



# Effectiveness and scalability of coastal nature-based solutions under climate impact drivers: A systematic review

Pradeep Marula Siddappanavara<sup>a,b,\*</sup>, Anushiya Jeganathan<sup>b,1</sup>, P Jayashree<sup>a</sup>

<sup>a</sup> Department of Studies in Geography, University of Mysuru, Mysuru, 570005, India

<sup>b</sup> Center for Study of Science, Technology and Policy, Bengaluru, 560094, India

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## ABSTRACT

Nature-based Solutions (NbS) are increasingly promoted to enhance coastal resilience to climate change, yet most evaluations focus on biophysical outcomes while overlooking the project-level processes that influence long-term effectiveness and scalability. This study applies an implementation-based analytical framework to assess how coastal NbS implementation processes engaged with multiple Climate Impact Drivers (CIDs), including sea-level rise, ocean warming, storm intensity, precipitation variability, and ocean acidification.

A structured qualitative review of 117 coastal NbS studies was conducted, of which 35 were CID-relevant and only 14 contained sufficient process-level information for detailed analysis. Eight key Implementation Components (ICs)—baseline assessment, stakeholder engagement, comparative analysis, economic analysis, performance indicators, monitoring, adaptive management, scalability and replicability—were identified and analysed using Jaccard similarity indices to quantify their co-occurrence. These ICs are related to implementation planning, governance, monitoring, learning, and scalability. The ICs were further mapped to the International Union for Conservation of Nature (IUCN) Global Standard for NbS to evaluate their conceptual alignment with recognised quality criteria.

Results show that foundational and measurement ICs such as baseline assessment, monitoring, and performance indicators dominate current NbS practice, whereas learning-orientated and enabling processes—particularly comparative analysis, adaptive management, stakeholder engagement, and economic assessment—are weakly integrated. This structural imbalance limits cross-site learning, adaptive capacity, and scalability under interacting climate pressures. NbS interventions exhibiting more complete process architectures demonstrate greater alignment with IUCN criteria related to governance, feasibility, and long-term sustainability.

The study demonstrates that scalability is an emergent property of implementation-process completeness rather than a function of ecosystem type or intervention outcomes. This study establishes a quantitative-conceptual framework that integrates CIDs, ICs, and NbS Standard, offering a transferable methodology for identifying implementation deficiencies and enhancing the design of resilient, policy-relevant coastal NbS.

## 1. Introduction

Nature-based Solutions (NbS) have emerged from a lineage of conservation and land management approaches developed since the 1990s, including forest landscape restoration, sustainable land management, and integrated land use planning (Cohen-Shacham et al., 2016; Seddon et al., 2021). These approaches have demonstrated tangible co-benefits for biodiversity, livelihoods, and climate regulations (Dhyani et al., 2020). The NbS principles build on these foundations by explicitly recognising people as active agents in protecting, managing, and restoring

ecosystems to address major societal challenges rather than as passive beneficiaries of nature (Adame and Lovelock, 2011). Since gaining international prominence at the Conference of Parties (COP 14) in 2018, NbS have been increasingly positioned as a central strategy for climate change mitigation, adaptation, and sustainable development across terrestrial, coastal, and urban systems (Bulkeley et al., 2023; Seddon et al., 2021). Despite this rapid policy uptake, scientific evidence of the performance of NbS in enhancing climate resilience remains fragmented. Most existing assessments have focused on biophysical or socio-economic outcomes, such as carbon storage, ecosystem extent, or

\* Corresponding author.

E-mail addresses: [pradeepphd2021@gmail.com](mailto:pradeepphd2021@gmail.com) (P. Marula Siddappanavara), [2dbclms@gmail.com](mailto:2dbclms@gmail.com) (A. Jeganathan), [drjayashreeram@gmail.com](mailto:drjayashreeram@gmail.com) (P. Jayashree).

<sup>1</sup> Independent Researcher, Chennai, 600101, India

avoided damages, while giving limited attention to the processes through which NbS projects are planned, implemented, governed, and monitored over time (Mahmood et al., 2023; Vogelsang et al., 2023). This gap becomes particularly critical under intensifying climate pressures, where the durability and scalability of NbS depend not only on ecological suitability but also on the robustness of institutional, financial, and governance arrangements that support long-term project performance (Billé et al., 2013; Hallegatte et al., 2019; Nelson et al., 2020).

Coastal ecosystems are among the most vulnerable to climate change while simultaneously providing essential ecosystem services such as coastal protection, carbon sequestration, and biodiversity conservation (Huo et al., 2023; Koch et al., 2013). These systems are exposed to multiple, interacting Climate Impact Drivers (CIDs), including sea-level rise, changes in ocean circulation, increasing storm intensity, shifts in precipitation regimes, ocean warming, and acidification (Marfai and King, 2008; Doney et al., 2009; Waycott et al., 2009; Peter Sheng et al., 2022). Although NbS are widely promoted as the cornerstone of coastal resilience strategies, there remains limited understanding of how different NbS interventions perform under specific CIDs and whether they are supported by project-level processes required to sustain effectiveness as climate risks escalate (Hansen et al., 2023).

Under such dynamic and uncertain conditions, outcome-based metrics alone are insufficient to explain why some NbS interventions succeed while others fail (IUCN, 2020; Kumar et al., 2021; Nelson et al., 2020). The long-term performance of NbS depends fundamentally on how projects are designed and managed, including the quality of stakeholder engagement, governance structures, financing mechanisms, monitoring systems, and adaptive management practices (Cohn et al., 2022; Breil et al., 2023). Weakness in these enabling processes can undermine even ecologically well-intended interventions, constraining their scalability and resilience to climate shocks. To capture these non-biophysical determinants of success, this study adopts a set of Implementation Components (ICs) that represent the core elements of NbS project planning, implementation, and governance. Accordingly, the objective of this study is to systematically evaluate how implementation components shape the effectiveness, scalability, and long-term sustainability of coastal NbS under multiple CIDs by quantifying their co-occurrence patterns and mapping their alignment with the International Union for Conservation of Nature (IUCN) NbS Global Standard.

## 2. Method

This study adopts a structured qualitative literature review combined with an implementation-based analytical framework to examine how coastal NbS are planned, evaluated, and positioned for scalability under

multiple CIDs.

### 2.1. Search criteria and articles selection

A structured qualitative literature search was conducted using Google Scholar. Search terms included combinations of “coastal protection”, “coastal restoration”, “climate change”, “nature-based solutions”, “disaster risk reduction”, “adaptation” and “mitigation”. The initial search yielded approximately 117 records after removal of duplicates and non-relevant document types (Fig. 1). A bibliographic network was subsequently created and used to visualise thematic linkages among keywords across the screened literature (Fig. 2). Retrieved records were screened using predefined inclusion criteria requiring that studies (i) addressed coastal ecosystems, (ii) involved NbS-type interventions, and (iii) explicitly or implicitly related to at least one CID. This screening resulted in 35 studies being retained for full-text review. Full-text screening then assessed whether the shortlisted studies contained information on implementation-level processes. As a result, only 14 of 35 studies were found to be sufficiently process-informative and were therefore included in the co-occurrence analysis. The remaining studies primarily focused on biophysical or outcome-based assessments.

### 2.2. Mapping CIDs and NbS strategies for coastal resilience

CIDs were defined as climate-related physical and biogeochemical drivers that directly or indirectly affect ecosystems and human systems, including sea-level rise, storm surge, etc. The literature was screened to ensure representation of major coastal CIDs, and studies addressing these drivers were shortlisted for full-text review and analysis. The NbS interventions reported in the selected studies were mapped to specific CIDs by extracting stated intervention objectives and problem contexts (Fig. 3). The mapped CID–NbS provided a contextual basis for the subsequent identification and evaluation of implementation components and their conceptual alignment with NbS principles. The analysis did not quantify outcome magnitudes but instead focused on linking interventions to the climate pressures they were intended to address.

### 2.3. Selection of implementation components

A set of implementation-based components were identified from established conservation planning, adaptive management, and natural resource governance frameworks that predate the formulation of the NbS concept (Table 1). These components represent widely recognised processes that support intervention planning, evaluation readiness, and learning in environmental management (Cohen-Shacham et al., 2016; IUCN, 2020; Nelson et al., 2020). Within the NbS context, ICs provide a

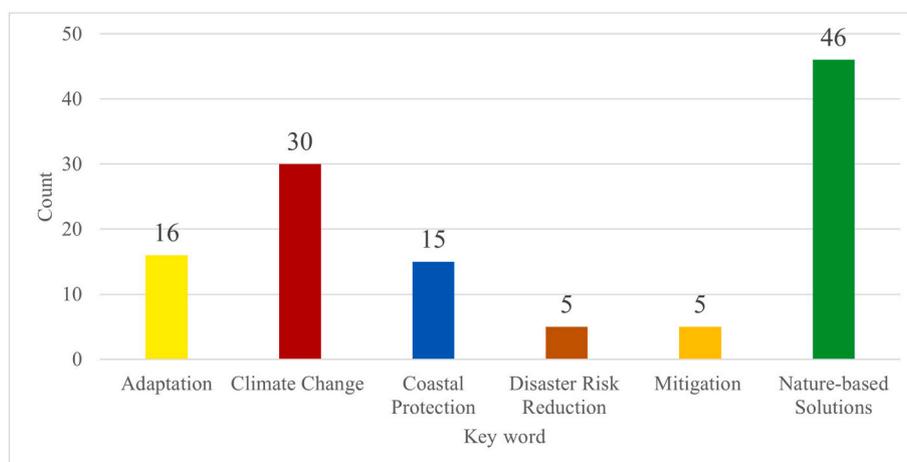


Fig. 1. Keyword frequency distribution in literature.

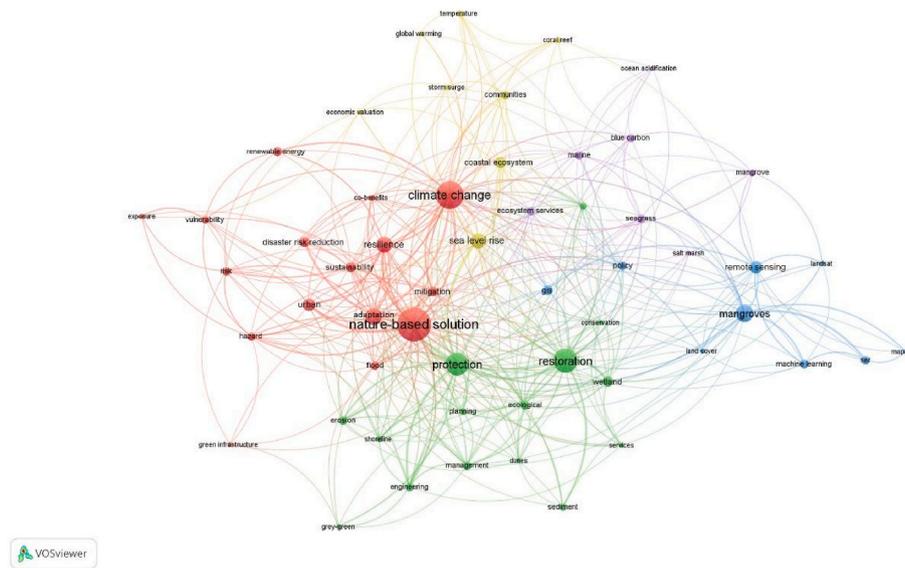


Fig. 2. Causal loop diagram of bibliographic analysis.

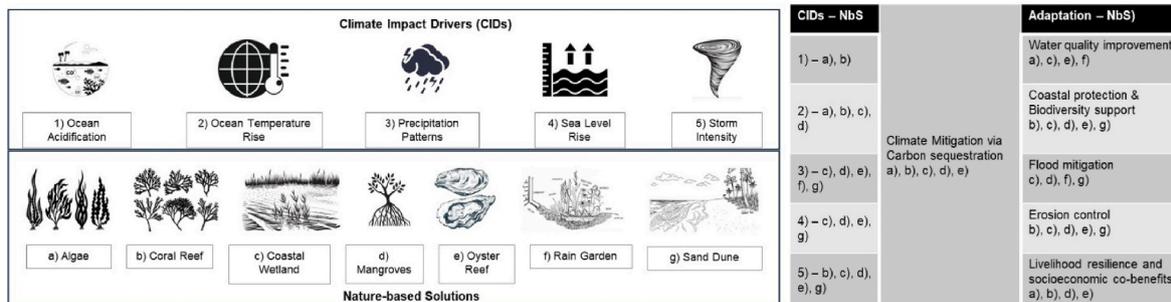


Fig. 3. Nature-based solutions for addressing the climate impact drivers and their mitigation and adaptation pathways.

structured framework for examining critical process dimensions of NbS projects, from problem diagnosis and feasibility assessment to evaluability, learning readiness, and long-term scalability. Their use makes it possible to systematically determine strengths, weaknesses, and knowledge gaps in NbS interventions and literature (IUCN, 2020). In this review, effectiveness is interpreted in a process-based sense, reflecting the adequacy of planning, evaluability, governance, and learning mechanisms, rather than as a direct measure of biophysical or economic outcomes.

2.4. Co-occurrence analysis of ICs and conceptual alignment with IUCN standard for NbS

To examine how ICs are jointly addressed in coastal NbS literature, a two-stage analytical framework was applied. First, a quantitative co-occurrence analysis was conducted to examine how ICs are combined across selected individual studies, revealing patterns of implementation integration and fragmentation. Second, the identified ICs were conceptually mapped to the IUCN Global standard for NbS to situate these processes within the recognised NbS quality framework.

2.4.1. IC co-occurrence analysis

Each study was systematically screened for the presence or absence of the eight predefined ICs (Table 1). Because ICs are rarely explicitly labelled in the literature, they were identified through a structured coding of reported methods, evaluation approaches, stakeholder engagements, and implementation pathways. A binary coding scheme was used to record IC presence (1) or absence (0) rather than intensity or

quality of implementation. Pairwise co-occurrence between ICs was quantified using Jaccard similarity indices (Equation (1)). The strategy was grounded in understanding that effective NbS are inherently process-integrative rather than component-specific.

$$J(P_i, P_j) = \frac{|P_i \cap P_j|}{|P_i \cup P_j|} \tag{Equation 1}$$

Where  $P_i$  and  $P_j$  represent two ICs,  $\cap$  denotes their co-occurrence across studies and  $\cup$  denotes their combined occurrence. Higher Jaccard values indicate frequent joint consideration of ICs across studies, whereas lower values indicate isolated consideration. This co-occurrence analysis was visualised using a heat map to highlight clusters of strongly associated ICs and identify weakly connected ICs.

2.4.2. Conceptual mapping of ICs to IUCN NbS criteria

ICs were mapped to the eight criteria of the IUCN global standard for NbS based on their functional roles in NbS project planning, implementation, governance, and learning. This mapping was based on the conceptual intent of each IC as described in the reviewed literature ( $n = 14$ ), rather than on explicit claims of compliance by the individual studies. The objective was not to evaluate NbS effectiveness or conformity to the IUCN standard but rather to situate implementation-orientated evidence within a recognised NbS quality framework. Overlaps between ICs and NbS criteria were visualised using a Sankey diagram (Fig. 6).

Together, this combined analytical framework enables a structured assessment of (i) how implementation components co-occur in coastal

**Table 1**  
Implementation components and their role in evaluating NbS project planning, implementation, and scalability.

Implementation Components	With IC	Without IC
Baseline assessment	Systematic assessment of climatic, ecological and socio-economic conditions prior to intervention	Problem diagnosis is weak; cannot be attributed to NbS; effectiveness claims are unreliable
Stakeholder engagement	Inclusion of local communities, institutions or stakeholders in design or implementation	Social legitimacy is weak; conflict may arise; continuity is at risk
Comparative analysis	Consideration of alternative NbS options, sites or design approaches	Scaling decisions lack evidence. NbS choice may be arbitrary
Economic analysis	Assessment of cost, benefits or financial feasibility	Financial risks are overlooked; scaling decision lack evidence
Performance indicators	Definition of measurable indicators, linked to project objectives	Process and outcome cannot be evaluated or compared across studies
Monitoring	Planned or implemented monitoring of ecological, social, or project variables over time	Learning is impossible; adaptive management cannot operate
Adaptive management	Evidence that management actions can be adjusted based on monitoring or new information	Interventions become rigid; long-term effectiveness declines under climate variability
Scalability and replicability	Assessment of whether the NbS can be expanded or transferred to other locations	NbS remain isolated pilots; uptake and long-term impact is constrained

NbS practice and (ii) how these processes align with IUCN NbS standard. This approach supports implementation-orientated understanding of NbS effectiveness and scalability under multiple CIDs while avoiding prescriptive or compliance-based evaluation.

### 3. Results

#### 3.1. Bibliographic analysis

Keyword frequency analysis of 117 records (Fig. 1) shows that 'nature-based solutions' and 'climate change' are the most frequent terms in the screened literature, followed by adaptation, coastal protection, and mitigation. The keyword bibliographic co-occurrence network at the title, abstract, and articles keyword level shows that there are structured thematic clusters in the NbS literature (Fig. 2). Central nodes such as nature-based solutions and climate change are strongly connected to terms including "sustainability", "resilience", "protection", "restoration", "adaptation", and "disaster risk reduction". A distinct cluster linking "mangroves" with "remote sensing" and "machine learning" is noticed, indicating the use of Earth observation and data-driven approaches in coastal NbS studies. Additional co-occurring terms such as "wetland", "shoreline", "erosion", and "flood" appear closer to NbS-related keywords, indicating a strong focus on coastal risk contexts. Terms such as "policy", "planning", "management", and "ecosystem services" highlight the essential role of governance in implementing these solutions.

#### 3.2. CID impacts and NbS strategies for coastal resilience

This section synthesises major CIDs that are relevant to coastal ecosystems and summarises the NbS strategies reported in the reviewed literature (n = 35) to mitigate them (Fig. 3). NbS interventions are primarily mapped to a dominant CID in the reviewed articles, although secondary or indirect contributions to other CIDs are also frequently reported.

##### 3.2.1. Ocean acidification

Ocean acidification, driven by increased atmospheric CO<sub>2</sub> uptake, alters seawater carbonate chemistry and negatively affects a wide range of marine and coastal ecosystems, including corals, oysters, seagrasses, and algae (Doney et al., 2009; Hall-Spencer and Harvey, 2019; Kumar et al., 2021). These changes disrupt ocean pH, habitat structure, species composition, and ecosystem functioning in coastal environments. The reviewed studies primarily associate NbS strategies such as seagrass conservation and restoration for the mitigation of ocean acidification. Seagrass meadows contribute to local pH regulation, carbon sequestration, and improved water quality (Koch et al., 2013; Kowalczyk et al., 2024), thereby buffering acidification effects in nearshore environments. The algal and coral systems also exhibit adaptive responses to acidification and thermal stress through physiological (Matsuda et al., 2023), morphological (McFadden et al., 2021), and behavioural mechanisms (Huo et al., 2023). However, their effectiveness as NbS depends on site-specific environmental and management context (Ferrario et al., 2014; Huo et al., 2023; Matsuda et al., 2023; McFadden et al., 2021; Yossi et al., 2019).

##### 3.2.2. Ocean temperature

A steady rise in ocean heat content since the late twentieth century has led to widespread warming across multiple ocean basins, with pronounced effects in tropical and subtropical regions (Cheng et al., 2024). Rising ocean temperatures disrupt ecological processes and increase stress on temperature-sensitive species such as corals, phytoplankton, invertebrates, and some fish, which may become vulnerable (Fuchs et al., 2020; Henley et al., 2024). Invasive species, opportunistic algae, and generalist predators may emerge as victors, underscoring the intricate ecological transformations prompted by climate change (Ipcc, 2022). NbS strategies addressing ocean warming in the reviewed literature focus on management, conservation, and restoration interventions that maintain or enhance thermal refugia and genetic diversity within coastal ecosystems. Vegetated systems such as mangroves and seagrass beds, when protected or restored, provide microclimatic buffering and support biodiversity under elevated temperature (Salois et al., 2022). Genetic diversity is also highlighted as a key resilience mechanism, enabling species and ecosystems to adapt to thermal stress and maintain ecosystem services under changing climatic conditions (Bulleri et al., 2018).

##### 3.2.3. Precipitation patterns

The Intergovernmental Panel on Climate Change AR6 reports significant alterations in global precipitation patterns, with implications for hydrological cycles, coastal erosion, flooding, and ecosystem health (Calvin et al., 2023). Changes in precipitation intensity and variability influence sediment dynamics, microbial processes, species distributions, and disease transmission in coastal zones (Breil et al., 2023; Farrer et al., 2022; Moraes et al., 2022; Subramanian et al., 2023). Wetland restoration and rain garden interventions are the primary NbS strategies associated with precipitation-related impacts in the reviewed studies. Coastal wetlands function as natural water storage systems, attenuating flood peaks, reducing erosion, and improving water quality through sediment retention and pollutant filtration. Rain gardens, especially in cities along the coast, help control stormwater runoff by encouraging water to soak into the ground and imitating natural water flow patterns. This helps prevent erosion and increases the number of different types of plants and animals in the area (Kasprzyk et al., 2022).

##### 3.2.4. Sea-level rise

Global mean sea-level rise, currently estimated at 3.2–4.2 mm/year, poses significant risks to coastal and human systems through inundation, erosion, saltwater intrusion, and habitat loss (Carretero et al., 2013; El-Nahry and Doluschitz, 2010; Saintilan et al., 2023; Toimil et al., 2020; Von Holle et al., 2019). These impacts generate cascading ecological and socio-economic stress in low-lying coastal regions

(Marfai and King, 2008). Management, conservation, and restoration of coastal ecosystems, such as mangroves, salt marshes, seagrasses, and tidal wetlands, are consistently identified as key Nbs strategies for addressing sea-level rise impacts. These ecosystems trap sediments, contribute to vertical land accretion, attenuate storm surges, and reduce coastal erosion, while providing carbon sequestration and biodiversity benefits (Adame and Lovelock, 2011; Billé et al., 2013; Damastuti et al., 2023; Duarte de Paula Costa et al., 2023; Duncan et al., 2016; Townend et al., 2011). Coastal dunes stabilised by vegetation also function as natural barriers, absorbing wave energy and protecting inland areas from storm impacts (Costa et al., 2023; Martinez et al., 2016).

### 3.2.5. Storm intensity

As ocean temperatures rise, evaporation and the amount of moisture in the air increase, which leads to stronger coastal storms and more damage to ecosystems (Martzikos et al., 2021). Storm impacts include shoreline erosion, habitat degradation, and loss of coastal protection services. Restored coral and oyster reefs are widely reported as Nbs that mitigate storm impacts by reducing wave energy and stabilising coastlines. Coral reefs can dissipate up to 86 % of incoming wave energy, functioning as natural breakwaters while supporting biodiversity and livelihoods through fishing and tourism (James et al., 2023; Shi et al., 2018; Ferrario et al., 2014). Oyster reefs similarly attenuate wave energy, reduce erosion, improve water quality, and enhance habitat complexity, providing multifunctional benefits under increasing storm intensity (Perricone et al., 2023; Ridge et al., 2017).

### 3.3. Co-occurrence patterns of ICs in coastal Nbs literature

This section presents the results of the co-occurrence analysis of ICs across the 14 implementation-informative coastal Nbs studies. The results show how frequently different ICs occur, revealing dominant evaluation practices and methodological clustering and under-represented process linkages in the literature.

#### 3.3.1. Distribution of ICs across reviewed studies

Fig. 4 displays the prevalence of each IC across 14 studies. All studies (100 %) include baseline assessment, comparative analysis, and performance indicators. This indicates that coastal Nbs research consistently prioritises problem definition, comparison, and outcome measurement. Implementation level monitoring is also widely reported (86 %), reflecting the frequent use of repeated or structured tracking of ecological and project variables. In contrast, scalability (57 %) and adaptive management (50 %) are only moderately represented, while economic analysis (36 %) and stakeholder engagement (29 %) are markedly under-represented.

#### 3.3.2. Pairwise IC associations based on Jaccard similarity index

High Jaccard values were observed among baseline assessment, comparative analysis, and performance indicators. Moderate values were identified between monitoring and scalability, as well as baseline and scalability. In contrast, stakeholder engagement, economic analysis, and adaptive management exhibited weak co-occurrence with most other ICs. Notable low Jaccard values were observed between economic analysis and adaptive management and between stakeholder engagement and monitoring (Fig. 5).

#### 3.3.3. Conceptual alignment of ICs and Nbs criteria

The conceptual alignment of ICs and Nbs criteria (C) is shown using a Sankey diagram (Fig. 6), which visualises the distribution of correspondence across components. Among Nbs criteria, design at scale (C2) shows the broadest alignment to seven of eight ICs. Societal challenges (C1) and economic feasibility (C4) show broad correspondence, each connecting to multiple ICs. Other criteria show more selective patterns of connection based on the process component that is involved. Several ICs show uneven correspondence with specific Nbs criteria. The baseline

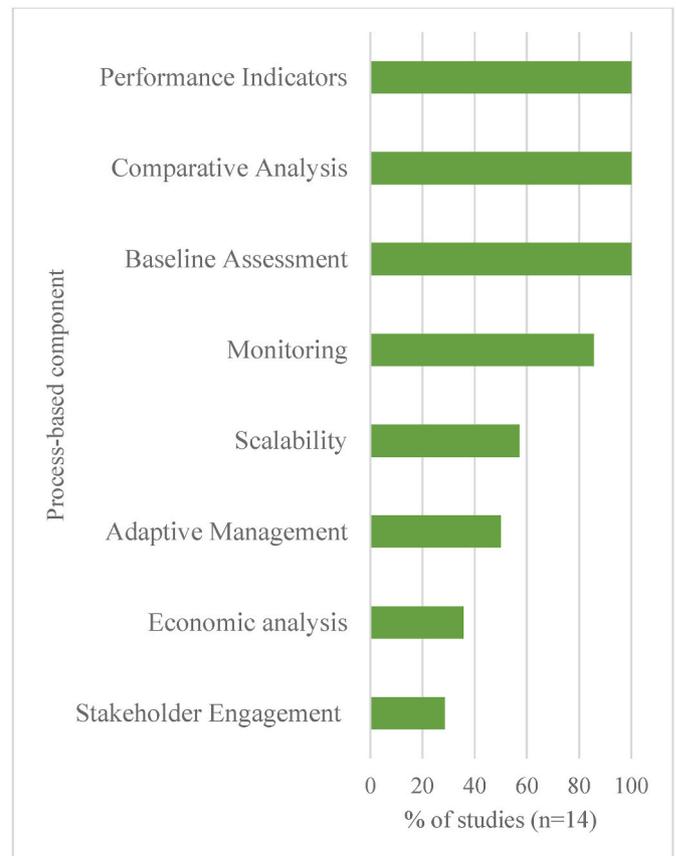


Fig. 4. Prevalence of implementation components across reviewed coastal Nbs studies.

assessment shows weaker correspondence with inclusive governance (C5) and balanced trade-offs (C6), reflecting its primary focus on establishing initial conditions rather than governance or trade-off negotiation. Monitoring shows stronger alignment with technically focused criteria than with social and economic dimensions, reflecting its emphasis on biophysical tracking. Comparative analysis shows weaker correspondence with trade-offs, concentrating on direct comparisons rather than multifaceted interests. Adaptive management demonstrates limited correspondence with planning-stage criteria such as economic feasibility. Stakeholder engagement exhibits a diminished correlation with biodiversity net gain (C3), as it predominantly represents social and institutional processes rather than direct ecological results. Economic analysis shows weaker correspondence with design at scale, reflecting its focus on financial assessments rather than implementation design. Finally, scalability and replicability show weaker alignment with criteria related to trade-offs and adaptive learning.

## 4. Discussion

This discussion interprets the review findings from an implementation-based, process-orientated viewpoint, investigating how the arrangement and simultaneous presence of ICs influence the effectiveness, scalability, and enduring resilience of coastal Nbs amidst various CIDs. The discussion emphasises that the completeness of implementation process—from baseline assessment to monitoring and adaptive learning—determines whether Nbs can transition from site-specific success to scalable, policy-relevant solutions rather than concentrating solely on Nbs outcomes.

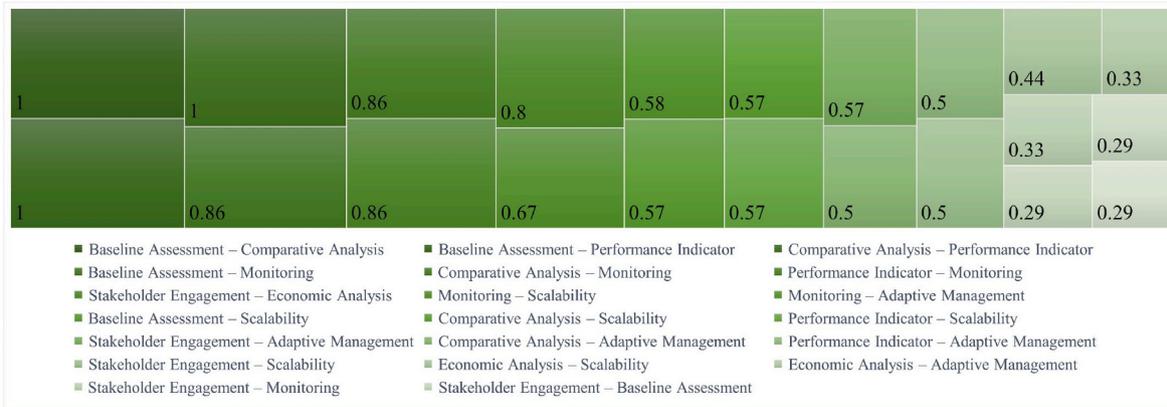


Fig. 5. Jaccard Index values between implementation components across the reviewed studies.

#### 4.1. Implementation components for NbS effectiveness and scalability

##### 4.1.1. Foundational and measurement processes: baseline assessment, monitoring and performance indicators

Baseline assessment, monitoring, and performance indicators together form the foundational measurement core for coastal NbS implementation. These components emerged as the most consistently reported elements across the reviewed studies and frequently co-occurred. This indicates that coastal NbS research emphasises documenting effectiveness through measurable outcomes rather than strengthening learning or governance-orientated processes.

Baseline assessments support the diagnosis of dominant CIDs and site-specific ecological, physical, and socio-economic conditions (Ruckelshaus et al., 2020). They establish reference conditions prior to intervention and enable informed NbS selection and, benchmarking of performance, and more credible attribution of observed changes to NbS implementation. Across the reviewed literature, baseline information is essential for contextualising NbS impacts and informing feasibility-related decisions. However, baseline assessment is often treated as a one-time diagnostic rather than as an input that is updated and fed into iterative learning cycles, limiting its contribution to adaptive management and long-term scalability. Monitoring gives us a way to measure how well a process is working over time by letting us keep track of NbS performance before, during, and after implementation (Cohn et al., 2022). In practice, monitoring in the reviewed studies primarily targets biophysical change, with less consistent attention to social, governance, and financial dimensions. When monitoring is designed as a feedback mechanism instead of merely a reporting exercise, it supports the early detection of implementation challenges, enables the adjustment of interventions as conditions evolve, and strengthens learning within dynamic and interacting CIDs. Performance indicators establish the visible and measurable dimensions of NbS effectiveness (Orta-Ortiz et al., 2021). The reviewed studies employ indicators spanning ecological, physical, and socio-economic dimensions (Paxton et al., 2023), but ecological and hazard-related metrics are most common. Well-designed indicators strengthen evaluability by clarifying objectives, enabling comparison across sites or intervention types, and supporting decision-making for scaling. However, inconsistent indicator selections and shorter monitoring horizons reduce comparability and limit the ability to generalise learning across contexts.

The predominance of CIDs in reviewed articles, such as storm intensity, coastal flooding, erosion, and sea-level rise, partly explains the strong emphasis on baseline assessment, monitoring, and performance indicators. These drivers lend themselves to short-term, biophysical measurement of protection outcomes, reinforcing a measurement-orientated approach to NbS evaluation (Damastuti et al., 2023; Duncan et al., 2016; Hochard et al., 2021; Van Hespén et al., 2023; Baptist

et al., 2021; Peh et al., 2014; Silliman et al., 2015; Townend et al., 2011).

Across the reviewed literature, baseline assessments and monitoring commonly draw on Earth observation technologies, field measurements, and evidence synthesis. Remote sensing supports tracking of land cover, shoreline dynamics, and vegetation change (Ridge et al., 2017), while field surveys provide site-level validation and measurements of hazard-relevant variables such as water levels, sediment dynamics, and ecosystem structure (Narayan et al., 2016; Carro et al., 2018). Literature synthesis supports contextual understanding of risk pathways, feasibility constraints, and policy relevance (IUCN, 2020; Cohn et al., 2022; Van Hespén et al., 2023). The reviewed articles also demonstrate diverse monitoring strategies, with indicators capturing shoreline change, vegetation cover, erosion rates, flood attenuation, storm protection, water levels, wave energy, bathymetry, dune morphology, sedimentation rates, and thermal exposure. Biological indicators include habitat quality, species diversity, biomass, stem density, and carbon stocks, while socio-economic indicators include fisheries outcomes, tourism-related measures, and proxies of economic recovery following extreme events. Several studies illustrate these approaches in practice. Scyphers et al. (2011) report bathymetric surveys and vegetation monitoring to evaluate oyster reefs for shoreline protection. Ridge et al. (2017) use LiDAR to assess reef resilience over time. Mahmood et al. (2023) employ satellite imagery to track mangrove extents, land stabilisation, and socio-economic outcomes. Damastuti et al. (2023) assess forest structure to infer the protective function of mangrove systems. Kasprzyk et al. (2022) evaluate rain garden performance using pressure transducers to track water levels. Across reef-based NbS, wave energy dissipation is a frequently reported indicator, while wetland restoration is monitored through biodiversity outcomes, vegetation survival, and (in some cases) greenhouse gas fluxes.

##### 4.1.2. Learning and comparison gaps: comparative analysis and adaptive management

Comparative analysis and adaptive management represent the primary learning-orientated ICs that support the transferability and robustness of NbS under variable-changing conditions. Comparative analysis enables assessment of NbS performance across locations, designs, and intervention types, including comparisons between NbS, grey infrastructure, and hybrid approaches. When used, comparative evidence helps choose the best design and helps decide if and how NbS can be used in new situations. Adaptive management promotes learning-by-doing through iterative monitoring, evaluation, and adjustment of implementation strategies. In coastal NbS settings where risks evolve under multiple CIDs, adaptive management supports timely course correction, reduces lock-in to ineffective designs, and increases the likelihood that interventions remain functional over the long term. However, the reviewed literature suggests that adaptive management is

under-reported relative to monitoring, indicating that feedback loops are often weak or not institutionalised (Bulleri et al., 2018; IUCN, 2020; Le Gouvello et al., 2023; Ridge et al., 2017; Scyphers et al., 2011).

Reviewed studies provide examples of comparative approaches, even when not explicitly framed as an IC. Duncan et al. (2016) compare rehabilitated intertidal zones and abandoned fishpond areas with natural mangroves. Van Hespen et al. (2023) compare mangrove-based approaches with engineered structures in terms of flood risk reduction and cost. Silliman et al. (2015) examine planting configurations and elevation effects on marsh establishments. Baptist et al. (2021) compare sediment composition and planting approaches to evaluate conditions supporting vegetation establishment. Kasprzyk et al. (2022) evaluate rain gardens across local contexts where implementation conditions influence performance. Evidence of adaptive management is more limited but demonstrates clear benefits where described. Kasprzyk et al. (2022) show how iterative monitoring informs refinement of rain garden design. Peh et al. (2014) highlight adaptive management in land conversion settings to sustain ecosystem service delivery. Kelleway et al. (2017) emphasise the need to manage dune vegetation and human pressures, such as tourism, to maintain protective functions. Vogelsang et al. (2023) note that adaptive management allows decision-makers to adjust strategies as new climate information becomes available. Bertolini and Da Mosto (2021) discuss restoration approaches that incorporate sea-level rise feedbacks, indicating the relevance of iterative adjustment. Overall, the limited reporting of comparative analysis and adaptive management indicates that learning is not consistently systematised, which constrains resilience and scalability for interacting CIDs. The narrow focus on event-driven CIDs, such as storms and erosion, also constrains learning-orientated ICs. Slow-onset and interacting drivers—including ocean warming, acidification, and long-term sea-level rise—are rarely incorporated into comparative analyses or adaptive management frameworks (Chowdhury et al., 2019; Ridge et al., 2017; Scyphers et al., 2011; Costa et al., 2023; Hanley et al., 2014; Martinez et al., 2016). As a result, NbS performance is seldom evaluated across time horizons or climate trajectories, weakening feedback loops and limiting anticipatory adaptation.

#### 4.1.3. Enabling conditions: stakeholder engagement and economic analysis

Stakeholder engagement and economic analysis act as enabling ICs that shape the legitimacy, feasibility, and long-term sustainability of coastal NbS. Unlike measurement-orientated ICs, these components directly influence how NbS are governed, financed, and maintained beyond pilot-scale implementation—particularly under complex and evolving CIDs.

Stakeholder engagement strengthens inclusivity and legitimacy by incorporating diverse perspectives in planning, implementation, and monitoring. Where embedded, it improves diagnosis of locally relevant risks and priorities, supports conflict management, and increases the likelihood of long-term maintenance and compliance. Stakeholder engagement can also improve feasibility by leveraging local knowledge and resources and by identifying trade-offs early in project design. Economic analysis aids feasibility and policy adoption by elucidating the costs, benefits, and trade-offs linked to implementation and maintenance. It can strengthen the case for investment by demonstrating avoided losses, co-benefits, and long-term returns relative to grey or hybrid alternatives. Economic valuation of ecosystem services (e.g., carbon sequestration, flood regulation, fisheries benefits) is particularly relevant where NbS are positioned as multi-benefit interventions, but direct economic assessment is inconsistently reported across the reviewed studies.

Within the reviewed literature, stakeholder engagement is most evident in community-based coastal NbS initiatives. Baptist et al. (2021) note participation in saltmarsh interventions in estuarine settings, while Carro et al. (2018) emphasise integrating local knowledge and securing institutional buy-in. Several studies imply the need for coordination among communities, researchers, and authorities, even when

engagement processes are not described in detail. While such inference should be interpreted cautiously, it reinforces the role of stakeholder processes in implementation and monitoring (e.g., Bertolini and Da Mosto (2021), Chowdhury et al. (2019), Kelleway et al. (2017), Narayan et al. (2016), Ridge et al. (2017), Vogelsang et al. (2023)). Also, the limited attention to gradual and less visible climate drivers further affects enabling ICs from the literature reviewed. Governance and economic processes are more difficult to mobilise when NbS are framed around episodic hazards rather than long-term climate trajectories, reducing incentives for sustained stakeholder engagement and forward-looking investment (Bertolini and Da Mosto, 2021; Cheng et al., 2024; Von Holle et al., 2019).

The reviewed evidence indicates that NbS often demonstrate cost advantages relative to conventional approaches, although results remain context-specific. Studies highlight the cost-effectiveness of mangroves in stabilising land and supporting carbon-related benefits (Mahmood et al., 2023), the advantages of reef restoration relative to engineered breakwaters (IUCN, 2020), and the protective value of oyster reefs (Baptist et al., 2021; Narayan et al., 2016). Wetland restoration yields enduring advantages, whereas some NbS interventions reduce maintenance demands compared to rigid infrastructure (Van Hespen et al., 2023). Nonetheless, numerous studies address economic relevance indirectly rather than through systematic valuation, highlighting the necessity for more consistent economic assessment to facilitate scaling decisions.

#### 4.1.4. Scalability as an emergent outcome of process completeness

The reviewed literature indicates that NbS is more likely to be scaled across spatial, social, and climate contexts when foundational, learning-orientated, and enabling ICs are jointly present rather than when ecological performance alone is demonstrated. CID prioritisation has direct implications for scalability. NbS designed primarily to address storm and erosion risks may demonstrate strong site-specific performance under current conditions, but their effectiveness can decline as slow-onset drivers such as sea-level rise, warming, and sediment regime shifts intensify. Without explicit integration of evolving CIDs into baseline assessments, monitoring frameworks, and adaptive management processes, scalability remains opportunistic rather than systematic (Chairat and Gheewala, 2024; Nelson et al., 2020). From a process perspective, scalability depends on whether NbS can remain effective across different social contexts and whether interventions can be adapted to larger areas or new locations without loss of function. This requires not only credible evidence of ecological outcomes and feasibility but also governance arrangements that can accommodate institutional diversity, mechanisms to reassess trade-offs as contexts change, and feedback processes that enable adaptation under uncertainty. When these conditions are satisfied, long-term policy and sustainability frameworks are more likely to mainstream NbS.

The reviewed literature evidence that mangroves afforestation, oyster reef restoration, and wetland rehabilitation are frequently cited as scalable interventions; however, replication remains contingent on site-specific conditions and enabling processes (Damastuti et al., 2023; Kasprzyk et al., 2022; Scyphers et al., 2011). Where comparative learning across sites and adaptive management are weak or absent, scaling tends to be opportunistic rather than systematic.

#### 4.2. Challenges, opportunities and potential associated with NbS implementation

NbS leverages natural processes to mitigate CIDs; however, their effectiveness and scalability are underlined by how implementation components are designed, integrated, and sustained. This section synthesises the implementation-level challenges, opportunities, and long-term potential of coastal NbS using an IC lens, based on patterns observed in the reviewed studies.

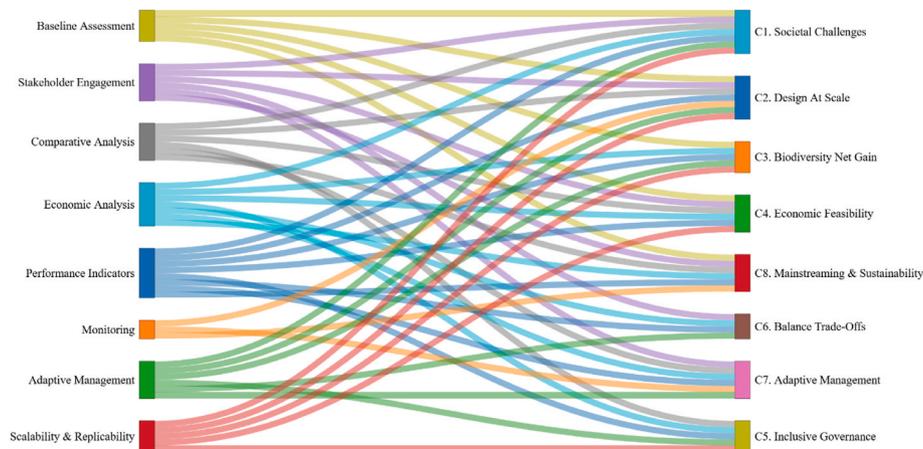


Fig. 6. Mapping alignment of implementation components to IUCN nature-based solutions criteria.

#### 4.2.1. Key implementation challenges

A dominant challenge revealed by the IC co-occurrence analysis (Fig. 5) is the fragmented implementation of NbS beyond baseline assessment and monitoring. While measurement-orientated components frequently co-occur, ICs related to learning, governance, adaptive management, and economic viability show weak and inconsistent integration, limiting the ability of NbS projects to translate monitoring into adaptive and scalable action. Short monitoring horizons, inconsistent indicators, and weak feedback loops therefore reflect not isolated methodological issues, but incomplete implementation architectures that constrain long-term effectiveness under interacting CIDs.

Studies by Chowdhury et al. (2019), Kasprzyk et al. (2022), and Mahmood et al. (2023) highlight the challenge of accurately gauging long-term effectiveness of NbS, emphasising the need for robust monitoring and evaluation. This includes addressing the environmental impacts of grey infrastructure and enhancing green solutions across habitats (Narayan et al., 2016). Duncan et al. (2016) discussed noncompliance with scientific guidelines and the need for effective spatial planning. Martinez et al. (2016) noted challenges in understanding vegetation, dune dynamics, and storm impacts. Baptist et al. (2021) identified obstacles in execution, technical difficulties, and ensuring tidal creeks' longevity. Adame and Lovelock (2011) and Martinez et al. (2016) note plant response variability due to environmental stresses, whereas Perricone et al. (2023) outlined uncertainties in predicting sea-level rise and storm patterns affecting flood risk assessments. Koch et al. (2013) outline challenges in managing multiple stress factors. Studies by Cohen-Shacham et al. (2016) and Nelson et al. (2020) expressed concerns about carbon release risks from NbS implementation. Billé et al. (2013) highlight the lack of integrated policy frameworks, coordination gaps between governance levels, and challenges in ensuring stakeholder participation and rights (Damastuti et al., 2023).

#### 4.2.2. Emerging opportunities through IC integration

In contrast to these challenges, the literature also highlights clear opportunities for enhancing NbS effectiveness and scalability through integrated implementation architectures. Studies demonstrate that when learning-orientated, governance, financial, and adaptive management ICs are embedded alongside monitoring and baseline assessment, NbS are better able to respond to changing climatic and socio-ecological conditions.

A study by Damastuti et al. (2023) emphasises integrated management and community involvement to enhance green coastal strategies while maximising ecosystem benefits and climate adaptation. Narayan et al. (2016) suggested investing in reef restoration to improve coastal resilience. Dhyanani et al. (2020) highlight the importance of habitat connectivity, ecosystem restoration, and sustainable resource management for resilient environments. Hallegatte et al. (2019) discuss cost

savings over traditional infrastructure, accessing green bonds, and attracting diverse funding for NbS sustainability. Malerba et al. (2023) and Walter Leal et al. (2022) advocated embedding NbS in national and international agendas to strengthen legal and policy frameworks, improve sectoral coherence, promote advanced technologies like remote sensing and Geographical Information Systems (GIS) to enhance NbS planning and decision-making, and democratise information access.

These integrated IC configurations also underpin the broader environmental, social, and economic potential of NbS. Sapkota and White (2020), Shi et al. (2018), and Zimmer (2024) show how NbS aids in climate change mitigation through carbon sequestration, offering environmental and economic benefits. Costello and Chaudhary (2017) and Timothy and Tapan (2022) emphasise the role of NbS in biodiversity conservation and enhanced ecosystem resilience. Camargo et al. (2009), Mahendra et al. (2023), and Walter Leal et al. (2022) emphasised NbS's capacity to bolster community resilience, sustain livelihoods, and yield socio-economic advantages via localised initiatives.

From an implementation perspective, financial, institutional, and technological ICs further strengthen NbS scalability and durability. Timothy and Tapan (2022) highlight that compared with traditional infrastructure, NbS attracts diverse funding sources and achieves long-term cost savings, fostering economic resilience in the green finance sector. NbS also strengthens policy support for sustainable development, improves natural resource governance, and enhances cross-sectoral collaboration. Technologically, NbS improves planning, implementation, and monitoring through tools like remote sensing and GIS, enhancing adaptive management, and democratising information access (Saleh and Weinstein, 2016). These potentials point to the transformative function of NbS in promoting a sustainable and resilient future.

#### 4.3. Gaps in knowledge and research limiting IC maturity under CIDs

Table 2 presents the gaps in knowledge and research on the application of NbS in areas impacted by multiple climatic drivers. It is organised into four main areas: integrated impact assessment, economic valuation, social and cultural dimensions, and policy and governance. Each aspect highlights deficiencies in understanding both the impact on social-ecological resilience and the sustainability of coastal ecosystems and communities. Integrated impact assessment is crucial for understanding climatic and ecological interactions, enhancing NbS effectiveness, and supporting informed decision-making (Chausson et al., 2020). Economic valuation justifies resource allocation and attracts investment by showing that NbS is more cost-effective than traditional infrastructure (Breil et al., 2023). Understanding social and cultural dimensions ensures community engagement and acceptance, addressing equity and justice (Sowińska-Świerkosz and García, 2022). Effective policy and

**Table 2**  
Gaps in knowledge and research on the NbS application in areas impacted by multiple climatic drivers.

Aspect	Knowledge	Impact on Social-Ecological Resilience	Impact on Sustainability of Coastal Ecosystems and Communities
Integrated Impact Assessment	Lack of comprehensive models that integrate multiple climatic drivers and their cumulative impacts on NbS (Baptist et al., 2021; Bulkeley et al., 2023; Ruckelshaus et al., 2020; Paxton et al., 2023); The knowledge gap in consideration of biological, ecological, and physical site-specific aspects (Koch et al., 2013; Narayan et al., 2016); insufficient longitudinal studies to assess long-term effectiveness of NbS against combined climatic threats (Baptist et al., 2021; Damastuti et al., 2023; Hochard et al., 2021; Ruckelshaus et al., 2020; Nelson et al., 2020).	Predicting the resilience of NbS to compound climatic events presents challenges, as does assessing the adaptability of social-ecological systems to changing conditions.	Uncertainty in long-term viability and effectiveness of NbS in protecting coastal communities; inadequate understanding of how NbS contribute to the sustainability of both ecosystems and human livelihoods over time.
Economic Valuation	Inadequate methodologies for valuing the full range of ecosystem services provided by NbS, especially non-market benefits (Calvin et al., 2023; Hochard et al., 2021); limited economic analyses of NbS compared to traditional infrastructure in the context of multiple climatic drivers (Cohen-Shacham et al., 2016).	The economic benefits of NbS in enhancing resilience are often underestimated, and securing funding and investment can be challenging without clear economic valuations.	Justifying NbS investments to stakeholders and policymakers can be challenging, and there is a possibility of underusing NbS due to a perceived lack of cost-effectiveness.
Social and Cultural Dimensions	Research on the social and cultural implications of implementing NbS in diverse communities is limited (Sowińska-Świerkosz and García, 2022), and there is insufficient understanding of community perceptions, traditional knowledge, and acceptance of NbS (Cheng et al., 2024).	There is a potential misalignment between NbS and community values, which could lead to reduced effectiveness and acceptance. Additionally, there are challenges in fully leveraging local knowledge to enhance the resilience of NbS.	The implementation of NbS may overlook social equity and justice issues, potentially leading to conflicts over resource use and land rights, which could negatively impact community cohesion and support for NbS.
Policy and Governance	Gaps in integrating NbS into existing coastal management and climate adaptation policies (Calvin et al., 2023); lack of clear guidelines and standards for the design, implementation, and monitoring of NbS (Seddon et al., 2021; Van Hespén et al., 2023).	Creating supportive policy frameworks that enhance the resilience benefits of NbS is difficult, and coordinating across governance levels and sectors for NbS implementation presents challenges.	Inconsistencies in policy support may hinder the scaling up of effective NbS and their integration into broader coastal management strategies; there are limited policy incentives for communities and stakeholders to adopt and support NbS.

governance provide necessary regulatory support and ensure coordinated policy across jurisdictions, enhancing the overall effectiveness and sustainability of NbS (Moraes et al., 2022). Each aspect highlights specific deficiencies in research and practice, ranging from incomplete models of climate impacts to gaps in social equity considerations and policy integration. These gaps highlight the necessity for additional research, enhanced valuation methodologies, and refined policy frameworks to augment the efficacy and adoption of NbS.

#### 4.4. Study limitations

The implementation components were coded as binary variables based on reported in each study, which capture whether key elements are described but not the quality or intensity of their implementation. As a result, differences in how strongly components such as monitoring, governance, or learning are applied cannot be fully resolved. In addition, the Jaccard similarity analysis quantifies structural associations among components but does not imply causal relationships with NbS performance. Finally, the detailed analysis is based on a subset of CID-relevant studies that reported sufficient implementation details, which may favour well-documented projects. Despite these limitations, the approach provides a transparent and reproducible basis for comparing implementation structures across diverse NbS contexts.

## 5. Conclusion

This review analyses the effectiveness and scalability of coastal nature-based solutions by evaluating implementation components in the context of various and interrelated climate impact drivers. The study goes beyond outcome-focused assessments, offering an implementation-based process-explicit synthesis of the design, implementation, evaluation, and adoption of NbS in diverse coastal contexts. By systematically extracting ICs from the literature, analysing their co-occurrence patterns, and conceptually aligning them with the IUCN NbS criteria, this review shows that NbS effectiveness and scalability are governed less by ecosystem type alone and more by process completeness. Baseline

assessment, monitoring, and performance indicators dominate current NbS practice, reflecting a strong emphasis on measurement and demonstration of effectiveness. However, learning-orientated processes—particularly comparative analysis and adaptive management—remain weakly institutionalised. This imbalance constrains long-term resilience, limits cross-site learning, and reduces the transferability of NbS under evolving climate regimes.

A key contribution of this study lies in showing that scalability emerges from integrated processes rather than a design feature introduced post hoc. NbS interventions that embed robust baseline assessments, consistent monitoring frameworks, stakeholder engagement, and economic analysis are better positioned for replication, policy uptake, and mainstreaming. In contrast, interventions lacking adaptive feedback and governance integration tend to remain context-specific, even when ecological performance is demonstrably strong. The application of Jaccard similarity analysis provides a quantitative perspective on IC co-occurrence, revealing structural asymmetries in how NbS processes are implemented. While measurement-orientated ICs frequently co-occur, enabling and learning processes show limited integration. This methodological approach offers a transferable framework for diagnosing process gaps in NbS portfolios and complements existing qualitative reviews by introducing evidence-based process comparison.

From a policy and practice perspective, the findings underscore the need to reframe coastal NbS planning around explicit process design, rather than treating governance, economics, and adaptation as secondary considerations. These ICs should be embedded from the outset to enhance resilience under compound and uncertain CIDs. Aligning NbS processes with adaptive policy frameworks, financing mechanisms, and long-term monitoring commitments is critical for sustaining effectiveness beyond project lifecycles. The review also highlights persistent research gaps that limit NbS maturity. These include the lack of integrated impact assessments capturing multiple interacting CIDs, incomplete economic valuation of ecosystem services, insufficient attention to social and cultural processes, and weak policy integration across governance scales. Addressing these gaps requires longitudinal, interdisciplinary research that explicitly links ICs to climate dynamics, socio-

ecological feedbacks, and institutional contexts.

Overall, this study advances NbS scholarship by shifting the analytical focus from “what NbS achieve” to “how NbS work over time”. By articulating an implementation framework for evaluating effectiveness and scalability, it provides a foundation for more resilient, transferable, and policy-relevant coastal NbS. Future efforts to operationalise NbS on a large scale will depend on embracing this process's completeness—ensuring that coastal NbS evolve as adaptive systems capable of responding to accelerating climate change rather than static interventions tied to specific sites or conditions.

#### CRedit authorship contribution statement

**Pradeep Marula Siddappanavara:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft. **Anushiya Jeganathan:** Methodology, Investigation, Writing – review & editing. **P Jayashree:** Writing – review & editing

#### Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author used OpenAI to improve the clarity, grammar, and readability of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Data availability

Data will be made available on request.

#### References

- Adame, M.F., Lovelock, C.E., 2011. Carbon and nutrient exchange of mangrove forests with the coastal ocean. *Hydrobiologia* 663, 23–50.
- Baptist, M.J., Dankers, P., Cleveringa, J., Sittoni, L., Willemsen, P.W.J.M., van Puijenbroek, M.E.B., de Vries, B.M.L., Leuven, J.R.F.W., Coumou, L., Kramer, H., Elschoot, K., 2021. Salt marsh construction as a nature-based solution in an estuarine social-ecological system. *Nat. Based Solut.* 1, 100005.
- Bertolini, C., Da Mosto, J., 2021. Restoring for the climate: a review of coastal wetland restoration research in the last 30 years. *Restor. Ecol.* 29, e13438.
- Billé, R., Kelly, R., Biastoch, A., Harroul-Kolieb, E., Herr, D., Joos, F., Kroeker, K., Laffoley, D., Oschlies, A., Gattuso, J.-P., 2013. Taking action against ocean acidification: a review of management and policy options. *Environ. Manag.* 52, 761–779.
- Breil, M., Castellani, C., Keesstra, S., Zimmer, D., Nieminen, H., Trozzo, C., Galluccio, G., 2023. Economic Enabling Conditions for Scaling of Nature Based Solutions, European Topic Centre on Climate Change Adaptation and LULUCF (ETC CA).
- Bulkeley, H., Chan, S., Fransen, A., Landry, J., Seddon, N., Deprez, A., Kok, M., 2023. Building Synergies Between Climate & Biodiversity Governance: a Primer for COP28.
- Bulleri, F., Eriksson, B.K., Queirós, A., Airoldi, L., Arenas, F., Arvanitidis, C., Bouma, T.J., Crowe, T.P., Davoult, D., Guizien, K., Ivesa, L., Jenkins, S.R., Michalet, R., Olabarria, C., Procaccini, G., Serrão, E.A., Wahl, M., Benedetti-Cecchi, L., 2018. Harnessing positive species interactions as a tool against climate-driven loss of coastal biodiversity. *PLoS Biol.* 16, e2006852.
- Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W.W.L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, Y.-Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F.E.L., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H.-O., Revi, A., Roberts, D.C., Roy, J., Ruane, A.C., Skea, J., Shukla, P.R., Slade, R., Slangen, A., Sokona, Y., Sörensson, A.A., Tignor, M., Van Vuuren, D., Wei, Y.-M., Winkler, H., Zhai, P., Zommers, Z., Hourcade, J.-C., Johnson, F.X., Pachauri, S., Simpson, N.P., Singh, C., Thomas, A., Totin, E., Arias, P., Bustamante, M., Elgizouli, I., Flato, G., Howden, M., Méndez-Vallejo, C., Pereira, J. J., Pichs-Madruga, R., Rose, S.K., Saheb, Y., Sánchez Rodríguez, R., Ülge-Vorsatz, D., Xiao, C., Yassaa, N., Alegria, A., Armour, K., Bednar-Friedl, B., Blok, K., Cissé, G., Dentener, F., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hansen, G., Hauser, M., Hawkins, E., Hermans, T., Kopp, R., Leprince-Ringuet, N., Lewis, J., Ley, D., Ludden, C., Niamir, L., Nicholls, Z., Some, S., Szopa, S., Trewin, B., Van Der Wijst, K.-I., Winter, G., Witting, M., Birt, A., Ha, M., Romero, J., Kim, J., Haites, E.F., Jung, Y., Stavins, R., Birt, A., Ha, M., Orendain, D.J.A., Ignon, L., Park, S., Park, Y., Reisinger, A., Cammaramo, D., Fischlin, A., Fuglestedt, J.S., Hansen, G., Ludden, C., Masson-Delmotte, V., Matthews, J.B.R., Mintenbeck, K., Pirani, A., Poloczanska, E., Leprince-Ringuet, N., Péan, C., 2023. IPCC, 2023: climate change 2023: synthesis report. In: Lee, H., Romero, J. (Eds.), Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, IPCC. First, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland].
- Camargo, C., Maldonado, J.H., Alvarado, E., Moreno-Sánchez, R., Mendoza, S., Manrique, N., Mogollón, A., Osorio, J.D., Grajales, A., Sánchez, J.A., 2009. Community involvement in management for maintaining coral reef resilience and biodiversity in southern Caribbean marine protected areas. *Biodivers. Conserv.* 18, 935–956.
- Carretero, S., Rapaglia, J., Bokuniewicz, H., Kruse, E., 2013. Impact of sea-level rise on saltwater intrusion length into the coastal aquifer, Partido de La Costa, Argentina. *Cont. Shelf Res.* 61–62, 62–70.
- Carro, I., Seijo, L., Nagy, G.J., Lagos, X., Gutiérrez, O., 2018. Building capacity on ecosystem-based adaptation strategy to cope with extreme events and sea-level rise on the Uruguayan coast. *Int. J. Clim. Change Strateg. Manag.* 10, 504–522.
- Chairat, S., Gheewala, S.H., 2024. The conceptual quantitative assessment framework for Nature-based Solutions (NbS). *Nat. Based Solut.* 6, 100152.
- Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C.A.J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., Seddon, N., 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. *Glob. Change Biol.* 26, 6134–6155.
- Cheng, L., Abraham, J., Trenberth, K.E., Boyer, T., Mann, M.E., Zhu, J., Wang, F., Yu, F., Locarnini, R., Fasullo, J., Zheng, F., Li, Y., Zhang, B., Wan, L., Chen, X., Wang, D., Feng, L., Song, X., Liu, Y., Reseghetti, F., Simoncelli, S., Gouretski, V., Chen, G., Mishonov, A., Reagan, J., Von Schuckmann, K., Pan, Y., Tan, Z., Zhu, Y., Wei, W., Li, G., Ren, Q., Cao, L., Lu, Y., 2024. New record ocean temperatures and related climate indicators in 2023. *Adv. Atmos. Sci.* 41, 1068–1082, 2024. <https://doi.org/10.1007/s00376-024-3378-5>.
- Chowdhury, M.S.N., Wallis, B., Sharifuzzaman, S.M., Shahadat Hossain, M., Ysebaert, T., Maal, A.C., 2019. Oyster breakwater reefs promote adjacent mudflat stability and salt marsh growth in a monsoon dominated subtropical coast. *Sci. Rep.* 9, 8549.
- Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S. (Eds.), 2016. Nature-Based Solutions to Address Global Societal Challenges. IUCN International Union for Conservation of Nature.
- Cohn, J.L., Copp Franz, S., Mandel, R.H., Nack, C.C., Brainard, A.S., Eallonardo, A., Magar, V., 2022. Strategies to work towards long-term sustainability and resilience of nature-based solutions in coastal environments: a review and case studies. *Integrated Environ. Assess. Manag.* 18, 123–134.
- Costa, G.P., Musumeci, R.E., Cáceres, I., 2023. Coastal dunes: a nature-based solution to face coastal hazards. In: *Coastal Sediments 2023*. WORLD SCIENTIFIC, New Orleans, LA, USA, pp. 615–626.
- Costello, M.J., Chaudhary, C., 2017. Marine biodiversity, biogeography, deep-sea gradients, and conservation. *Curr. Biol.* 27, R511–R527.
- Damastuti, E., van Wesenbeeck, B.K., Leemans, R., de Groot, R.S., Silvius, M.J., 2023. Effectiveness of community-based mangrove management for coastal protection: a case study from Central Java, Indonesia. *Ocean Coast Manag.* 238, 106498.
- Dhyani, S., Karki, M., Gupta, A.K., 2020. Opportunities and advances to mainstream nature-based solutions in disaster risk management and climate strategy. In: Dhyani, S., Gupta, A.K., Karki, M. (Eds.), *Nature-Based Solutions for Resilient Ecosystems and Societies*. Springer Singapore, Singapore, pp. 1–26.
- Doney, S.C., Fabry, V.J., Feely, R.A., Kleyvas, J.A., 2009. Ocean acidification: the other CO2 problem. *Ann. Rev. Mar. Sci.* 1, 169–192.
- Duarte de Paula Costa, M., Adame, M.F., Bryant, C.V., Hill, J., Kelleway, J.J., Lovelock, C.E., Ola, A., Rasheed, M.A., Salinas, C., Serrano, O., Waltham, N., York, P. H., Young, M., Macreadie, P., 2023. Quantifying blue carbon stocks and the role of protected areas to conserve coastal wetlands. *Sci. Total Environ.* 874, 162518.
- Duncan, C., Primavera, J.H., Pettorelli, N., Thompson, J.R., Loma, R.J.A., Koldewey, H. J., 2016. Rehabilitating mangrove ecosystem services: a case study on the relative

- benefits of abandoned pond reversion from Panay Island, Philippines. *Mar. Pollut. Bull.* 109, 772–782.
- El-Nahry, A.H., Doluschitz, R., 2010. Climate change and its impacts on the coastal zone of the Nile Delta, Egypt. *Environ. Earth Sci.* 59, 1497–1506.
- Farrer, E.C., Van Bael, S.A., Clay, K., Smith, M.K.H., 2022. Plant-microbial symbioses in coastal systems: their ecological importance and role in coastal restoration. *Estuaries Coasts* 45, 1805–1822.
- Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., Airoldi, L., 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat. Commun.* 5, 3794.
- Fuchs, H.L., Chant, R.J., Hunter, E.J., Curchitser, E.N., Gerbi, G.P., Chen, E.Y., 2020. Wrong-way migrations of benthic species driven by ocean warming and larval transport. *Nat. Clim. Change* 10, 1052–1056.
- Hall-Spencer, J.M., Harvey, B.P., 2019. Ocean acidification impacts on coastal ecosystem services due to habitat degradation. *Emerging Topics. Life Sci.* 3, 197.
- Hallegraeff, S., Rentschler, J., Rozenberg, J., 2019. Lifelines: the Resilient Infrastructure Opportunity. The World Bank.
- Hanley, M.E., Hoggart, S.P.G., Simmonds, D.J., Bichot, A., Colangelo, M.A., Bozzeda, F., Heurtefeux, H., Ondiviela, B., Ostrowski, R., Recio, M., Trude, R., Zawadzka-Kahlau, E., Thompson, R.C., 2014. Shifting sands? Coastal protection by sand banks, beaches and dunes. *Coast. Eng.* 87, 136–146.
- Hansen, L.J., Braddock, K.N., Rudnick, D.A., 2023. A good idea or just an idea: which adaptation strategies for conservation are tested? *Biol. Conserv.* 286, 110276. <https://doi.org/10.1016/j.biocon.2023.110276>.
- Henley, B.J., McGregor, H.V., King, A.D., Hoegh-Guldberg, O., Arzey, A.K., Karoly, D.J., Lough, J.M., DeCarlo, T.M., Linsley, B.K., 2024. Highest ocean heat in four centuries places Great Barrier Reef in danger. *Nature* 632, 320–326.
- Hochard, J.P., Barbier, E.B., Hamilton, S.E., 2021. Mangroves and coastal topography create economic “safe havens” from tropical storms. *Sci. Rep.* 11, 15359.
- Huo, D., Gaitán-Espitia, J.D., Spicer, J.I., Yang, H., 2023. Editorial: the adaptation and response of aquatic animals in the context of global climate change. *Front. Mar. Sci.* 10.
- Ipcc, 2022. Global warming of 1.5°C: IPCC special report on impacts of global warming of 1.5°C above pre-industrial levels in context of strengthening response to climate change. Sustainable Development, and Efforts to Eradicate Poverty, first ed. Cambridge University Press.
- IUCN, 2020. IUCN Global Standard for Nature-based Solutions: a user-friendly Framework for the Verification, Design and Scaling up of Nbs, first ed., first ed. IUCN, International Union for Conservation of Nature.
- James, R.K., Keyzer, L.M., Van De Velde, S.J., Herman, P.M.J., Van Katwijk, M.M., Bouma, T.J., 2023. Yossi. *Sci. Total Environ.* 857, 159576.
- Kasprzyk, M., Szpakowski, W., Poznańska, E., Boogaard, F.C., Bobkowska, K., Gajewska, M., 2022. Technical solutions and benefits of introducing rain gardens – gdańsk case study. *Sci. Total Environ.* 835, 155487.
- Kelleway, J.J., Cavanaugh, K., Rogers, K., Feller, I.C., Ens, E., Doughty, C., Saintilan, N., 2017. Review of the ecosystem service implications of mangrove encroachment into salt marshes. *Glob. Change Biol.* 23, 3967–3983.
- Koch, M., Bowes, G., Ross, C., Zhang, X., 2013. Climate change and ocean acidification effects on seagrasses and marine macroalgae. *Glob. Change Biol.* 19, 103–132.
- Kowalczyk, K.A., Amann, T., Strefler, J., Vorrath, M.-E., Hartmann, J., Marco, S.D., Renforth, P., Foteinis, S., Krieger, E., 2024. Marine carbon dioxide removal by alkalization should no longer be overlooked. *Environ. Res. Lett.* 19, 074033.
- Kumar, P., Debele, S.E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S.M., Basu, B., Basu, A.S., Bowyer, P., Charizopoulos, N., Gallotti, G., Jaakko, J., Leo, L.S., Loupis, M., Menenti, M., Mickovski, S.B., Mun, S.-J., Gonzalez-Ollauri, A., Pfeiffer, J., Pilla, F., Pröll, J., Rutzinger, M., Santo, M.A., Sannigráhi, S., Spyrou, C., Tuomenvirta, H., Zieher, T., 2021. Nature-based solutions efficiency evaluation against natural hazards: modelling methods, advantages and limitations. *Sci. Total Environ.* 784, 147058.
- Le Gouvello, R., Cohen-Shacham, E., Herr, D., Spadone, A., Simard, F., Brugere, C., 2023. The IUCN Global Standard for Nature-based Solutions™ as a tool for enhancing the sustainable development of marine aquaculture. *Front. Mar. Sci.* 10, 1146637.
- Mahendra, R.S., Mohanty, P.C., Francis, P.A., Joseph, S., Nair, T.M.B., Kumar, T.S., 2023. Socioeconomic vulnerability assessment of coastal villages and buildings along Andhra Pradesh East Coast of India. *Environ. Dev. Sustain* 27, 2055–2082 (2025). <https://doi.org/10.1007/s10668-023-03955-x>.
- Mahmood, R., Zhang, L., Li, G., 2023. Assessing effectiveness of nature-based solution with big earth data: 60 years mangrove plantation program in Bangladesh coast. *Ecol. Process.* 12, 11.
- Malerba, M.E., Duarte de Paula Costa, M., Friess, D.A., Schuster, L., Young, M.A., Lagomasino, D., Serrano, O., Hickey, S.M., York, P.H., Rasheed, M., Lefcheck, J.S., Radford, B., Atwood, T.B., Ierodiaconou, D., Macreadie, P., 2023. Remote sensing for cost-effective blue carbon accounting. *Earth Sci. Rev.* 238, 104337.
- Marfai, M.A., King, L., 2008. Potential vulnerability implications of coastal inundation due to sea level rise for the coastal zone of Semarang city, Indonesia. *Environ. Geol.* 54, 1235–1245.
- Martinez, M.L., Silva, R., Mendoza, E., Odériz, I., Pérez-Maqueo, O., 2016. Coastal Dunes and plants: an ecosystem-based alternative to reduce dune face erosion. *J. Coast Res.* 75, 303–307.
- Martzikios, N.T., Prinos, P.E., Memos, C.D., Tsoukala, V.K., 2021. Key research issues of coastal storm analysis. *Ocean Coast Manag.* 199, 105389.
- Matsuda, S.B., Opalek, M.L., Ritson-Williams, R., Gates, R.D., Cuning, R., 2023. Symbiont-mediated tradeoffs between growth and heat tolerance are modulated by light and temperature in the coral *Montipora capitata*. *Coral Reefs* 42, 1385–1394.
- McFadden, C.S., Quattrini, A.M., Brugler, M.R., Cowman, P.F., Duenías, L.F., Kitahara, M. V., Paz-García, D.A., Reimer, J.D., Rodríguez, E., 2021. Phylogenomics, Origin, and Diversification of Anthozoans (Phylum Cnidaria). *Syst. Biol.* 70, 635–647.
- Moraes, R.P.L., Reguero, B.G., Mazzarasa, I., Ricker, M., Juanes, J.A., 2022. Nature-Based solutions in coastal and estuarine areas of Europe. *Front. Environ. Sci.* 10, 829526.
- Narayan, S., Beck, M.W., Reguero, B.G., Losada, I.J., Van Wesenbeeck, B., Pontee, N., Sanchirico, J.N., Ingram, J.C., Lange, G.-M., Burks-Copes, K.A., 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS One* 11, e0154735.
- Nelson, D.R., Bledsoe, B.P., Ferreira, S., Nibbelink, N.P., 2020. Challenges to realizing the potential of nature-based solutions. *Curr. Opin. Environ. Sustain.* 45, 49–55.
- Orta-Ortiz, M.S., Geneletti, D., 2021. Reviewing the performance of nature-based solutions for stormwater management in urban areas. In: La Rosa, D., Privitera, R. (Eds.), *Innovation in Urban and Regional Planning*. Springer International Publishing, Cham, pp. 15–22.
- Paxton, A.B., Riley, T.N., Steenrod, C.L., Smith, C.S., Zhang, Y.S., Gittman, R.K., Silliman, B.R., Buckel, C.A., Viehman, T.S., Puckett, B.J., Davis, J., 2023. What evidence exists on the performance of nature-based solutions interventions for coastal protection in biogenic, shallow ecosystems? A systematic map protocol. *Environ. Evid.* 12, 11.
- Peh, K.S.-H., Balmford, A., Field, R.H., Lamb, A., Birch, J.C., Bradbury, R.B., Brown, C., Butchart, S.H.M., Lester, M., Morrison, R., Sedgwick, I., Soans, C., Stattersfield, A.J., Stroh, P.A., Swetnam, R.D., Thomas, D.H.L., Walpole, M., Warrington, S., Hughes, F. M.R., 2014. Benefits and costs of ecological restoration: rapid assessment of changing ecosystem service values at a U.K. wetland. *Ecol. Evol.* 4, 3875–3886.
- Perricone, V., Mutalipassi, M., Mele, A., Buono, M., Vicinanza, D., Contestabile, P., 2023. Nature-based and bioinspired solutions for coastal protection: an overview among key ecosystems and a promising pathway for new functional and sustainable designs. *ICES (Int. Counc. Explor. Sea) J. Mar. Sci.* 80, 1218–1239.
- Peter Sheng, Y., Paramygin, V.A., Rivera-Nieves, A.A., Zou, R., Fernald, S., Hall, T., Jacob, K., 2022. Coastal marshes provide valuable protection for coastal communities from storm-induced wave, flood, and structural loss in a changing climate. *Sci. Rep.* 12, 3051.
- Ridge, J.T., Rodriguez, A.B., Fodrie, F.J., 2017. Evidence of exceptional oyster-reef resilience to fluctuations in sea level. *Ecol. Evol.* 7, 10409–10420.
- Ruckelshaus, M., Reguero, B.G., Arkema, K., Compeán, R.G., Weekes, K., Bailey, A., Silver, J., 2020. Harnessing new data technologies for nature-based solutions in assessing and managing risk in coastal zones. *Int. J. Disaster Risk Reduct.* 51, 101795.
- Saintilan, N., Horton, B., Törnqvist, T.E., Ashe, E.L., Khan, N.S., Schuerch, M., Perry, C., Kopp, R.E., Gardner, G.G., Murray, N., Rogers, K., Albert, S., Kelleway, J., Shaw, T.A., Woodroffe, C.D., Lovelock, C.E., Goddard, M.M., Hutley, L.B., Kovalenko, K., Feher, L., Guntenspergen, G., 2023. Widespread retreat of coastal habitat is likely at warming levels above 1.5 °C. *Nature* 621, 112–119.
- Saleh, F., Weinstein, M.P., 2016. The role of nature-based infrastructure (NBI) in coastal resiliency planning: a literature review. *J. Environ. Manag.* 183, 1088–1098.
- Salois, S.L., Gouhier, T.C., Helmuth, B., Choi, F., Seabra, R., Lima, F.P., 2022. Coastal upwelling generates cryptic temperature refugia. *Sci. Rep.* 12, 19313.
- Sapkota, Y., White, J.R., 2020. Carbon offset market methodologies applicable for coastal wetland restoration and conservation in the United States: a review. *Sci. Total Environ.* 701, 134497.
- Scyphers, S.B., Powers, S.P., Jr, K.L.H., Byron, D., 2011. Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS One* 6, e22396.
- Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., Turner, B., 2021. Getting the message right on nature-based solutions to climate change. *Glob. Change Biol.* 27, 1518–1546.
- Shi, T., Zheng, X., Zhang, H., Wang, Q., Zhong, X., 2018. Coral Reefs: Potential Blue Carbon Sinks for Climate Change Mitigation.
- Silliman, B.R., Schrack, E., He, Q., Cope, R., Santoni, A., Van Der Heide, T., Jacobi, R., Jacobi, M., Van De Koppel, J., 2015. Facilitation shifts paradigms and can amplify coastal restoration efforts. *Proc. Natl. Acad. Sci. U.S.A.* 112, 14295–14300.
- Sowińska-Swierkosz, B., García, J., 2022. What are Nature-based solutions (NBS)? Setting core ideas for concept clarification. *Nat. Based Solut.* 2, 100009.
- Subramanian, A., Nagarajan, A.M., Vinod, S., Chakraborty, S., Sivagami, K., Theodore, T., Sathyanarayanan, S.S., Tamizhdurai, P., Mangesh, V.L., 2023. Long-term impacts of climate change on coastal and transitional eco-systems in India: an overview of its current status, future projections, solutions, and policies. *RSC Adv.* 13, 12204–12228.
- Timothy, C., Tapan, S. (Eds.), 2022. *De Gruyter Handbook of Sustainable Development and Finance*.
- Toimil, A., Camus, P., Losada, I.J., Le Cozannet, G., Nicholls, R.J., Idier, D., Maspataud, A., 2020. Climate change-driven coastal erosion modelling in temperate sandy beaches: methods and uncertainty treatment. *Earth Sci. Rev.* 202, 103110.
- Townend, I., Fletcher, C., Knappen, M., Rossington, K., 2011. A review of salt marsh dynamics. *Water Environ. J.* 25, 477–488.
- Van Hespden, R., Hu, Z., Borsje, B., De Dominicis, M., Friess, D.A., Jevrejeva, S., Kleinhans, M.G., Maza, M., Van Bijsterveldt, C.E.J., Van Der Stocken, T., Van Wesenbeeck, B., Xie, D., Bouma, T.J., 2023. Mangrove forests as a nature-based solution for coastal flood protection: biophysical and ecological considerations. *Water Sci. Eng.* 16, 1–13.
- Vogelsang, L.G., Weikard, H.-P., Van Loon-Steensma, J.M., Bednar-Friedl, B., 2023. Assessing the cost-effectiveness of nature-based Solutions under climate change uncertainty and learning. *Water Resources and Economics* 43, 100224.
- Von Holle, B., Irish, J.L., Spivy, A., Weishampel, J.F., Meylan, A., Godfrey, M.H., Dodd, M., Schweitzer, S.H., Keyes, T., Sanders, F., Chaplin, M.K., Taylor, N.R., 2019. Effects of future sea level rise on coastal habitat. *J. Wildl. Manag.* 83, 694–704.

Walter Leal, F. (Ed.), 2022. Handbook of Human and Planetary Health.

Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck, K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T., Williams, S.L., 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc. Natl. Acad. Sci.* 106, 12377–12381.

Yossi, L., Kimberly, A.P., Tom, C.L.B. (Eds.), 2019. Mesophotic Coral Ecosystems.

Zimmer, M., 2024. Searching for solutions for carbon-sequestration in coastal ecosystems: an international and interdisciplinary approach. EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-5956, <https://doi.org/10.5194/egusphere-egu24-5956>, 2024.Copernicus Meetings.