

Coastal Protected Areas as Nature-Based Climate Solutions: A Comparative Assessment of Carbon Storage, Cost-Efficiency and Socio-Ecological Co-Benefits

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Abstract

Coastal protected areas can provide climate mitigation while simultaneously supporting biodiversity, livelihoods and coastal resilience, yet their multifunctional value is rarely assessed within a common comparative framework. This study evaluates five globally significant protected coastal systems as Nature-based Solutions for climate mitigation and coastal sustainability. Using published estimates of organic carbon stocks and spatial boundaries, we calculated area-normalized carbon densities and applied a scenario-based cost-efficiency framework to estimate carbon secured relative to management expenditure. A qualitative matrix was additionally used to assess biodiversity, livelihood, fisheries and disaster-risk-reduction co-benefits, complemented by a comparative SWOT analysis of management opportunities and constraints. Estimated carbon densities varied substantially among sites, from 101 Mg C ha⁻¹ in the Great Barrier Reef to 743 Mg C ha⁻¹ in Ses Salines Ibiza, demonstrating the importance of ecosystem type and sedimentary characteristics rather than protected-area size alone. The comparative economic scenarios indicated high apparent carbon-stock-to-management-cost ratios for coastal conservation relative to the industrial carbon-capture benchmark used in this study. However, these estimates should be interpreted as indicative rather than directly equivalent carbon-abatement costs because the underlying studies differ in carbon pools, spatial boundaries and cost structures. Across the five systems, conservation also generated multiple co-benefits, particularly biodiversity protection, fisheries support, livelihoods and coastal-risk reduction. The findings support the integration of blue-carbon ecosystems and coastal protected areas into spatial planning, climate policy and sustainable financing frameworks, while highlighting the need for standardized carbon accounting, dynamic sequestration measurements and site-specific economic valuation.

1. INTRODUCTION

1.1 Climate change and coastal ecosystems

Anthropogenic greenhouse gas emissions have catalyzed global warming, causing severe socio-ecological anomalies on both global and local scales (Al-Ghussain, 2019; IPCC, 2021). The continuous emission of greenhouse gases, predominantly carbon dioxide, methane, and nitrous oxide, has disrupted the natural mass and energy balance of the planetary climate system. These gases absorb outgoing longwave radiation, steadily elevating global surface temperatures and driving physical anomalies such as prolonged droughts, intense storm surges, and erratic weather patterns (Arnell et al., 2016; Gettelman & Rood, 2016; Koll & Cronin, 2018). Recent datasets indicate that global greenhouse gas concentrations continue to rise, exalting the vulnerability of human communities and marine ecological systems alike (Ritchie & Roser, 2020).

Climate change is placing increasing pressure on coastal ecosystems and the communities and economic activities that depend on them. Rising temperatures, sea-level rise, changing storm regimes, ocean warming, and acidification interact with land-use change and other anthropogenic pressures to alter the structure and functioning of coastal systems (Arnell et al., 2016; IPCC, 2021; Mukul et al., 2019). These interacting pressures are particularly important in protected coastal landscapes, where ecological integrity, human livelihoods, resource use and institutional responsibilities frequently overlap.

1.2 Coastal protected areas as Nature-based Solutions

In response to these compounding risks, international climate agreements have prioritized rapid decarbonization and mitigation frameworks (Cook et al., 2016; IPCC, 2021). While diverse technological innovations have been proposed, such as industrial carbon capture and storage (CCS) and negative emission technologies, their deployment remains heavily constrained by high capital costs, scalability limitations, and localized environmental trade-offs (Schmelz et al., 2020). These constraints have prompted researchers and planners to investigate regenerative, low-input, and natural alternatives to bolster carbon storage and climate adaptation.

Nature-based Solutions (NbS) encompass actions that protect, sustainably manage and restore ecosystems to address societal challenges while providing benefits for human well-being and biodiversity. Coastal and marine ecosystems are particularly relevant because mangroves, seagrass meadows, salt marshes and other vegetated coastal habitats can store substantial quantities of organic carbon in biomass and sediments while providing additional ecosystem services (Serrano et al., 2019).

These services can include habitat and biodiversity conservation, fisheries support, tourism and livelihood opportunities, sediment stabilization and coastal-risk reduction.

1.3 Blue carbon and multifunctional ecosystem services

The contribution of coastal ecosystems to climate mitigation should therefore not be considered independently from their broader conservation and management functions. Protected areas can provide an institutional mechanism for maintaining ecosystem extent and integrity, thereby helping preserve existing carbon stocks and associated ecosystem services. At the same time, protected areas are not immune to climate change or local anthropogenic pressures. Coastal reclamation, pollution, agricultural runoff, overfishing, aquaculture conversion and other forms of land- and resource-use change can reduce ecological integrity even where formal protection exists (Ghosh, 2015; Hossain et al., 2021). Climate-driven pressures, including sea-level rise, ocean warming and acidification, may further alter the persistence and function of coastal ecosystems (Mukul et al., 2019).

1.4 Research gap

A further challenge concerns how the value of coastal conservation is evaluated. Carbon-storage assessments often emphasize ecological stocks or rates, whereas conservation and management assessments may focus on biodiversity, livelihoods, fisheries, tourism or coastal protection. Economic analyses likewise frequently evaluate individual interventions rather than the combined benefits of protected coastal ecosystems. This separation can obscure the multifunctional character of coastal protected areas and make comparisons across ecosystems difficult.

Comparative assessments are particularly useful because coastal protected areas differ substantially in ecosystem type, geographic extent, carbon-storage characteristics, governance arrangements and management pressures. A large protected area may contain a large total carbon stock but a relatively modest area-normalized density, whereas a smaller seagrass or wetland system may exhibit high carbon density. Consequently, spatial extent alone is insufficient to characterize the climate-mitigation relevance of a protected coastal ecosystem.

1.5 Study objectives

This study addresses this gap through a comparative synthesis of five globally significant protected coastal systems: the Great Barrier Reef in Australia, the Sundarbans in India and Bangladesh, Everglades National Park in the United States, Ses Salines Ibiza in Spain, and the Wadden Sea across the Netherlands, Germany and Denmark. The analysis combines published organic-carbon stock estimates, spatial normalization, an indicative management-cost framework, qualitative assessment of socio-ecological co-benefits, and comparative management analysis.

The study has four objectives: (1) to compare published carbon stocks and area-normalized carbon densities across five geographically diverse coastal protected areas; (2) to assess the indicative economic efficiency of coastal conservation using a standardized, scenario-based management-cost framework; (3) to synthesize documented ecological and socioeconomic co-benefits associated with the selected protected areas; and (4) to identify management opportunities, constraints and policy implications for integrating coastal protected areas into climate and coastal-planning strategies.

The five sites are treated as purposively selected comparative cases rather than as a statistically representative sample of global coastal protected areas. The objective is therefore to identify patterns and management implications across contrasting systems rather than to estimate a global mean or establish universal cost parameters.

2. MATERIALS AND METHODS

2.1 Comparative case-study design

This study applies a comparative synthesis framework to five protected coastal systems representing contrasting ecosystem types, geographic regions and institutional contexts. The analytical framework consists of five components: (1) case-study selection and classification, (2) compilation and normalization of published carbon-stock estimates, (3) scenario-based

economic assessment of management expenditure, (4) qualitative synthesis of socio-ecological co-benefits, and (5) comparative assessment of management strengths, constraints, opportunities and threats.

The analysis is designed as a synthesis of published evidence rather than a primary field survey. Consequently, the results are interpreted as comparative indicators derived from heterogeneous secondary datasets. The selected sites are illustrative cases and are not intended to represent a statistically random sample of global coastal protected areas.

2.2 Selection and classification of coastal protected areas

The five sites (Fig. 1) were selected purposively based on three criteria: (1) established institutional or legal protection, (2) representation of contrasting coastal or wetland ecosystem types, and (3) availability of published information on carbon stocks and associated ecological or socioeconomic benefits.

The Great Barrier Reef represents a large-scale marine ecosystem protection context. The Sundarbans represents a transboundary mangrove-forest system spanning India and Bangladesh. Everglades National Park represents a subtropical wetland system containing seagrass and mangrove habitats. Ses Salines Ibiza represents a Mediterranean protected seagrass system associated with *Posidonia oceanica*. The Wadden Sea represents a transboundary coastal wetland system involving the Netherlands, Germany and Denmark.

The sites differ substantially in spatial extent, ecosystem composition, governance arrangements and ecological pressures. These differences are treated as part of the comparative design rather than controlled statistically.

2.3 Carbon-stock data compilation and normalization

Published estimates of total organic carbon (TOC) were compiled from peer-reviewed literature. The primary sources utilized are Serrano et al. (2019) for the Great Barrier Reef, Kaviarasan et al. (2019) for the Sundarbans mangroves, Thorhaug et al. (2019) for the Everglades subtropical wetlands, Ouyang and Lee (2014) for Ses Salines Ibiza, and Mueller et al. (2019) for the Wadden Sea salt marshes. Area-normalized carbon density is calculated mathematically as follows:

$$CD_i = C_i / A_i$$

where CD_i is the area-normalized organic carbon stock density for site i (expressed in $Mg\ C\ ha^{-1}$), C_i represents the compiled total organic carbon stock for site i ($Mg\ C$), and A_i represents the corresponding spatial extent for site i (hectares). This calculation specifically isolates ecological stock density rather than dynamic annual sequestration flux.

2.4 Scenario-based economic assessment

To evaluate the relationship between carbon storage and management expenditure, initial establishment and annual recurring maintenance cost parameters were obtained from McCrea-Strub et al. (2011). These parameters are scaled to the spatial boundaries of the selected reserves. Crucially, McCrea-Strub et al. (2011) demonstrate that unit costs decrease nonlinearly with increasing marine protected area (MPA) size. Accordingly, representative cost rates are assigned based on spatial scaling classes:

For large-scale reserves (spatial scale $\sim 50,000\ km^2$: Great Barrier Reef, the Sundarbans, and Everglades National Park), the establishment unit cost (CE) is set at USD 254 per km^2 and the annual maintenance unit cost (CM) is set at USD 33 per km^2 -year. For smaller, highly-intensive European and Mediterranean reserves (spatial scale $\sim 500\ km^2$: Ses Salines Ibiza and Wadden Sea), the CE is assigned at USD 2,315 per km^2 and the CM at USD 1,253 per km^2 -year.

To provide a realistic temporal perspective, we separate one-time establishment expenditure from recurring annual management costs and calculate cumulative management expenditure across four distinct time horizons ($T = 1, 10, 20$, and 30 years):

$$C_{cumulative,i}(T) = (CE_i * Area_{km2,i}) + (CM_i * Area_{km2,i} * T)$$

We derive two primary economic metrics: (1) the indicative carbon-stock-to-management-cost ratio (CSR, Mg C per USD spent), representing the existing carbon stock maintained per dollar of cumulative management expenditure:

$$CSR_i(T) = C_i / C_{cumulative,i}(T)$$

and (2) the management cost per unit of existing carbon stock (MCR, USD per Mg C):

$$MCR_i(T) = C_{cumulative,i}(T) / C_i$$

Importantly, we note that these ratios do not constitute marginal abatement costs, as they evaluate standing ecological stocks rather than newly sequestered incremental carbon. Finally, these ratios are contextually benchmarked against industrial mechanical carbon capture and storage (CCS) systems, which operate at an average economic threshold of approximately 70 USD per Mg CO₂ (equivalent to 257 USD per Mg C) as reported by Schmelz et al. (2020).

2.5 Socio-ecological co-benefit assessment

To evaluate the secondary ecological, social, and physical services provided by these protected landscapes, we utilize a qualitative evidence-synthesis matrix across four critical domains: (1) habitat and biodiversity protection, (2) local livelihoods and ecotourism support, (3) sustainable fisheries support, and (4) disaster-risk reduction (e.g., shoreline sediment stabilization and wave attenuation). Impact ratings are explicitly defined as: + represents limited or indirect documented benefits; ++ indicates moderate, clearly documented benefits; and +++ signifies strong, prominent, and repeatedly documented benefits in peer-reviewed scientific studies.

2.6 Comparative management assessment

A structured, qualitative SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was completed to systematize operational bottlenecks and expansion opportunities across the selected programs. This assessment bridges natural carbon-accounting dynamics with localized regulatory and administrative realities.

2.7 Uncertainty and limitations

This comparative study is subject to several systemic limitations, including differences in sampling methods, varying sedimentary depths and carbon pool definitions in the primary sources, currency fluctuations, the static nature of standing organic carbon stocks, and the challenges of direct spatial boundary harmonization.

3. RESULTS

3.1 Characteristics and carbon stocks of the five sites

The five protected coastal systems encompass highly diverse spatial scales and ecological typologies. While large-scale reserves hold massive total organic carbon pools, the area-normalized analysis reveals varying concentrations of stored organic carbon. Table 1 summarizes the details of the core spatial parameters and total organic carbon stocks compiled across the sites.

Table 1
Spatial parameters, total organic carbon stocks, and calculated densities across the evaluated coastal systems.

NBS Program	Geographic Location	Primary NbS Classification	Area Covered (ha)	TOC Stock (Mg C)	Normalized Density (Mg C/ha)
Great Barrier Reef	Australia	Marine Ecosystem Protection	4,963,700	502,045,690	101
The Sundarbans	India/Bangladesh	Mangrove Forest Protection	1,027,700	168,000,000	163
Everglades Park	USA	Seagrass & Mangrove Protection	1,992,200	400,000,000	201
Ses Salines Ibiza	Spain	Seagrass Protection	55,795	41,427,788	743
Wadden Sea	Trilateral	Coastal Wetland Protection	63,114	11,231,673	178

3.2 Area-normalized carbon density

Our area-normalized carbon density modeling indicates a wide variation across the evaluated ecosystems, ranging from 101 Mg C ha⁻¹ in the Great Barrier Reef to an exceptional 743 Mg C ha⁻¹ in the Mediterranean seagrass meadows of Ses Salines Ibiza (Table 1, Fig. 2). Significantly, the high density in Ses Salines Ibiza reflects the unique sedimentological capacity of *Posidonia oceanica* meadows to lock organic carbon deep within anoxic sedimentary soils, highlighting that reserve size does not dictate local organic carbon storage concentration.

3.3 Scenario-based economic assessment

By addressing the mixed-unit calculation error present in earlier literature, where unit costs expressed per square kilometer were erroneously scaled as if they were per hectare, this study provides the first mathematically consistent scenario-based cost assessment for these coastal protected areas. Table 2 illustrates initial and recurring annual costs, demonstrating the non-linear economies of scale where larger reserves require substantially lower management expenditures per unit area.

Table 2
Economic parameters and scenario-based cumulative management costs.

NBS Program	Area (km ²)	CE (USD/km ²)	CM (USD/km ² -yr)	Y1 Cumulative (USD)	Y10 Cumulative (USD)	Y20 Cumulative (USD)	Y30 Cumulative (USD)
Great Barrier Reef	49,637.00	254.00	33.00	14,245,819.00	28,988,008.00	45,368,218.00	61,748,428.00
The Sundarbans	10,277.00	254.00	33.00	2,949,499.00	6,001,768.00	9,393,178.00	12,784,588.00
Everglades Park	19,922.00	254.00	33.00	5,717,614.00	11,634,448.00	18,208,708.00	24,782,968.00
Ses Salines Ibiza	557.95	2,315.00	1,253.00	1,990,765.60	8,282,767.75	15,273,881.25	22,264,994.75
Wadden Sea	631.14	2,315.00	1,253.00	2,251,907.52	9,369,273.30	17,277,457.50	25,185,641.70

Using these corrected cumulative expenditures, Table 3 details the indicative carbon-stock-to-management-cost ratios (CSR) alongside management costs per unit of existing carbon stock (MCR). As the scenario time horizon increases, the cumulative maintenance costs naturally accumulate, driving a gradual rise in unit carbon costs. Nonetheless, even at the 30-year horizon, unit carbon costs remain extremely competitive (Fig. 3): ranging from 0.06 USD per Mg C in Everglades National Park to 2.24 USD per Mg C in the Wadden Sea.

Table 3

Indicative carbon-stock-to-management-cost ratios (CSR, Mg C/USD) and management costs per unit of existing carbon stock (MCR, USD/Mg C).

NBS Program	TOC Stock (Mg C)	CSR Y1 (Mg C/USD)	CSR Y10	CSR Y20	CSR Y30	MCR Y1 (USD/Mg C)	MCR Y10	MCR Y20	MCR Y30
Great Barrier Reef	502,045,690	35.24	17.32	11.07	8.13	0.0284	0.0577	0.0904	0.1230
The Sundarbans	168,000,000	56.96	27.99	17.89	13.14	0.0176	0.0357	0.0559	0.0761
Everglades Park	400,000,000	69.96	34.38	21.97	16.14	0.0143	0.0291	0.0455	0.0620
Ses Salines Ibiza	41,427,788	20.81	5.00	2.71	1.86	0.0481	0.2000	0.3687	0.5374
Wadden Sea	11,231,673	4.99	1.20	0.65	0.45	0.2005	0.8342	1.5383	2.2424

3.4 Socio-ecological co-benefits

A qualitative synthesis of secondary ecosystem services confirms that habitat and biodiversity protection is a highly successful primary outcome across all sites, directly linked to the environmental conservation mandates under which these reserves were established (Fig. 4 provides the qualitative matrix of secondary co-benefits). Socio-economic spillovers are also prominent, driven by ecotourism in the Great Barrier Reef (+++) and sustainable fisheries support in the Sundarbans (+++). In contrast, wave attenuation and shoreline protection (disaster risk reduction) are historically under-represented in the literature reviewed for these specific sites..

3.5 Management strengths, constraints, opportunities and threats

Table 4 presents our comparative management assessment (SWOT), aligning cross-site findings with concrete coastal-management and spatial planning implications.

Table 4

Comparative management assessment (SWOT) and planning implications.

Dimension	Cross-site Finding	Management & Planning Implication
Strengths	Existing legal protections and institutional bases preserve massive core carbon pools while safeguarding localized biodiversity.	Strengthen active enforcement and ecological monitoring systems.
Weaknesses	Jurisdictional overlaps and administrative fragmentation among municipal, regional, and national agencies dilute enforcement.	Improve inter-agency coordination and harmonize cross-boundary policies.
Opportunities	Mainstreaming blue carbon assets into regional planning can unlock innovative, private conservation finance mechanisms.	Develop blue finance schemes tied to verifiable, long-term ecological outcomes.
Threats	Escalating coastal land-use conversion, agricultural run-off, and sea-level rise threaten habitat extent and structural integrity.	Integrate strict ecosystem conservation targets directly into coastal spatial planning frameworks.

4. DISCUSSION

4.1 Variation in carbon-storage potential among coastal protected areas

The comparison demonstrates that the total carbon stock and area-normalized carbon density of a protected coastal system provide different forms of information. The Great Barrier Reef has the largest reported total carbon stock among the five cases,

reflecting its extensive spatial footprint, whereas Ses Salines Ibiza has the highest reported carbon density at 743 Mg C ha⁻¹. This contrast indicates that spatial extent alone cannot be used to identify coastal blue-carbon priorities.

The high reported density associated with Ses Salines Ibiza is consistent with the importance of seagrass ecosystems as carbon-storage environments, particularly where organic matter is retained in underlying sediments. However, the comparison should not be interpreted as evidence that seagrass ecosystems universally store more carbon than mangroves, salt marshes, coral-reef-associated systems or other coastal habitats. The estimates originate from different studies with different boundaries, carbon pools and methodological approaches. Therefore, the principal implication is methodological as well as ecological: blue-carbon planning should consider carbon density and ecosystem characteristics alongside total protected-area extent.

For conservation planning, area-normalized carbon density can help identify candidate ecosystems where relatively small areas contain substantial existing carbon stocks. However, carbon density should be considered together with ecosystem condition, permanence, vulnerability, biodiversity, restoration feasibility and social context. A high carbon stock that is highly vulnerable to disturbance does not necessarily represent a secure long-term mitigation asset.

4.2 Economic interpretation and implications for conservation investment

The economic analysis provides an indicative comparison between published carbon stocks and management expenditure. The principal advantage of the revised framework is that it separates establishment costs from recurring management costs and makes the time horizon explicit. This avoids treating a one-time establishment investment and an annual management cost as if they were incurred over an undefined period.

The results should nevertheless be interpreted as a comparison of existing carbon stocks with management expenditure rather than as a conventional marginal abatement-cost analysis. Protecting an ecosystem that already contains a large carbon stock does not mean that the entire stock is newly sequestered as a consequence of the management expenditure. The economic value of protection lies partly in preventing future loss, degradation or emissions, but the avoided-emissions component would require a counterfactual baseline that is not developed in the present study.

This distinction is especially important when comparing coastal conservation with industrial CCS. Industrial CCS is generally evaluated in terms of the cost of capturing, transporting and storing additional CO₂, whereas the present coastal analysis begins with an existing ecosystem carbon stock. The two metrics therefore address related but different questions. Accordingly, the CCS comparison is best interpreted as contextual benchmarking. The analysis can demonstrate that coastal conservation may have a highly favorable relationship between management expenditure and the quantity of carbon already stored in an ecosystem, but it cannot by itself establish that coastal ecosystems remove carbon at a particular multiple of the cost of industrial CCS.

The principal contribution of this study is not to establish a universal cost advantage of coastal Nature-based Solutions over industrial carbon capture, but to demonstrate how protected coastal ecosystems can be evaluated as multifunctional climate and conservation assets by jointly considering stored carbon, management expenditure and documented socio-ecological benefits.

4.3 Multifunctionality and ecosystem-service co-benefits

The co-benefit assessment highlights a central characteristic of coastal NbS: they are multifunctional systems unlike a single-purpose engineered intervention wherein a protected coastal ecosystem can simultaneously conserve biodiversity, support fisheries, provide livelihood opportunities and contribute to coastal-risk reduction.

The Great Barrier Reef illustrates the importance of tourism and livelihood benefits associated with protected coastal ecosystems while the Sundarbans illustrates the connection between coastal ecosystem conservation and fisheries resources. Across the five cases, habitat and biodiversity conservation represent a consistent outcome of protection.

However, the disaster-risk-reduction dimension requires particular caution. The present matrix identifies documented protective benefits, but the literature reviewed for the selected cases does not provide a harmonized quantitative estimate of wave attenuation, sediment stabilization or avoided storm damage. The lack of comparable monetary values should not be interpreted as evidence that the benefits are absent, but instead, indicates a measurement gap to estimate how habitat extent and condition affect wave attenuation, erosion, flood exposure and storm-surge damages under different climate scenarios.

4.4 Governance and implementation constraints

The comparative management assessment identifies several recurring constraints: overlapping jurisdictions, land-use change, pollution, runoff, overfishing and climate-driven ecosystem degradation. Transboundary systems such as the Sundarbans and Wadden Sea demonstrates the importance of coordination across administrative and national boundaries. Protection on paper may not produce effective conservation if enforcement, monitoring and financing are fragmented.

The results also reinforce the importance of site-specific restoration as coastal ecosystems are shaped by hydrology, sediment supply, salinity, geomorphology and biological interactions. Restoration approaches that ignore these characteristics can produce ecological incompatibilities or fail to deliver expected ecosystem functions.

Implications for coastal planning and climate policy

1. Carbon-storage information should be incorporated into spatial planning to help identify potential blue-carbon hotspots, but it should be combined with ecosystem condition, vulnerability and conservation feasibility.
2. Coastal protected areas should be incorporated into climate mitigation and adaptation planning simultaneously. The same ecosystem may store carbon while reducing coastal hazards and supporting livelihoods.
3. Sustainable financing mechanisms should recognize multifunctionality and should not rely exclusively on carbon credits. Where feasible, financing frameworks should also recognize biodiversity, fisheries, tourism and coastal-protection benefits.
4. Monitoring systems should move beyond static inventories with repeated measurements of carbon stocks and fluxes are required to determine whether ecosystems are accumulating, maintaining or losing carbon over time.
5. Coastal policy should strengthen coordination among environmental agencies, spatial planners, local governments, resource users and communities.

5. CONCLUSIONS

The comparative assessment demonstrates how coastal protected areas can function as multifunctional NbS by simultaneously supporting carbon storage, biodiversity conservation, livelihoods, fisheries and coastal resilience. Across the evaluated systems, reported carbon densities varied considerably, highlighting the influence of ecosystem characteristics and sedimentary conditions rather than protected-area size alone. The highest reported normalized carbon density was associated with the seagrass ecosystem of Ses Salines Ibiza, while the Great Barrier Reef contained the largest reported total carbon stock among the evaluated systems.

The scenario-based economic assessment provides an indicative perspective on the relationship between existing ecosystem carbon stocks and management expenditure. However, the resulting carbon-to-cost ratios should not be interpreted as direct marginal costs of carbon sequestration or as evidence that management expenditure caused the entirety of the measured carbon stock.

The assessment also demonstrates that the value of coastal protected areas extends beyond carbon and consider biodiversity conservation, fisheries, tourism and livelihoods, together with coastal-risk-reduction functions. These co-benefits contribute to the multifunctionality of these ecosystems that strengthen the rationale for incorporating coastal protected areas into integrated climate and coastal-management strategies.

Limitations

While this assessment highlights the multi-benefit value of coastal NbS, the paper acknowledges inherent limitations such as organic carbon density calculations relying on heterogeneous secondary datasets compiled across different sampling design

frameworks. The scenario-based economic assessment uses generalized historical management cost parameters derived from McLeod et al. (2011), does not reflect the dynamic, site-specific realities of conservation finance or direct marginal carbon abatement costs. The economic model also operates on static carbon stock estimates and lacks a dynamic representation of real-time carbon dioxide flux, permanence, leakage, or potential feedback emissions. The qualitative evaluation of co-benefits is based on a synthesis of documented outcomes rather than primary field measurements, and the purposive selection of five flagship protected areas limits the statistical generalizability of these findings. Lastly, the economic analysis lacks a counterfactual baseline, which is a prerequisite for establishing the precise quantity of carbon emissions avoided through conservation enforcement. Future research should develop harmonized these limitations to provide a stronger evidence base integration of coastal NbS into national climate strategies, protected-area planning, coastal spatial planning and sustainable-finance mechanisms.

Declarations

Author Contribution

AJFR conducted the study conception, design, and framework development, data collection, mathematical cost-modeling, and initial drafting, writing and review.

Data Availability

The organic carbon stocks, spatial boundaries, and financial valuation metrics analyzed during this study are fully compiled from published, peer-reviewed scientific literature and are included entirely within the manuscript.

References

1. Al-Ghussain L (2019) Global warming: review on driving forces and mitigation. *Environ Prog Sustain Energy* 38(1):13–21. <https://doi.org/10.1002/ep.13041>
2. Arnell NW, Brown S, Gosling SN, Gottschalk P, Hinkel J, Huntingford C, Lloyd-Hughes B, Lowe JA, Nicholls RJ, Osborn TJ, Osborne TM, Rose GA, Smith P, Wheeler TR, Zelazowski P (2016) The impacts of climate change across the globe: A multi-sectoral assessment. *Clim Change* 134(3):457–474. <https://doi.org/10.1007/s10584-014-1281-2>
3. Atisa G (2020) Using historical information and data to strengthen planning for environmental protection and management at Everglades National Park, South Florida. *J Environ Stud Sci* 10:399–409. <https://doi.org/10.1007/s13412-020-00599-5>
4. Choe Y, Schuett M (2020) Stakeholders' perceptions of social and environmental changes affecting Everglades National Park in South Florida. *Environ Dev* 35:100524. <https://doi.org/10.1016/j.envdev.2020.100524>
5. Cook J, Oreskes N, Doran PT, Anderegg WR, Verheggen B, Maibach EW, Carlton JS, Lewandowsky S, Skuce AG, Green SA, Nuccitelli D (2016) Consensus on consensus: a synthesis of consensus estimates on human-caused global warming. *Environ Res Lett* 11(4):048002. <https://iopscience.iop.org/article/10.1088/1748-9326/11/4/048002/pdf>
6. Dasgupta S, Huq M, Sobhan I, Wheeler J (2018) Sea-Level Rise and Species Conservation in Bangladesh's Sundarbans Region. *J Manage Sustain* 8(1):1–10. <https://doi.org/10.5539/jms.v8n1p1>
7. De Valck J, Rolfe J (2018) Comparing biodiversity valuation approaches for the sustainable management of the Great Barrier Reef, Australia. *Ecosyst Serv* 35:23–31. <https://doi.org/10.1016/j.ecoser.2018.11.003>
8. Fischer C, Kannen A (2016) The Trilateral Wadden Sea Cooperation: a model for transnational cooperation in MSP and MSFD (Extended abstract). Chapter 4.2 in *Multidisciplinary perspectives in the use (and misuse) of science and scientific advice in marine spatial planning*. ICES Coop Res Rep 333:11–13
9. Gerkenmeier B, Ratter BM, Vollmer M, Walsh C (2018) Managing coastal risks at the Wadden Sea: a societal perspective. *Disaster Prev Management: Int J* 27(1):15–27. <https://doi.org/10.1108/DPM-04-2017-0074>
10. Gettelman A, Rood RB (2016) Components of the Climate System. *Demystifying Climate Models, Earth Systems Data and Models*, vol 2. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-48959-8_2

11. Ghosh P (2015) Conservation and Conflicts in the Sundarban Biosphere Reserve, India. *Geogr Rev* 105(4):505–524. <https://doi.org/10.1111/j.1931-0846.2015.12101.x>
12. Habib K, Neogi A, Oh J, Nahar N, Kim C-G, Lee Y-H (2020) An overview of fishes of the Sundarbans, Bangladesh and their present conservation status. *J Threatened Taxa* 12(1):15154–15172. <https://doi.org/10.11609/jott.4893.12.1.15154-15172>
13. Hossain M, Ahmed M, Islam T, Uddin M, Ahmed Z, Saha C (2021) Paradigm shift in the management of the Sundarbans mangrove forest of Bangladesh: Issues and challenges. *Trees, Forests and People*, 5, 100094. <https://doi.org/10.1016/j.tfp.2021.100094>
14. IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press
15. Jerath M, Bhat M, Rivera-Monroy VH, Castañeda-Moya E, Simard M, Twilley RR (2016) The role of economic, policy, and ecological factors in estimating the value of carbon stocks in Everglades mangrove forests, South Florida, USA. *Environ Sci Policy* 66:160–169. <https://doi.org/10.1016/j.envsci.2016.09.005>
16. Kaviarasan T, Dahms HU, Gokul MS et al (2019) Seasonal Species Variation of Sediment Organic Carbon Stocks in Salt Marshes of Tuticorin Area, Southern India. *Wetlands* 39:483–494. <https://doi.org/10.1007/s13157-018-1094-6>
17. Koll D, Cronin TW (2018) Earth's outgoing longwave radiation linear due to H₂O greenhouse effect. *Proceedings of the National Academy of Sciences*, 115(41), 10293–10298. <https://doi.org/10.1073/pnas.1809868115>
18. McCrear-Strub A, Zeller D, Rashid Sumaila U, Nelson J, Balmford A, Pauly D (2011) Understanding the cost of establishing marine protected areas. *Mar Policy* 35(1):1–9. <https://doi.org/10.1016/j.marpol.2010.07.001>
19. McLeod E, Chmura GL, Bouillon S, Salm R, Bjork M, Duarte CM, Lovelock CE, Schlesinger WH, Silliman BR (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Front Ecol Environ* 9(10):552–560. <https://doi.org/10.1890/110004>
20. Mellin C, Matthews S, Anthony K, Brown S, Caley M, Johns K, Osborne K, Puotinen M, Thompson A, Wolff N, Fordham D, Macneil A (2019) Spatial resilience of the Great Barrier Reef under cumulative disturbance impacts. *Glob Change Biol* 25(6):2011–2024. <https://doi.org/10.1111/gcb.14625>
21. Mellin C, Peterson EE, Puotinen M, Schaffelke B (2020) Representation and complementarity of the long-term coral monitoring on the Great Barrier Reef. *Ecol Appl* 30(6):e02122. <https://doi.org/10.1002/eap.2122>
22. Mooser A, Anfuso G, Gómez-Pujol L, Rizzo A, Williams A, Aucelli P (2021) Coastal Scenic Beauty and Sensitivity at the Balearic Islands, Spain: Implication of Natural and Human Factors. *Land* 10(5):456. <https://doi.org/10.3390/land10050456>
23. Mueller P, Ladiges N, Jack A, Schmiedl G, Kutzbach L, Jensen K, Nolte S (2019) Assessing the long-term carbon-sequestration potential of the semi-natural salt marshes in the European Wadden Sea. *Ecosphere* 10(1):e02556. <https://doi.org/10.1002/ecs2.2556>
24. Mukul S, Alamgir M, Sohel MS, Pert P, Herbohn J, Turton S, Khan MS, Munim S, Reza A, Laurance W (2019) Combined effects of climate change and sea-level rise project dramatic habitat loss of the globally endangered Bengal tiger in the Bangladesh Sundarbans. *Sci Total Environ* 663:830–840. <https://doi.org/10.1016/j.scitotenv.2019.01.383>
25. Ouyang X, Lee SY (2014) Updated estimates of carbon accumulation rates in coastal marsh sediments. *Biogeosciences* 11(18):5057–5071. <https://doi.org/10.5194/bg-11-5057-2014>
26. Ramón Cardona J, Peña Miranda D, Fernández MD, Ibiza (2021) Spain) *Sustain*, 13(23), 13250. <https://doi.org/10.3390/su132313250>
27. Richards ZT, Day JC (2018) Biodiversity of the Great Barrier Reef—how adequately is it protected? *PeerJ*, 6, e4747. <https://doi.org/10.7717/peerj.4747>
28. Ritchie H, Roser M (2020) CO₂ and Greenhouse Gas Emissions. *Our World in Data*. <https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions>
29. Schmelz W, Hochman G, Miller K (2020) Total Cost of Carbon Capture and Storage Implemented at a Regional Scale: Northeastern and Midwestern United States. *Interface Focus* 10(5):20190065. <https://doi.org/10.1098/rsfs.2019.0065>
30. Serrano O, Lovelock CE, Atwood TB et al (2019) Australian vegetated coastal ecosystems as global hotspots for climate change mitigation. *Nat Commun* 10:4313. <https://doi.org/10.1038/s41467-019-12176-8>

31. Thorhaug AL, Poulos HM, López-Portillo J, Barr J, Lara-Domínguez AL, Ku TC, Berlyn GP (2019) Gulf of Mexico estuarine blue carbon stock, extent and flux: Mangroves, marshes, and seagrasses: A North American hotspot. *Sci Total Environ* 653:1253–1261. <https://doi.org/10.1016/j.scitotenv.2018.10.011>
32. UNESCO (2020) UNESCO Marine World Heritage: Custodians of the globe's blue carbon assets. Paris, France. <https://ioc.unesco.org/news/unesco-marine-world-heritage-custodians-globes-blue-carbon-assets>
33. Urry J (2015) *Climate Change and Society*. In: Michie J, Cooper CL (eds) *Why the Social Sciences Matter*. Palgrave Macmillan, London. https://doi.org/10.1057/9781137269928_4
34. Walsh C, Ratter B, Gerkenmeier B, Vollmer M (2017) Managing coastal risks at the Wadden Sea: A societal perspective. *Disaster Prev Manage* 26(1):58–71. <https://doi.org/10.1108/DPM-04-2017-0074>

Figures

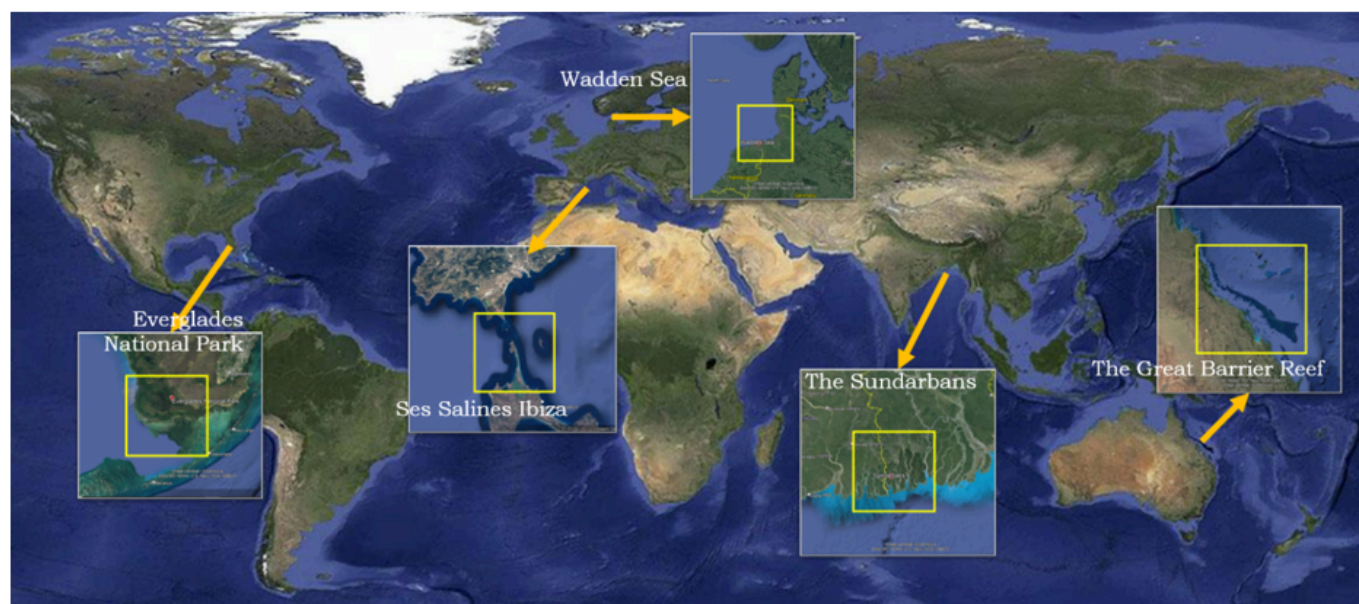


Figure 1

Global geographic distribution and localized inset maps of the five evaluated coastal Nature-based Solutions (NbS) initiatives.

Ses Salines Ibiza Seagrass Meadows Hold the Highest Organic Carbon Density

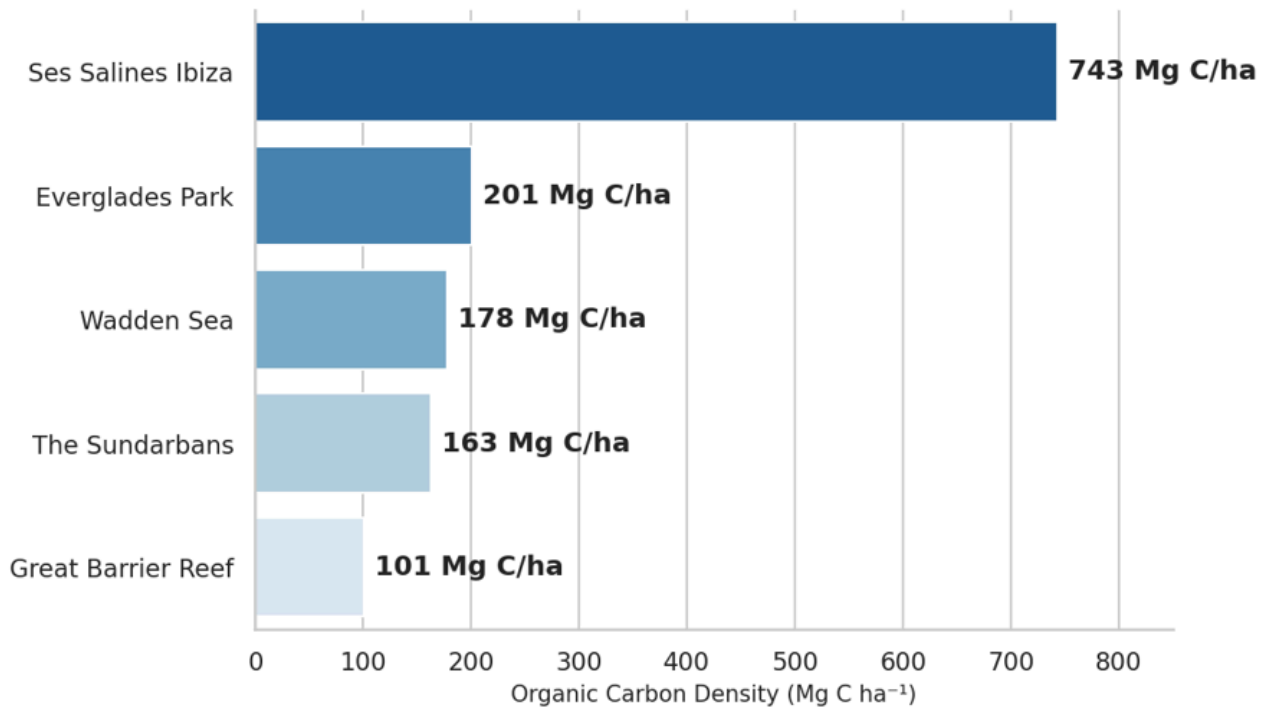


Figure 2

Published area-normalized organic carbon stocks across the five evaluated coastal protected areas.

Coastal Conservation Offers Far Higher Carbon Returns Per Dollar Spent Than CCS

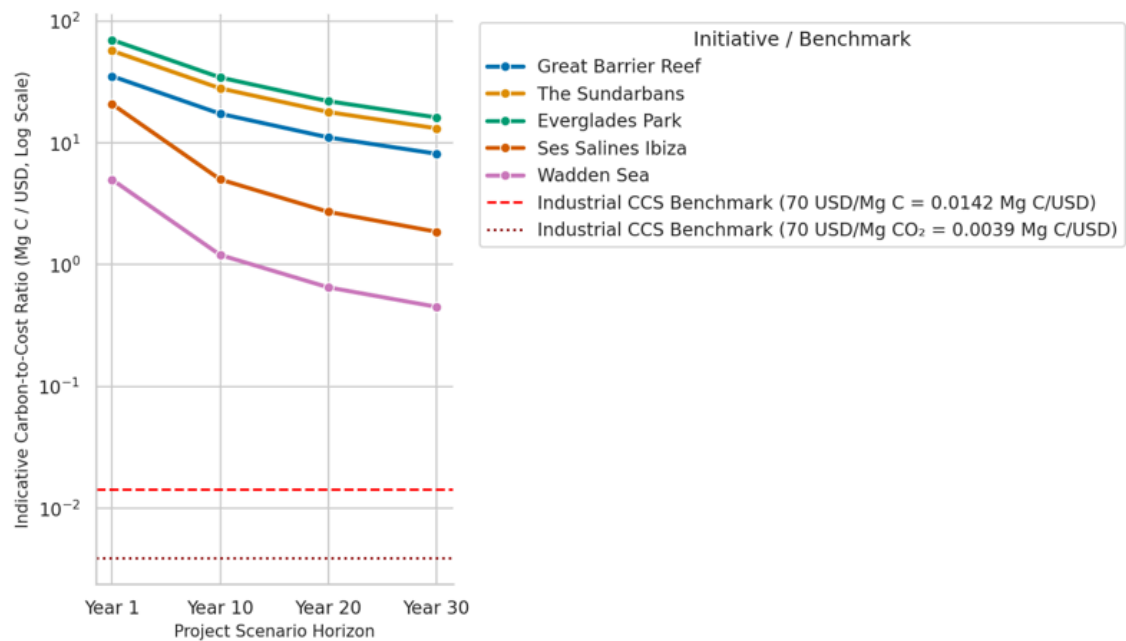
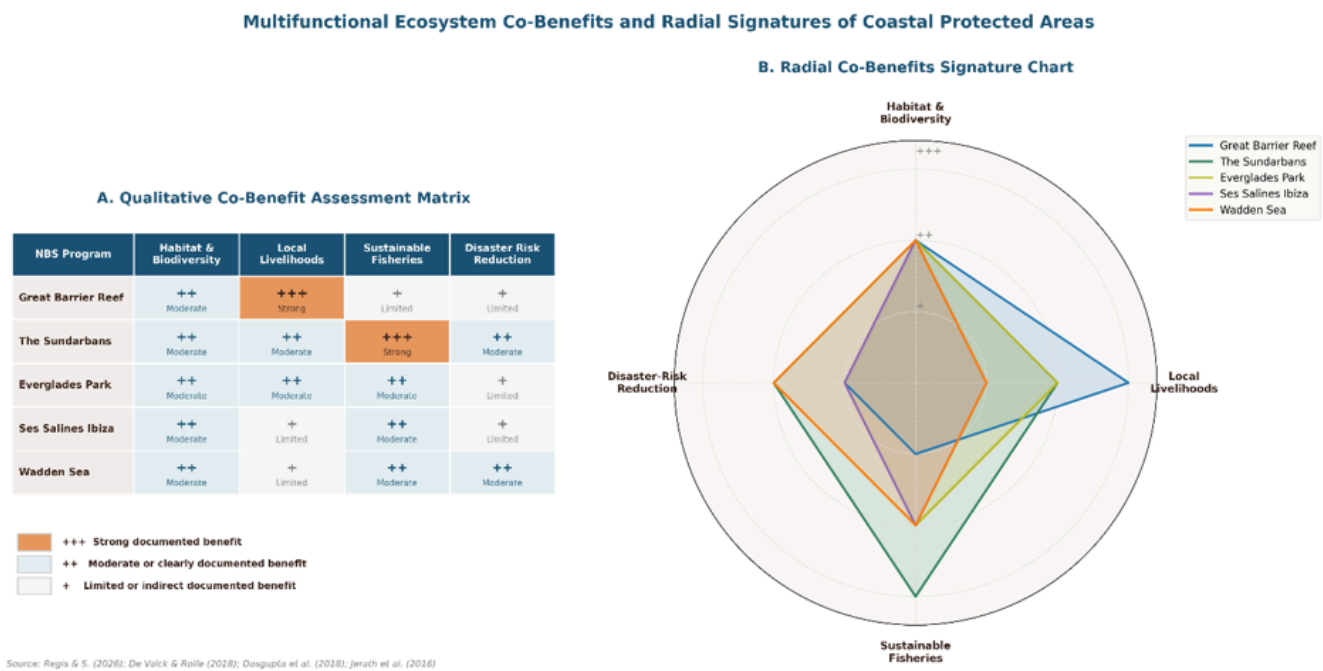


Figure 3

Scenario-based comparison of cumulative management expenditure and indicative carbon-stock-to-management-cost ratios across the five protected coastal systems.



Source: Regis & S. (2026); De Volck & Rolfe (2028); Dasgupta et al. (2028); Jenath et al. (2016)

Figure 4

Multi-dimensional evaluation of secondary socio-ecological and protective co-benefits across five global coastal protected areas.