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Soft shores or hard lines? Comparing perceived ecosystem services for coastal protection

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Abstract

Coastal protection is increasingly shifting from engineered defences towards green and hybrid approaches, yet the wider benefits and robustness of these approaches across stakeholder priorities remain uncertain. We compare the perceived provisioning, regulating, supporting and cultural ecosystem services of grey, green and mixed coastal protection strategies across three climate-vulnerable sites in Bangladesh, integrating household perceptions and expert assessments through participatory decision analysis. Mixed strategies performed best overall, followed closely by green approaches, while grey infrastructure consistently ranked lowest. Mixed approaches balanced coastal protection with livelihood and socioeconomic benefits, whereas green approaches provided stronger biodiversity, fisheries, carbon and cultural benefits. These patterns remained broadly robust across different risk attitudes and levels of uncertainty, although preferences shifted between mixed and green strategies. Our findings challenge a binary choice between engineered and nature-based protection and instead support context-specific combinations that reduce coastal hazards while sustaining ecosystems, livelihoods and community benefits under uncertain futures.

Introduction

Low-lying coastal regions support approximately 900 million people and contribute around US$1 trillion to the global economy each year, yet they are vulnerable to climate and environmental change (Haasnoot et al., 2021; Kirezci et al., 2020). These regions are increasingly exposed to sea-level rise, storm surges, coastal erosion and extreme weather events, driven by climate change and intensified human development. Traditionally, hard engineering solutions, such as seawalls, bulkheads and groynes, have dominated shoreline management, offering immediate and visible protection but often at the expense of ecological integrity and long-term adaptability (Gittman et al., 2016; Mamo et al., 2022).

In response, there is a growing shift toward soft, nature-based solutions (NbS), including green approaches such as mangrove restoration, salt marsh conservation, dune rehabilitation and living shorelines and hybrid approaches that integrate both natural and engineered elements (Capobianco & Stive, 2000; Cohen-Shacham et al., 2019; Cohen-Shacham et al., 2016; Gittman et al., 2016; Pontee et al., 2016). Therefore, coastal protection is increasingly viewed along a grey–green continuum (Singhvi et al., 2022; Van der Nat et al., 2016). Hybrid approaches are attracting growing interest because they integrate the protective capacity of engineered structures with the ecological and social benefits of natural ecosystems, offering more resilient and sustainable adaptation pathways than either grey or green solutions alone (Marino et al., 2025; Shan et al., 2025; Waryszak et al., 2021).

However, despite increasing enthusiasm for nature-based approaches, evidence regarding their perceived benefits relative to conventional engineering remains limited (Seddon et al., 2020; Welden et al., 2021), particularly from the perspective of local communities who directly experience the outcomes of coastal protection interventions (Anderson et al., 2022; Hekrle, 2022; Woroniecki et al., 2023).

Most evaluations of coastal protection measures focus on biophysical performance, engineering effectiveness or economic efficiency (Dai et al., 2026; Hummel et al., 2021; Narayan et al., 2016). While these assessments are essential, they often overlook how communities perceive and value the diverse ecosystem services generated by different coastal protection strategies (Angnuureng et al., 2025; Prayunita et al., 2026). Such perceptions matter because public acceptance influences the legitimacy, effectiveness and long-term sustainability of adaptation interventions. This reflects the 'extended peer community' principle central to sustainability science, which holds that all knowledge relevant to a problem's solution, including lay and experiential knowledge, must be integrated for outcomes to be both legitimate and effective. Coastal protection measures that align with local priorities and values are more likely to receive community support, encourage stewardship and deliver socially equitable outcomes (Demeter et al., 2025; Weishaupt et al., 2026). Conversely, interventions that fail to recognise local perceptions may face resistance, conflict or unintended trade-offs (Orchard et al., 2025).

Although coastal adaptation increasingly encompasses grey, green and hybrid protection pathways, little is known about how communities perceive the ecosystem services associated with these alternatives (Gain et al., 2022; Seddon, 2022; Sowińska-Świerkosz & García, 2021). Existing studies tend to focus on single interventions (Morris et al., 2018; Paxton et al., 2024), specific ecosystem services (Kumar et al., 2021) or expert-based assessments (Martin et al., 2021), limiting understanding of how people evaluate the broader suite of benefits and trade-offs generated by alternative coastal protection strategies in the Global South (Esraz-Ul-Zannat et al., 2024; Okello et al., 2024; Zyoud & Zyoud, 2025). Whereas prior work has examined what shapes public preferences for grey, hybrid and green disaster risk reduction measures in general terms (Anderson et al., 2022), it remains unclear which specific ecosystem services drive these preferences and how robust they are to expert judgement and decision uncertainty. We address this by combining a 20-indicator ecosystem-service framework with community and expert elicitation within a multi-criteria decision-support system, and by formally testing the robustness of resulting preferences through sensitivity, uncertainty and classification (CART) analysis. We address this gap by comparing community perceptions of ecosystem services across three distinct coastal protection regimes in Bangladesh: grey infrastructure, green solutions, and hybrid systems.

The coastal zone of Bangladesh's central region represents an incomparable example of how developing countries can use green, grey, and hybrid infrastructures as a means of climate adaptation (Smith et al., 2021). Located in a low-lying delta region, this area is experiencing many climate-induced hazards (high sea levels, cyclones, saline intrusion), which have led to significant climate hazard risk (Roy et al., 2022). Therefore, the central coast is an ideal location for exploring different infrastructure solutions to address the potential impacts of climate change. On the central coast of Bangladesh, there is a unique combination of traditional grey infrastructure (embankments, cyclone shelters) and green infrastructure(mangrove restoration, floating agriculture) and new hybrid types of solutions that incorporate engineered and nature-based elements (Gijón Mancheño et al., 2025; Mahmood et al., 2023).

By integrating ecological modelling, stakeholder perception analysis and a multi-criteria assessment framework, we examine how people perceive provisioning, regulating, cultural and supporting ecosystem

services. We further assess the relative performance of each protection strategy using multi-criteria decision analysis and sensitivity testing to identify the ecosystem services that most strongly shape community preferences. This approach offers an innovative and sustainable perspective on NbS implementation, aiming to inform evidence-based coastal resilience strategies in climate-vulnerable coastal regions, such as Bangladesh.

Results

Community perceptions on coastal protection measures

Three locations in central Bangladesh were studied: Char Alexendar (grey infrastructure with built sea walls), Nijhum Dwip (green infrastructure with planted mangroves), and Hatiya Upazila (combined grey and green infrastructure) (See Fig. S1 of supplementary material). Green and mixed infrastructure meet the IUCN's definition of nature-based solutions (Cohen-Shacham et al., 2019), and evidence shows a spectrum of grey/green infrastructure for coastal protection (Singhvi et al., 2022). These sites represent contrasting coastal protection strategies that integrate varying degrees of structural and ecosystem-based resilience.

Across the three coastal regions, Char Alexendar (grey infrastructure), Nijhum Dwip (green infrastructure) and Hatiya (mixed infrastructure), community perceptions of aggregated ecosystem (dis)services varied substantially with the type of coastal protection (see Fig. 1). In Hatiya, Green and Mixed infrastructure both received high median scores (0.9–1.0), while Grey scored notably lower (median ≈ 0.7), indicating that community recognition of ecological and protective co-benefits was concentrated in the nature-inclusive options. These findings align with reported co-benefits of coastal mangroves in South Asia (Islam & Gnauck, 2008; Mahmood et al., 2023; Sarker et al., 2024; Smith et al., 2021). In Nijhum Dwip, both Green (median ≈ 0.82) and Mixed (median ≈ 0.86) infrastructure were highly valued, with Mixed slightly favoured, reflecting recognition of the regulating, supporting and provisioning services associated with mangrove-based protection. This reflects community recognition of the regulating, supporting and provisioning services of mangrove plantations, including their contributions to coastal protection and local livelihoods.

In contrast, grey infrastructure received the lowest median scores (0.6–0.7) and showed greater variation in community perceptions, particularly in Nijhum Dwip. Respondents primarily associated engineered structures with physical protection and flood control but perceived them as providing limited provisioning and cultural benefits. The narrower interquartile ranges for green and mixed infrastructure indicate stronger agreement among respondents regarding these benefits. By comparison, the wider distribution of scores for grey infrastructure suggests uneven levels of satisfaction, potentially reflecting recurrent embankment failures, high maintenance costs and limited capacity to adapt to geomorphological change.

Grey infrastructure can create path dependencies and rigidity traps because its immediate, visible protective benefits reinforce long-term institutional reliance on existing infrastructure (Gain et al., 2022; Seddon et al., 2020). However, communities in this study preferred green infrastructure, recognising the limited ecological and cultural benefits of single-purpose grey interventions. Green infrastructure was perceived as providing multiple benefits by combining coastal protection with ecosystem functions, thereby supporting community well-being and offering more sustainable, long-term solutions in a dynamic deltaic environment.

Comparison of coastal protection measures using a decision support tool

Building on the perception analysis of coastal protection strategies, we assessed ecosystem (dis)services using a Driver-Pressure-State-Impact-Response (DPSIR)-based decision-support framework (Tscherning et al., 2012) to compare grey, green and hybrid infrastructures. Community survey data (150 households across three sites) and expert-derived indicator weights (35 specialists) were integrated within the MULINO Decision Support System (mDSS) (Giupponi, 2007; Giupponi et al., 2024; Giupponi et al., 2004) to perform a multi-criteria evaluation grounded in social–ecological systems theory. Ecosystem service (W. V. Reid et al., 2005) indicators spanning provisioning, regulating, cultural, and supporting functions were classified across the DPSIR components and quantitatively assessed to capture causal linkages among drivers, pressures, system states, impacts and management responses (see Table S1). The multi-criteria assessment revealed clear differences in the sustainability of the three coastal protection strategies (Fig. 2). This composite metric assumes that the 20 selected ecosystem-service indicators adequately represent each strategy's sustainability performance (see Methods, Indicator selection). Across all 20 ecosystem-service indicators, the mixed strategy achieved the highest pooled simple additive weighting (SAW) score (0.88), followed by green (0.84) and grey infrastructure (0.63). This ranking was consistent across all three study sites, indicating that combining engineered and ecosystem-based measures provided the highest overall sustainability performance.

The magnitude of the differences varied spatially. In Char Alexendar, mixed infrastructure scored 0.88, compared with 0.81 for green and 0.64 for grey infrastructure. The advantage of green infrastructure was strongest in Hatiya, where its score (0.88) was nearly equal to that of the mixed strategy (0.89), whereas grey infrastructure scored substantially lower (0.62). In Nijhum Dwip, mixed infrastructure again ranked highest (0.86), followed by green (0.82) and grey infrastructure (0.63). Thus, although the relative ranking of the three strategies was stable across sites, their comparative performance varied with local conditions.

Mixed infrastructure consistently outperformed either green or grey measures alone, while grey infrastructure showed the lowest composite sustainability scores across all sites. The relatively small differences between mixed and green strategies (0.01–0.07), compared with their larger advantages over grey infrastructure (0.18–0.27), indicate that much of the sustainability benefit is associated with

ecosystem-based measures. The additional advantage of mixed strategies may reflect the combination of immediate structural protection from engineered elements with the slower-maturing ecological benefits of nature-based components. These results support context-specific combinations of green and engineered measures rather than reliance on grey infrastructure alone in dynamic coastal environments.

Figure 3 disaggregates the composite SAW scores to show how individual ecosystem-service indicators contribute to the sustainability ranking of the three coastal protection strategies. Community perceptions showed that mixed infrastructure performed strongly across most of the 20 indicators, resulting in the highest overall sustainability score (0.876), followed closely by green infrastructure (0.836), whereas grey infrastructure ranked substantially lower (0.632) (Fig. 3).

The relative strengths of green and mixed infrastructure differed across ecosystem services. Mixed infrastructure performed particularly strongly for sediment deposition (0.89), habitat provision (0.91), storm-surge protection (0.91), coastal erosion control (0.94), freshwater storage (1.00), land-use conflict abatement (0.98), agricultural production (0.97), and tourism and property values (both 1.00). Green infrastructure performed particularly well for biogeochemical cycling and biodiversity (both 1.00), carbon sequestration (0.95), forest products (0.94), fish stocks (1.00), community cultural and spiritual values (0.91), and aesthetic values (0.95). Grey infrastructure exceeded the other strategies for only a small number of indicators, including reclaimed land for economic use.

Expert weighting preserved these contrasting patterns but altered the contribution of individual indicators to overall sustainability (Fig. 3b). Mixed infrastructure derived its largest weighted contributions from biodiversity (0.064), land-use conflict abatement (0.060), sediment deposition (0.053), and agricultural production (0.050). For green infrastructure, biodiversity (0.071), biogeochemical cycling (0.058), aesthetic values (0.053), fish stocks (0.052), and carbon sequestration (0.050) made prominent contributions. These indicator-level results show that the higher composite scores for mixed and green infrastructure stem from broader ecosystem service delivery, whereas the lower score for grey infrastructure reflects more limited performance across multiple supporting, regulating, provisioning and cultural services.

Robustness across decision attitudes

The relative performance of the three coastal protection strategies remained consistent across alternative risk attitudes assessed using Weighted Ordered Weighted Averaging (WOWA) (Fig. 4; indicator-level breakdown in Figure S2). Mixed infrastructure ranked highest under risk-averse (0.82), risk-neutral (0.85) and risk-taking (0.94) decision profiles. Green infrastructure consistently ranked second (0.76, 0.82 and 0.91, respectively), whereas grey infrastructure had the lowest scores (0.52, 0.59 and 0.74).

Composite sustainability scores increased from risk-averse to risk-taking profiles for all three strategies, but the ranking did not change. The difference between mixed and green infrastructure was small across

the three profiles (0.03–0.06), whereas both substantially outperformed grey infrastructure. Under the risk-averse profile, mixed infrastructure exceeded grey infrastructure by 0.30, compared with differences of 0.26 under the risk-neutral and 0.20 under the risk-taking profiles. The relative disadvantage of grey infrastructure was greatest when greater emphasis was placed on avoiding poor performance.

These results show that the preference for mixed infrastructure is robust to changes in decision attitude, rather than depending on a particular weighting of favourable or unfavourable outcomes. Green infrastructure similarly maintained strong performance across all three profiles, while grey infrastructure remained consistently lower. The stability of these rankings across contrasting risk attitudes indicates that mixed infrastructure provides the most robust sustainability performance under the decision preferences examined here.

Sensitivity and uncertainty of sustainability rankings

Sensitivity analysis showed that the overall ranking was generally robust to changes in indicator weights, although the distinction between mixed and green infrastructure was sensitive to a small subset of ecosystem-service indicators (Fig. S3 and Table S1). In particular, the analysis showed that relatively small changes in the weighting of sediment deposition and habitat provision may reverse the ranking between mixed and green infrastructure. By contrast, substantially larger changes were required for most other indicators, and especially to shift the ranking in favour of grey infrastructure. Thus, uncertainty in stakeholder preferences primarily affected the relative preference between mixed and green strategies rather than the advantage of green strategies over grey infrastructure.

This pattern was reinforced by the uncertainty analysis. Across 1,050 simulations combining alternative stakeholder weights, decision attitudes and performance assumptions, mixed infrastructure maintained the highest median sustainability score, followed closely by green infrastructure, whereas grey infrastructure remained substantially lower (Fig. S4 and Table S2). Mixed and green strategies also showed strongly overlapping score distributions, while the distribution for grey infrastructure was concentrated at lower values. Although individual ecosystem-service contributions varied across simulations, these variations rarely changed the overall ordering of the alternatives.

The sensitivity and uncertainty analyses show that the principal result—the higher sustainability of mixed and green infrastructure relative to grey infrastructure—is robust to alternative stakeholder preferences and analytical assumptions. Uncertainty is therefore concentrated primarily in the choice between mixed and green strategies, rather than in whether either provides greater overall sustainability than grey infrastructure.

CART analysis of the 1,050 simulated decision settings showed that uncertainty primarily shifted the preferred strategy between mixed and green infrastructure, while grey infrastructure was never selected as the preferred option (Fig. S5). The decision tree identified a small number of criterion weights that explained these shifts. Mixed infrastructure dominated most simulated conditions, but green

infrastructure became preferred under specific combinations of stakeholder priorities. These results reinforce the uncertainty analysis by showing that changes in assumptions affect the choice between mixed and green strategies rather than reversing their overall advantage over grey infrastructure.

The indicator-level uncertainty analysis further showed substantial heterogeneity in performance across criteria (Fig. S6). Mixed and green infrastructure generally maintained stronger performance across ecological, regulating and socio-cultural indicators, whereas grey infrastructure performed strongly on a narrower subset of criteria. Although uncertainty intervals varied considerably among individual indicators, the broader separation between grey infrastructure and the two ecosystem-based alternatives persisted. As with any participatory process, we found heterogeneity in individual opinions, but their combination yielded results that appear quite solid in demonstrating that green and mixed infrastructure outperform grey infrastructure.

Discussion and policy implications

Our findings show that coastal protection involves a broader choice than simply whether infrastructure can reduce physical hazards. Across community perceptions, ecosystem-service performance and alternative decision attitudes, green and mixed strategies consistently delivered greater overall sustainability than grey infrastructure. Mixed infrastructure ranked highest overall, but its advantage over green infrastructure was relatively small and varied with local conditions and stakeholder priorities. This advantage was driven mainly by Mixed infrastructure's stronger performance on provisioning indicators such as agricultural production, which more than offset its comparatively lower scores on some core ecological indicators (Table S3). By contrast, grey infrastructure remained substantially lower across the composite assessments and did not emerge as the preferred strategy under the simulated decision conditions. These results suggest that the principal adaptation choice is not simply between ‘hard’ and ‘soft’ protection, but between different configurations of ecological and engineered functions.

The advantage of green and mixed strategies arises primarily from their multifunctionality. Grey infrastructure provides important and visible protective functions, but communities associate it with a narrower range of benefits. Green infrastructure extended these benefits across biodiversity, fisheries, carbon sequestration, biogeochemical processes, cultural values, and other ecosystem services, consistent with the growing evidence that nature-based coastal adaptation can generate ecological and social co-benefits alongside hazard reduction (Janssen et al., 2026; Van der Nat et al., 2016). Mixed infrastructure retained many of these ecosystem functions while performing well in storm-surge protection, erosion control, freshwater storage, agricultural production and property-related benefits (Walter V Reid et al., 2005; TEEB, 2010). This complementarity helps explain why mixed infrastructure achieved the highest aggregate sustainability performance: engineered protection and ecosystem processes can contribute different, rather than interchangeable, functions (Gain et al., 2022; Roy et al., 2022).

This distinction is important because the highest aggregate score does not imply that mixed infrastructure should replace green infrastructure everywhere. Green infrastructure performed comparably to mixed infrastructure overall and exceeded it for several ecological and cultural services, most clearly on biodiversity (5.00 vs. 4.00) and biogeochemical cycling (5.00 vs. 3.19), whereas mixed infrastructure scored higher on provisioning indicators such as agricultural production (4.68 vs. 1.99) (Table S3). The preferred choice between mixed and green, therefore, depends on which of these functions local decision-makers weight more heavily: where agricultural production is prioritised, mixed infrastructure is favoured, whereas where biodiversity or biogeochemical cycling are prioritised, green infrastructure is favoured. Moreover, sensitivity, uncertainty and CART analyses (Giupponi, 2007; Giupponi & Sgobbi, 2013) showed that changes in stakeholder priorities primarily shifted the preferred option between green and mixed strategies; grey infrastructure did not become the preferred alternative across the simulated decision space (Singhvi et al., 2022; Van der Nat et al., 2016). The appropriate balance between green and engineered components should therefore depend on local geomorphology, ecosystem condition, livelihood priorities, exposure and development objectives (De Groot et al., 2012; Walter V Reid et al., 2005; TEEB, 2010). Where functioning mangrove systems provide sufficient protection, maintaining or restoring them may offer substantial benefits without unnecessary engineering (Anderson et al., 2022; Gain et al., 2022; Smith et al., 2021). Engineered components may become more valuable where exposure, settlement patterns or critical assets require additional levels of protection (Morris et al., 2018; Paxton et al., 2024).

The results also raise a broader concern about reliance on conventional coastal engineering. Immediate and visible protection can reinforce investment, maintenance systems and institutional expectations around existing structures, potentially creating path dependencies (Kay, 2005; Martin et al., 2025) and rigidity traps(Kiss et al., 2022). Such dependence becomes problematic where fixed infrastructure constrains adaptation to changing sediment dynamics, sea-level rise or ecosystem migration. Green and mixed strategies potentially expand the adaptation portfolio by retaining ecological processes that can adjust to environmental change while simultaneously providing livelihood and cultural benefits (Pörtner, 2022; Singhvi et al., 2022; Van der Nat et al., 2016). The relevant policy question is therefore not whether engineered protection should be abandoned, but where it is necessary, how much is required and how it can be designed to complement rather than displace ecosystem functions.

Community perceptions are central to this choice. Coastal infrastructure is experienced not only as protection against hazards but also through its effects on livelihoods, access to resources, landscapes and cultural relationships with place (Seddon, 2022; Welden et al., 2021). The differences observed among Char Alexendar, Hatiya and Nijhum Dwip demonstrate why a uniform coastal-protection model is unlikely to be appropriate (Mahmood et al., 2023; Roy et al., 2022). Participatory assessment can reveal which ecosystem services communities value, where trade-offs occur and when additional engineered protection is socially desirable. This makes participation more than a mechanism for obtaining acceptance of a predetermined intervention: it becomes part of determining the composition and objectives of the intervention itself (Sowińska-Świerkosz & García, 2021; Woroniecki et al., 2023).

These findings have direct implications for adaptation policy in Bangladesh and other densely populated deltas. The Bangladesh Delta Plan 2100 provides an opportunity to move beyond treating embankments, mangroves and other interventions as separate investment categories and instead evaluate them as components of integrated social–ecological protection systems (Ahmed et al., 2018; Smith et al., 2021). The same principle is relevant to climate finance and international commitments under the Paris Agreement, Nationally Determined Contributions and the Kunming–Montreal Global Biodiversity Framework (Browder et al., 2019), where investments capable of delivering joint adaptation, livelihood and biodiversity outcomes are increasingly important (CBD, 2022; Cohen-Shacham et al., 2019; UNFCCC, 2015). However, support for hybrid approaches should not become a new universal prescription. Their value lies precisely in allowing the composition of coastal protection to respond to local ecological conditions, risks and social priorities.

Our analysis also demonstrates the value of combining community perceptions with expert knowledge and explicitly treating decision uncertainty. Integrating ecosystem-service assessment with SAW, WOWA, sensitivity analysis and scenario-based uncertainty analysis makes the assumptions underlying infrastructure choices visible rather than embedding them implicitly within technical appraisal (Giupponi & Sgobbi, 2013; Liquete et al., 2016). Importantly, uncertainty in individual ecosystem-service contributions did not translate directly into instability of the overall conclusion. Instead, uncertainty was concentrated around the boundary between green and mixed strategies. This distinction between uncertainty in individual criteria and robustness of the overall decision is particularly relevant for adaptation planning, where decisions must often be made despite incomplete knowledge of future climatic, ecological and socioeconomic conditions.

The analysis captures perceived ecosystem-service performance rather than long-term ecological or engineering outcomes, and community perceptions may reflect local experience and livelihood dependence (Mahmood et al., 2023; Martin et al., 2021; Pörtner, 2022). Expert weighting also introduces normative judgements into the assessment (Welden et al., 2021; Woroniecki et al., 2023). Longitudinal studies should therefore test the performance of green and mixed strategies under changing climatic conditions and incorporate distributional dimensions—including livelihoods, health, gender, land tenure and equity—to identify who benefits and who bears the costs of alternative adaptation strategies (Campbell et al., 2020; Woroniecki et al., 2023).

The future of coastal protection need not be framed as a choice between soft shores and hard lines. Grey infrastructure remains important where high levels of engineered protection are required, while green infrastructure provides ecological functions and social benefits that conventional structures cannot readily reproduce. Mixed strategies can connect these strengths, but their value depends on how, where and why engineered and ecological components are combined (Costanza et al., 1997). In climate-vulnerable deltas, resilient coastal adaptation therefore requires moving from selecting infrastructure types towards designing context-specific portfolios of protection, ecosystem function and community benefit. Participatory social–ecological decision frameworks can support this transition by making

trade-offs explicit and identifying strategies that remain effective across divergent stakeholder values and uncertain futures (Dunlop et al., 2024; Patrício et al., 2016).

Methods

To understand how communities weigh different options for coastal protection, we select three representative sites along the central Bangladesh coast; identify key ecosystem service indicators; and analyse their linkages through the DPSIR framework (Driver, Pressure, State, Impact, Response) (Patrício et al., 2016) and a multi-criteria decision support tool (m-DSS) (Giupponi, 2007). This is done with a view to informing evidence-based management at the coast.

First, this study was conducted across three sites in the central coastal zone of Bangladesh, Char Alexendar, Nijhum Dwip, and Hatiya Upazila (Figure S1), representing three distinct coastal protection strategies: grey, green, and hybrid infrastructures. The central coast was chosen due to its dynamic geomorphological processes and high rates of both erosion and accretion, which are greater than in the eastern and western coasts. Between 1985 and 2015, the region experienced 1,576 km² of erosion and 1,813 km² of accretion, resulting in a net gain of 237 km². This dynamic landscape offers an ideal setting for evaluating the effectiveness and community perception of various coastal protection measures.

Char Alexendar in Laxmipur District represents the grey infrastructure approach. It is protected by earthen and Reinforced Cement Concrete (RCC) embankments, including a 3.2 km revetment built in 2017 to reduce storm surges and salinity intrusion. These engineered structures primarily serve physical protection functions but offer limited ecosystem services. Nijhum Dwip, situated within Hatiya Upazila of Noakhali District, exemplifies a green infrastructure system characterised by extensive coastal mangrove plantations. These act as natural buffers against storm surges and erosion while delivering co-benefits such as biodiversity conservation, carbon sequestration, and livelihood support. Hatiya Upazila, adjacent to Nijhum Dwip, represents a hybrid approach combining embankments with mangrove plantations to integrate structural protection with ecosystem-based resilience. These three sites were selected to capture contrasting socio-ecological contexts and adaptation strategies under varying exposure to coastal hazards. Their inclusion enables comparison among engineered, nature-based, and combined systems, offering insights into trade-offs among physical protection, ecological functionality, and community well-being. Collectively, they represent a microcosm of Bangladesh's evolving coastal management approaches and offer a good opportunity for comparative assessment of alternative strategies within the broader framework of Nature-based Solutions (NbS).

Indicators of ecosystem services and the DPSIR framework

We selected a set of indicators representing provisioning, regulating, cultural, and supporting (dis)services across green, grey, and hybrid coastal infrastructures for the central coastal zone of Bangladesh. The selection of ecosystem service indicators followed a deductive approach as recommended by Adger et al. (2004). This approach is grounded in theoretical understanding rather than

statistical correlations, enabling the systematic operationalisation of key concepts related to coastal ecosystem (dis)services. First, the study developed a conceptual understanding of the interlinked social–ecological processes governing coastal protection systems, identifying provisioning, regulating, cultural, and supporting services as the main functional dimensions. Second, a review of the relevant literature on Nature-based Solutions (NbS), ecosystem service frameworks, and coastal protection studies was conducted to identify potential indicators for the ecological and socio-economic context of Bangladesh's coastal region. Third, a preliminary list of indicators was prepared to capture critical ecological functions (e.g., carbon sequestration, sediment deposition, biodiversity), livelihood-related outcomes (e.g., agricultural production, fisheries, forest products), and socio-cultural dimensions (e.g., property value, spiritual values, education).

Each indicator was evaluated against four criteria: (i) relevance to coastal protection and ecosystem service dynamics, assessed through a targeted literature review; (ii) data availability, based on the feasibility of obtaining reliable information from field surveys; (iii) measurability, defined as the ability of respondents and experts to consistently score the indicator using the Likert-scale framework; and (iv) stakeholder validity. Stakeholder validation and refinement were conducted in two stages. First, the preliminary list of indicators was discussed with local water managers and researchers to assess conceptual clarity, redundancy, and alignment with management objectives, which led to the merging of overlapping indicators and the exclusion of those deemed ambiguous or weakly linked to ecosystem services. Second, the refined list was reviewed during the science–policy workshop, where experts provided structured feedback on indicator definitions, DPSIR classification, and practical interpretability.

Indicators that were consistently rated as unclear or contextually inappropriate were reformulated or removed, and final definitions were adjusted to reflect local socio-ecological conditions. This iterative process resulted in the final indicator set reported in Table 1. This participatory and theory-driven process ensured that the chosen indicators reflect both ecological functionality and human dimensions of coastal resilience, enabling empirical assessment of trade-offs and synergies in ecosystem (dis)service delivery under different coastal protection strategies.

We classified the selected ecosystem service indicators based on their functional roles within the DPSIR framework (Table 1) (Delgado et al., 2021; Patrício et al., 2016; Smeets & Weterings, 1999). This framework provides a clear structure for linking environmental changes to ecosystem services across three types of coastal infrastructure: green, grey, and hybrid systems.

In this framework, Drivers (D) denote underlying socio-economic or ecological forces that motivate human actions or management interventions, such as land reclamation, property development, or biogeochemical cycles that sustain productivity. Pressures (P) identify the specific mechanisms deriving from the presence of Drivers and affecting the State of the social and environmental system, such as hydrological modifications or tourism activities that alter ecosystem processes. State (S) indicators describe the existing biophysical and ecological condition of the system—capturing shoreline stability, habitat quality, fish stocks, biodiversity, and landscape aesthetics under different infrastructure types.

Impacts (I) denote the resulting changes in ecosystem services and human wellbeing, including carbon sequestration, water quality improvement, freshwater storage, and cultural or educational benefits.

As shown in Table 1, provisioning services (e.g., agricultural production, fish stocks, forest products) largely reflect the state of ecological productivity, whereas regulating services (e.g., hydrological improvement, erosion control, storm-surge protection) mediate pressures and impacts through biophysical regulation. Cultural services span all categories, linking socio-economic drivers (e.g., property values) to impacts on wellbeing and identity (e.g., spiritual and educational values). Supporting services, such as biodiversity and sediment deposition, predominantly reflect the state of ecosystem structure, whereas biogeochemical cycles serve as foundational drivers that maintain system functioning.

Data collection

A semi-structured questionnaire was developed to assess local community perceptions of the ecosystem services provided by various types of coastal infrastructures, including grey (embankments), green (mangrove forests), and hybrid (mixed) infrastructures. The questionnaire contained specific indicators (see Table 1) to evaluate perceived benefits/services and dis-services of different interventions. Respondents rated each item on an 11-point Likert scale ranging from − 5 (strongly negative/disservice) to + 5 (strongly positive/service), with 0 indicating no effect. In addition to the rating scale, open-ended questions captured contextual insights, including awareness of local flood defence infrastructure, perceived changes before and after implementation, current livelihood challenges, and alternative coastal defence experiences. The questionnaire began with a brief introduction explaining the study's purpose, confidentiality, and the voluntary nature of participation to ensure informed consent. This mixed-format design facilitated the integration of quantitative assessments of ecosystem service trade-offs with qualitative narratives of local adaptation experiences, thereby supporting a comprehensive understanding of the effectiveness of NbS from community perspectives.

The semi-structured questionnaire survey was conducted with 150 respondents, 50 from each site. The sample size ensured balanced representation across the three coastal protection contexts. Participants were selected through stratified purposive sampling to represent diverse groups, including farmers, fishers, small business owners, local leaders, and women's household representatives, reflecting variations in livelihoods and exposure to coastal hazards.

Following the community survey, an online science–policy workshop was conducted to gather expert opinions on the ecosystem services provided by various coastal protection measures in Bangladesh. The primary objective was to complement community perceptions with expert insights on the ecological, social, and policy implications of Nature-based Infrastructure (NbI) within coastal social–ecological systems (SES). The workshop also aimed to validate the results obtained from field surveys and refine the DPSIR conceptual model developed for coastal Bangladesh.

A total of 35 experts participated in the workshop, representing environmental scientists, coastal engineers, policymakers, and practitioners from national universities, international research organisations, and public agencies. The participants had extensive experience in coastal protection, disaster risk reduction, and the assessment of ecosystem services. The event was organised in three main sessions: (i) presentation and discussion of the key results from the community surveys, (ii) collective review and refinement of the DPSIR-based conceptual framework for coastal SES, and (iii) weighting exercise to evaluate the relative relevance of ecosystem services provided by mangrove-based and other coastal infrastructures.

During the ranking exercise, participants evaluated a list of ecosystem services under four categories—provisioning, regulating, cultural, and supporting—using a Likert scale (Likert, 1932). They were asked to assign scores such that the total summed to 100, reflecting the relative importance of each service category. This participatory approach enabled the integration of scientific, technical, and policy perspectives, ensuring a more holistic interpretation of ecosystem service trade-offs and synergies identified across green, grey, and hybrid coastal systems.

Evaluation of coastal protection strategies with the DPSIR-based decision support tool

The DPSIR framework adopted for the shared conceptual model and for problem structuring was also implemented by the decision support system (DSS) used for the comparative assessment of responses for coastal protection, i.e. green, grey or hybrid infrastructures (Elliott et al., 2017; Elliott & O'Higgins, 2020). The framework is presented in Fig. 5.

This diagnostic framework was provided by the MULINO Decision Support System (mDSS) (Giupponi, 2007; Giupponi et al., 2024) to translate complex socio-ecological relationships into interpretable, decision-relevant information. The mDSS tool facilitates multi-criteria decision analysis (MCDA) by integrating quantitative and qualitative inputs to support evidence-based environmental management. In particular, perceptions and expert evaluations of ecosystem services were incorporated as input variables into the DPSIR structure and used in a multi-criteria evaluation of trade-offs and synergies among green, grey, and hybrid coastal infrastructures, based on both ecological and socio-economic criteria.

The mDSS operates through four key phases: Conceptual, Design, Choice, and Group Decision (Giupponi et al., 2011). In the conceptual phase, the decision problem was structured using the DPSIR model. In the design phase, evaluation criteria and alternatives were defined. In the choice phase, MCA techniques were applied to rank infrastructure options. In the group decision phase, the results were validated through expert consensus.

The adoption of mDSS enabled us to combine qualitative insights and quantitative stakeholder scores, providing a transparent and replicable procedure to prioritise protection strategies focused on

ecosystem services and to support evidence-based decision-making for sustainable coastal management in Bangladesh.

We analysed data collected from the community survey and expert workshop using the mDSS (Giupponi et al., 2024) We developed an analysis matrix (Table S3) using average scores from 150 community respondents across three study sites and applied weight vectors (Table S4) derived from 35 expert evaluations to represent the relative importance of indicators within the SES framework.

Each coastal protection measure was evaluated against ecosystem service criteria classified within the DPSIR framework to trace causal relationships between human activities, environmental changes, and ecosystem service outcomes. Indicators were weighted based on their perceived significance, as determined through stakeholder consultations and expert input in mDSS for their quantitative assessment.

To test the reliability of results, we performed an uncertainty and robustness analysis in both mDSS and R, assessing sensitivity to data variability, expert judgement, and potential future scenarios such as sea-level rise and economic change.

Declarations

Author Contribution

M.H.S.: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Investigation, Data curation and Project administration. A.K.G.: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Supervision. C.G.: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Supervision. All authors reviewed and approved the final manuscript.

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Data Availability

The data supporting the findings of this study are not publicly available because they contain information collected from human participants and are subject to ethical and confidentiality requirements. De-identified data may be made available by the corresponding author upon reasonable request, subject to applicable ethical approvals and data-sharing requirements.

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Tables

Table 1 is available in the Supplementary Files section.

Figures

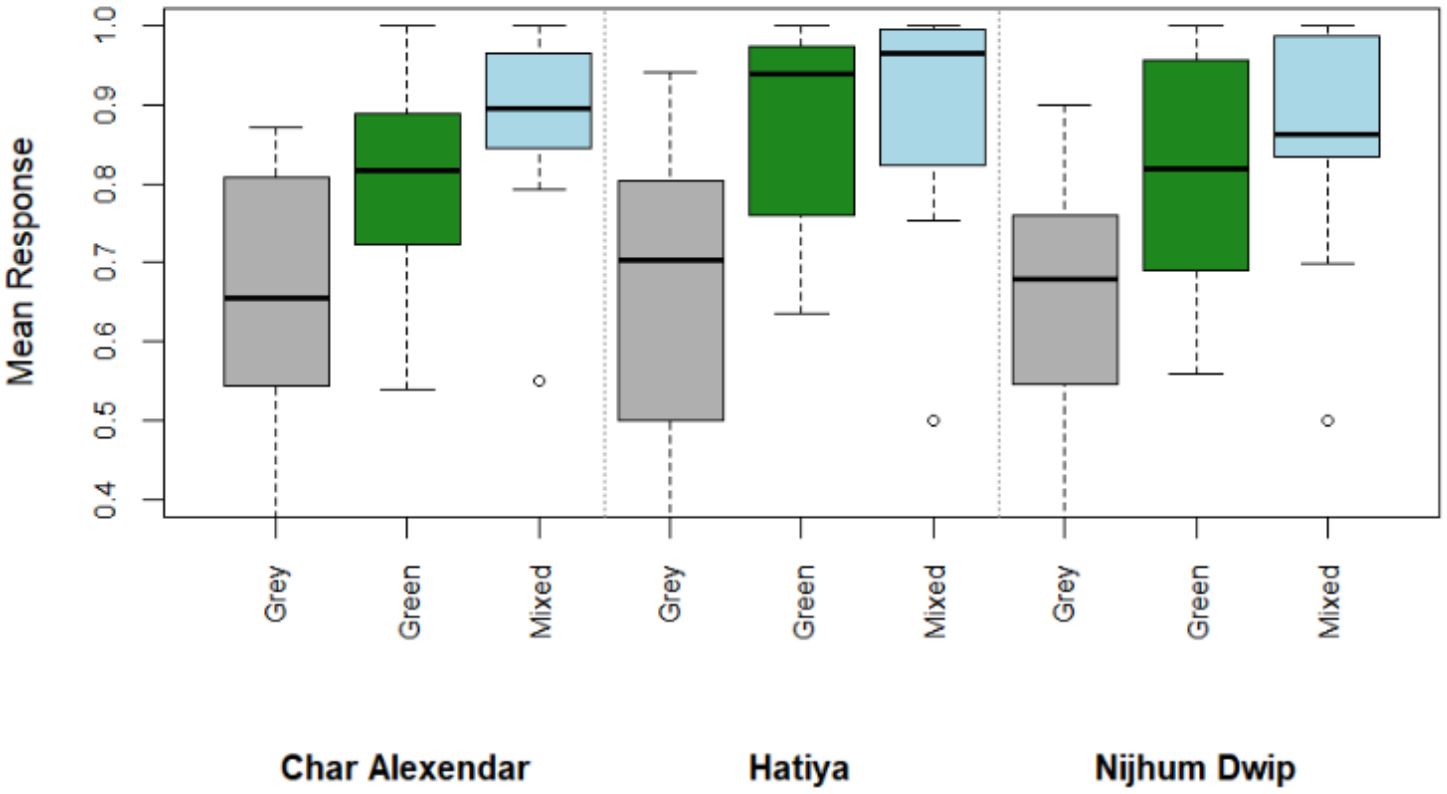

Figure 1

Boxplots of community perceptions of aggregated ecosystem services across three coastal protection strategies at Char Alexendar (CA, grey), Nijhum Dwip (ND, green), and Hatiya (H, Mixed). Data represent mean responses from 150 households (50 per site) rated on an 11-point Likert scale (Hekrle, 2022b; Reid et al., 2005), normalised to a 0–1 scale. The plots illustrate higher and more consistent perceptions of green and mixed infrastructures compared to grey, reflecting stronger community recognition of the multifunctional benefits of green infrastructure and integrated coastal protection systems.

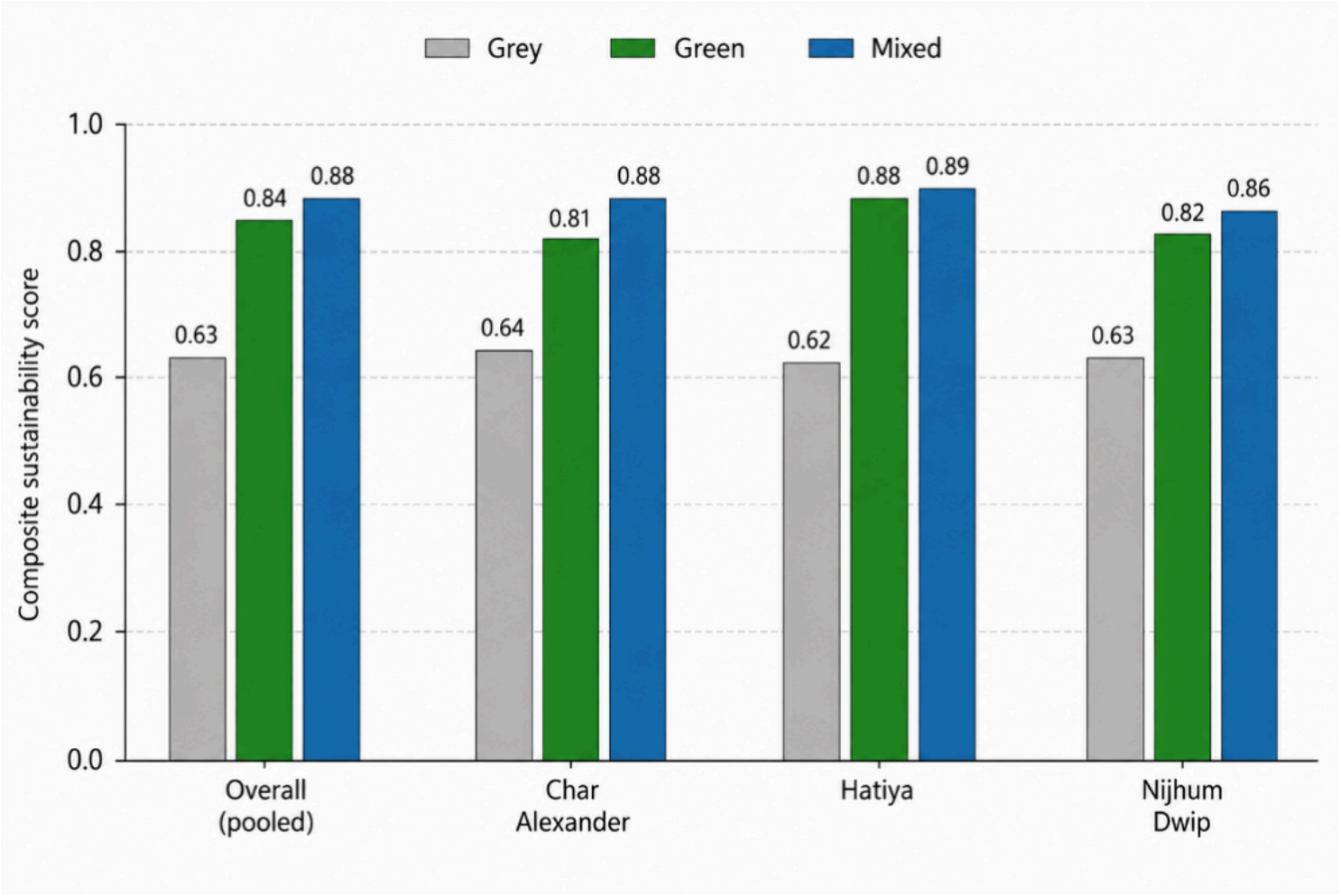

Figure 2

Composite sustainability scores for grey, green and mixed coastal protection measures, calculated using simple additive weighting (SAW). Composite scores integrate 20 ecosystem-service indicators across environmental, social and economic criteria, weighted through expert elicitation. Spatial variation in composite sustainability scores across the three study sites, including the pooled estimate and site-specific scores for Char Alexendar, Hatiya and Nijhum Dwip.

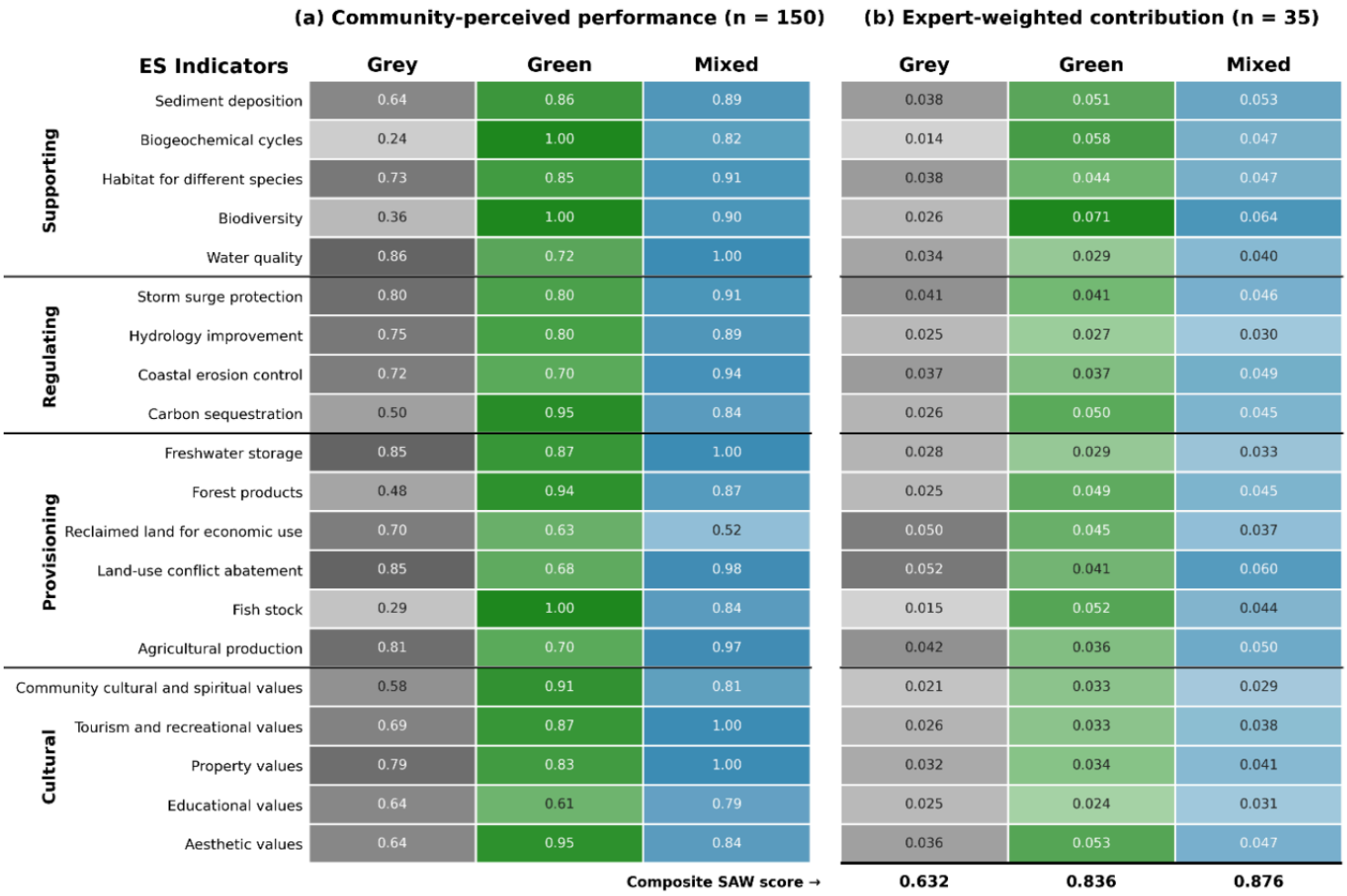

Figure 3

Ecosystem-service contributions to the sustainability of coastal protection strategies. (a) Community-perceived performance of grey, green and mixed infrastructure across 20 ecosystem-service indicators, based on household survey data (n = 150). **(b)** Expert-weighted contribution of each indicator to the composite simple additive weighting (SAW) score, based on expert elicitation (n = 35 specialists). Results are pooled across the three study sites. Indicators are grouped into supporting, regulating, provisioning and cultural ecosystem services. Column totals in **(b)** represent the composite SAW scores for grey, green and mixed infrastructure reported in Fig. 3.

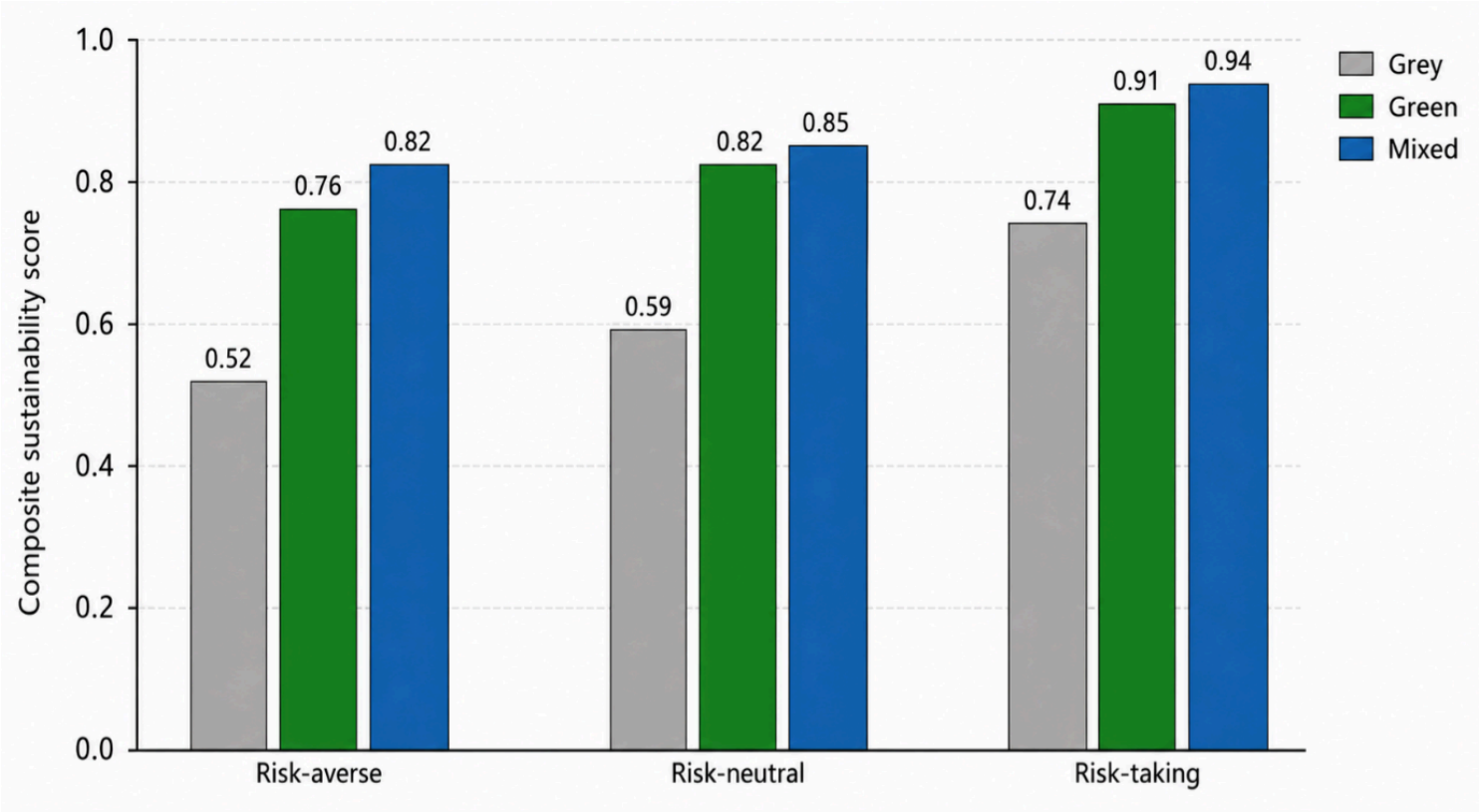

Figure 4

Composite sustainability scores for grey, green and mixed coastal protection measures under alternative stakeholder risk attitudes, estimated using Weighted Ordered Weighted Averaging (WOWA). WOWA incorporates stakeholders' attitudes toward uncertainty by assigning greater influence to less favourable outcomes under a risk-averse (pessimistic) perspective, balancing favourable and unfavourable outcomes under a risk-neutral perspective, and assigning greater influence to favourable outcomes under a risk-taking (optimistic) perspective. Scores integrate the environmental, social and economic dimensions of the coastal protection measures, with higher values indicating greater overall sustainability.

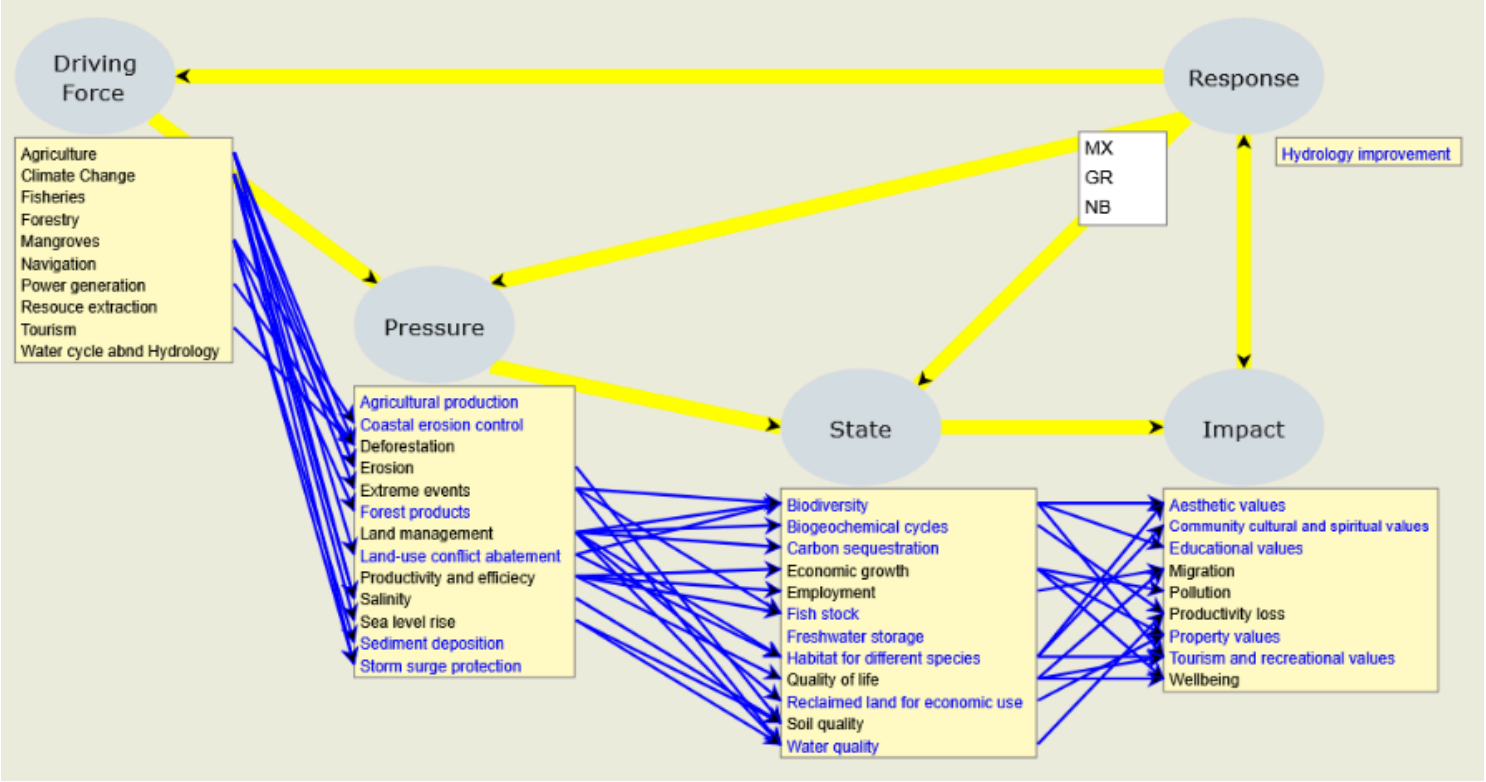

Figure 5

System representation of ecosystem services for coastal infrastructure in Bangladesh using DPSIR framework. Indicators selected for multicriteria analysis are highlighted in blue.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial.docx
- Table1.docx