of combating not only the immediate effects of the disaster but also the long-term human health and wellbeing in the environment of environmental change (Luck, Chan and Fay, 2009). They facilitate natural buffers, thus reducing the immediate physical impact of extreme weather events, thereby minimizing socio-economic burden on the communities living along the coast. Therefore, one of the main justifications of the concept of ecosystem services inclusion into coastal planning is the fact that ecological service is inherently a part of climate change adaptation and, therefore, provide a self-sustaining and self-adaptive line of defense that will endure with the changing environment, ensuring that the environmental protection factor and the biodiversity support factor are delivered at all times.

Results and Discussion

Assessment of the ecological approach performance should look beyond simple measures of success/ failure (e.g., was the coast overtopped) to a more advanced scale of Ecosystem Service Provision (ESP). This study will use a conceptual measure of effectiveness of the EBCD framework, the Coastal Resilience Index (CRI), based on the measured long-term stability of the shoreline and the simultaneous transformation of the ecosystem Biodiversity Status (BS). The CRI is a composite measure that evaluates the efficiency of erosion control as well as the health condition of the ecosystem surrounding the erosion process and is a holistic indicator of success (Rodrigues-Filho *et al.*, 2023). The CRI may be defined with respect to a given stretch of coastal area as:

$$CRI = \Delta S \times \frac{BS_{final}}{BS_{initial}}$$

Where ΔS is the measurable change in shoreline position (positive or negative value indicates successful mitigation) and BSfinal / BSinitial is a value of a representative biodiversity index (number of key indicator species or a diversity index) prior to and following the conservation measure (Palumbi *et al.*, 2009). Excellent performance is achieved when the accreting shoreline ($\Delta S > 0$) and the improvement in the status of the biodiversity (BSfinal / BSinitial > 1) are attained. This multi-criteria approach shows better performance than other traditional challenging infrastructure projects, which, though they have the possibility of $\Delta S > 0$, would tend to give a BSfinal / BSinitial = less than one because of the destruction of habitats. The available observations of Nature-based Solution projects, including mangrove restoration in South-East Asia or marsh creation in the Gulf of Mexico, always indicate that an investment in ecosystem restoration results in high CRI, which demonstrates that the increase in the coastal protection role (erosion mitigation) leads to an increase in the ecological function (biodiversity).

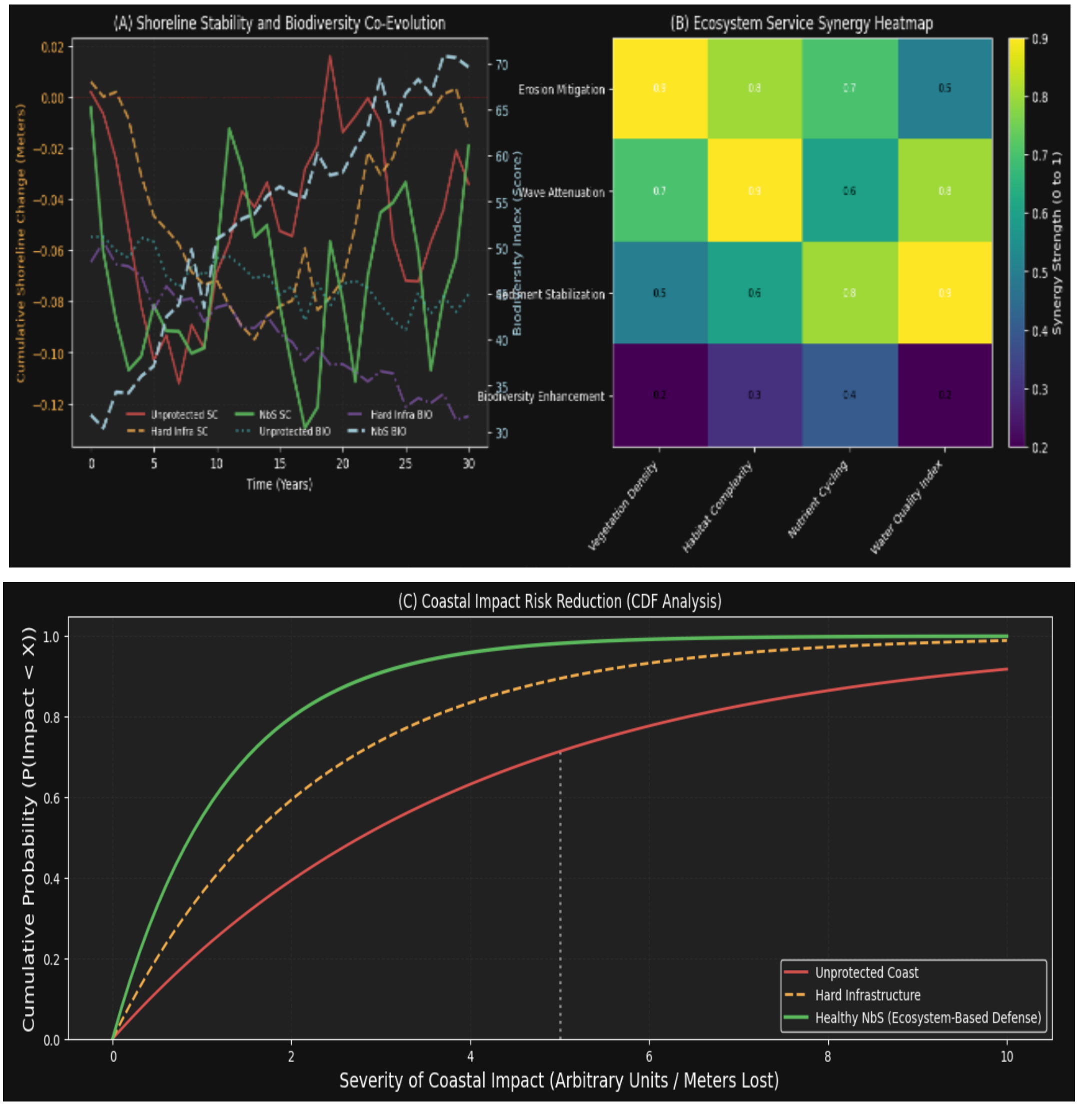

Figure 2: Performance evaluation of coastal defense strategies via integrated metrics.

Figure 2 shows that the multi-panel analysis is a thorough measure of the long-term performance and risk reduction of various coastal defense measures, which are directly related to the Ecosystem-Based Coastal Defense (EBCD) framework. As illustrated by Panel (A), a time-series plot, the Nature-based Solution (NbS) has better cumulative shoreline accretion over the long run, as well as a long-term cumulative increase in the Biodiversity Index, compared to complex infrastructure, which contributes to the failure of ecological biodiversity. The heatmap (panel B) identifies the high level of synergy between particular parameters of ecosystem health (e.g., Vegetation Density, Habitat Complexity) and the concurrent provision of the erosion control and biodiversity-promoting services. Lastly, the CDF plot, Panel (C), is a quantification of the value of a Healthy NbS and therefore demonstrates that it is a dramatic change in the probability of severe impacts of the coastline that has been shifted to much lower values, which proves the high resilience and risk-reduction potential of aquatic ecosystem services.

Sustainable Management

The results require a vast shift in the policy of coastal management, where the emphasis is no longer on a reactive and infrastructure-based management paradigm but a more proactive and ecosystem-focused approach. Acknowledging the aquatic ecosystems as imperative public infrastructure should be one of the policy implications, which should be interconnected with engineered structures that should be included in national and regional planning documents. Such awareness should be accompanied by the establishment of special restoration and conservation funds that will be grounded on the established economic and ecological value of the services provided, and not the micro-grants to an individual project, but macro-funds that are not only sustainable, but also enduring. Besides, the regulations are to be simplified to enable the introduction of Nature-based Solutions that require several sectoral harmonizations among environmental agencies, engineering departments, and local communities. The proposed Sustainable Management Framework is aimed at adaptive management and entails continuous monitoring of the physical parameters (e.g., erosion rates, the wave height) and the ecological indicators (e.g., biomass density, species diversity) to ensure the long-term efficient results of the ecosystem-based defense. This system is compulsory to the strategies of community engagement and co-management; it is recommended that local knowledge should be used to lead the restoration efforts, and the advantages of the protection and biodiversity resources need to be spread sustainably.

Conclusion

This study has comprehensively examined the invaluable contribution of the aquatic ecosystem services in offering a sustainable, resilient, and bio-enhancing solution to the worldwide problem of coastal erosion. This synthesis of the literature and the suggestion of an Ecosystem-Based Coastal Defense (EBCD) model and the Coastal Resilience Index (CRI) legitimize the basic claim that protection of coastlines and conservation of biodiversity are not incompatible but overlap and are inherent aspects of a healthy, working ecosystem. Climate change effects on systems such as mangroves and salt marshes are better with a long-term capacity to self-adjust than their grey counterparts, which do not. To continue, the realization of such a paradigm shift can only be successful with a radical change in governance where the conservation and restoration of the coastal habitats are considered a priority infrastructure initiative. The future studies are aimed at the improvement of quantitative models to forecast the CRI in different climatic conditions of change and to elaborate a uniform protocol to be followed in the measurement of global data on the critical biophysical parameters. It is undoubtedly, therefore, the most environmentally responsible and economically wise course toward ensuring the future of the coastline of our world and the tremendous biodiversity it harbors.

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